AFWAL-TR-80-3045

LEVEL II

AD A089137

# EXPERIMENTAL INVESTIGATION OF THE CRACK GROWTH GAGE

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Structural Integrity Branch
Structures & Dynamics Division

June 1980

TECHNICAL REPORT AFWAL-TR-80-3045

Final Report for Period January 1978 to November 1979

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## REPORT DOCUMENTATION PAGE

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| | | |
|---|---|---|
| 1. REPORT NUMBER AFWAL-TR-80-3045 | 2. GOVT ACCESSION NO. AD-A089 137 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle) EXPERIMENTAL INVESTIGATION OF THE CRACK GROWTH GAGE | | 5. TYPE OF REPORT & PERIOD COVERED Final Report for Period January 1978 to November 1979 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s) Donald R. Holloway, Capt, USAF | | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Wright Aeronautical Laboratories (AFWAL/FIBE) Wright-Patterson Air Force Base, Ohio | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project 2401 Task 240101 Work Unit 24010109 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS | | 12. REPORT DATE June 1980 |
| | | 13. NUMBER OF PAGES 91 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | | 15. SECURITY CLASS. (of this report) Unclassified |
| | | 15a. DECLASSIFICATION DOWNGRADING SCHEDULE |

14 6 9 10 16 17 11 12 100 21

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aircraft Structural Integrity Program
Crack Growth
Crack Growth Gage
Crack Growth Prediction
Individual Aircraft Tracking
Life Management
Service Life Tracking

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this program was to determine the feasibility of the crack growth gage as a more direct method for monitoring potential crack growth damage in fatigue critical areas of F-4 aircraft structure. The major task consisted on mounting crack growth gages on a full-scale F-4C/D fatigue test article and collecting crack growth data from the gages at specified intervals. Two additional tasks were comprised of (1) conducting a gage qualification test program in accordance with MIL-STD-810C (Environmental Test Method) requirements, and (2) determining an appropriate method for collecting data from the

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gage. Inconsistencies in constant amplitude test results and bonding problems encountered on the F-4C/D full-scale fatigue test article prevented the MIL-STD-810C qualification tests from being started. Results of this investigation indicated that further research and development of the crack growth gage concept is required before the gage can be recommended as a fleetwide tracking device.

# FOREWORD

This report describes an in-house effort conducted under Project 2401, "Structures and Dynamics," Task 240101, "Structural Integrity for Military Aerospace Vehicles," Work Unit 24010109, "Life Analysis and Design Methods for Aerospace Structure."

This work was performed for the Structural Integrity Branch, Structures and Dynamics Division, Air Force Flight Dynamics Laboratory (AFFDL/FBE). This organization is currently the Structural Integrity Branch, Structures and Dynamics Division, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL/FIBE), Wright-Patterson Air Force Base, Ohio. The research was conducted under the direction of Captain D.R. Holloway and Mr. T.D. Gray from January 1978 through November 1979.

The author wishes to recognize Messrs. Harold Stalnaker, Jack Smith, Richard Kleismit, and Larry Bates for their contributions in the accomplishment of the experimental phases of this study. In addition, the efforts of Mr. Jeff Wead for drafting the figures, Mr. Pete Dodaro for preparing the data plotting routines, and Mr. John Potter for his guidance throughout the program were much appreciated.

The completed report was submitted in December 1979.



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## SUMMARY

Before crack growth gages can be recommended to track aircraft service life, the performance and predictability of the gages must be verified. This requires engineering analysis and verification by test.

An on-going fatigue test of a full-scale F-4 C/D test article being conducted by the Air Force Flight Dynamics Laboratory provided a convenient test bed for evaluating the crack growth gage concept for use with actual aircraft. The purpose of the F-4 C/D full-scale fatigue test is to provide full-scale test verification of several life extension modifications, including those designed to extend the life to 8000 flight hours of F-4 ASIP baseline usage. During one modification implementation, while the test was in a hold status, crack growth gages were adhesively bonded to the test structure. Testing of the gages attached to the fatigue article was directed towards developing data that would verify that the gages would provide meaningful and predictable output for scheduling structural modifications, repairs, inspections, and retirement of individual F-4 airframes.

Besides the above major task, two additional tasks were required. These tasks consisted of (1) conducting a gage qualification test program in accordance with MIL-STD-810C (Environmental Test Methods) requirements, and (2) determining an appropriate method for collecting data from the gage. Inconsistencies in constant amplitude test results prevented the MIL-STD-810C qualification tests from being started. These inconsistencies, along with problems encountered with the bonding of the gages to the full-scale fatigue article, indicated that further research and development of the crack growth gage concept is required before the gage can be recommended as a fleet-wide tracking device.

## SECTION I

## INTRODUCTION

Maintaining the damage tolerance and durability of USAF aircraft structures is dependent on the capability of the appropriate Air Force Command to perform specific inspection, maintenance, and possibly modification or replacement tasks at specific intervals throughout the service life (i.e., at specified depot or base level maintenance times and special inspection periods). Experience has shown that the actual usage of military aircraft may differ significantly from the usage assumed during design. Likewise, individual aircraft within a force may experience a widely varied pattern of usage severity as compared to the average aircraft. Thus, inspection intervals, which are determined by predicting the amount of time the structure can safely sustain subcritical crack growth, must be continually adjusted for individual aircraft to ensure safety and to allow for modification and repair on a timely and economical basis.

Force management is the responsibility of the Air Force and is accomplished in accordance with the force management tasks of MIL-STD-1530A, Aircraft Structural Integrity Program (ASIP) [Reference 1], using a data package provided by the contractor for each new aircraft system. This data package consists of the necessary data acquisition and reduction techniques and analysis methods needed to acquire, evaluate, and utilize operational usage data in order to provide a continual update of in-service structural integrity.

A basic element of the force management data package is the individual aircraft tracking (IAT) program. The objective of the IAT program is to predict potential flaw growth in critical areas of each airframe based on individual aircraft usage data. A tracking analysis method is developed to establish and adjust inspection and repair intervals for each critical structural location of the airframe. This analysis provides the capability to predict crack growth rates, time to reach crack size limits, and crack length as a function of total flight time and usage. A data acquisition system is developed which is as simple as possible and is the minimum required to monitor those parameters necessary to support the tracking analysis method.

Current practice for acquisition of IAT usage data for fighter aircraft includes recording strain or center of gravity motion parameters (eg., normal load factor, $n_z$). The tracking analysis method then utilizes this data to estimate crack growth from assumed initial flaws in each critical point in the structure. Initial flaw size assumptions required for new aircraft are specified in Reference 2.

1. Background

The first IAT program for tracking crack growth in fighter aircraft was developed in conjunction with the F/RF-4 C/D and the F-4E(S) damage tolerance assessments (References 3-5). The present F-4 IAT program employs a counting accelerometer for data acquisition and a tracking analysis methodology which is termed the "damage index and equivalent S-N curve" system. Data acquisition is accomplished by recording normal load factor exceedances via counting accelerometers installed in each aircraft. The F-4 counting accelerometers are set to record $n_z$ counts at 3, 4, 5, and 6 g's. Extrapolation techniques are used to determine $n_z$ counts at

7 and 8 g's. In addition, VGH data (airspeed, load factor, altitude) are recorded on approximately thirteen percent of the force in order to provide background data for the IAT analysis.

The "damage and equivalent S-N curve" system (Reference 6) was developed for the F-4 to simplify the crack growth tracking process. Instead of conducting a cycle-by-cycle crack growth analysis for each critical location of each individual aircraft, only one number (the damage index) is computed for each aircraft based on individual usage. Through the damage index, crack growth at one location (the monitoring location) is determined. The amount of crack growth at other critical locations is evaluated by damage index limits that relate to the monitoring location. Individual flaw size assumptions used for all F-4 critical locations are based on the results of the previously mentioned damage tolerance assessments.

Equivalent S-N curves are used to convert individual aircraft counting accelerometer data to a damage index for each aircraft. These are not the standard S-N curves for fatigue which present stress versus number of cycles to failure for constant amplitude loading. These equivalent S-N curves represent flight-by-flight crack growth at the monitoring location and were developed from crack growth curves for three usages; mild, baseline, and severe (see Figure 1). To construct the equivalent S-N curves, crack growth testing was used to determine the percentage of total crack growth by each stress level in the flight-by-flight load history. Then, knowing the percent crack growth of each stress level and the number of cycles of each stress level at the operational limit and establishing the damage index at 1.0 at the

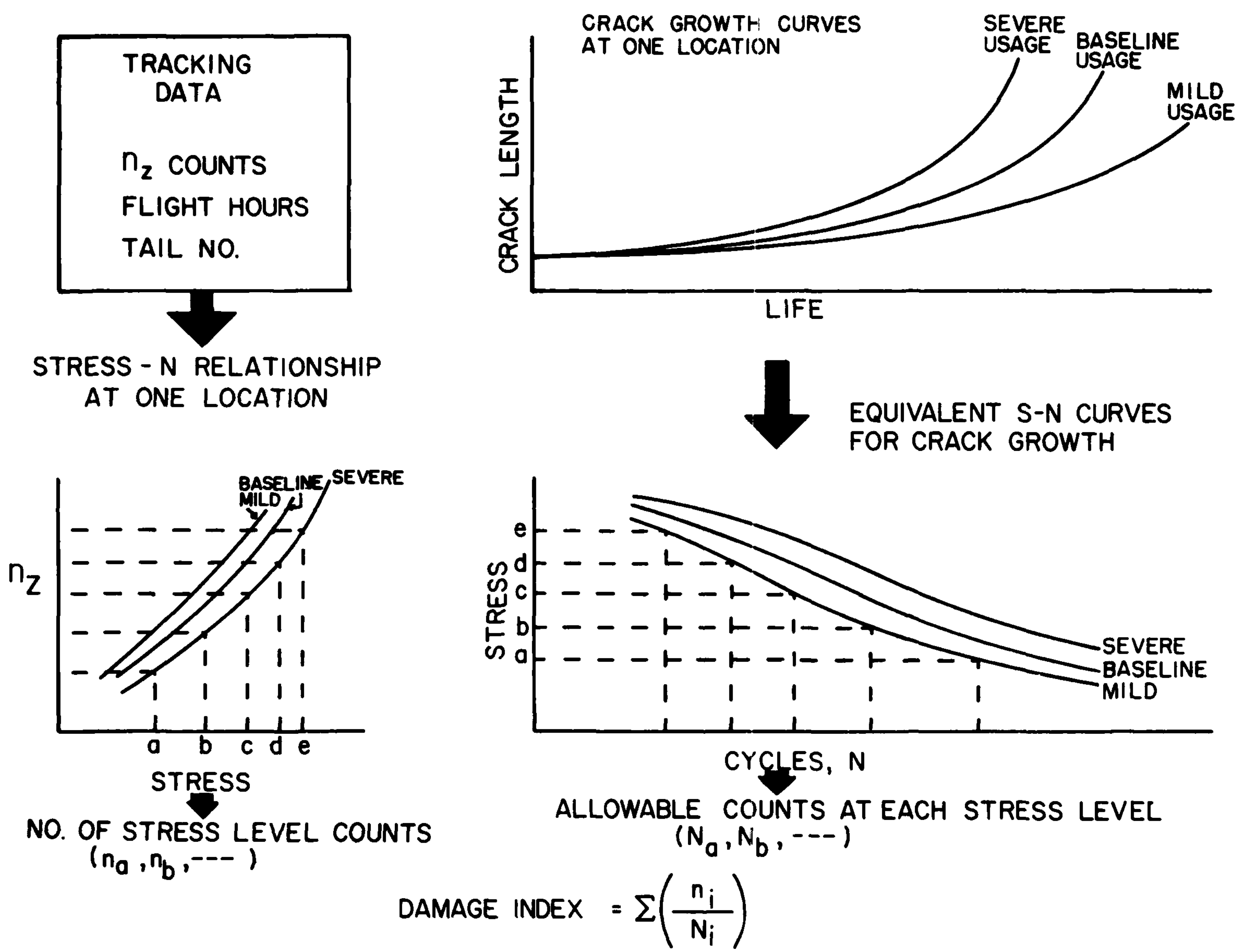



Figure 1. Schematic Representation of Current F-4 Tracking Analysis Method Employing the Damage Index and Equivalent S-N Curve System

operational limit, the allowable counts at each stress level were determined. Thus, the equivalent S-N curves show the number of cycles at each stress level necessary to reach the operational limit of the monitoring location (i.e., to obtain a damage index of 1.0).

Tracking data consisting of $n_z$ counts, flight hours, and tail numbers are received from field operations on a periodic basis (normally monthly). Actual flight hours are not used directly in the structural life calculations but are used for other maintenance considerations involving avionics and engines. The $n_z$ counts are examined and grouped into one of three usage categories according to severity. Then, using the known stress-$n_z$ relationship for the monitoring location, the number of counts of cycles of each stress level are determined. Note that these stress level counts are those experienced by a particular aircraft in a particular time increment. These stress level counts are then divided by the allowable counts at each stress level and summed in a Miner's type analysis (Reference 7) to compute damage index for a particular aircraft.

For the F-4, the damage indices for all critical locations are based on $n_z$ counts, airspeed, altitude, and gross weight. Relating the airspeed, altitude and gross weight of the aircraft to the number of load factor exceedances is a complex process and requires detailed analysis. Clearly, there is a need for a simpler and more direct method for tracking aircraft damage than the counting accelerometer method.

2. Crack Growth Gage Technique for IAT

A possible alternative IAT system which employs cracked metal coupons (ie., crack growth gages) as the recording device was evaluated and is the central subject of this report. The approach consists of mounting a precracked coupon onto a load-bearing structural member [References 8-14]. Theoretically, the coupon receives the same load excursions encountered by the structure (to within a predictable scaling factor) and responds with a measurable crack extension which may be related to the growth of another crack assumed to be present in a remote structural component. One may consider the cracked coupon as an analog computer which senses the load history, determines its effect on crack growth, and responds with measurable output (i.e., coupon crack extension).

Introducing an intentional flaw in a gage that is mounted on an aircraft would provide a direct method for assessing crack growth damage and for determining rates of crack growth as a function of usage. Using the crack growth gage as a tracking device would eliminate the gross assumptions associated with using the counting accelerometer (i.e., the assumed relationship between the values for airspeed, altitude, and gross weight and the number of $n_z$ counts actually experienced). In addition, the crack growth gage would eliminate the need to go through the $n_z$ counts analysis using Miner's rule to compute the aircraft damage index. Therefore, the damage index calculated by the crack growth gage method would be more accurate, more meaningful, and have less risk associated with it than the damage index computed by the counting accelerometer method.

The concept of the crack growth gage is shown schematically in Figure 2. The approach consists of employing linear elastic fracture mechanics analysis to relate the crack length measured in the gage ($a_g$) with the length of a real or assumed initial flaw located in the structure ($a_s$). The structural crack length is then related to the fraction of total aircraft life expended ($N_i/N_f$) in a normalized life scheme.

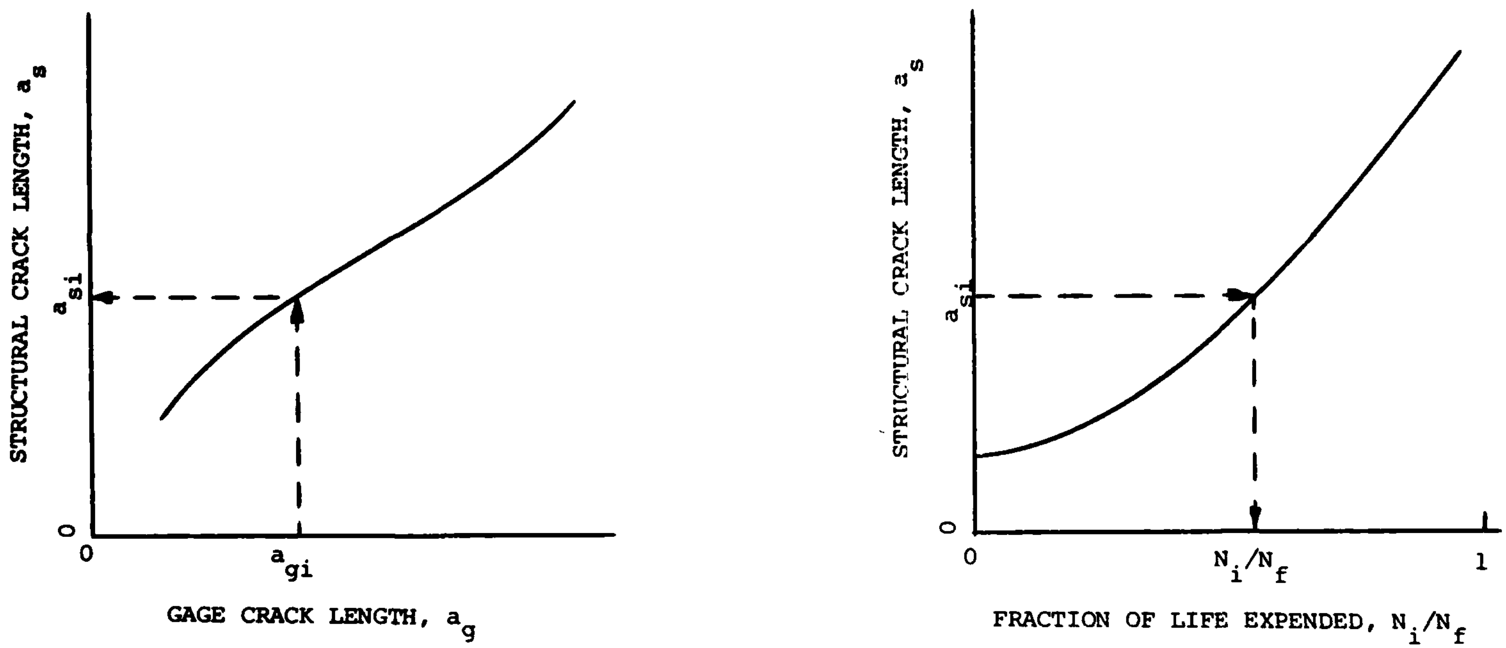



Figure 2. Schematic Representation of Damage Tracking Using the Crack Growth Gage Concept

A mathematical model (Reference 15) for relating the crack length in the coupon (crack growth gage) $a_g$ to the growth of an assumed structural flaw $a_s$ is shown schematically in Figure 3. The initial structural flaw size and shape is based on the appropriate design criteria (Reference 2), while the gage geometry may be selected for a given response. The ends of the crack growth gage are assumed to be fastened (eg., adhesively bonded, riveted, welded, etc.) to the structural member so that when the structural component is subjected to some remote stress ($\sigma_s$), an effective stress ($\sigma_g$) is transferred to the cracked gage. This relationship between structural and gage loads can be expressed in the form

$$\sigma_g = f\sigma_s \qquad (1)$$

Here the load transfer function f may depend on geometry and material properties, but not on stress levels. Determining an expression for f is essentially a stress analysis problem which can be readily approached by several analytical and/or experimental techniques (References 8-10).

Now, assume that crack growth in the gage and structural materials can be described by a model of the form

$$\frac{da}{dN} = F(K) \qquad (2)$$

Here da/dN is the fatigue crack growth rate and F(K) is an appropriate function relating the stress intensity factor K, material properties, and other significant load variables. Much of the success of fracture mechanics techniques for analyzing crack growth problems lies in the fact that such crack growth models are readily available and are applicable for many structural materials. Solving Equation 2 for cyclic life N, and observing that at any instant of time the gage and structural defects receive the same number of load cycles leads to

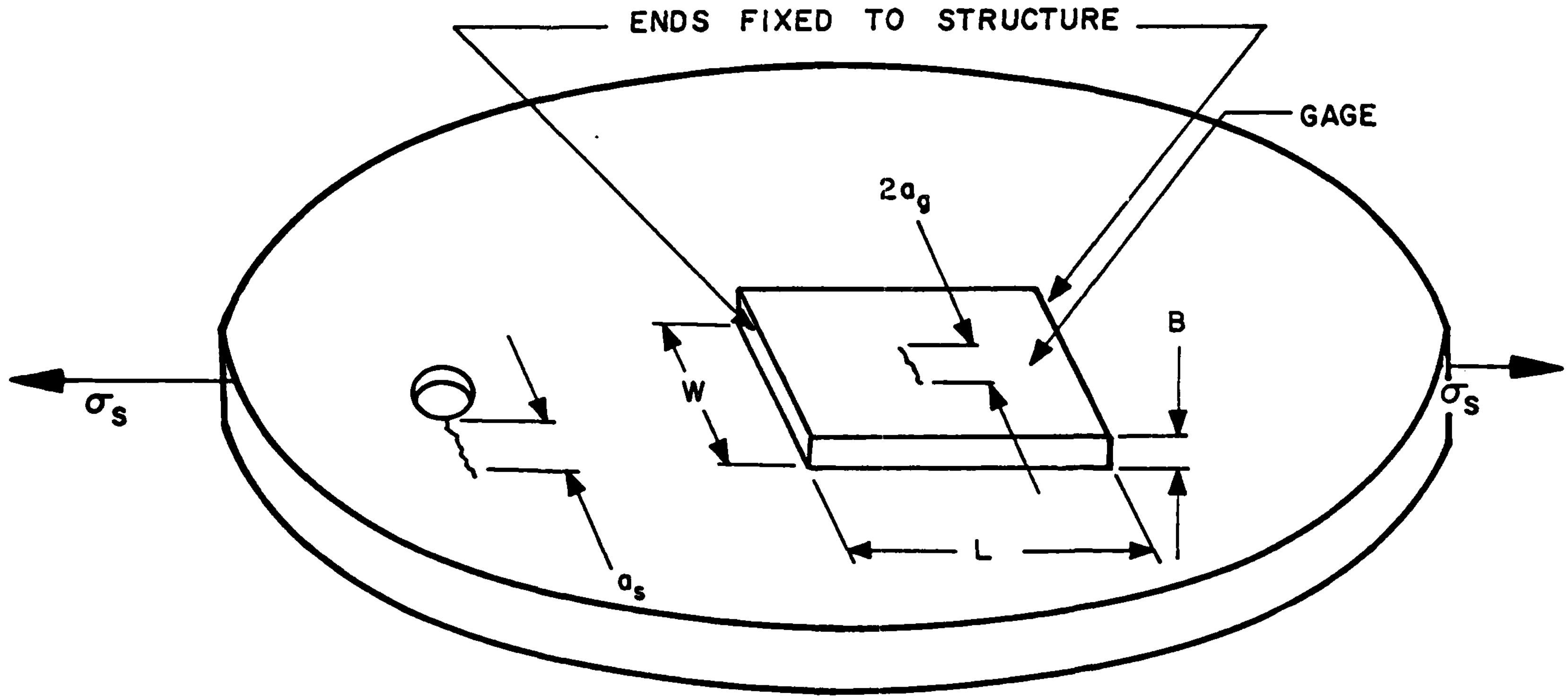



Figure 3. Schematic View of Crack Growth Gage Attached To Flawed Structural Component

$$N = \int_{a_{is}}^{a_s} \frac{da}{F_s(K)} = \int_{a_{ig}}^{a_s} \frac{da}{F_g(K)} \qquad (3)$$

Here $a_i$ and a are the initial and final crack lengths, while the subscripts s and g refer, respectively, to structural and gage quantities.

An interesting special case occurs when crack growth in the structural and gage materials can be described by the Paris law (Reference 16)

$$\frac{da}{dN} = C\overline{K}^m = F(K) \qquad (4)$$

Here $\overline{K}$ is the range in cyclic stress intensity factor and C and m are empirical constants. Now, expressing $\overline{K}$ in the standard form

$$\overline{K} = \overline{\sigma}\,\beta\sqrt{\pi a} \qquad (5)$$

where $\overline{\sigma}$ is the cyclic stress, $\beta$ is the flaw geometry dependent stress intensity factor coefficient (References 17-19), and a is the crack length, and combining Equations 1, 3, 4, and 5 leads to

$$N = \int_{a_{is}}^{a_s} \frac{da}{C_s(\overline{\sigma}_s\beta_s\sqrt{\pi a})^{m_s}} = \int_{a_{ig}}^{a_g} \frac{da}{C_g(f\overline{\sigma}_s\beta_g\sqrt{\pi a})^{m_g}} \qquad (6)$$

Note that a is the dummy variable of integration in Equation 6 and that, while f and $\beta$ depend on geometries and possibly material properties, neither function depends on the load level $\overline{\sigma}_s$.

Further assuming that the gage and structural materials have the same crack growth exponent $m_s=m_g=m$ (a reasonable assumption if gage and structure are made from the same material) leads to

$$\int_{a_{is}}^{a_s} \frac{da}{C_s(\beta_s\sqrt{\pi a})^m} = \int_{a_{ig}}^{a_g} \frac{da}{C_g(f\beta_g\sqrt{\pi a})^m} \qquad (7)$$

Note that all stress level terms effectively cancel in Equation 7. Although the expression no longer specifies the cyclic life N, it still represents a valid relationship between gage and structural quantities. The material properties, $C_s$, $C_g$, and m can be determined from conventional baseline testing, the stress intensity factor coefficients, $\beta$, are readily available from handbooks (References 17-19) or are obtainable by standard analysis methods, and the initial gage and structural crack lengths $a_{ig}$ and $a_{is}$ are specified. Equation 7 can then be integrated numerically to obtain the structural crack size $a_s$ as a function of gage crack size $a_g$. Thus, measuring the gage crack length determines the growth of the initially assumed structural defect during service.

### 3. Program Objective

The objective of this program was to determine the feasibility of the crack growth gage as a method for monitoring potential crack growth damage in fatigue critical areas of F-4 C/D aircraft structure. Testing was divided into three tasks. The major task consisted of mounting crack growth gages to a full-scale F-4 C/D test article and collecting crack growth data from the gages at specified intervals. The second task was comprised of conducting gage qualification tests in accordance with MIL-STD-810C (Environmental Test Methods) requirements. This military standard establishes uniform environmental test methods for determining the resistance of equipment to the effects of natural and induced environments peculiar to military operations. (Inconsistencies in constant amplitude test results prevented the MIL-STD-810C qualification tests from being started.) The third task was to determine an appropriate method for collecting data from the gage.

# SECTION II

# TEST PROGRAM

## 1. Introduction

The purpose of the test program was to obtain the experimental data necessary to characterize and validate the behavior of the crack growth gage. The testing was divided into two phases. Phase I consisted of laboratory testing required to determine gage response and predictability when the gage was mounted on a carrier specimen and subjected to constant amplitude and spectrum load conditions. Phase II consisted of testing crack growth gages attached to the F-4 C/D full-scale fatigue test article located in the Structural Test Branch (FBT) facility of the Air Force Flight Dynamics Laboratory (AFFDL).

## 2. Test Materials

### 2.1 Alloy Selection

The material selected for both the crack growth gage and the carrier specimen was 7075-T651 aluminum. This material has minimal lot-to-lot variability, is readily obtainable from vendor stores, and has readily available da/dN, $K_C$, and standard mechanical data required for crack growth analysis. 7075-T651 was selected because of its wide usage in aircraft components, including the F-4 wing skin.

### 2.2 da/dN Coupons

These test coupons were fabricated from the same material as the crack growth gages. They consisted of 0.08 inch thick end sections and a 0.04 inch thick neck-down section. The neck-down test section was 1.50 inches wide by 4.75 inches long. The initial flaw was a 0.050 inch diameter hole with a 0.025 inch electric discharge machined (EDM) notch on both sides of the hole so that the total starter flaw was 0.100 inch in length. See Figure 4 for details.

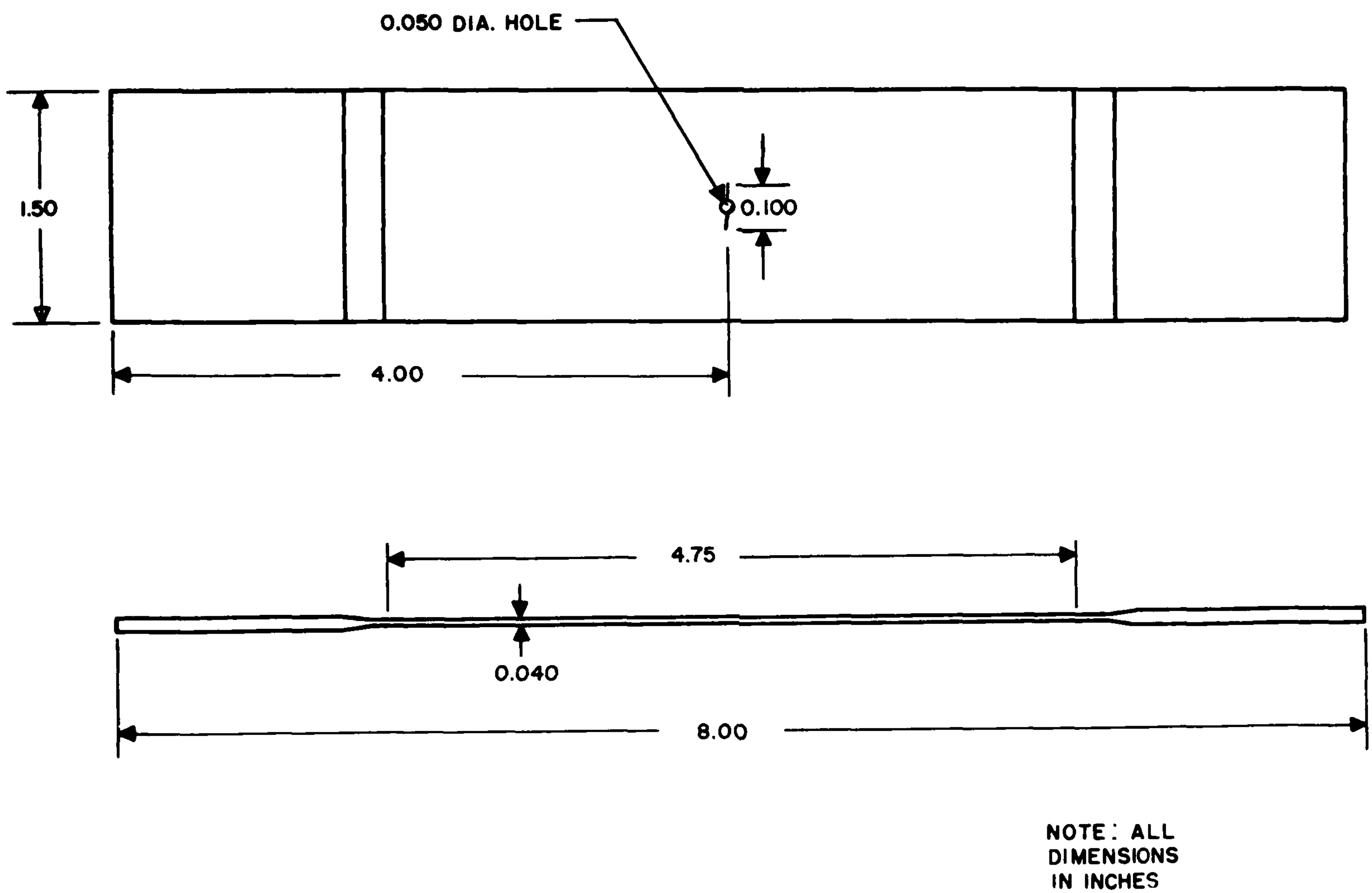



Figure 4. da/dN Coupon

## 2.3 Crack Growth Gage Design

The crack growth gage for this program was designed by McDonnell Aircraft Company (McAir) specifically for application to the lower wing skin of the F-4 (Reference 14). The design was based upon the following criteria: (1) the gage must give measurable crack growth for each 1000 spectrum hours of test life, (2) the gage must be durably bonded to the aircraft, and (3) the gage must not buckle under the maximum compressive stress in the spectrum.

The objective in selecting gage dimensions was to create the smallest gage that would produce (1) adequate crack growth to permit measurement with simple equipment and (2) good load transfer through the adhesive and the gage. The gage as dimensioned in Figure 5 was designed to produce approximately one inch of crack growth in 12000 spectrum hours, an average of 0.09 inch growth for each ten percent of the gage life. The configuration as shown in Figure 5 has a 0.100 inch starter slot created by drilling a 0.050 inch diameter hole, then 0.025 inch EDM notches are cut on each side of the hole.

## 2.4 Adhesive Selection

American Cyanimid's FM-73 was selected for this program. It was chosen over the other state-of-the art epoxy film adhesives as having the best combination of strength, temperature resistance, environmental durability, and superiority for in-the-field bonding. FM-73 was demonstrated in the Primary Adhesively Bonded Structure Technology (PABST) program (Reference 20) as a feasible adhesive for bonding aluminum aircraft structure.

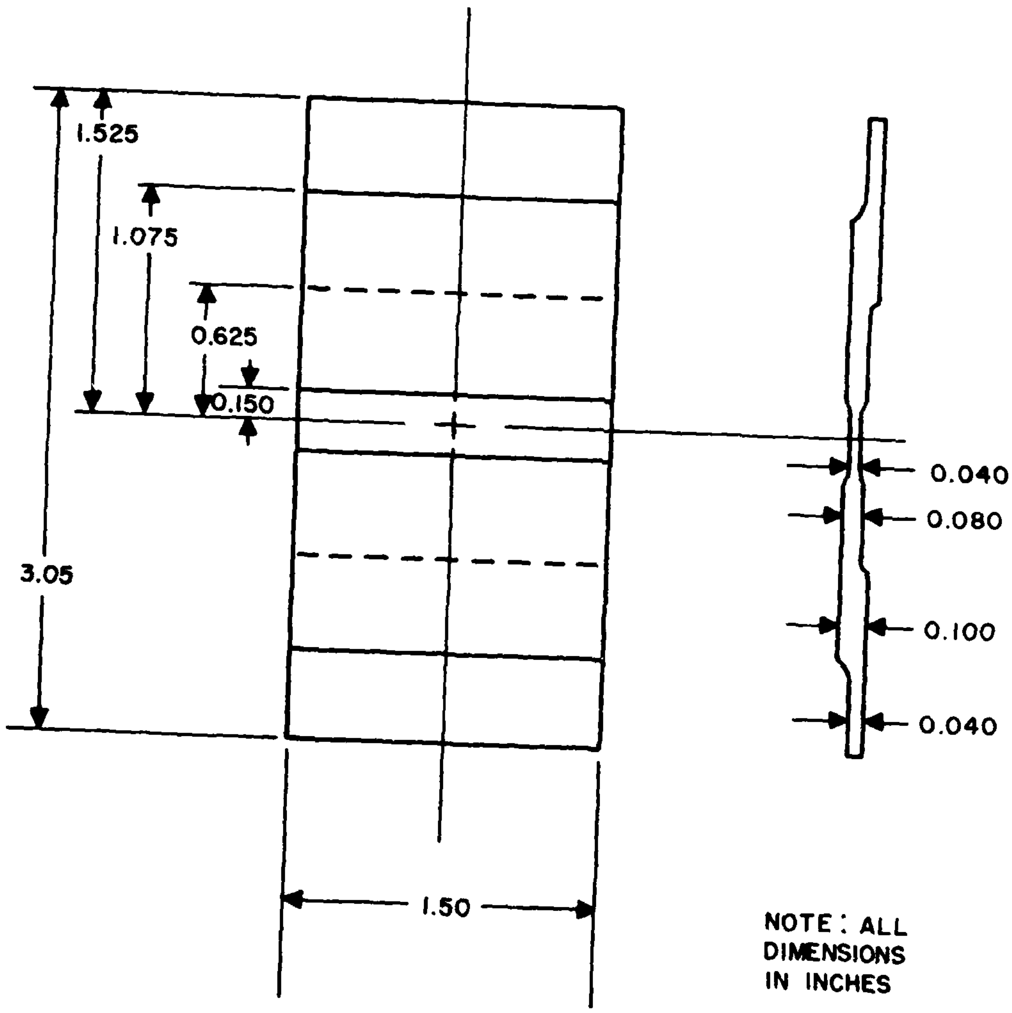



Figure 5. Crack Growth Gage

## 3. Test Procedures

### 3.1 Crack Growth Gage Bonding Technique

The following list describes the essential steps used to prepare the carrier specimens and the procedure used to bond the crack growth gages to the carrier specimens.

1. Carrier Specimen Preparation
   a. Sand blast surface to be bonded.
   b. Clean surface with soap and water and wipe dry.
   c. Etch surface with M-Prep Conditioner A (a water based acidic surface cleaner).
   d. Rinse with clear water and air dry.
   e. Wipe with MEK.
2. Bonding Procedures
   a. Cut cold FM-73 sheet to size and insert between parts.
   b. Place carrier specimen-crack growth gage combination (Figure 6) in oven.
   c. Raise temperature of oven so thermocouple alongside carrier specimen measures 255°F.
   d. Bond at 255°F for one hour.
   e. Oven cool to room temperature.

### 3.2 Crack Monitoring

Crack growth was monitored either by visual observation using stereo zoom microscopes and ruled scales or by using Fax-Film.

Fax-Film, a registered trade name of the Clevite Corporation, is a facsimile film which has the unique ability to produce a replica of the surface to which it has been applied. This ability has a tremendous

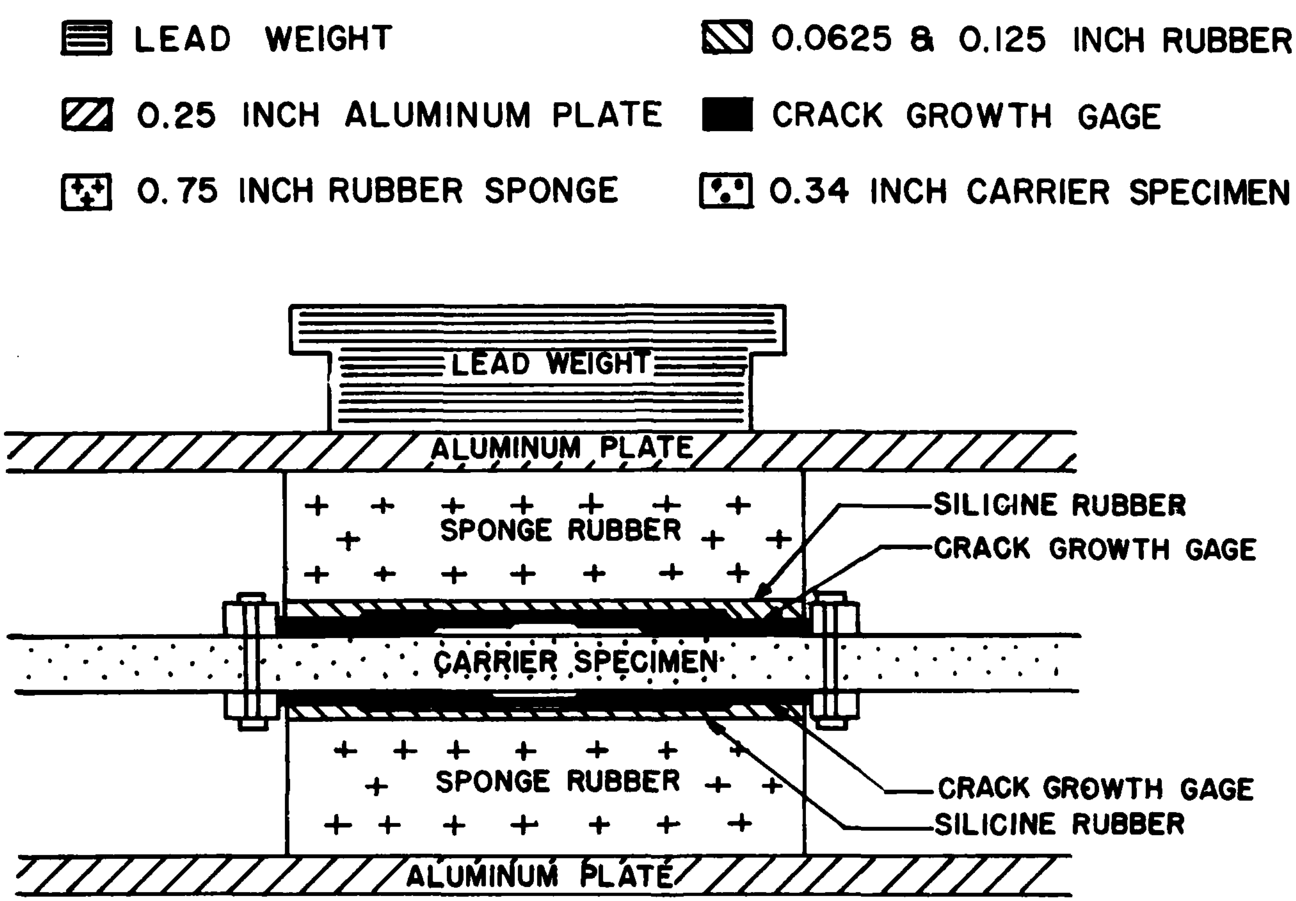



Figure 6. Crack Growth Gage Bonding Technique

advantage over the human eye. Fax-Film replicas can be magnified to several hundred power, microscopically studied, photographed, viewed by many people at the same time with the aid of the slide projector, and stored as a permanent record.

The materials needed to produce a Fax-Film replica include:

1. Fax-Film (cellulose acetate)
2. Film holder (2 inch x 2 inch slide mount)
3. Solvent (usually acetone)
4. Cleaning materials (cotton, applicators)

The following list describes the steps needed to obtain replicas using Fax-Film.

1. Clean surface thoroughly with acetone and cotton. Remove all grease, dirt, and lint from the surface.

2. Cut Fax-Film to size larger than the area to be inspected. Care should be exercised in keeping all foreign matter, finger prints, and scratches from the surface of the film.

3. Moisten either the film or the surface to be inspected with acetone and place the film on the surface. Avoid air bubbles and prevent any lateral movement or sliding of the film.

4. Hold film securely with constant pressure for approximately one minute. This time may vary according to the amount of acetone used.

5. Peel the replica from the surface and immediately place in the film holder.

The replica is now ready to be viewed in a microscope or to be projected through a lens system onto a screen. Figure 7 represents Fax-Film replica of the five precracked crack growth gages which were bonded to the lower wing skin of the full-scale F-4 C/D fatigue test article.

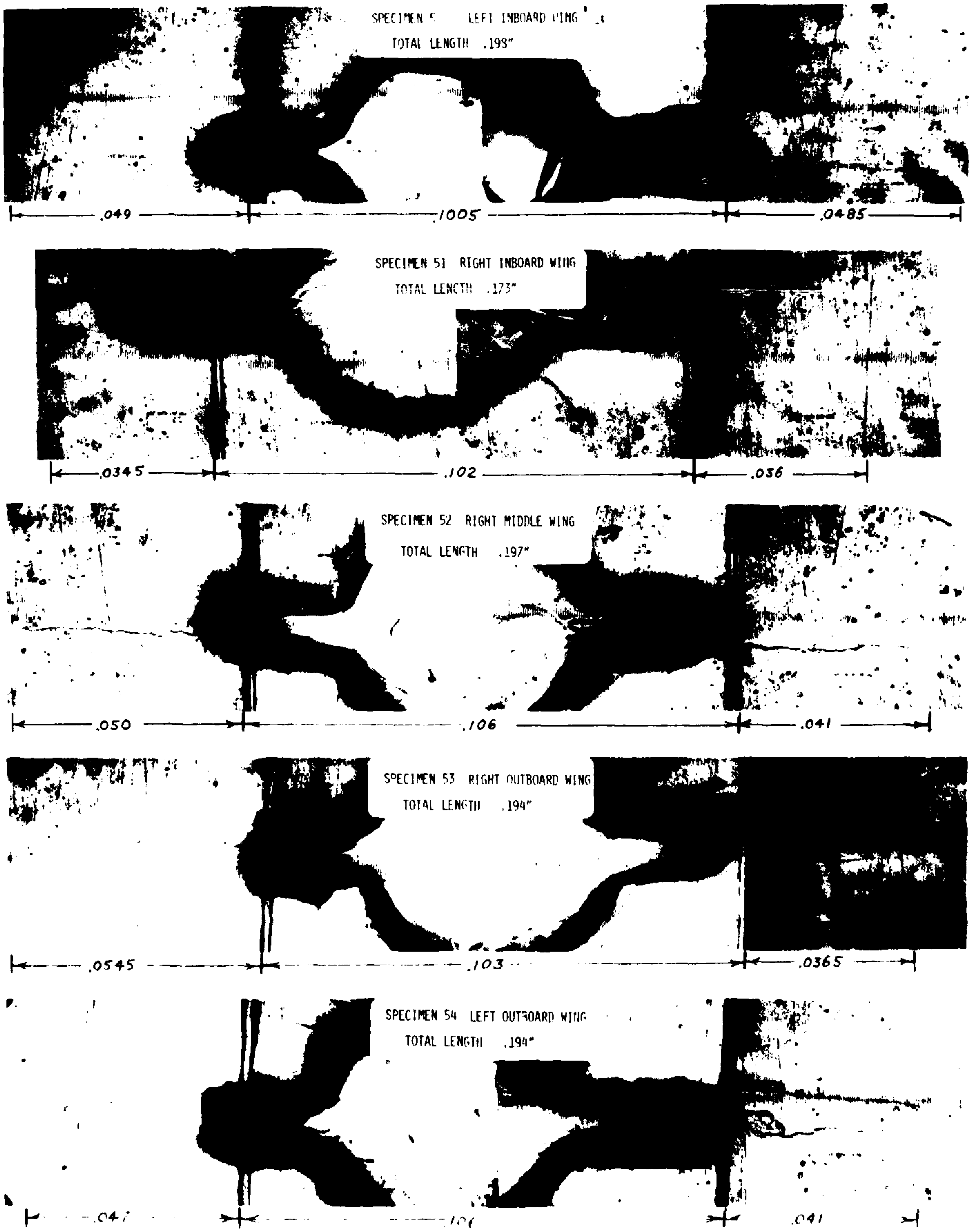



Figure 7. Example of Fax-Film Replication (Magnification 70X)

The accuracy of both systems, stereo zoom microscope and Fax-Film, is plus or minus 0.002 inch.

### 3.3 Precracking of Crack Growth Gages

The crack growth gages that were bonded to the lower wing skin of the F-4 full-scale fatigue test article and those used early in the test program were precracked by clamping them back-to-back with a non-slotted crack growth gage and fatigue cycling them at 10-12 ksi at a stress ratio of zero. Precracking was halted when crack lengths on both sides of the slot reached a nominal 0.050 inch. The configuration shown in Figure 8 was used when the gages were precracked. Two inches of length were cut from both sides of the gage after the precracking procedure was complete.

During testing it was determined that precracking was not required for crack growth gages which were to be bonded to carrier specimens. This determination was a result of a comparison of test data using precracked and non-precracked gages.

### 3.4 Primary Specimen Testing

All specimens were tested in analog controlled hydraulically driven servo-valve test machines (MTS Systems). Specimens were clamped by hydraulic powered grips.

### 3.5 da/dN Coupon Testing

Testing consisted of applying constant amplitude loading at 10-12 ksi and periodically recording crack length and cycles. Testing was conducted in a 20 KIP MTS machine utilizing a 20 KIP capacity load cell. The cyclic rate used was 2.5 Hz. Appendix A contains detailed results of the da/dN coupon tests.

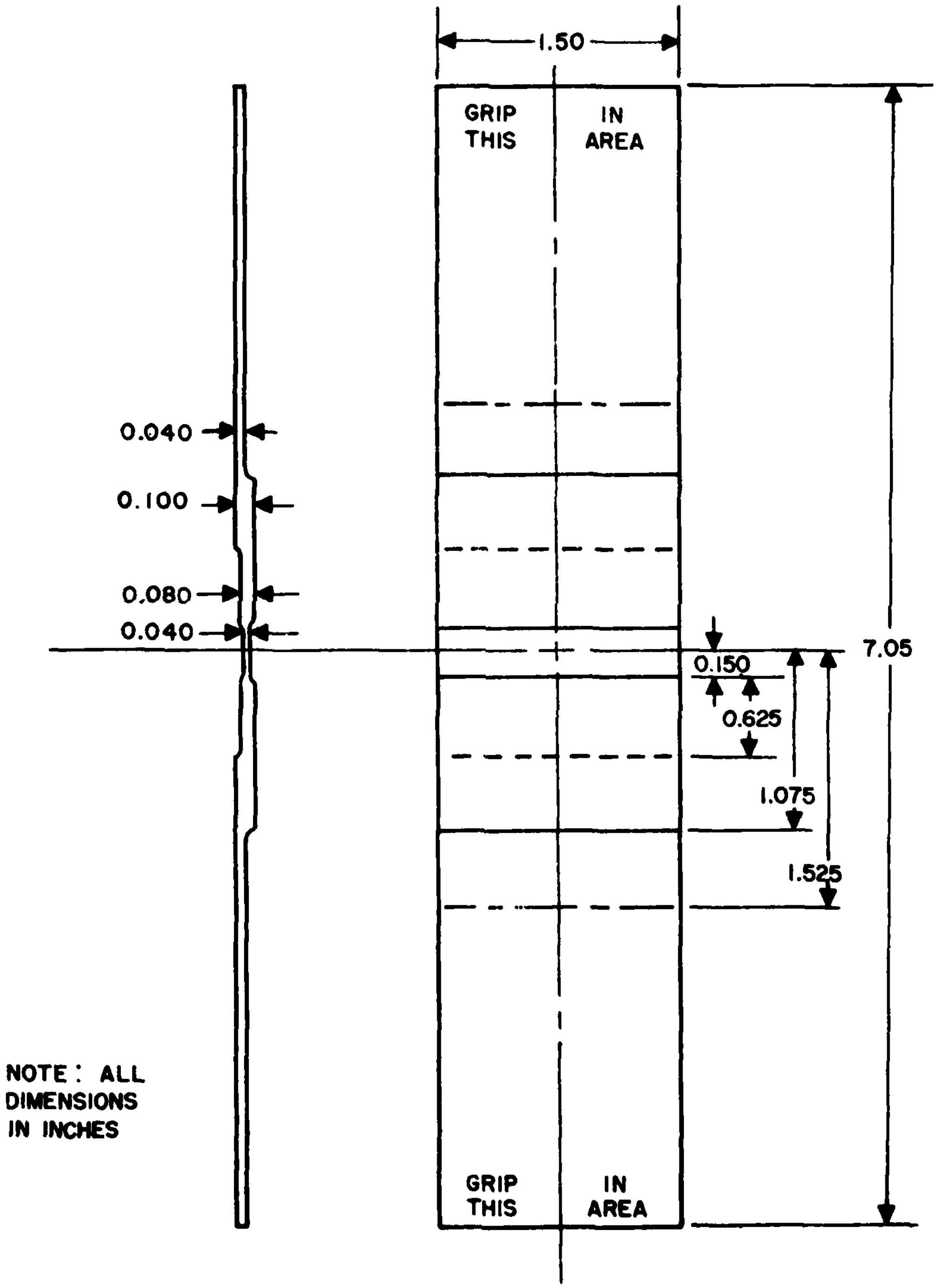



Figure 8. Crack Growth Gage Precracking Configuration

### 3.6 Constant Amplitude Testing

Constant amplitude tests on carrier specimens with attached crack growth gages were run at a stress ratio of zero with a maximum stress of 21.0 ksi. Testing was conducted in a 100 KIP MTS machine utilizing a 100 KIP capacity load cell. The cyclic rate used was 0.5 Hz. Three gage configurations were tested: (1) normal length gage - bonded, (2) full length gage (precracking length) - bonded, and (3) full length gage (precracking length) - bonded and bolted. The three configurations are shown in Figures 9, 10 and 11.

### 3.7 Strain Gage Instrumentation

Selected carrier specimens and crack growth gages were strain gaged with Micro-Measurement foil-type miniature strain gages to measure load transferred through the crack growth gage. The strain gages and the applied loads were monitored through the AFFDL-FBT Data Acquisition System. This system uses multi-channel high-speed A-to-D multiplexers output to PDP-11 minicomputers which are linked to a SEL-86 computer. Data sampling rates were as high as 50,000 samples per second. The strain surveys were performed under static load conditions. Appendix B contains detailed drawings of strain gage locations and tabulated data resulting from the strain gage measurments.

## 4. Fatigue Test Article

An on-going fatigue test of a full-scale F-4 C/D test article provided a convenient test bed for evaluating the crack growth gage concept for use with actual aircraft. The purpose of the F-4 C/D full-scale fatigue test is to provide full-scale test verification of several

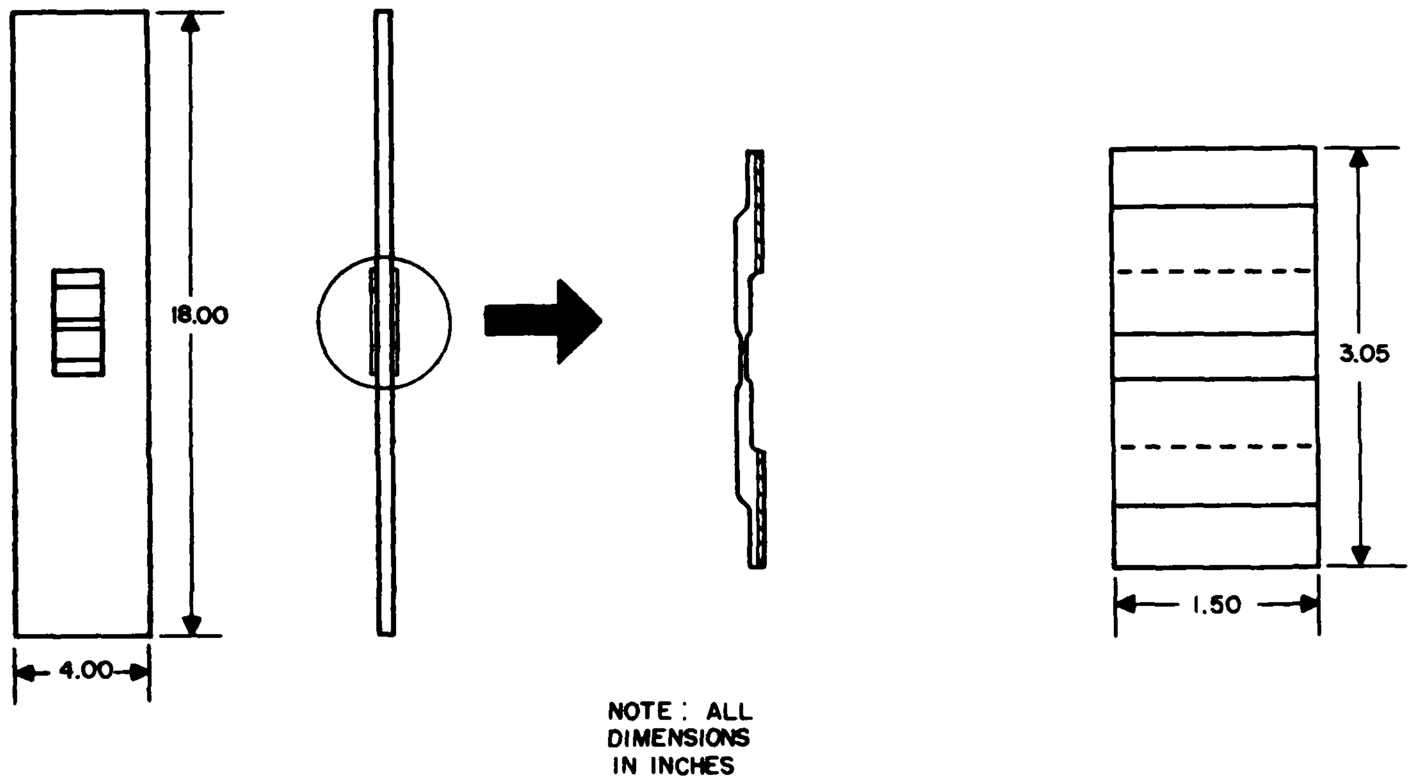
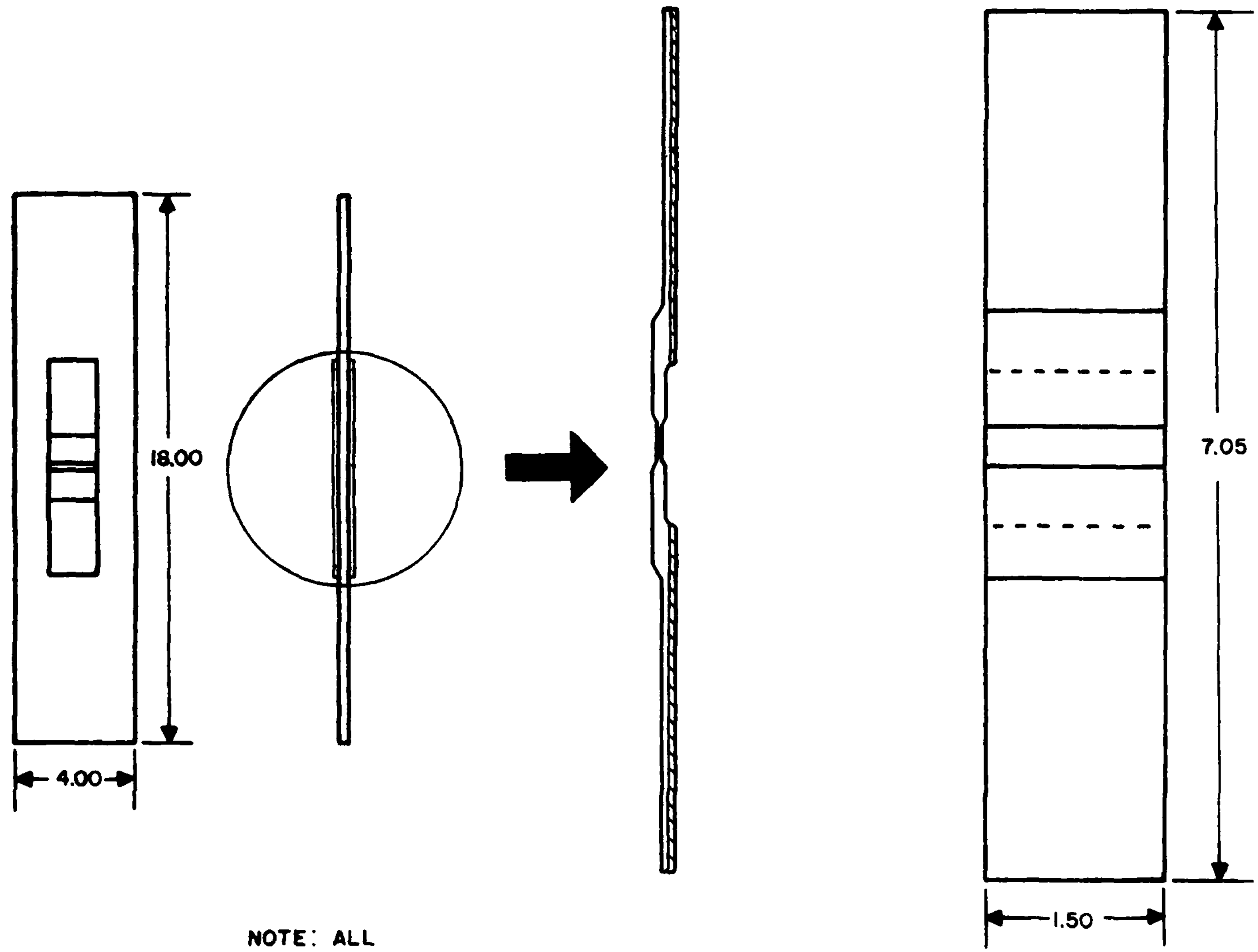



Figure 9. Crack Growth Gage Test Configuration: Normal Length Gage - Bonded




NOTE: ALL
DIMENSIONS
IN INCHES

Figure 10. Crack Growth Gage Test Configuration: Full Length Gage (With Precracking Tabs) - Bonded

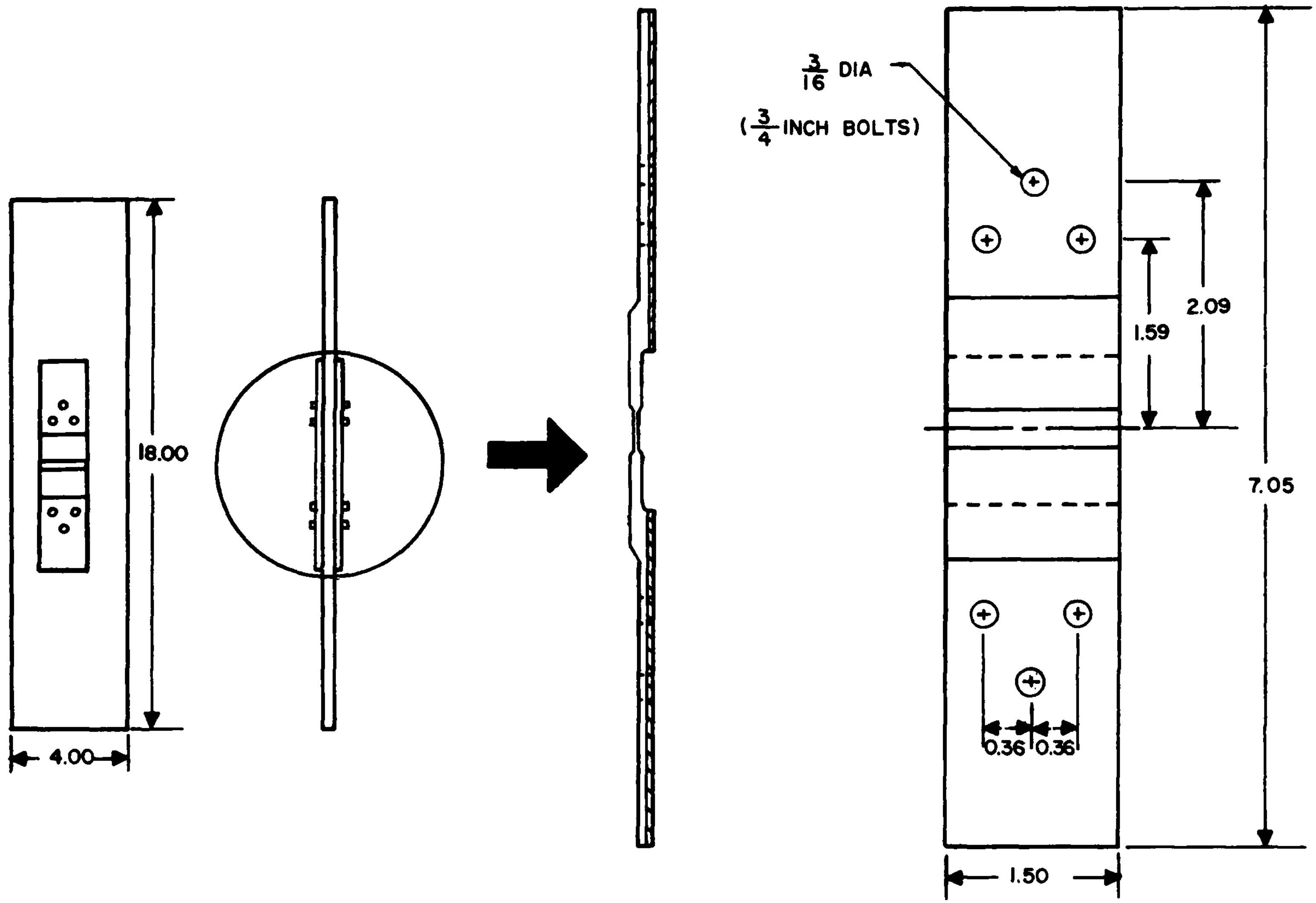



Figure 11. Crack Growth Gage Test Configuration: Full Length Gage (With Precracking Tabs) - Bonded and Bolted

life extension modifications including those designed to extend the life to 8000 flight hours of F-4 ASIP baseline usage. At the equivalent of 4000 flight hours of baseline usage, the full-scale fatigue test was stopped temporarily to implement the modifications mentioned above. Thus, the test was in a hold status and provided an excellent opportunity to attach crack growth gages to the test structure.

A contract was established with McAir to conduct detailed analysis and testing which would evaluate the ability of the crack growth gage concept to monitor potential crack growth damage in fatigue critical areas of the F-4 C/D aircraft structure. Under the contract, McAir selected three external locations on the lower wing skin for monitoring wing fatigue critical regions. Gage application sites were based on gage configuration, predicted behavior, bonding procedure, and the following criteria: (1) sites should be near fracture critical areas, (2) sites should experience about 30 ksi limit stress level, (3) sites should avoid high stress gradients, fastener patterns, taper-loks, and load pads.

The locations chosen for attaching the crack growth gages to the lower wing skin of the right wing are shown in Figure 12. These locations were chosen because they are at or near control points for which crack growth damage is calculated in the present F-4 IAT program. Also, stress spectra were already developed and crack growth analysis and test data were available from the previous F-4 damage tolerance assessments.

Site 1 is an area of moderately high design limit stress (see design limit stress contours for the lower wing skin in Figure 13), and cracks have been found in this area in previous full-scale fatigue tests. Site 2 is located in an area near Butt Line (B. L.) 100 which has a slightly

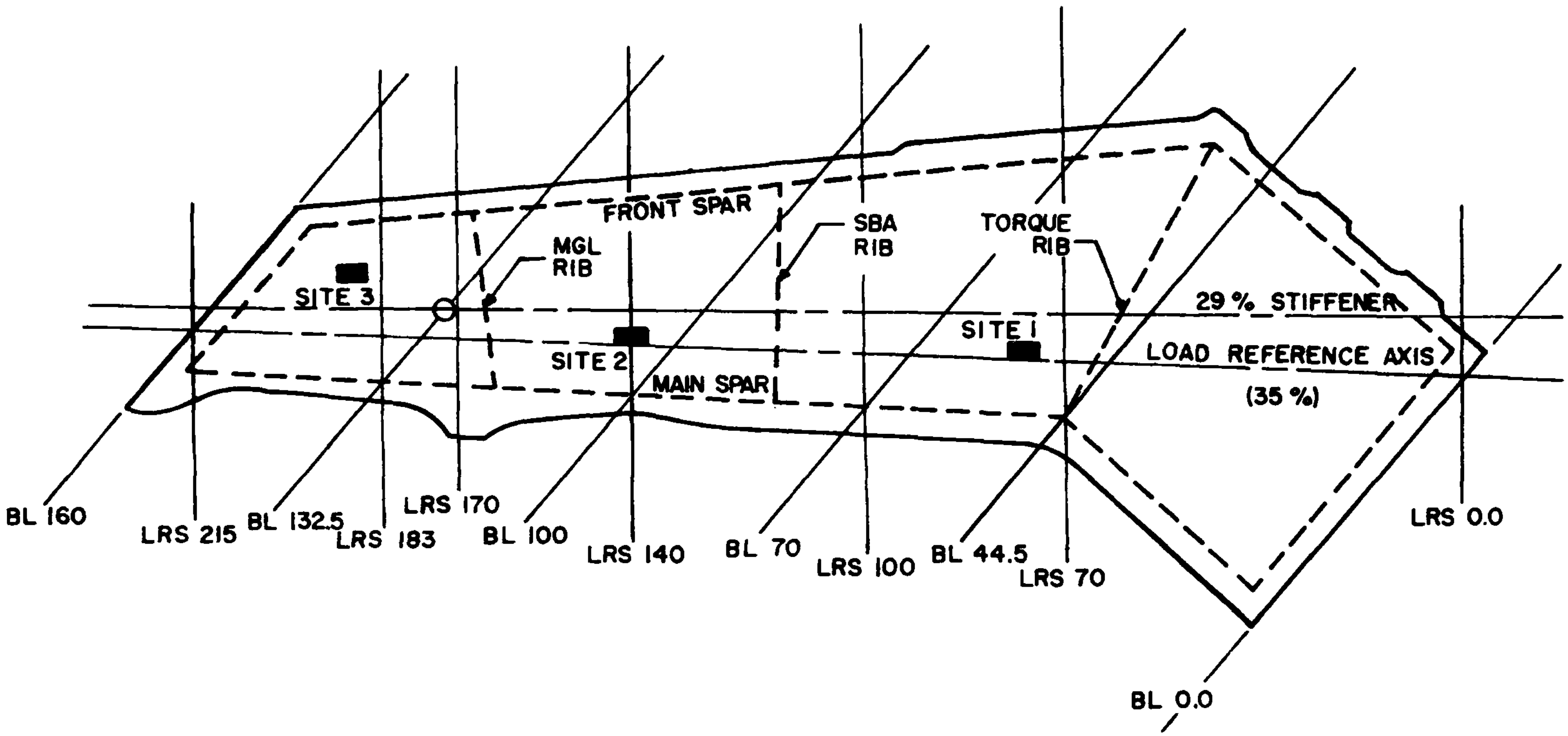



Figure 12. Selected Gage Sites

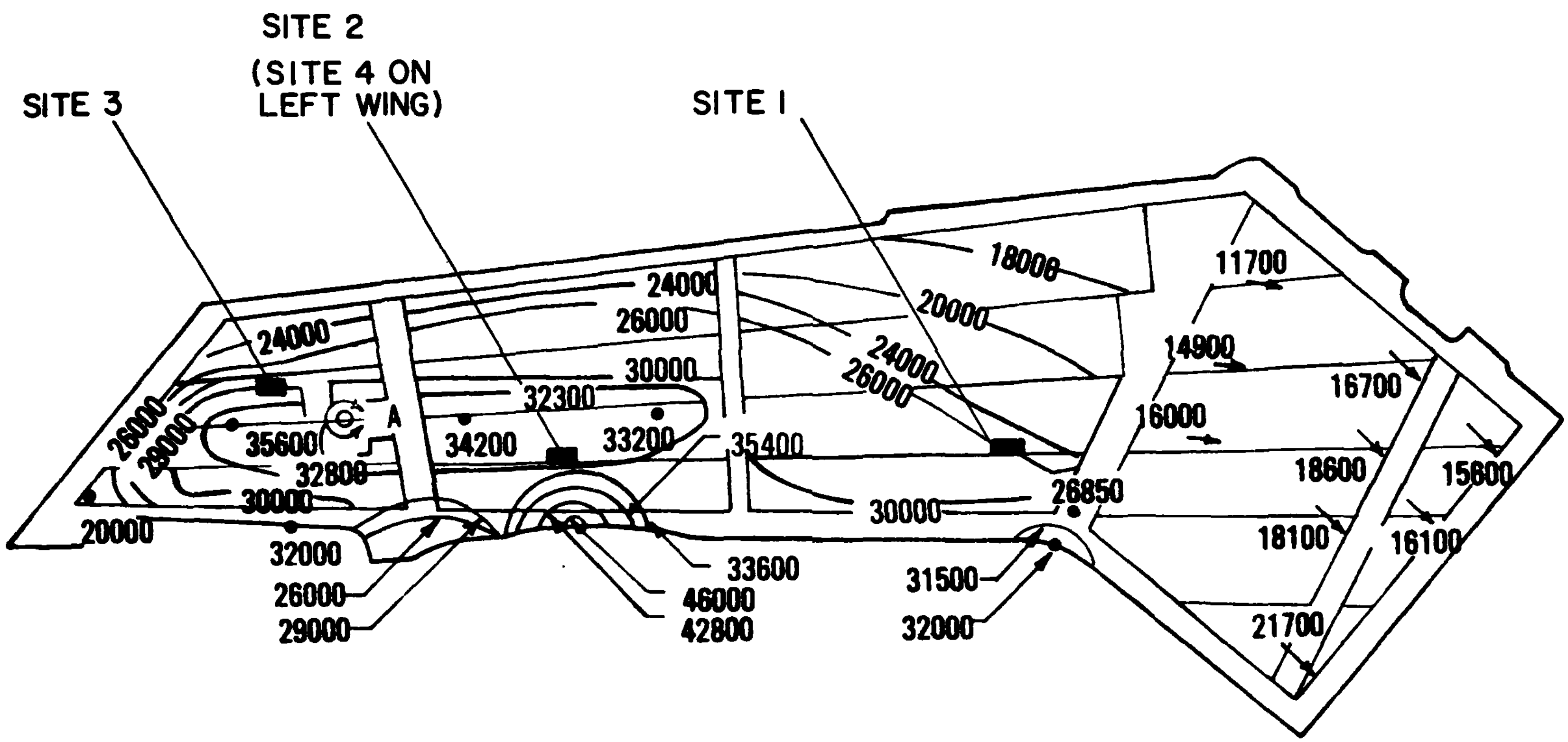



Figure 13. Relationship of Selected Gage Sites to Stress Contours on Lower Wing Skin

higher stress level (between 32.3 ksi and 33.6 ksi at limit load) than the other gage sites. Site 3 is located near the pylon hole. This is also an area of moderately high stresses, and cracks have been found in this area in operational aircraft during service as well as in previous full-scale fatigue tests. A fourth gage was installed at the duplicate location of Site 2 on the left wing.

## 4.1 Fatigue Test Article Surface Preparation

The surface of the lower wing skin where the gages were attached was prepared in the following manner. The preparation consisted of abrasion, followed by solvent wiping, followed by Pasa Jell 105 treatment, and finally by a decomped water rinse. This treatment, standard for field repair, was performed by McAir personnel.

The crack growth gages were treated with sulfuric acid and sodium dichromite. In addition, the gages were primed with a corrosion inhibiting primer (BR-127) before attachment.

## 4.2 Bonding Process

The technique used in bonding the gages to the lower wing is shown in Figure 14. The FM-73 film adhesive was sandwiched between the crack growth gage and the wing skin. A thermocouple was affixed to the wing skin, and glass breather material and a vacuum bag were applied. A heating blanket was placed over the vacuum bag, and the bond area was heated to the cure temperature of the adhesive (250°F). The cure cycle involved a half-hour heat-up to the control temperature (300°F), one to 1.5 hours at temperature, followed by a half-hour cool down.

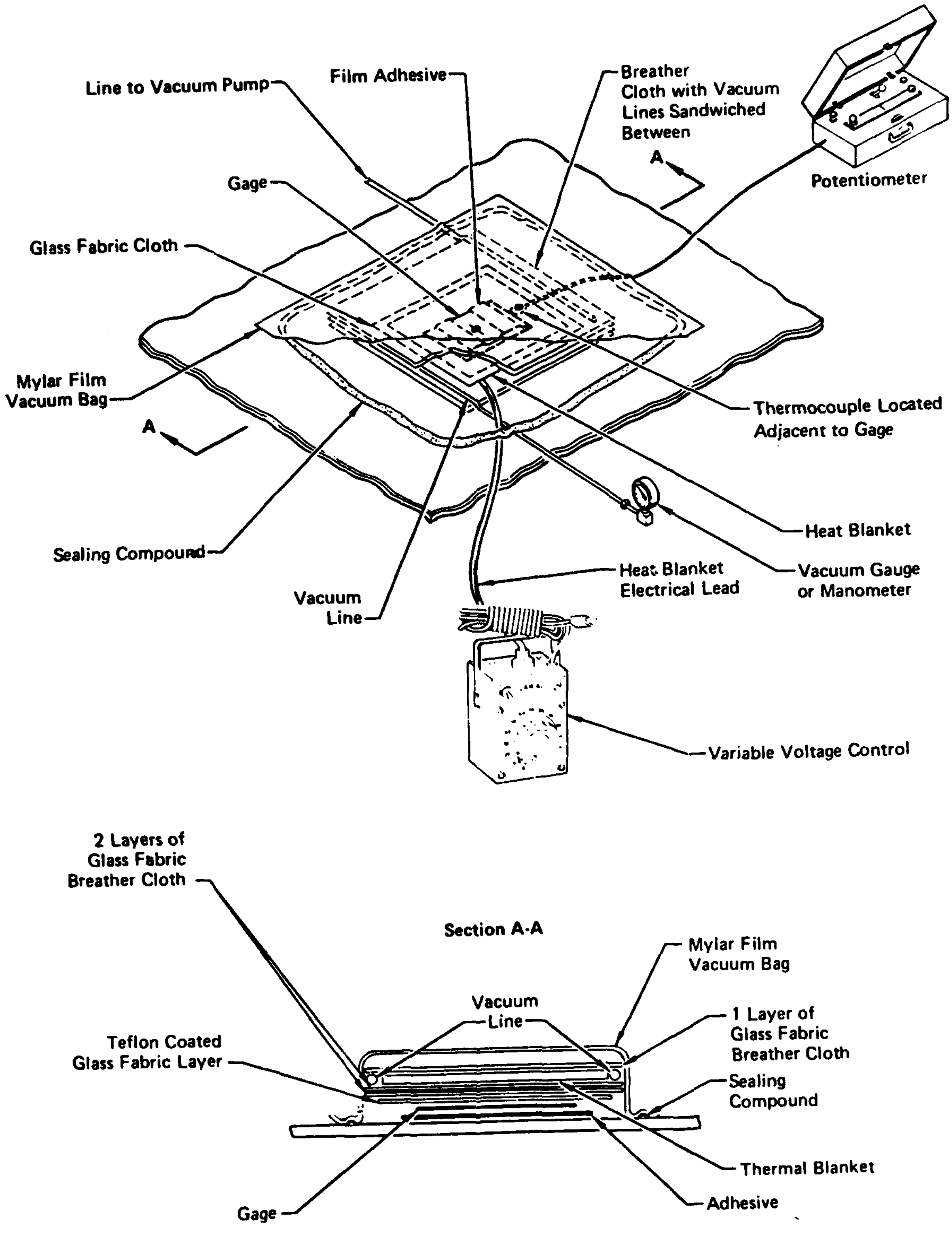



Figure 14. Vacuum Bag Technique of Bonding Crack Growth Gages

The elevated skin temperature associated with the bonding procedure required special precautions and controls to prevent residual stress relaxation near taper-loks and cold-worked holes. Gage bonding was performed so that temperatures near such areas were held to a maximum of 200°F. This was accomplished by locating the crack growth gages at least 2.5 inches from the nearest fastener pattern. In addition, thermocouples at the nearest fastener pattern were monitored during bonding and the temperature was held to a maximum of 200°F.

## SECTION III

## PRESENTATION AND DISCUSSION OF EXPERIMENTAL RESULTS

The purpose of the experimental test program was to obtain data necessary to verify the performance and predictability of the crack growth gage. The constant amplitude tests and the fatigue test article effort are described in detail in the following sections.

### 1. Constant Amplitude Test Results

All tests performed in this phase of the test program were intended to determine the crack growth behavior of the crack growth gage. Gages were bonded with FM-73 adhesive to carrier specimens and tested under constant amplitude conditions (21.0 ksi) in order to determine gage performance and predictability.

Four constant amplitude tests (i.e., two crack growth gages per carrier specimen) were completed and results showed two areas for concern. Figure 15 is a plot of the first eight crack growth gage tests compared with the results of tests performed by McAir. Scatter in the McAir tests was minimal while tests performed by AFFDL had a large amount of scatter. Also note that the crack growth rate was much slower for the AFFDL gages when compared with the McAir tested gages.

Gages 8A/B, 30A/B, and 24A/B were precracked prior to being bonded on the carrier specimens. Gages 18A/B were not precracked. All the gages tested by McAir were precracked to a 2a of approximately 0.2 inch. Since gages that were installed on the F-4 fatigue article were precracked to a 2a of 0.2 inch, this length was used as an initial starting point for all

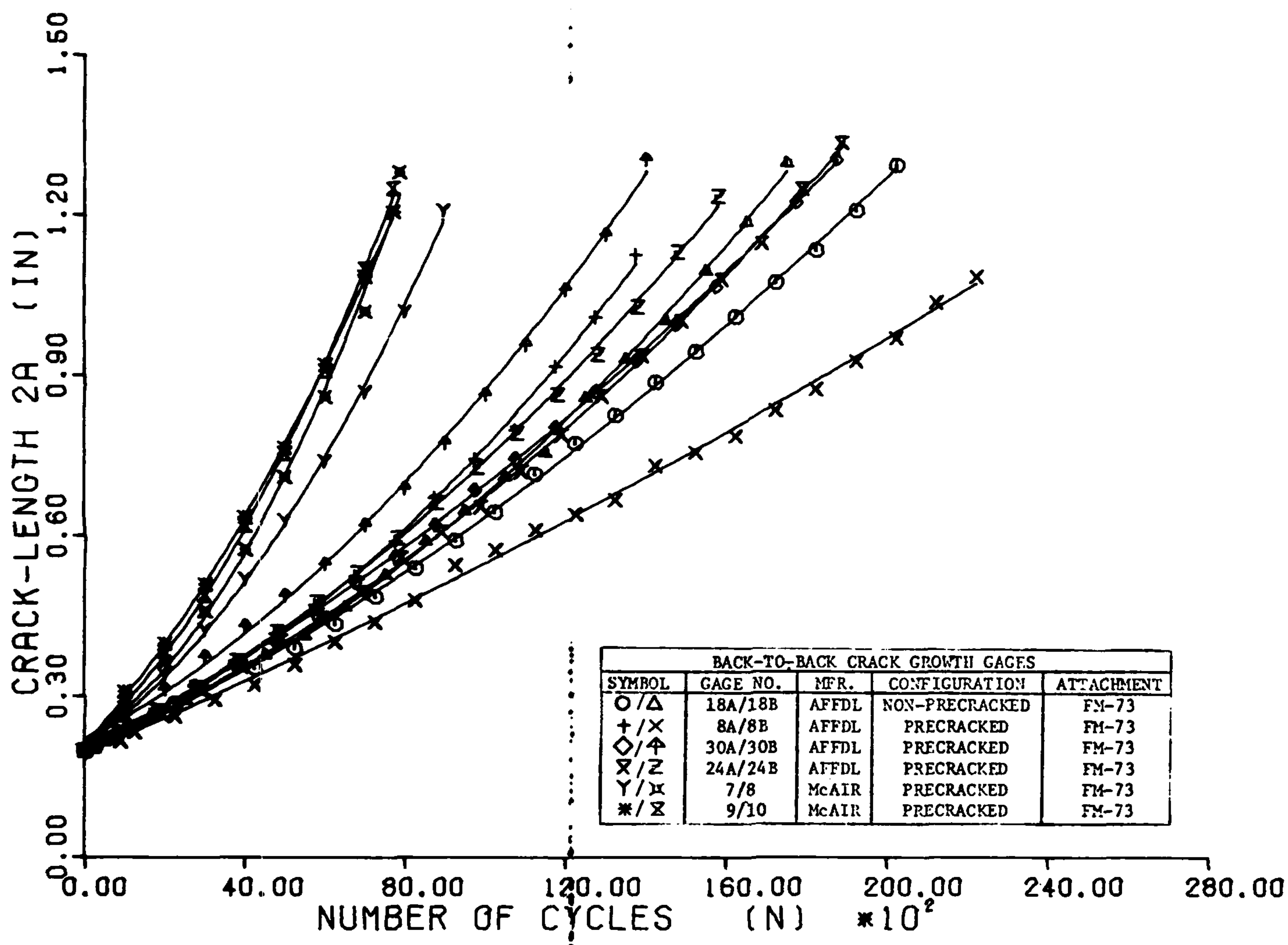



Figure 15. Constant Amplitude Tests - AFFDL Tests of AFFDL Gages Compared with McAir Tests of McAir Gages

constant amplitude test results. The number of cycles used to reach a 2a of 0.2 inch was not considered.

Differences in procedures used by McAir and AFFDL were investigaged in an attempt to explain the variations in the test results. It was discovered that gages manufactured for the AFFDL were machined as opposed to chem-milled McAir gages. Therefore, the possibility of residual stresses existed in AFFDL manufactured gages that could have caused non-uniform crack growth through the gage thickness. McAir also installed a 0.020 inch thick teflon pad under the unbonded section of the gage to help prevent the adhesive from entering the cracked portion of the gage and also to restrain out of plane deformations. No such pad was used by AFFDL. During the bonding process, McAir used a vacuum bag to apply the necessary pressure for attaching the gage to the carrier specimen. AFFDL used lead weights to provide the required load.

To investigate the possibility of residual stresses in the AFFDL manufactured gages, four chem-milled gages were obtained from McAir and were bonded and tested by AFFDL personnel. Results of these tests are shown in Figure 16 along with the results of McAir previous tests. It can be seen in Figure 16 that the results of the AFFDL tests with McAir gages fall between the original results of McAir and the results obtained by the AFFDL with the machined gages. Therefore, the possibility of both the residual stresses in the AFFDL machined gages and improper bonding procedures by AFFDL personnel remained as a possible explanation for the inconsistent results.

The next tests consisted of using full length gages (i.e., gage with precracking tabs attached). In the first test a full length gage was bonded

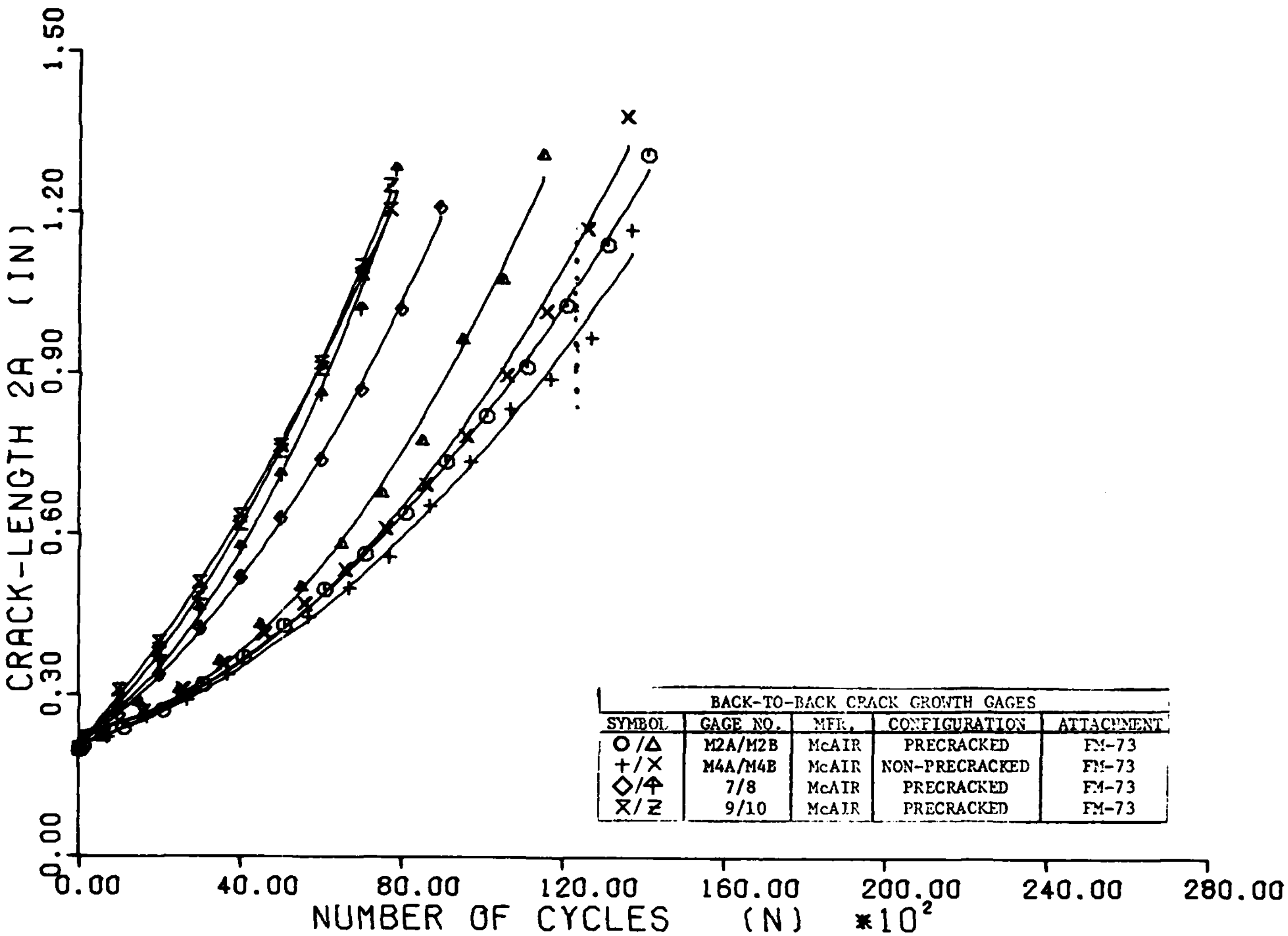



Figure 16. Constant Amplitude Tests - AFFDL Tests of McAir Gages Compared with McAir Tests of McAir Gages

with FM-73 (Figure 9) and a constant amplitude test was performed. The second test consisted of bonding and bolting full length gages on a carrier specimen (Figure 10). The objective of using the bolts was to determine if this method of gage attachment would eliminate (1) the variation between McAir and AFFDL test results and (2) the scatter in the AFFDL test.

Figure 17 shows the results of these tests compared with the McAir curves. Both gages that were bolted on showed very consistent results. One of the non-bolted full length gage tests showed the same trend as the two bolted gages. However, the test results for the other non-bolted full length gage fell approximately half-way between the other full length gage tests and the McAir curves. No explanation could be found for the latter results.

Since residual stresses were suspected in the AFFDL machined gages, the machining procedure was modified to include smaller cuts during manufacture of the gages and tighter specifications for the final product. One set of these new gages was tested. The results of this test (Figure 18) show that the scatter between the gages was reduced but the crack growth rate still remained less than the crack growth rate in the McAir tests.

As a result of these tests, McAir performed a constant amplitude test on gages that were bonded by AFFDL personnel. The results of this test are shown in Figure 19. These curves fall well within the AFFDL scatter band of previous tests; therefore, both the theories on residual stress in the AFFDL machined gages and the AFFDL bonding procedure were still suspect.

A test matrix by gage number is shown in Table 1. A summary of the test program and its results is shown in a flow diagram in Table 2.

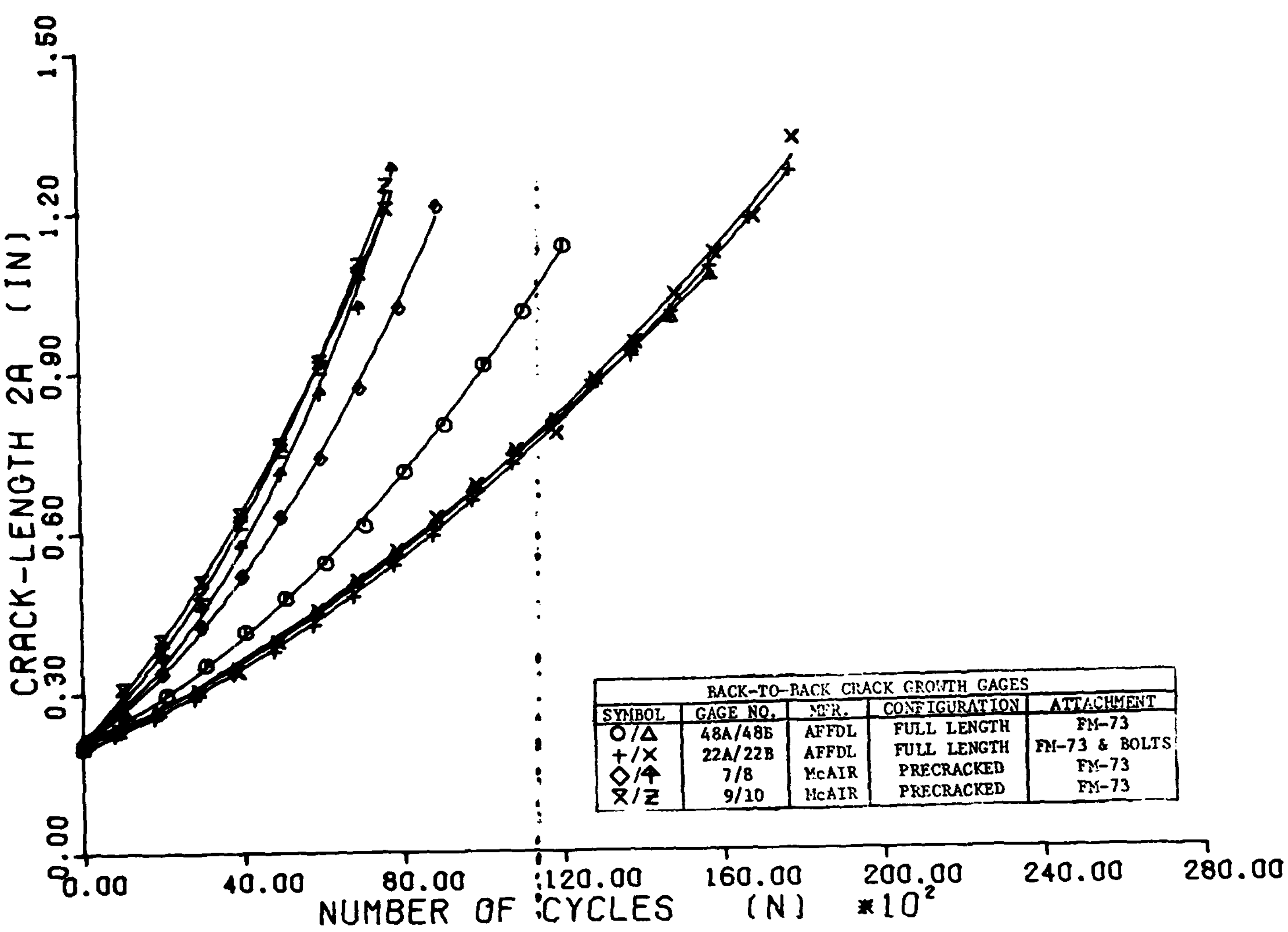



Figure 17. Constant Amplitude Tests - AFFDL Tests of AFFDL Full Length Gages (Precracking Tabs Attached) Compared with McAir Tests of McAir Gages

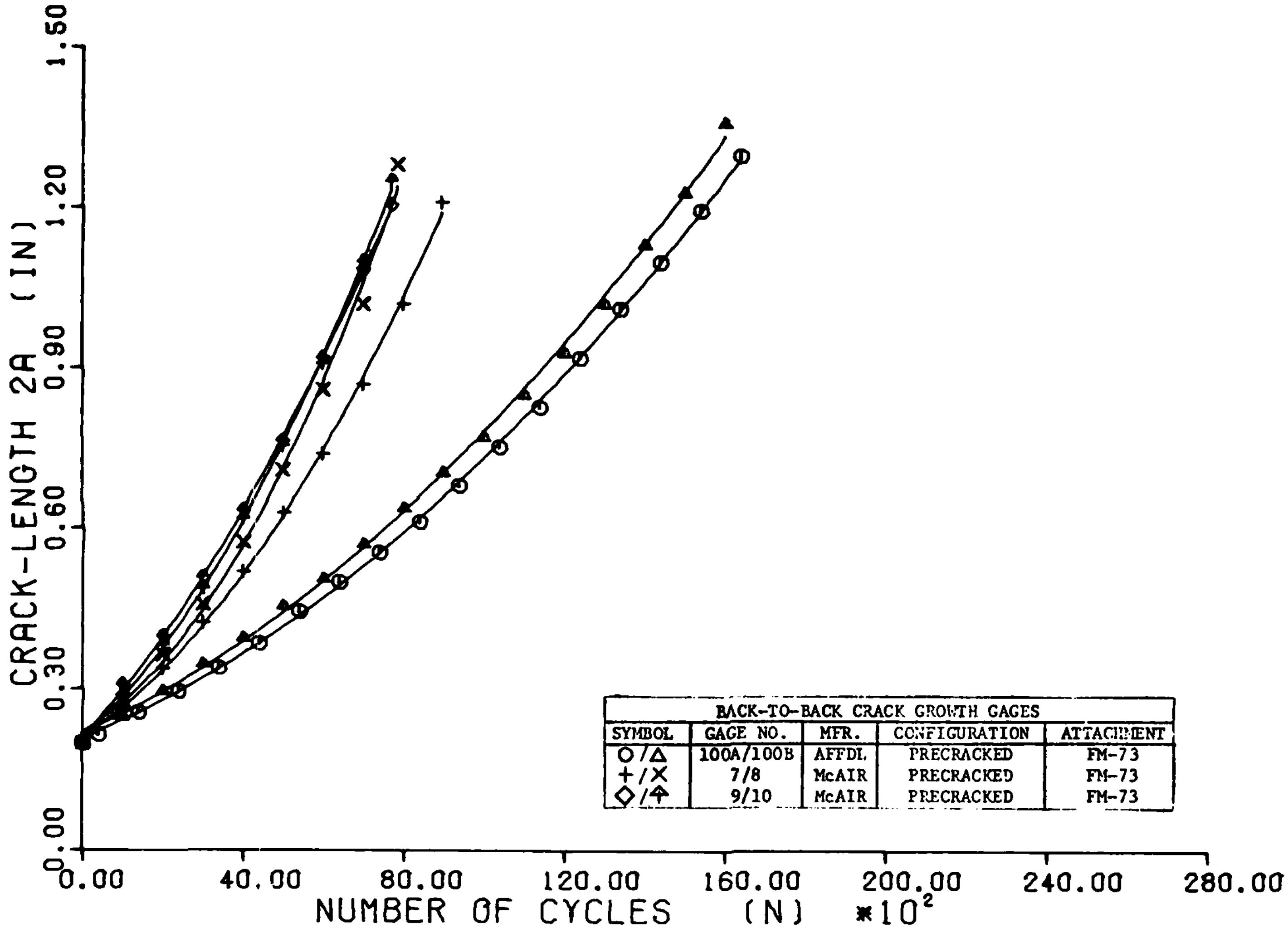



Figure 18. Constant Amplitude Tests - AFFDL Tests of AFFDL Gages Having Tighter Manufacturing Specifications Compared with McAir Tests of McAir Gages

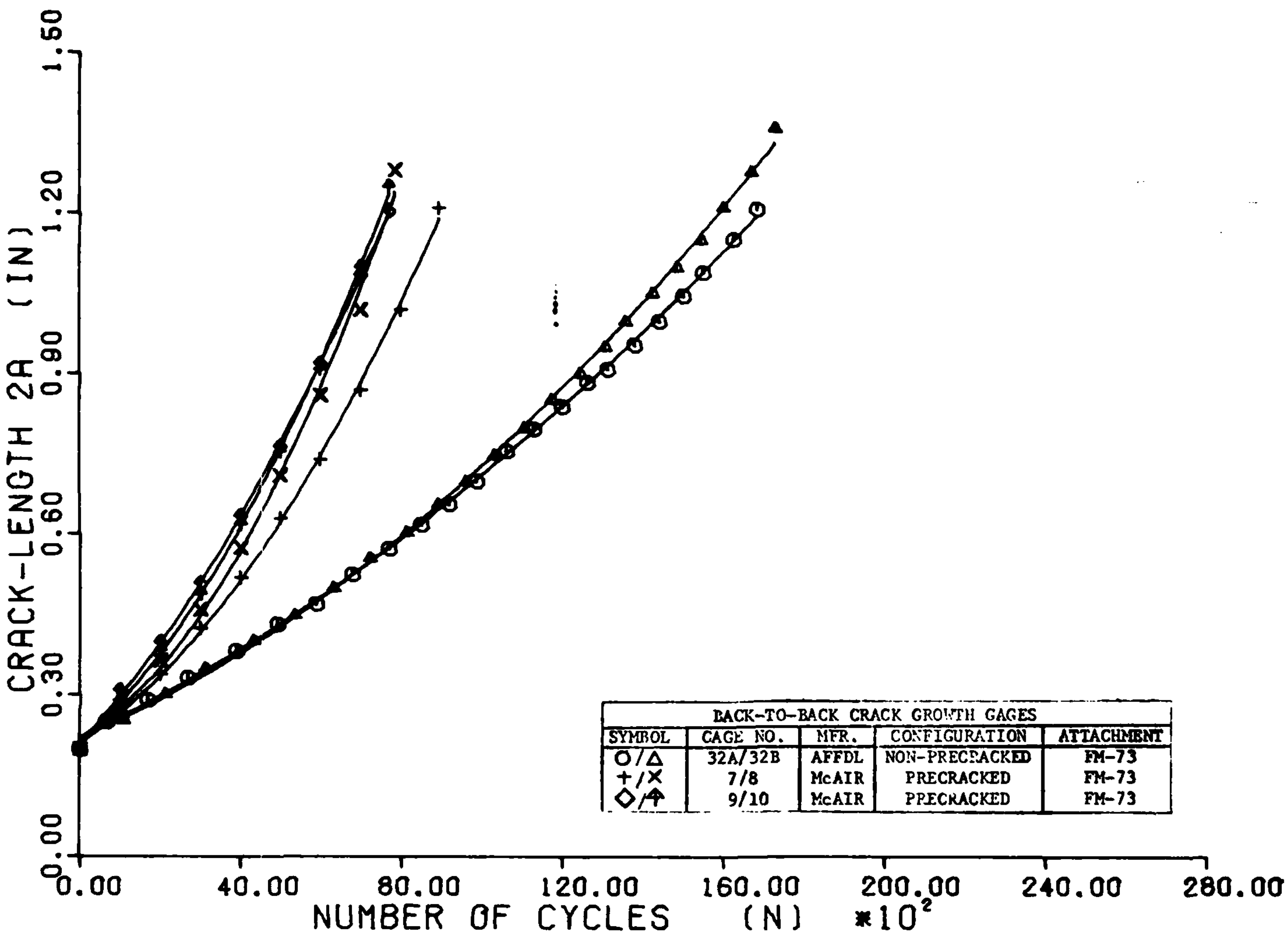



Figure 19. Constant Amplitude Tests - McAir Tests of AFFDL Gages Compared with McAir Tests of McAir Gages

TABLE 1.

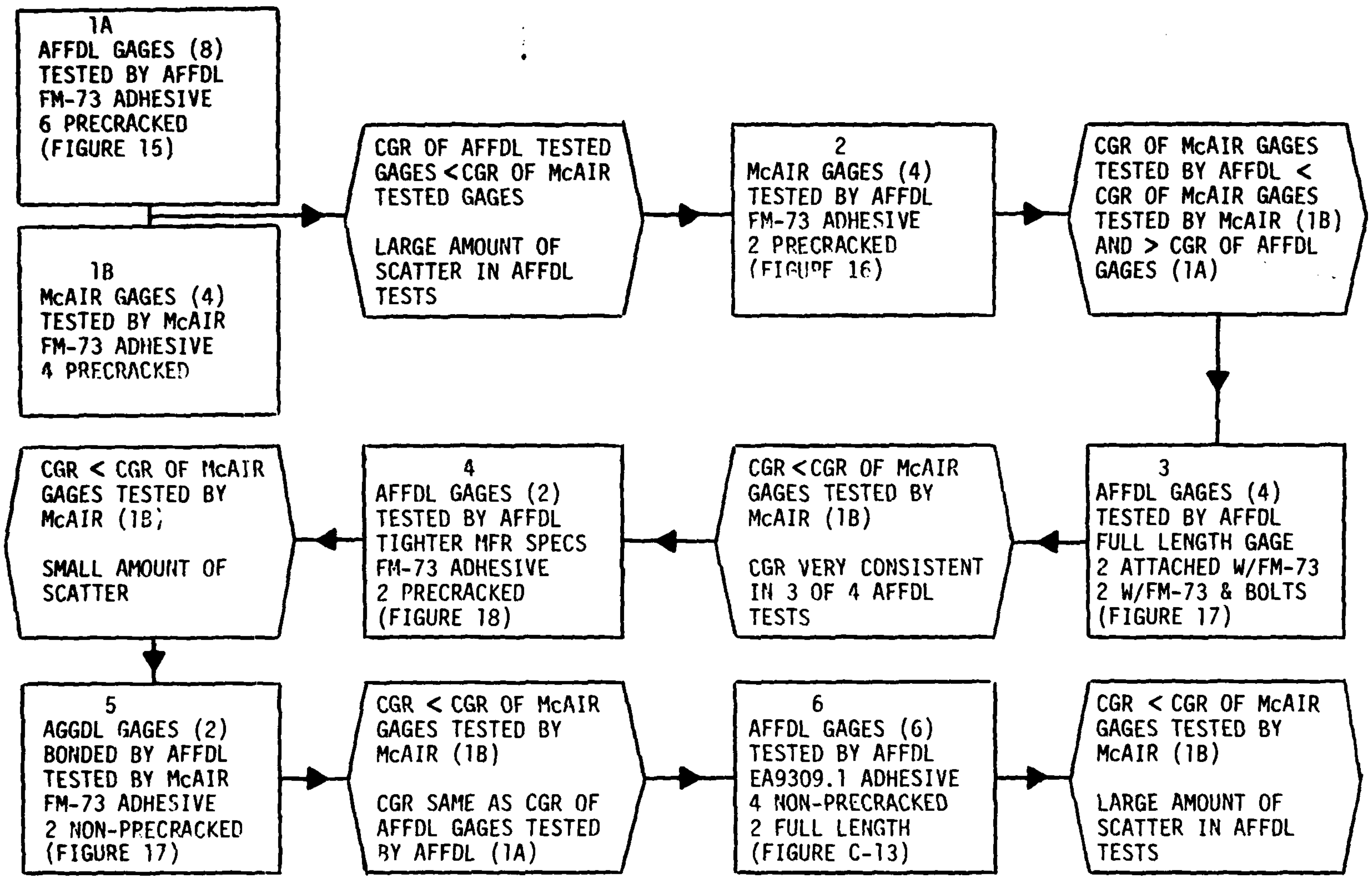
TEST MATRIX

| GAGE NO. | MANUFACTURER | CONFIGURATION | ATTACHMENT | TESTER |
|---|---|---|---|---|
| 7 | McAir | Precracked | FM-73 | McAir |
| 8 | McAir | Precracked | FM-73 | McAir |
| 9 | McAir | Precracked | FM-73 | McAir |
| 10 | McAir | Precracked | FM-73 | McAir |
| 8A/B | AFFDL | Precracked | FM-73 | AFFDL |
| 30A/B | AFFDL | Precracked | FM-73 | AFFDL |
| 24A/B | AFFDL | Precracked | FM-73 | AFFDL |
| 18A/B | AFFDL | Non-Precracked | FM-73 | AFFDL |
| M2A/B | McAir | Precracked | FM-73 | AFFDL |
| M4A/B | McAir | Non-Precracked | FM-73 | AFFDL |
| 48A/B | AFFDL | Full-Length | FM-73 | AFFDL |
| 22A/B | AFFDL | Full-Length | FM-73 & Bolts | AFFDL |
| 100A/B | AFFDL | Non-Precracked | FM-73 | AFFDL |
| 32A/B | AFFDL | Non-Precracked | FM-73 | McAir |
| 118A/B | AFFDL | Non-Precracked | EA9309.1 | AFFDL |
| 110A/B | AFFDL | Full-Length | EA9309.1 | AFFDL |

NOTE:
1) All gages tested at 21.0 KSI
2) A/B indicates back-to-back gages on individual specimens (i.e., 8A and 8B).
3) Full length gages have precracking tabs attached (i.e., gage length is 7.05 inches).
4) All other gages 3.05 inches in length.

TABLE 2.

SUMMARY OF CONSTANT AMPLITUDE TEST PROGRAM




NOTE: CGR = Crack Growth Rate

## 2. Fatigue Test Article Results

At the equivalent of 4000 flight hours of baseline usage the F-4 full scale fatigue article test was put into a hold status in order to implement certain modifications in an attempt to extend the life of the aircraft. During this down time, McAir personnel installed four crack growth gages on the lower wing skin of the aircraft as explained in Sections 4, 4.1, and 4.2. No problems were encountered during the three day effort; however, soon after the McAir team departed, it was discovered that the FM-73 adhesive had not cured properly. Subsequent tests showed that the adhesive had not been heated to the recommended curing temperature of 250°F. The problem was the result of faulty thermocouple placement and insufficient heating blanket capacity. McAir later returned, stripped off the gages, and rebonded them using a larger heating blanket. Additional thermocouples were used to ensure the proper cure temperature was reached and also to ensure that the wing skin was not heated above 350°F in the vicinity of the gages or above 200°F in the vicinity of the fastener patterns.

During this time a team from Douglas Aircraft Company bonded a fifth crack growth gage on the lower skin of the left wing in a location duplicating the McAir site 1 gage on the right wing (See Figure 13). The fifth gage was bonded after using a surface preparation designed for environmental tests. The objective of the fifth gage was to demonstrate a non-tank phosphoric acid anodize surface preparation. A McAir crack growth gage was used for this test.

Since the crack growth gage was designed for a life of 12,000 hours with a measurable crack growth in one thousand hours, it was decided that Fax-Film measurements would be taken at 500 hour intervals. After the first 500 hours of equivalent flight time, only two of the five gages showed any significant crack growth. Cycling of the test article continued with Fax-Film measurements being taken at 1000 and 1500 hours of simulated flight. During this thousand hour interval (i.e., from 500 to 1500 hours) no new crack growth was detected. A strain gage was attached to one of the crack growth gages to determine if the proper load transfer was occurring through the adhesive. Results of this strain survey showed no load going to the crack growth gage. A visual inspection was made and all five crack growth gages were found to be debonded.

Several theories were investigated as the posssible cause for debonding. These included: (1) the surface of the wing skin was improperly prepared prior to bonding, (2) the adhesive was improperly cured during the bonding process (i.e., the proper curing temperature was not reached), and (3) the adhesive in its raw form had absorbed moisture prior to the bonding process and thus the quality of the bond was reduced. (Later analysis of the adhesive showed the presence of silicone contaminants in the adhesive. It was also later discovered that the entire bare metal-skinned fatigue article had been previously coated with a silicone spray as a corrosion prohibitor. This could be a possible explanation as to why debonding occurred.)

While the above theories were being investigated, it was decided that the crack growth gages would be rebonded to the fatigue article during the next down time for aircraft inspection. This inspection came after 6000 hours of baseline flight.

The heating blanket procedure used in the first bonding process could not be used again because of the numerous loading pads attached to the fatigue article. During the first bonding, the load pads were removed to facilitate heating the required area to the curing temperature. EA9309.1, a two-part room temperature cure adhesive from the Hysol Division of the Dexter Corporation, was chosen for the rebonding process. Since this room temperature cure adhesive does not have the strength, temperature resistance or environmental durability of FM-73 (a heat cure adhesive), more constant amplitude tests were completed to determine adhesive performance under cyclic loading (see Appendix C). At this time in the program, it was decided to drop the MIL-STD-810C environmental tests and to concentrate on an attempt to obtain usable data from the gages bonded to the fatigue article.

Eight crack growth gages were attached to the lower wing skin of the F-4 fatigue article using EA9309.1 adhesive. Bonding was performed by AFFDL personnel. Five AFFDL machined gages and three McAir chem-milled gages were used. Five gages were bonded to the lower wing skin of the right wing; three gages were attached to the left wing. Gage locations are shown in Figure 20. Gages bonded to the left wing were in duplicate locations of sites on the right wing. Five crack growth gages were strain gaged to determine if load was being transferred through the adhesive.

Raw crack growth data from the crack growth gages attached to the fatigue article with EA9309.1 adhesive is shown in Table 3. Plots of actual crack growth compared with McAir predictions are shown in Figures 21 through 25. In general, the experimental measurements agree quite well with McAir precictions.

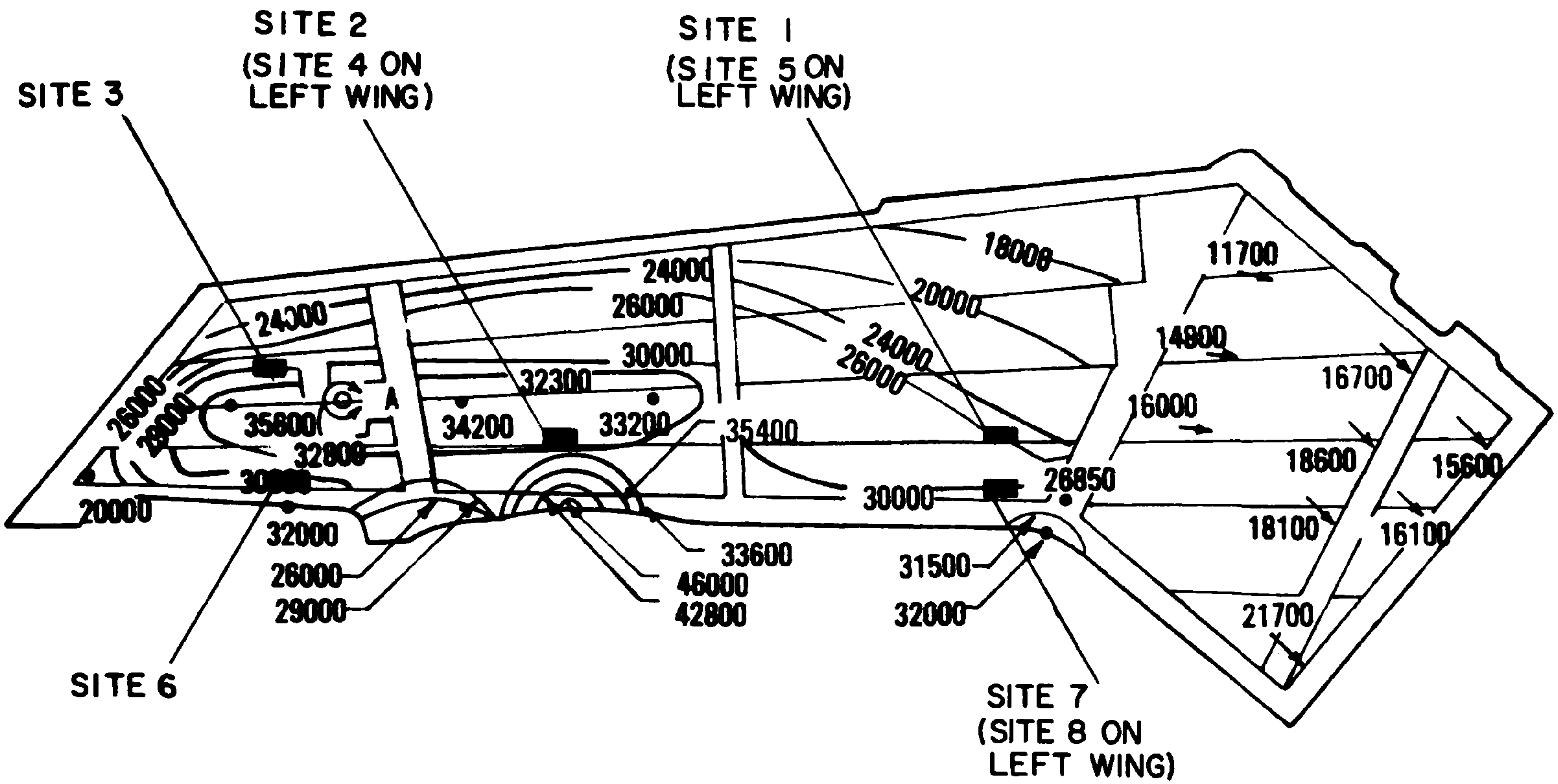



Figure 20. Selected Sites on the Lower Wing Skin of the F-4 Fatigue Article for Bonding Crack Growth Gages with EA9309.1 Adhesive

TABLE 3. CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES BONDED TO F-4 FATIGUE TEST ARTICLE WITH EA9309.1 ADHESIVE

| SITE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| GAGE | 52 | 53 | 54 | 104B | 102A | 148 | 146B | 102B |
| MFR | McAir | McAir | McAir | AFFDL | AFFDL | AFFDL | AFFDL | AFFDL |
| STRESS (KSI) | 26 | 33 | 30 | 33 | 26 | 30 | 30 | 30 |
| FLT HRS | 2a (INCHES) | | | | | | | |
| BASELINE | 0.197 | 0.197 | 0.194 | 0.190 | 0.427 | 0.379 | 0.223 | 0.246 |
| 438 | 0.200 | 0.217 | 0.195 | BAD FAX-FILM | 0.446 | BAD FAX-FILM | 0.259 | 0.270 |
| 1000 | 0.201 | 0.223 | 0.198 | 0.222 | 0.465 | 0.415 | 0.227 | 0.296 |
| 1525 | 0.204 | 0.246 | VISUAL DEBOND | 0.229 | 0.481 | 0.442 | 0.280 | 0.303 |
| 2000 | 0.207 | 0.252 | | VISUAL DEBOND | 0.499 | 0.424 | VISUAL DEBOND | 0.315 |
| 2500 | NO DATA | NO DATA | | | NO DATA | NO DATA | | NO DATA |
| 3000 | NO DATA | NO DATA | | | NO DATA | NO DATA | | NO DATA |
| 3500 | VISUAL DEBOND | BAD FAX-FILM | | | 0.533 | VISUAL DEBOND | | 0.368 |
| 4000 | | 0.286 | | | 0.544 | | | 0.383 |
| 4520 | | NO CHANGE | | | 0.550 | | | 0.385 |
| 5000 | | | | | 0.564 | | | NO CHANGE |
| 5566 | | | | | 0.575 | | | |
| 6000 | | | | | 0.590 | | | 0.392 |

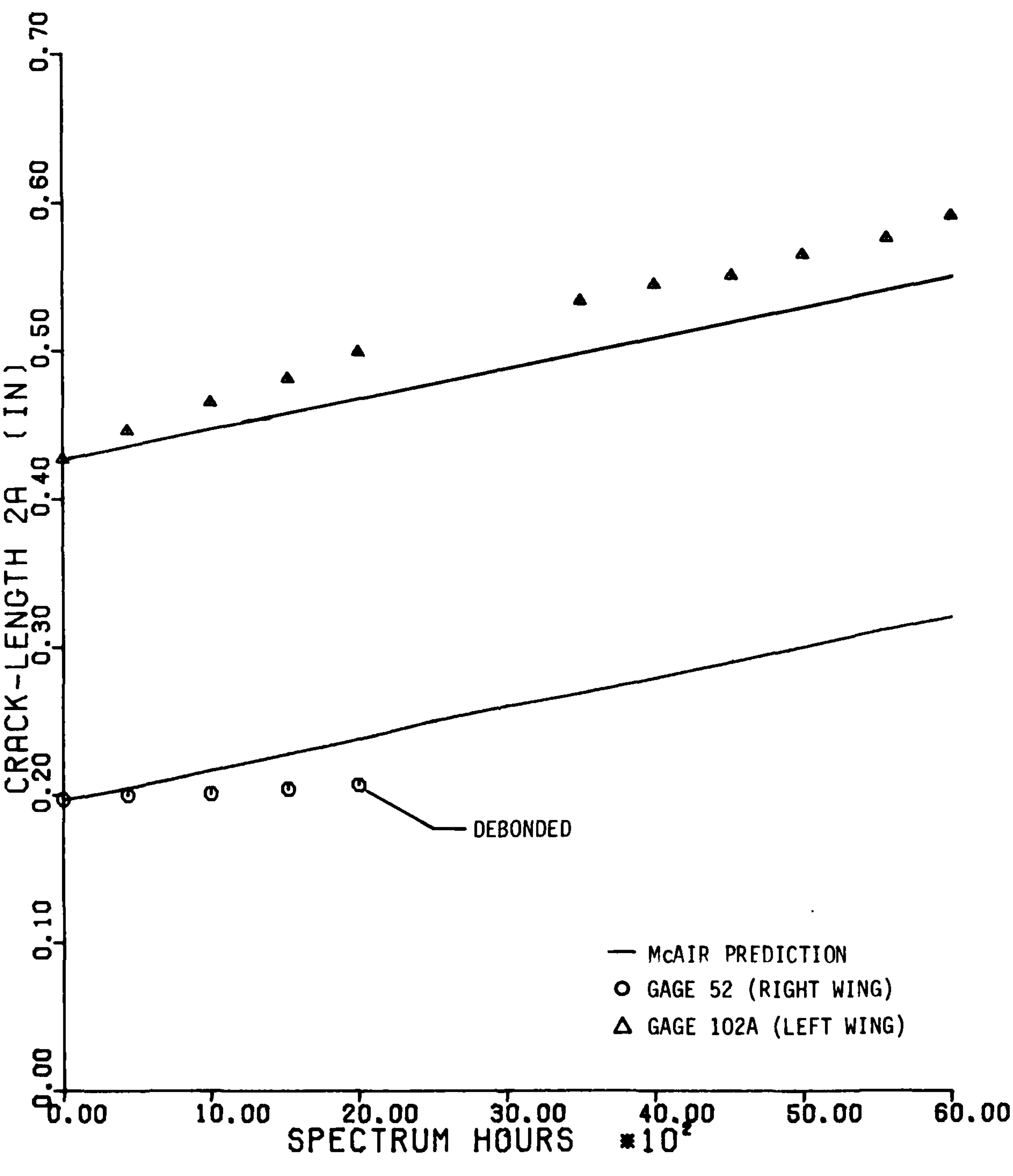



Figure 21. Comparison of Crack Length Measurements and Predictions for Site 1 (Site 5 on Left Wing)

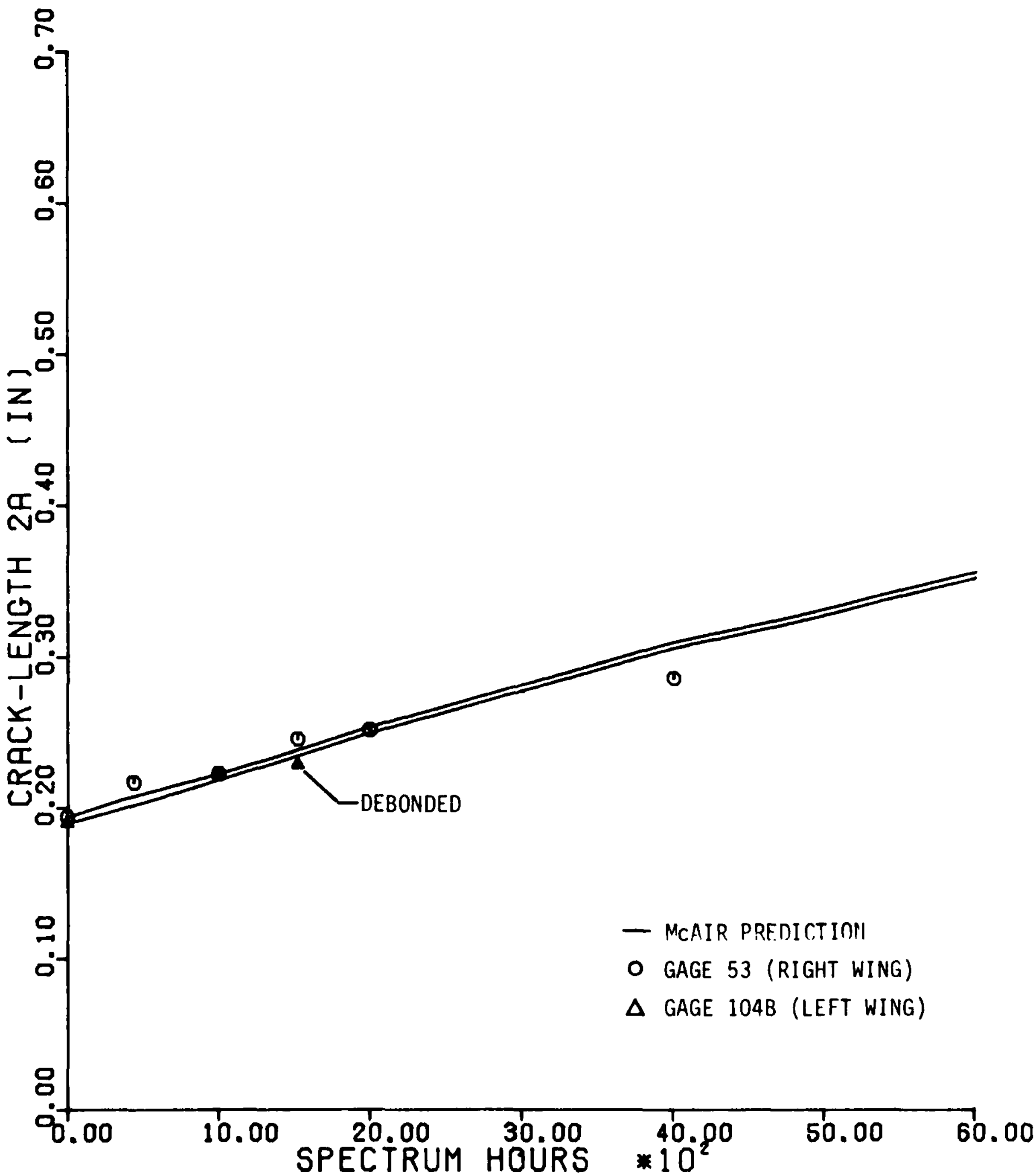



Figure 22. Comparison of Crack Length Measurements and Predictions for Site 2 (Site 4 on Left Wing)

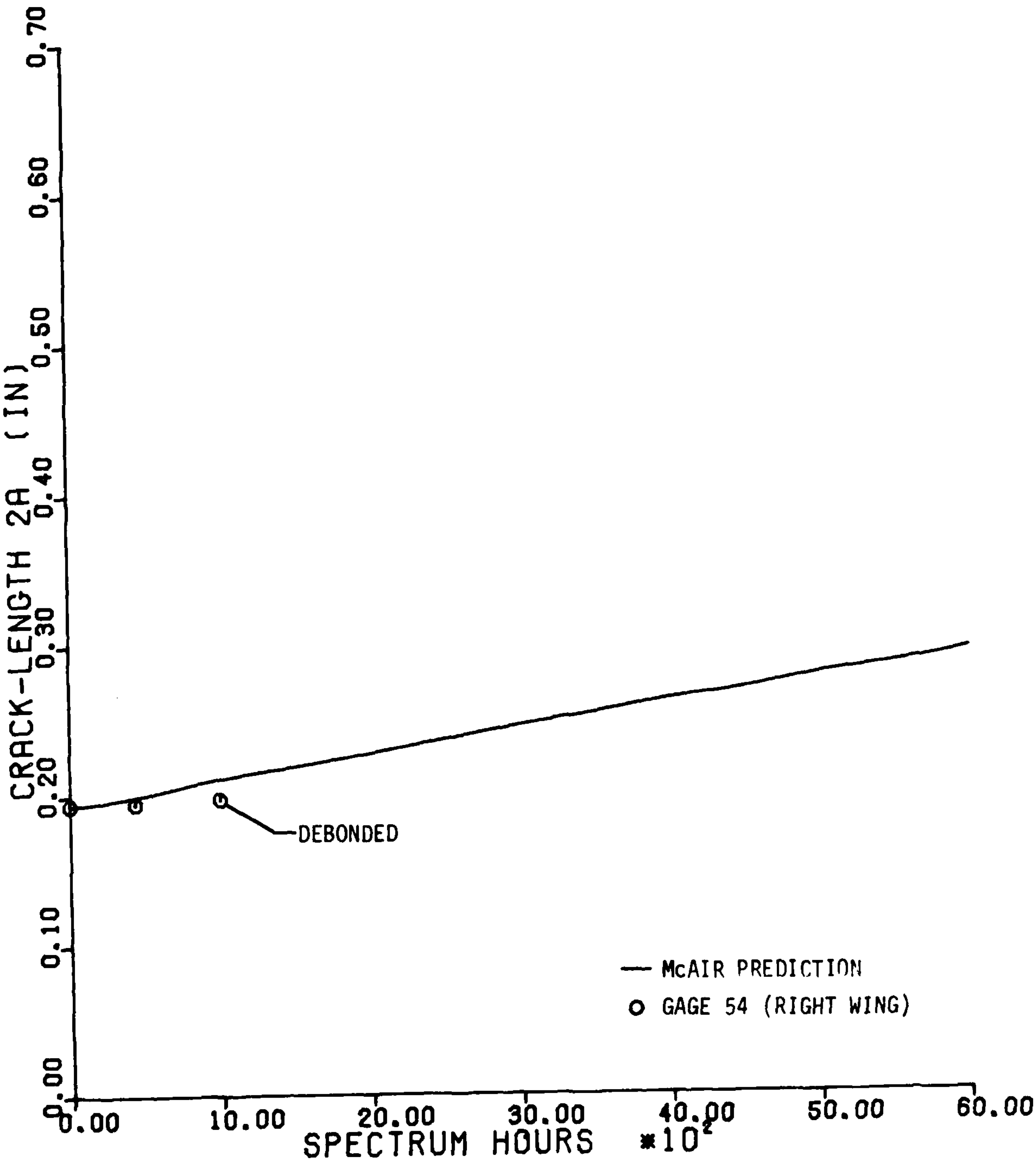



Figure 23. Comparison of Crack Length Measurements and Predictions for Site 3

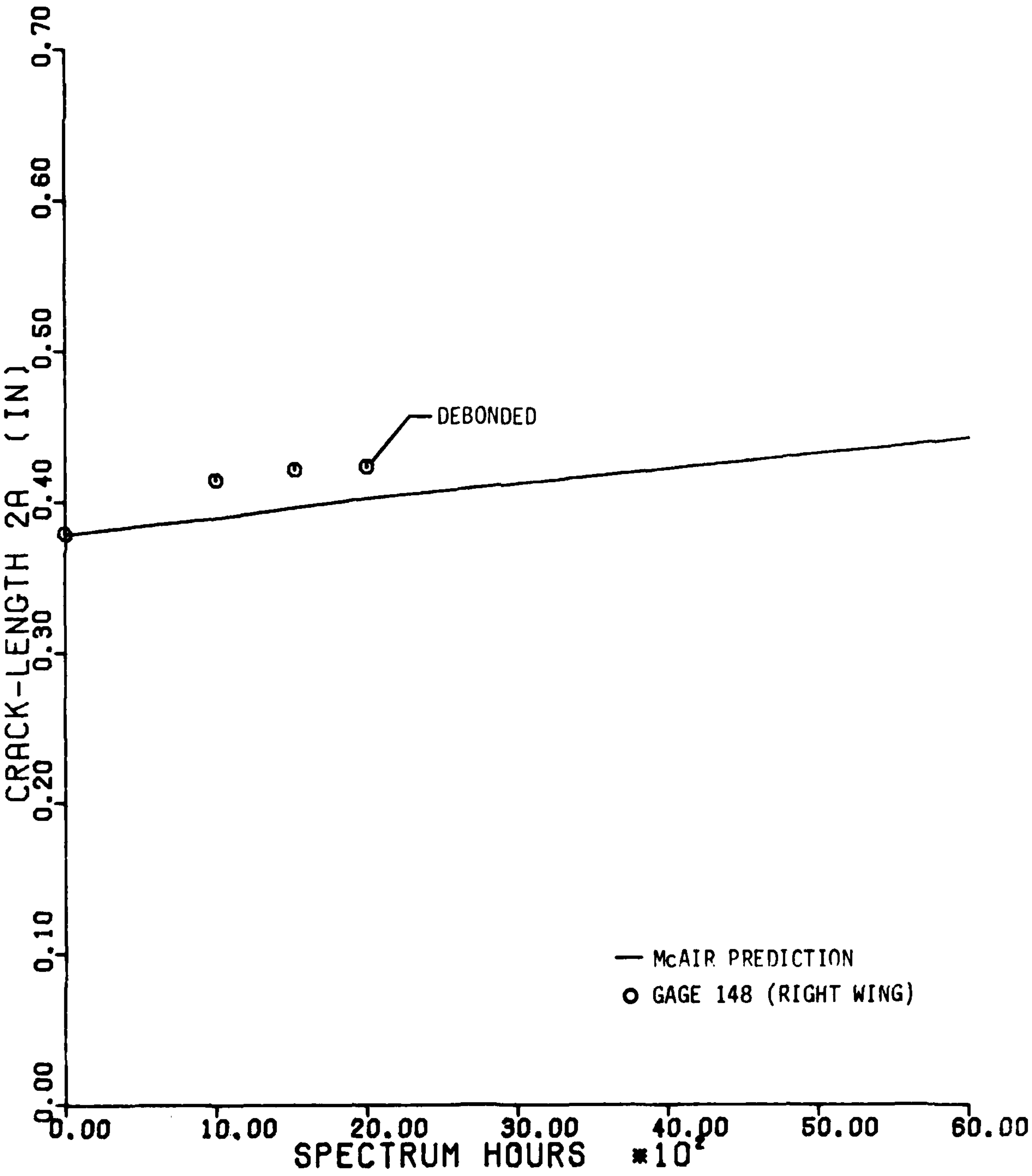



Figure 24. Comparison of Crack Length Measurements and Predictions for Site 6

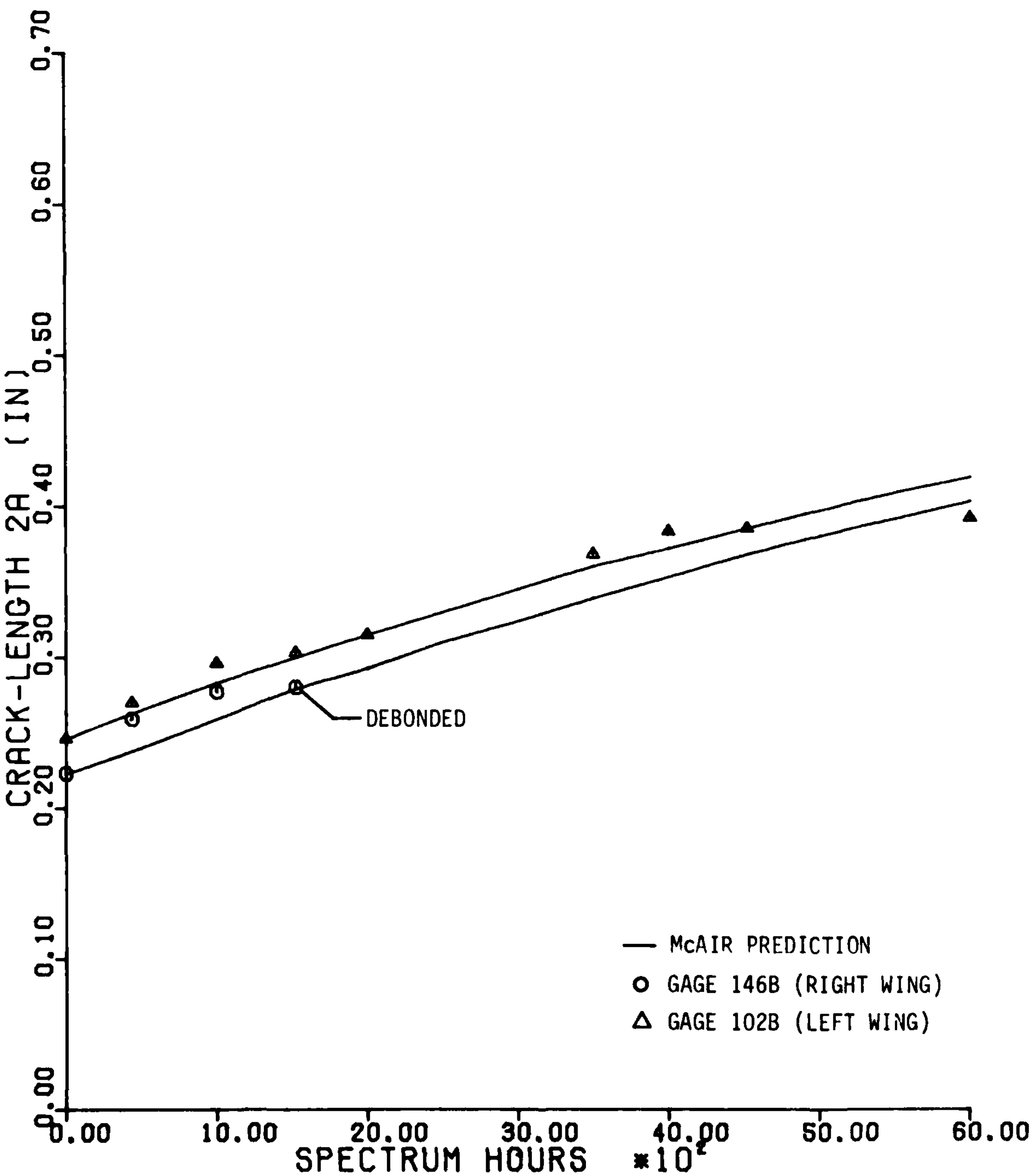



Figure 25. Comparison of Crack Length Measurements and Predictions for Site 7 (Site 8 on Left Wing)

## SECTION IV

## CONCLUSIONS

Results obtained from this program suggest that crack growth in crack growth gages adhesively bonded to an aircraft is generally predictable using techniques developed by McAir personnel. However, there are problems that still exist in the crack growth gage concept. Considerable further research is required to (1) develop a simple procedure for reliably bonding gages to an aircraft structure, (2) demonstrate reproducibility of crack growth from gage to gage, and (3) complete gage qualification and service evaluation testing. These tasks must be completed before the crack growth gage can be implemented fleet-wide to track aircraft service life.

The main observations of this program are summarized in the following paragraphs.

1. Bonding of the crack growth gages to the F-4 full-scale fatigue article with FM-73, a heat cure adhesive, was unsuccessful due to circumstances peculiar to this structure. Investigation led to the discovery that the entire aircraft structure had been coated with a silicone spray. This is a possible explanation as to why debonding occurred within a very short period of time (i.e., less than 1500 flight hours). Therefore, this test did not aid in qualifying FM-73 adhesive for bonding of the gages to fleet aircraft.

2. Although it was known that EA-9309.1, a room temperature cure adhesive, did not have the strength, temperature resistance, or environmental durability of FM-73, EA9309.1 was used to bond eight crack growth gages to the fatigue article in an attempt to obtain usable data from the full-scale

test. Because of durability limitations of EA9309.1, three of the eight gages had visually debonded after 2000 hours of simulated flight. After 4000 spectrum hours only three gages (one McAir gage; two AFFDL gages) remained attached to the structure. Data obtained from these remaining gages generally agreed with behavior predicted by McAir personnel.

3. Considerable variations were noted between constant amplitude tests performed by McAir and AFFDL personnel. Crack growth rates were considerably slower for gages manufactured and bonded by AFFDL personnel. A large amount of scatter was observed in the AFFDL constant amplitude tests. Unfortunately, no definite explanations could be found for these dissimilarities.

4. The Fax-Film method of recording crack length in the gages was found to provide an adequate replica of the crack.

## SECTION V

## RECOMMENDATIONS

Due to inconsistencies in constant amplitude test results and problems encountered during bonding of the gages to the F-4 full-scale fatigue article, it is recommended that research and development of the crack growth gage as a possible fleet-wide tracking device be continued.

It is also recommended that further research be undertaken to:

1. Develop a simple procedure for reliably bonding crack growth gages to an aircraft structure.

2. Demonstrate reproducibility of crack growth from gage to gage.

3. Complete a comprehensive gage qualification test program in accordance with MIL-STD-810C requirements.

4. Complete a comprehensive gage qualification test program defining the operational parameters and limitations for using Fax-Film under actual field conditions.

5. Determine the protection required (i.e., cover, sealant, paint, etc.) for an externally mounted gage.

6. Consider developing a crack growth gage with a life less than the life of the aircraft (eg, a gage that would last 1000 or 2000 hours). This type of gage could have the capability of producing more data points throughout the life of the aircraft than a gage that was developed to last the design life of the aircraft.

## APPENDIX A

## da/dN COUPON TEST RESULTS

This appendix contains tabulated data (Tables A-1 and A-2) and log-log plots of da/dN versus $\Delta K$ (Figure A-1) for the da/dN coupon tests.

TABLE A-1. da/dN COUPON TESTS

| da/dn Specimen | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| TEST SECTION THICKNESS(IN) | 0.041 | 0.041 | 0.038 | 0.040 |
| SLOT LENGTH (IN) | 0.098 | 0.093 | 0.104 | 0.104 |
| Pmax (LBS) | 1000 | 900 | 700 | 700 |
| Pmin (LBS) | 0 | 0 | 0 | 0 |
| CYCLIC RATE (Hz) | 2.5 | 2.5 | 2.5 | 2.5 |

TABLE A-2. CRACK PROPAGATION DATA FOR da/dN COUPON TESTS

| da/dN - 1 | | da/dN - 2 | | da/dN - 3 | | da/dN - 4 | |
|---|---|---|---|---|---|---|---|
| N | 2a (in.) | N | 2a(in.) | N | 2a(in.) | N | 2a(in.) |
| 0 | 0.098 | 0 | 0.093 | 0 | .104 | 0 | 0.104 |
| 9000 | 0.135 | 11000 | 0.100 | 25000 | .108 | 50000 | 0.197 |
| 14000 | 0.219 | 12000 | 0.110 | 29000 | .122 | 52000 | 0.210 |
| 16000 | 0.274 | 13000 | 0.121 | 30000 | .132 | 54000 | 0.221 |
| 18000 | 0.350 | 14000 | 0.128 | 31000 | .138 | 56000 | 0.243 |
| 20000 | 0.454 | 15000 | 0.131 | 32000 | .144 | 57000 | 0.249 |
| 22000 | 0.625 | 16000 | 0.133 | 34000 | .154 | 58000 | 0.261 |
| 24000 | 0.914 | 17000 | 0.139 | 36000 | .169 | 59000 | 0.271 |
| | | 18000 | 0.145 | 36000 | .197 | 60000 | 0.282 |
| | | 19000 | 0.157 | 40000 | .212 | 61000 | 0.295 |
| | | 20000 | 0.169 | 42000 | .239 | 62000 | 0.306 |
| | | 21000 | 0.184 | 44000 | .272 | 63000 | 0.316 |
| | | 22000 | 0.194 | 46000 | .306 | 64000 | 0.336 |
| | | 23000 | 0.211 | 48000 | .345 | 65000 | 0.345 |
| | | 24000 | 0.224 | 50000 | .390 | 66000 | 0.372 |
| | | 25000 | 0.244 | 52000 | .437 | 67000 | 0.393 |
| | | 26000 | 0.257 | 54000 | .513 | 68000 | 0.413 |
| | | 27000 | 0.272 | 55000 | 0.551 | 69000 | 0.446 |
| | | 28000 | 0.299 | 56000 | 0.600 | 70000 | 0.472 |
| | | 29000 | 0.327 | 57000 | 0.653 | 71000 | 0.500 |
| | | 30000 | 0.357 | 58000 | 0.712 | 72000 | 0.535 |
| | | 31000 | 0.385 | 59000 | 0.789 | 73000 | 0.568 |
| | | 32000 | 0.427 | 60000 | 0.884 | 74000 | 0.609 |
| | | 33000 | 0.465 | 61000 | 1.017 | 75000 | 0.661 |
| | | 34000 | 0.519 | 61500 | 1.164 | 76000 | 0.714 |
| | | 35000 | 0.570 | | | 77000 | 0.767 |
| | | 36000 | 0.630 | | | 78000 | 0.828 |
| | | 37000 | 0.705 | | | 79000 | 0.920 |
| | | 37500 | 0.760 | | | 80000 | 1.005 |
| | | 38000 | 0.857 | | | | |
| | | 38500 | 0.930 | | | | |

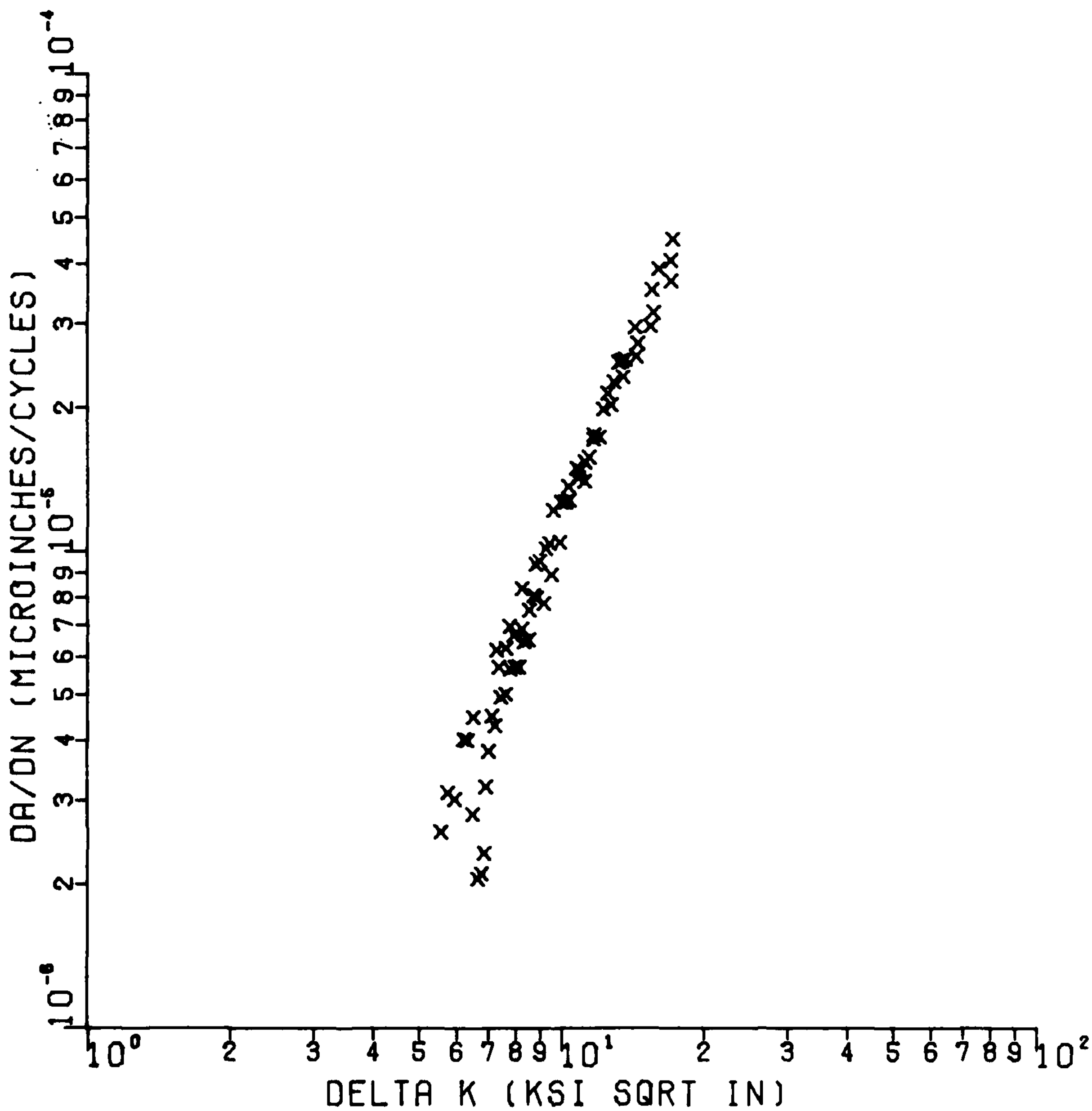



Figure A-1. Crack Growth Rate for 7075-T6 da/dN Coupons

# APPENDIX B

## STRAIN MEASUREMENTS

Prior to testing of the slotted crack growth gages, one carrier specimen and its adhesively bonded crack growth gages were extensively instrumented with strain gages to measure stresses on the specimen as well as the stresses transferred from the specimen through the adhesive to the crack growth gage. Strain gage locations are shown in Figure B-1. Strain measurements taken under static load conditions are shown in Table B-1.

During the primary testing of the slotted crack growth gages, several carrier specimens and crack growth gages were instrumented with strain gages. Strain gage locations are shown in Figure B-2. Strain measurements taken under static load conditions are shown in Table B-2.

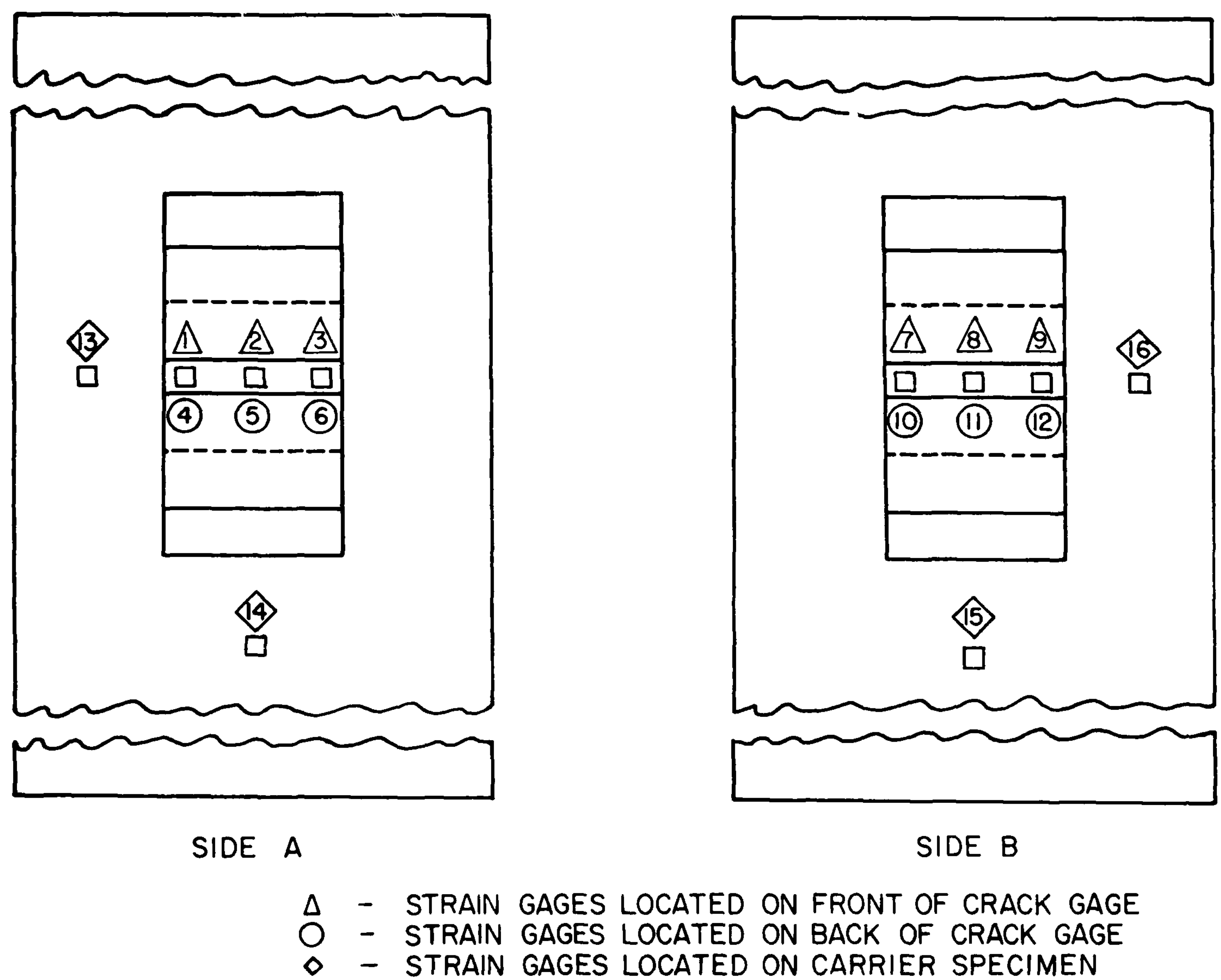



Figure B-1. Strain Gage Locations on Load Transfer Specimen

TABLE B-1. STRAIN SURVEY RESULTS FOR LOAD TRANSFER SPECIMEN 1-1-1

| SPECIMEN CONDITION | STRESS (KSI) | LOAD (KIPS) | STRAIN (MICRO-INCHES) 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Prior to Fatigue Cycling | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 6695 | 650 | 620 | 605 | 689 | 660 | 665 | 750 | 725 | 735 | 695 | 720 | 735 | 460 | 500 | 515 | 480 |
| | 10 | 13390 | 1310 | 1250 | 1230 | 1380 | 1330 | 1340 | 1500 | 1465 | 1480 | 1400 | 1455 | 1475 | 925 | 1015 | 1035 | 965 |
| | 15 | 20085 | 2070 | 1970 | 1940 | 2165 | 2085 | 2095 | 2345 | 2285 | 2305 | 2195 | 2275 | 2310 | 1450 | 1590 | 1620 | 1505 |
| | 20 | 26780 | 2675 | 2550 | 2515 | 2790 | 2690 | 2710 | 3020 | 2950 | 2975 | 2840 | 2930 | 2975 | 1875 | 2050 | 2085 | 1940 |
| After 22000 Fatigue Cycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 6695 | 655 | 625 | 615 | 700 | 670 | 675 | 755 | 755 | 735 | 705 | 730 | 750 | 470 | 505 | 525 | 485 |
| | 10 | 13390 | 1325 | 1275 | 1250 | 1410 | 1350 | 1360 | 1520 | 1495 | 1485 | 1425 | 1480 | 1500 | 950 | 1040 | 1065 | 985 |
| | 15 | 20085 | 2095 | 2000 | 1980 | 2205 | 2120 | 2135 | 2370 | 2335 | 2335 | 2230 | 2310 | 2340 | 1490 | 1630 | 1655 | 1535 |
| | 20 | 26780 | 2680 | 2565 | 2535 | 2815 | 2710 | 2730 | 3035 | 2985 | 2990 | 2760 | 2965 | 3005 | 1920 | 2100 | 2120 | 1970 |
| After 42000 Fatigue Cycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | △ | 0 |
| | 5 | 6695 | 630 | 600 | 595 | 670 | 650 | 650 | 730 | 715 | 715 | 680 | 715 | 730 | 470 | 510 | | 475 |
| | 10 | 13390 | 1330 | 1275 | 1255 | 1400 | 1355 | 1355 | 1515 | 1480 | 1490 | 1420 | 1480 | 1500 | 965 | 1050 | | 975 |
| | 15 | 20085 | 2050 | 1965 | 1940 | 2155 | 2080 | 2085 | 2325 | 2275 | 2290 | 2185 | 2275 | 2300 | 1480 | 1615 | | 1505 |
| | 20 | 26780 | 2595 | 2480 | 2450 | 2720 | 2625 | 2630 | 2925 | 2865 | 2885 | 2755 | 2855 | 2890 | 1865 | 2020 | | 1920 |
| After 62000 Fatigue Cycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | △2 |
| | 5 | 6695 | 650 | 620 | 615 | 685 | 665 | 670 | 750 | 720 | 735 | 705 | 730 | 710 | 440 | 500 | 515 | |
| | 10 | 13390 | 1310 | 1265 | 1245 | 1390 | 1340 | 1450 | 1510 | 1460 | 1475 | 1410 | 1450 | 1450 | 910 | 1015 | 1035 | |
| | 15 | 20085 | 2055 | 1980 | 1950 | 2165 | 1985 | 2205 | 2345 | 2275 | 2310 | 2205 | 2265 | 2275 | 1440 | 1590 | 1610 | |
| | 20 | 26780 | 2690 | 2580 | 2545 | 2820 | 2620 | 2840 | 3040 | 2965 | 3000 | 2865 | 2960 | 3060 | 1910 | 2070 | 2090 | |
| After 84000 Fatigue Cycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | 5 | 6695 | 665 | 630 | 625 | 700 | 680 | 685 | 760 | 740 | 745 | 710 | 735 | 740 | 500 | 530 | 530 | |
| | 10 | 13390 | 1325 | 1265 | 1245 | 1395 | 1350 | 1355 | 1510 | 1475 | 1485 | 1415 | 1470 | 1480 | 1025 | 1045 | 1055 | |
| | 15 | 20085 | 1990 | 1905 | 1885 | 2095 | 2025 | 2035 | 2265 | 2210 | 2230 | 2130 | 2205 | 2220 | 1415 | 1570 | 1575 | |
| | 20 | 26780 | 2665 | 2550 | 2525 | 2790 | 2695 | 2710 | 3005 | 2940 | 2965 | 2835 | 2930 | 2950 | 2015 | 2090 | 2090 | |
| After 102000 Fatigue Cycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | △2 | 0 | 0 | △2 | 0 | 0 | 0 | |
| | 5 | 6695 | 650 | 625 | 620 | 700 | 675 | 680 | 770 | 755 | | 715 | 745 | | 515 | 525 | 530 | |
| | 10 | 13390 | 1295 | 1245 | 1235 | 1390 | 1340 | 1350 | 1525 | 1540 | | 1415 | 1505 | | 990 | 1045 | 1050 | |
| | 15 | 20085 | 1935 | 1860 | 1840 | 2070 | 1990 | 1905 | 2260 | 2300 | | 2110 | 2245 | | 1455 | 1555 | 1560 | |
| | 20 | 26780 | 2605 | 2500 | 4215 | 2770 | 2670 | 2585 | 3015 | 3090 | | 2825 | 3020 | | 2100 | 2085 | 2090 | |

△ Wire Broke Lose

△2 Strain Gage Failed

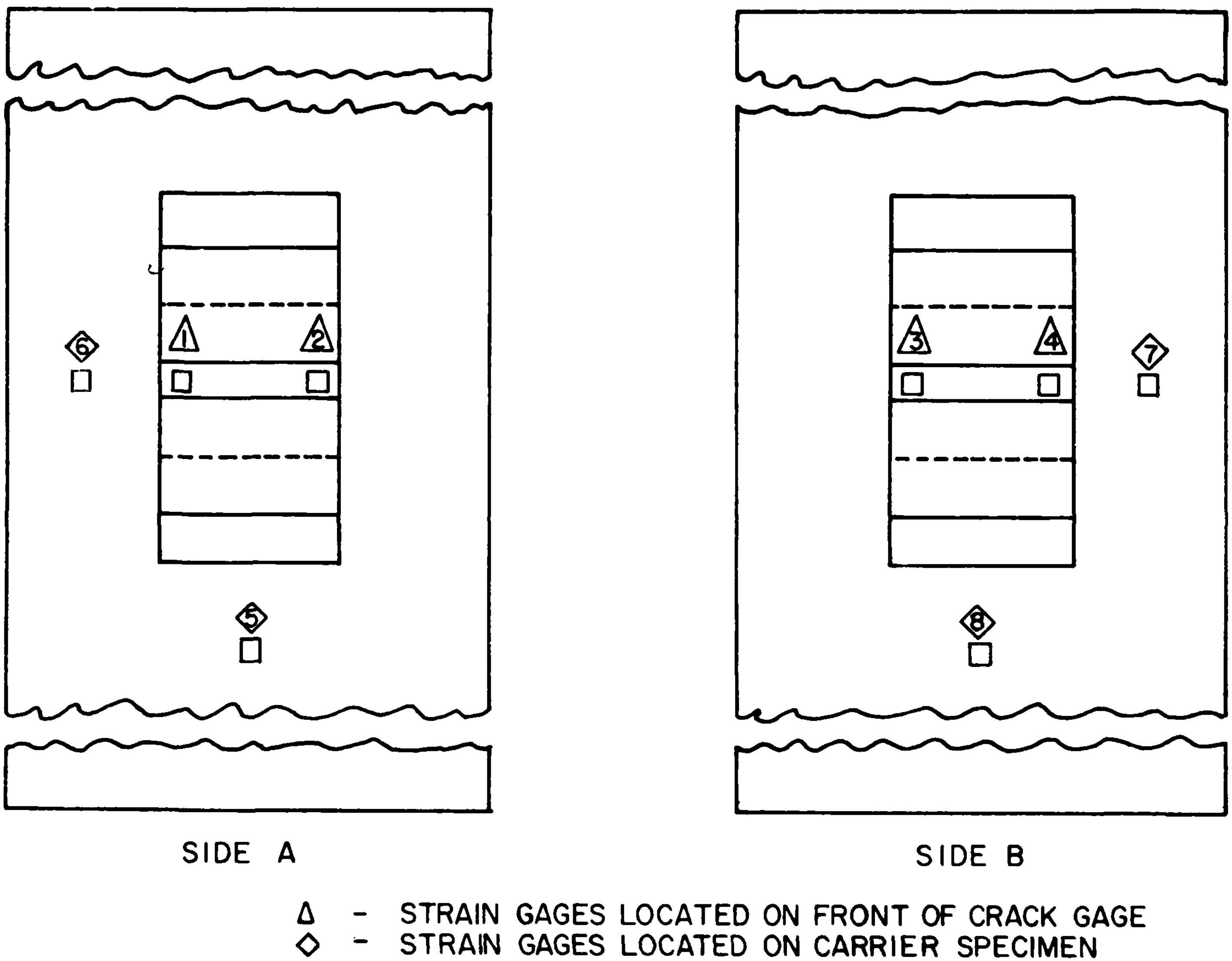



Figure B-2. Strain Gage Locations on Slotted Crack Growth Gages

TABLE B-2. STRAIN SURVEY RESULTS FOR THREE CRACK GROWTH GAGES PRIOR TO CYCLIC TESTING

| SPECIMEN NUMBER | STRESS (KSI) | LOAD (KIPS) | STRAIN (MICRO-INCHES) 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| 100A/100B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 6695 | 645 | 630 | 695 | 720 | 510 | 445 | 470 | 545 |
| | 10 | 13390 | 1290 | 1275 | 1375 | 1430 | 1030 | 900 | 940 | 1085 |
| | 15 | 20085 | 2005 | 1980 | 2125 | 2210 | 1600 | 1400 | 1460 | 1680 |
| | 21 | 28120 | 2710 | 2680 | 2855 | 2965 | 2170 | 1900 | 1975 | 2270 |
| 110A/110B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 6695 | 600 | 599 | 660 | 639 | 519 | 395 | 412 | 510 |
| | 10 | 13390 | 1225 | 1220 | 1303 | 1269 | 1016 | 812 | 838 | 1007 |
| | 15 | 20085 | 1920 | 1907 | 2022 | 1973 | 1574 | 1280 | 1304 | 1565 |
| | 21 | 28120 | 2605 | 2584 | 2722 | 2660 | 2131 | 1742 | 1772 | 2106 |
| 48A/48B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 6695 | 635 | 615 | 710 | 745 | 560 | 440 | 470 | 535 |
| | 10 | 13390 | 1275 | 1335 | 1425 | 1510 | 1130 | 890 | 945 | 1065 |
| | 15 | 20085 | 1975 | 2010 | 2190 | 2235 | 1695 | 1345 | 1445 | 1620 |
| | 21 | 28120 | 2660 | 2770 | 2920 | 3110 | 2310 | 1895 | 1950 | 2205 |

# APPENDIX C

## CONSTANT AMPLITUDE TEST RESULTS

This appendix contains tabulated results and graphical plots of crack length versus cycles for each specimen tested. The crack propagation results are presented in Tables C-1 through C-12. Plots of the test data are presented in Figures C-1 through C-12. Figure C-13 shows the results of constant amplitude tests performed on crack growth gages bonded with EA9309.1 adhesive compared with the McAir test results on gages bonded with FM-73 adhesive.

TABLE C-1. CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES 8A AND 8B

| | |
|---|---|
| GAGE SIZE NORMAL (W/O TABS) | $P_{MAX}$ 28120 LBS |
| ATTACHMENT FM-73 | $P_{MIN}$ 0 LBS |
| ENVIRONMENT LAB AIR | CYCLIC RATE 0.5 HZ |

| CRACK GROWTH GAGE 8A | | CRACK GROWTH GAGE 8B | |
|---|---|---|---|
| CYCLES N | CRACK LENGTH 2a (INCHES) | CYCLES N | CRACK LENGTH 2a (INCHES) |
| EDM | 0.105 | EDM | 0.103 |
| PRECRACK | 0.151 | PRECRACK | 0.113 |
| 1000 | 0.190 | 1000 | 0.136 |
| 2000 | 0.234 | 2000 | 0.158 |
| 3000 | 0.277 | 3000 | 0.183 |
| 4000 | 0.319 | 4000 | 0.207 |
| 5000 | 0.366 | 5000 | 0.234 |
| 6000 | 0.417 | 6000 | 0.263 |
| 7000 | 0.471 | 7000 | 0.294 |
| 8000 | 0.525 | 8000 | 0.322 |
| 9000 | 0.590 | 9000 | 0.359 |
| 10000 | 0.671 | 10000 | 0.402 |
| 11000 | 0.744 | 11000 | 0.439 |
| 12000 | 0.798 | 12000 | 0.479 |
| 13000 | 0.917 | 13000 | 0.545 |
| 14000 | 1.009 | 14000 | 0.574 |
| 15000 | 1.126 | 15000 | 0.611 |
| 16000 | | 16000 | 0.640 |
| 17000 | | 17000 | 0.667 |
| 18000 | | 18000 | 0.731 |
| 19000 | | 19000 | 0.756 |
| 20000 | | 20000 | 0.787 |
| 21000 | | 21000 | 0.835 |
| 22000 | | 22000 | 0.874 |
| 23000 | | 23000 | 0.926 |
| 24000 | | 24000 | 0.969 |
| 25000 | | 25000 | 1.036 |
| 26000 | | 26000 | 1.084 |

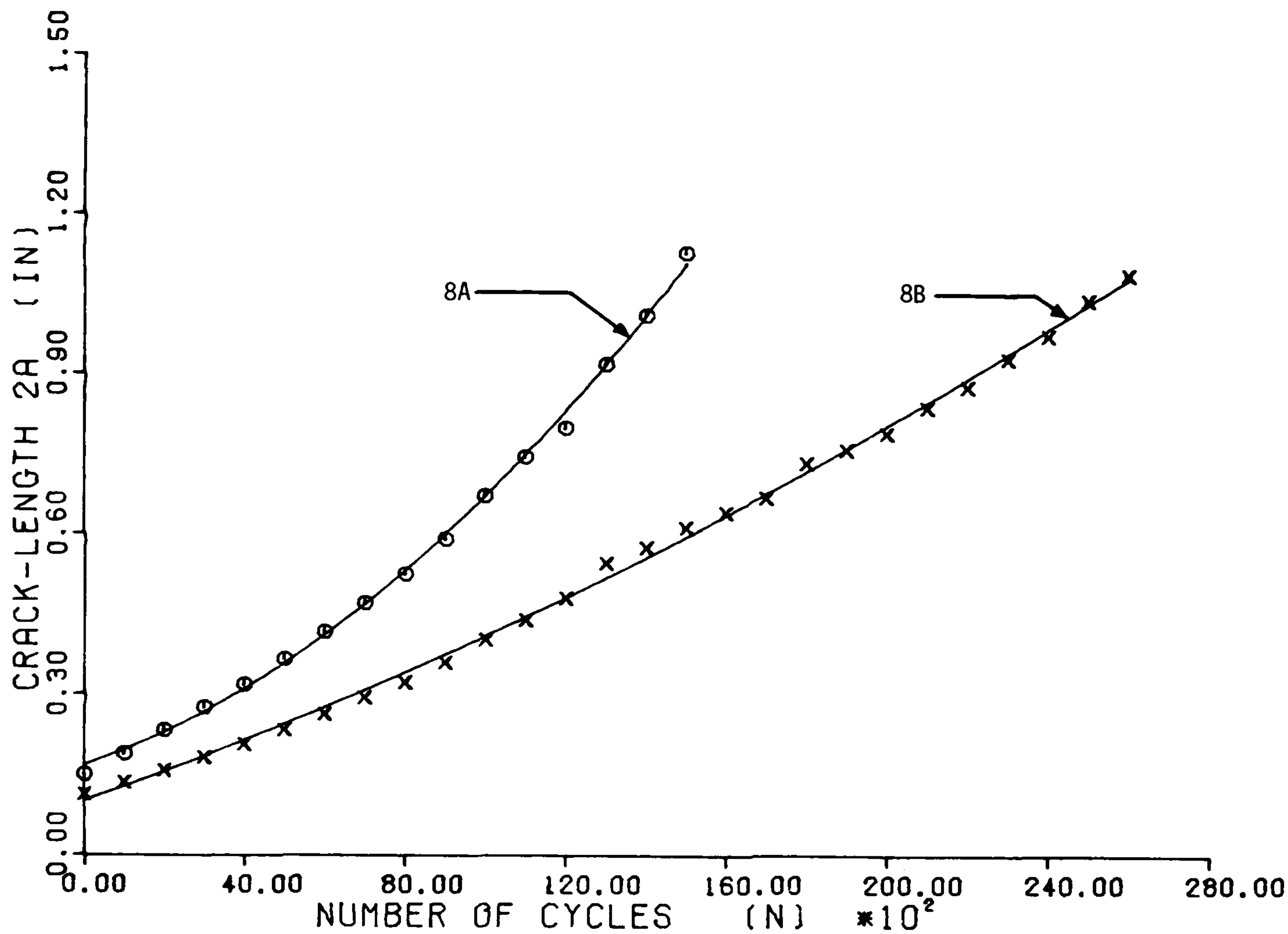



Figure C-1. Constant Amplitude Tests of Crack Growth Gages 8A and 8B

TABLE C-2 CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES 18A AND 18B

| | | | |
|---|---|---|---|
| GAGE SIZE | NORMAL (W/O TABS) | $P_{MAX}$ | 28120 LBS |
| ATTACHMENT | FM-73 | $P_{MIN}$ | 0 LBS |
| ENVIRONMENT | LAB AIR | CYCLIC RATE | 1.0 Hz |

| CRACK GROWTH GAGE 18A | | CRACK GROWTH GAGE 18B | |
|---|---|---|---|
| CYCLES N | CRACK LENGTH 2a (INCHES) | CYCLES N | CRACK LENGTH 2a (INCHES) |
| EDM | 0.100 | EDM | 0.103 |
| 2000 | 0.117 | 2000 | 0.117 |
| 4000 | 0.155 | 4000 | 0.164 |
| 6000 | 0.208 | 6000 | 0.216 |
| 8000 | 0.287 | 8000 | 0.294 |
| 10000 | 0.353 | 10000 | 0.378 |
| 11000 | 0.391 | 11000 | 0.414 |
| 12000 | 0.436 | 12000 | 0.467 |
| 13000 | 0.487 | 13000 | 0.527 |
| 14000 | 0.540 | 14000 | 0.590 |
| 15000 | 0.592 | 15000 | 0.647 |
| 16000 | 0.645 | 16000 | 0.711 |
| 17000 | 0.716 | 17000 | 0.755 |
| 18000 | 0.773 | 18000 | 0.858 |
| 19000 | 0.826 | 19000 | 0.931 |
| 20000 | 0.888 | 20000 | 1.003 |
| 21000 | 0.945 | 21000 | 1.096 |
| 22000 | 1.010 | 22000 | 1.185 |
| 23000 | 1.074 | 23000 | 1.297 |
| 24000 | 1.134 | | |
| 25000 | 1.208 | | |
| 26000 | 1.293 | | |

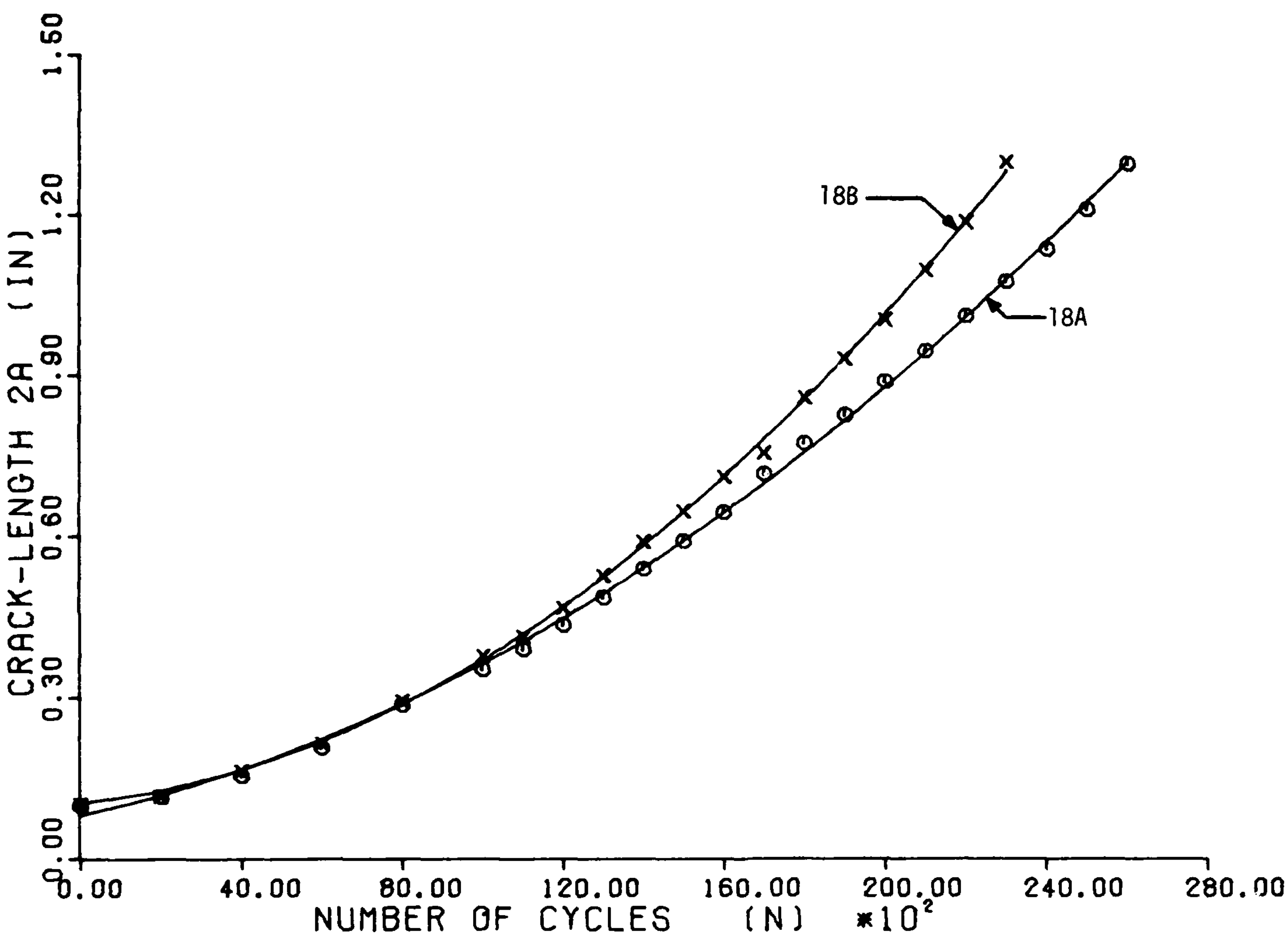



Figure C-2. Constant Amplitude Test of Crack Growth Gages 18A and 18B

TABLE C-3 CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES 30A AND 30B

| | |
|---|---|
| GAGE SIZE NORMAL (W/O TABS) | $P_{MAX}$ 28120 LBS |
| ATTACHMENT FM-73 | $P_{MIN}$ 0 LBS |
| ENVIRONMENT LAB AIR | CYCLIC RATE 0.5 HZ |

| CRACK GROWTH GAGE 30A | | CRACK GROWTH GAGE 30B | |
|---|---|---|---|
| CYCLES N | CRACK LENGTH 2a (INCHES) | CYCLES N | CRACK LENGTH 2a (INCHES) |
| EDM | 0.100 | EDM | 0.102 |
| PRECRACK | 0.186 | PRECRACK | 0.314 |
| 1000 | 0.226 | 1000 | 0.375 |
| 2000 | 0.271 | 2000 | 0.432 |
| 3000 | 0.320 | 3000 | 0.482 |
| 4000 | 0.360 | 4000 | 0.548 |
| 5000 | 0.402 | 5000 | 0.621 |
| 6000 | 0.455 | 6000 | 0.689 |
| 7000 | 0.515 | 7000 | 0.774 |
| 8000 | 0.562 | 8000 | 0.865 |
| 9000 | 0.621 | 9000 | 0.958 |
| 10000 | 0.687 | 10000 | 1.061 |
| 11000 | 0.745 | 11000 | 1.163 |
| 12000 | 0.804 | 12000 | 1.304 |
| 13000 | 0.870 | | |
| 14000 | 0.928 | | |
| 15000 | 0.996 | | |
| 16000 | 1.067 | | |
| 18000 | 1.225 | | |
| 19000 | 1.305 | | |

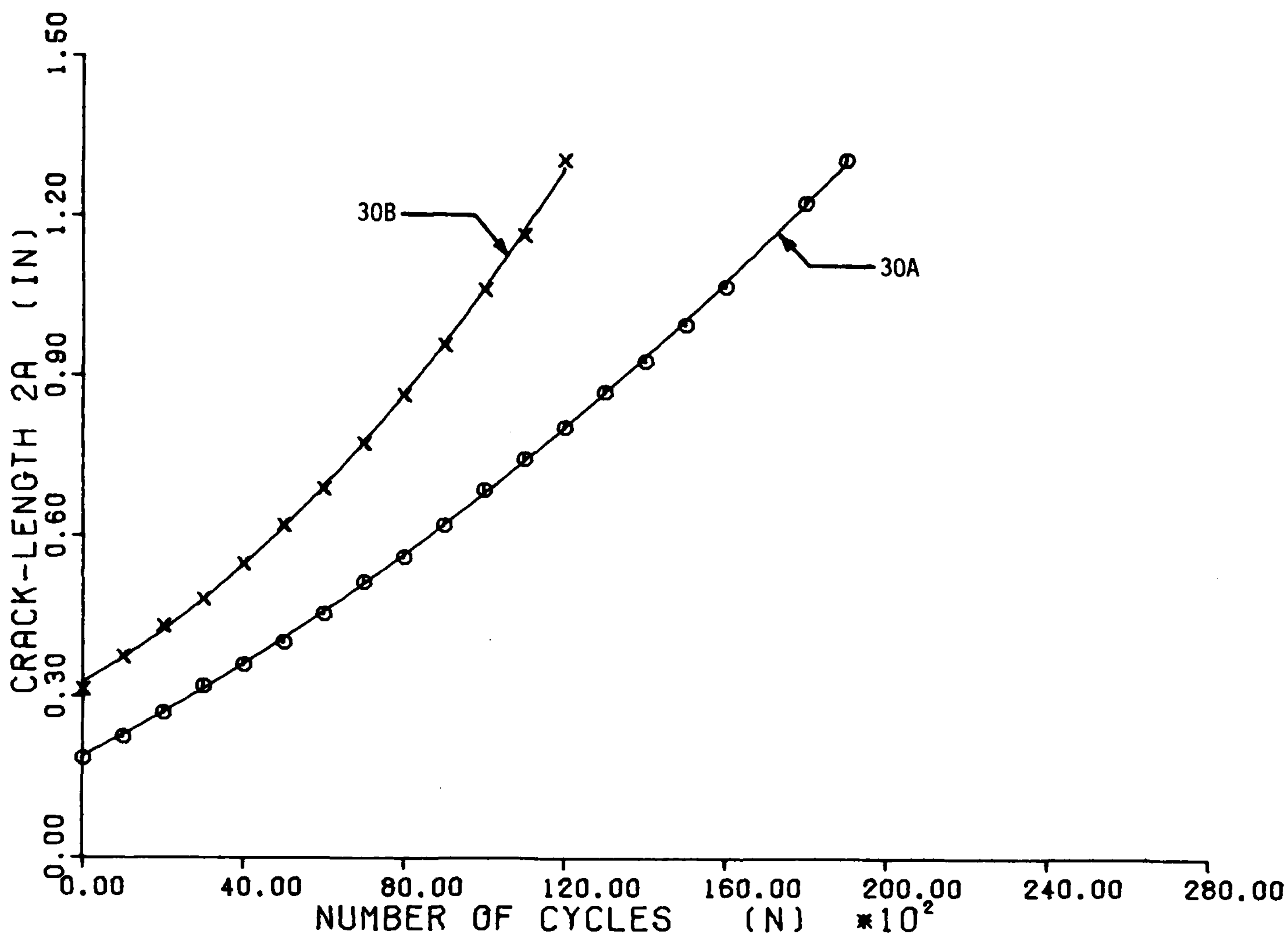



Figure C-3. Constant Amplitude Test of Crack Growth Gages 30A and 30B

TABLE C-4. CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES 24A AND 24B

| | |
|---|---|
| GAGE SIZE NORMAL (W/O TABS) | $P_{MAX}$ 28120 LBS |
| ATTACHMENT FM-73 | $P_{MIN}$ 0 LBS |
| ENVIRONMENT LAB AIR | CYCLIC RATE 0.5 HZ |

| CRACK GROWTH GAGE 24A | | CRACK GROWTH GAGE 24B | |
|---|---|---|---|
| CYCLES N | CRACK LENGTH 2a (INCHES) | CYCLES N | CRACK LENGTH 2a (INCHES) |
| EDM | 0.101 | EDM | 0.103 |
| PRECRACK | 01268 | PRECRACK | 0.233 |
| 1000 | 0.312 | 1000 | 0.274 |
| 2000 | 0.356 | 2000 | 0.317 |
| 3000 | 0.404 | 3000 | 0.367 |
| 4000 | 0.446 | 4000 | 0.421 |
| 5000 | 0.494 | 5000 | 0.477 |
| 6000 | 0.559 | 6000 | 0.532 |
| 7000 | 0.607 | 7000 | 0.597 |
| 8000 | 0.654 | 8000 | 0.663 |
| 9000 | 0.720 | 9000 | 0.729 |
| 10000 | 0.788 | 10000 | 0.793 |
| 11000 | 0.860 | 11000 | 0.865 |
| 12000 | 0.936 | 12000 | 0.939 |
| 13000 | 1.001 | 13000 | 1.028 |
| 14000 | 1.079 | 14000 | 1.131 |
| 15000 | 1.147 | 15000 | 1.236 |
| 16000 | 1.249 | | |
| 17000 | 1.334 | | |

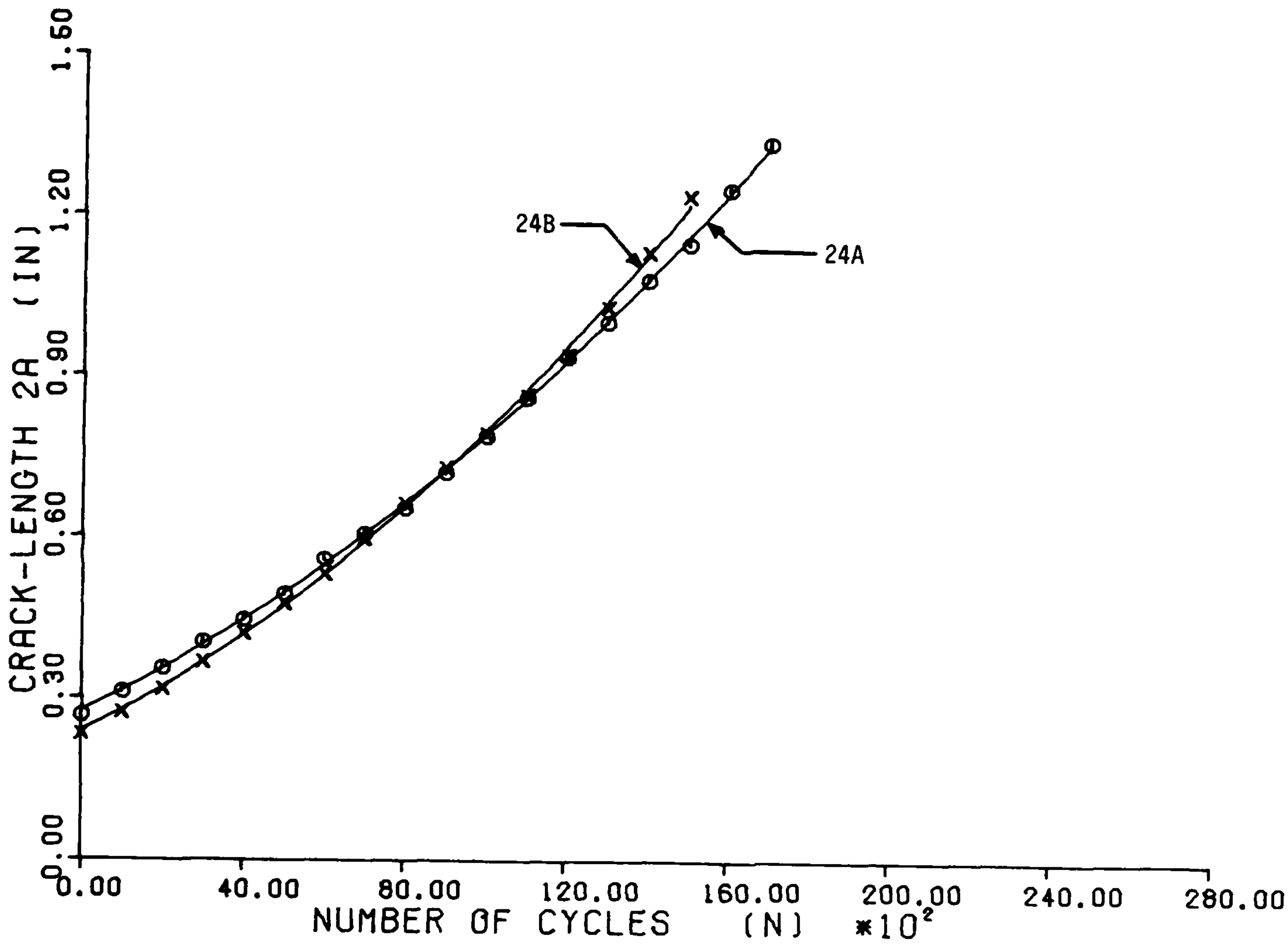



Figure C-4. Constant Amplitude Tests of Crack Growth Gages 24A and 24B

TABLE C-5. CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES M2A AND M2B

| | | | |
|---|---|---|---|
| GAGE SIZE | NORMAL (W/O TABS) | $P_{MAX}$ | 28120 LBS |
| ATTACHMENT | FM-73 | $P_{MIN}$ | 0 LBS |
| ENVIRONMENT | LAB AIR | CYCLIC RATE | 0.5 HZ |

| CRACK GROWTH GAGE M2A | | CRACK GROWTH GAGE M2B | |
|---|---|---|---|
| CYCLES N | CRACK LENGTH 2a (INCHES) | CYCLES N | CRACK LENGTH 2a (INCHES) |
| EDM | 0.101 | EDM | 0.087 |
| PRECRACK | 0.143 | PRECRACK | 0.177 |
| 1000 | 0.169 | 1000 | 0.221 |
| 2000 | 0.205 | 2000 | 0.287 |
| 3000 | 0.204 | 3000 | 0.310 |
| 4000 | 0.272 | 4000 | 0.363 |
| 5000 | 0.320 | 5000 | 0.431 |
| 6000 | 0.371 | 6000 | 0.502 |
| 7000 | 0.430 | 7000 | 0.581 |
| 8000 | 0.498 | 8000 | 0.676 |
| 9000 | 0.564 | 9000 | 0.774 |
| 10000 | 0.640 | 10000 | 0.963 |
| 11000 | 0.736 | 11000 | 1.075 |
| 12000 | 0.821 | 12000 | 1.308 |
| 13000 | 0.913 | | |
| 14000 | 1.027 | | |
| 15000 | 1.140 | | |
| 16000 | 1.308 | | |

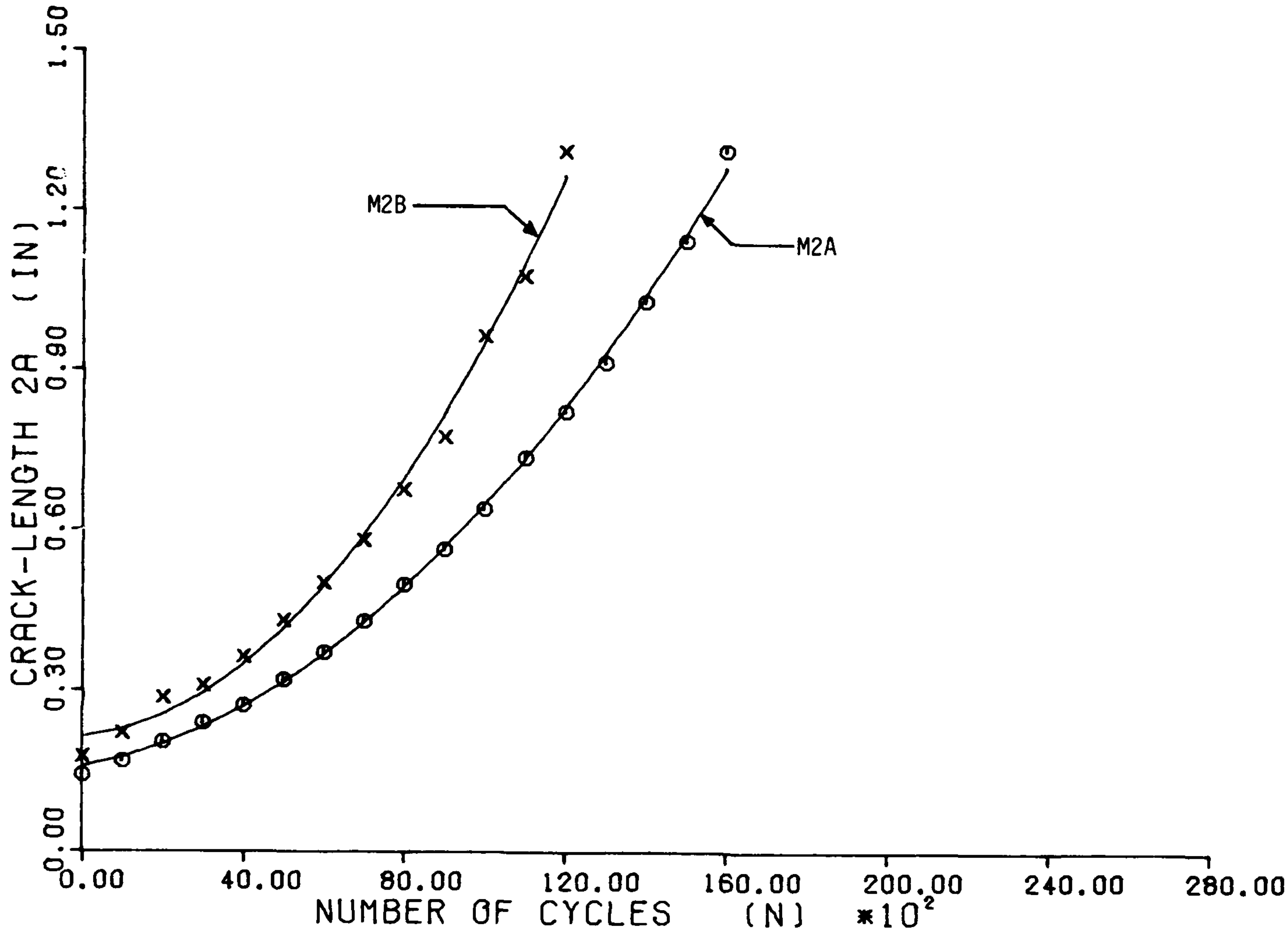



Figure C-5. Constant Amplitude Tests of Crack Growth Gages M2A and M2B

TABLE C-6. CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES M4A AND M4B

| | |
|---|---|
| GAGE SIZE NORMAL (W/O TABS) | $P_{MAX}$ 28120 LBS |
| ATTACHMENT FM-73 | $P_{MIN}$ 0 LBS |
| ENVIRONMENT LAB AIR | CYCLIC RATE 0.5 Hz |

| CRACK GROWTH GAGE M4A: CYCLES N | CRACK GROWTH GAGE M4A: CRACK LENGTH 2a (INCHES) | CRACK GROWTH GAGE M4B: CYCLES N | CRACK GROWTH GAGE M4B: CRACK LENGTH 2a (INCHES) |
|---|---|---|---|
| EDM | 0.106 | EDM | 0.105 |
| 1000 | 0.111 | 1000 | 0.114 |
| 2000 | 0.141 | 2000 | 0.136 |
| 3000 | 0.163 | 3000 | 0.164 |
| 4000 | 0.191 | 4000 | 0.190 |
| 5000 | 0.223 | 5000 | 0.227 |
| 6000 | 0.260 | 6000 | 0.270 |
| 7000 | 0.292 | 7000 | 0.312 |
| 8000 | 0.339 | 8000 | 0.359 |
| 9000 | 0.403 | 9000 | 0.415 |
| 10000 | 0.446 | 10000 | 0.471 |
| 11000 | 0.500 | 11000 | 0.535 |
| 12000 | 0.558 | 12000 | 0.612 |
| 13000 | 0.653 | 13000 | 0.693 |
| 14000 | 0.736 | 14000 | 0.784 |
| 15000 | 0.834 | 15000 | 0.897 |
| 16000 | 0.890 | 16000 | 1.016 |
| 17000 | 0.967 | 17000 | 1.170 |
| 18000 | 1.168 | 18000 | 1.380 |

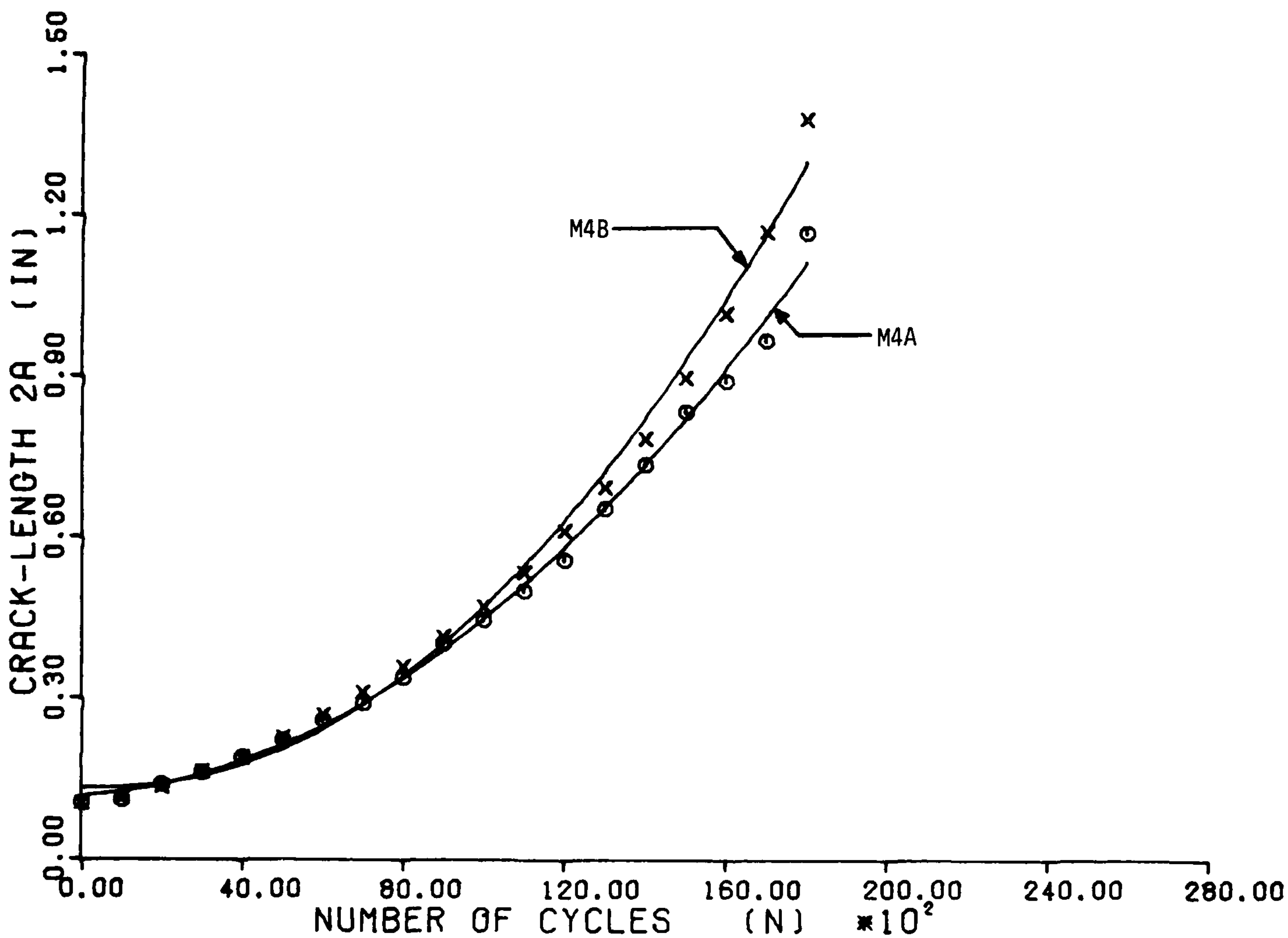



Figure C-6. Constant Amplitude Tests of Crack Growth Gages M4A and M4B

TABLE C-7. CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES 22A AND 22B

| | |
|---|---|
| GAGE SIZE LONG (WITH TABS) | $P_{MAX}$ 28120 LBS |
| ATTACHMENT FM-73 & BOLTS | $P_{MIN}$ 0 LBS |
| ENVIRONMENT LAB AIR | CYCLIC RATE 0.5 Hz |

| CRACK GROWTH GAGE 22A | | CRACK GROWTH GAGE 22B | |
|---|---|---|---|
| CYCLES N | CRACK LENGTH 2a (INCHES) | CYCLES N | CRACK LENGTH 2a (INCHES) |
| EDM | 0.102 | EDM | 0.100 |
| 1000 | 0.110 | 1000 | 0.104 |
| 2000 | 0.122 | 2000 | 0.118 |
| 3000 | 0.142 | 3000 | 0.140 |
| 4000 | 0.167 | 4000 | 0.166 |
| 5000 | 0.194 | 5000 | 0.194 |
| 6000 | 0.223 | 6000 | 0.233 |
| 7000 | 0.254 | 7000 | 0.271 |
| 8000 | 0.290 | 8000 | 0.307 |
| 9000 | 0.336 | 9000 | 0.340 |
| 10000 | 0.378 | 10000 | 0.397 |
| 11000 | 0.427 | 11000 | 0.455 |
| 12000 | 0.479 | 12000 | 0.510 |
| 13000 | 0.538 | 13000 | 0.565 |
| 14000 | 0.593 | 14000 | 0.627 |
| 15000 | 0.658 | 15000 | 0.687 |
| 16000 | 0.726 | 16000 | 0.752 |
| 17000 | 0.802 | 17000 | 0.783 |
| 18000 | 0.878 | 18000 | 0.884 |
| 19000 | 0.926 | 19000 | 0.952 |
| 20000 | 1.008 | 20000 | 1.042 |
| 21000 | 1.091 | 21000 | 1.118 |
| 22000 | 1.182 | 22000 | 1.184 |
| 23000 | 1.269 | 23000 | 1.331 |

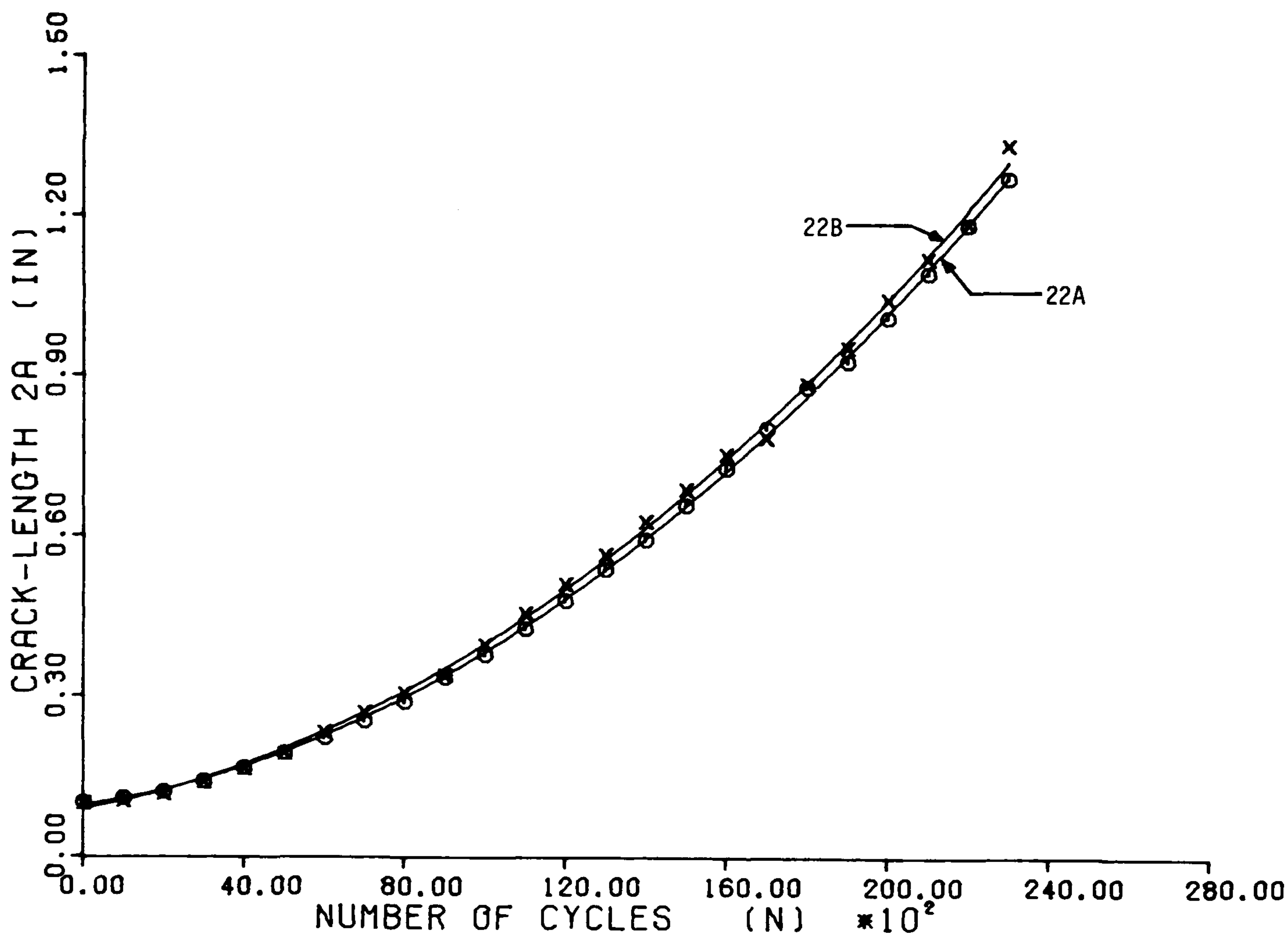



Figure C-7. Constant Amplitude Tests of Crack Growth Gages 22A and 22B

TABLE C-8. CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES 100A AND 100B

| | |
|---|---|
| GAGE SIZE NORMAL (W/O TABS) | $P_{MAX}$ 28120 LBS |
| ATTACHMENT FM-73 | $P_{MIN}$ 0 LBS |
| ENVIRONMENT LAB AIR | CYCLIC RATE 0.5 Hz |

| CRACK GROWTH GAGE 100A | | CRACK GROWTH GAGE 100B | |
|---|---|---|---|
| CYCLES N | CRACK LENGTH 2a (INCHES) | CYCLES N | CRACK LENGTH 2a (INCHES) |
| EDM | 0.104 | EDM | 0.103 |
| 1000 | 0.216 | 1000 | 0.199 |
| 2000 | 0.258 | 2000 | 0.249 |
| 3000 | 0.297 | 3000 | 0.297 |
| 4000 | 0.341 | 4000 | 0.347 |
| 5000 | 0.387 | 5000 | 0.396 |
| 6000 | 0.446 | 6000 | 0.455 |
| 7000 | 0.501 | 7000 | 0.506 |
| 8000 | 0.556 | 8000 | 0.571 |
| 9000 | 0.613 | 9000 | 0.638 |
| 10000 | 0.681 | 1000 | 0.705 |
| 11000 | 0.753 | 11000 | 0.771 |
| 12000 | 0.827 | 12000 | 0.850 |
| 13000 | 0.919 | 13000 | 0.928 |
| 14000 | 1.011 | 14000 | 1.019 |
| 15000 | 1.098 | 15000 | 1.130 |
| 16000 | 1.195 | 16000 | 1.228 |
| 17000 | 1.296 | 17000 | 1.356 |

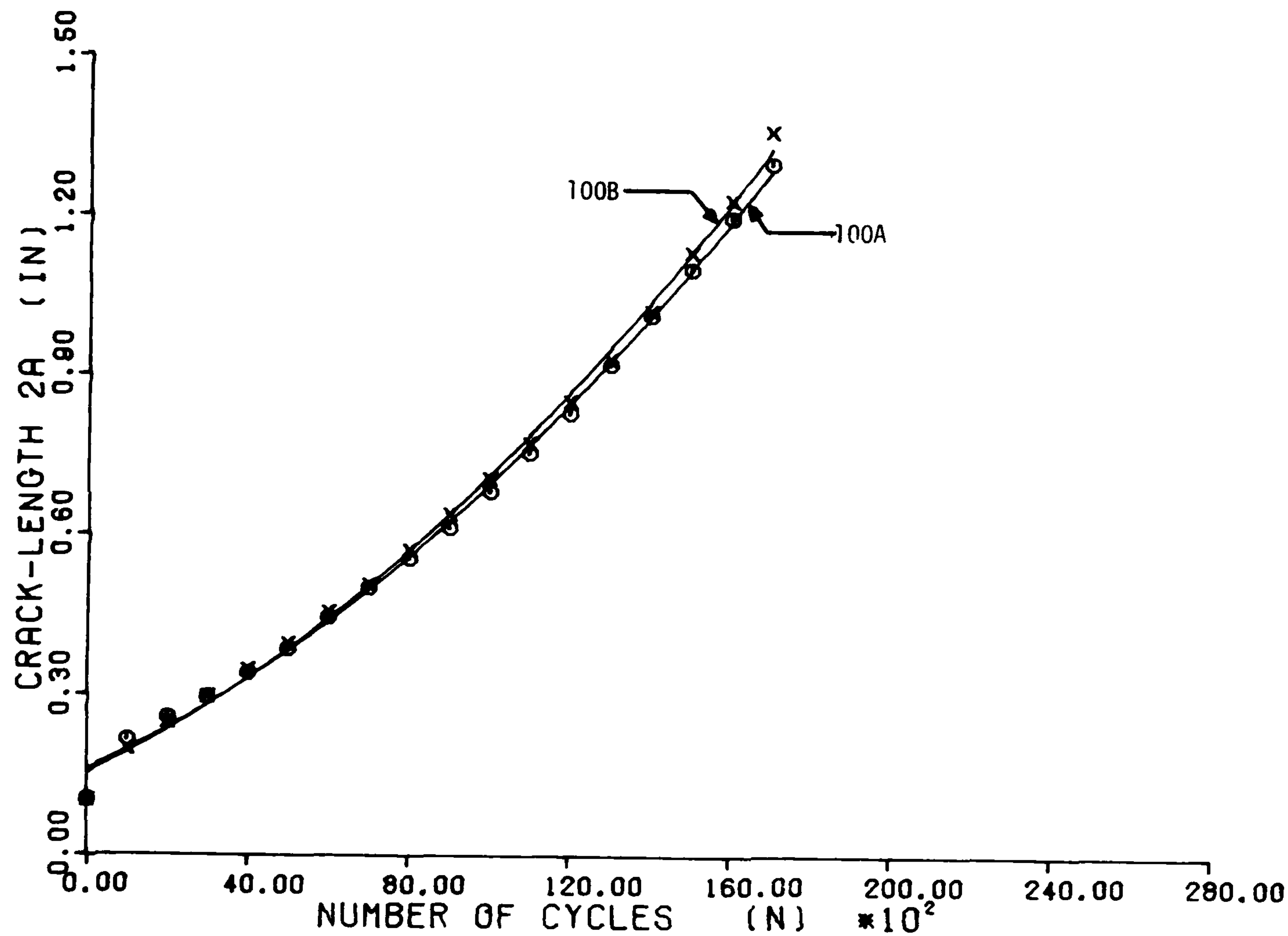



Figure C-8. Constant Amplitude Tests of Crack Growth Gages 100A and 100B

TABLE C-9. CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES 48A AND 48B

| | |
|---|---|
| GAGE SIZE LONG (WITH TABS) | $P_{MAX}$ 28120 LBS |
| ATTACHMENT FM-73 | $P_{MIN}$ 0 LBS |
| ENVIRONMENT LAB AIR | CYCLIC RATE 0.5 Hz |

| CRACK GROWTH GAGE 48A | | CRACK GROWTH GAGE 48B | |
|---|---|---|---|
| CYCLES N | CRACK LENGTH 2a (INCHES) | CYCLES N | CRACK LENGTH 2a (INCHES) |
| EDM | 0.102 | EDM | 0.100 |
| 1000 | 0.111 | 1000 | 0.107 |
| 2000 | 0.126 | 2000 | 1.129 |
| 3000 | 0.162 | 3000 | 0.158 |
| 4000 | 0.213 | 4000 | 0.189 |
| 5000 | 0.250 | 5000 | 0.224 |
| 6000 | 0.298 | 6000 | 0.262 |
| 7000 | 0.353 | 7000 | 0.302 |
| 8000 | 0.415 | 8000 | 0.348 |
| 9000 | 0.478 | 9000 | 0.397 |
| 10000 | 0.544 | 10000 | 0.447 |
| 11000 | 0.613 | 11000 | 0.503 |
| 12000 | 0.713 | 12000 | 0.555 |
| 13000 | 0.800 | 13000 | 0.610 |
| 14000 | 0.912 | 14000 | 0.678 |
| 15000 | 1.011 | 15000 | 0.747 |
| 16000 | 1.134 | 16000 | 0.808 |
| 17000 | | 17000 | 0.873 |
| 18000 | | 18000 | 0.938 |
| 19000 | | 19000 | 0.994 |
| 20000 | | 20000 | 1.073 |

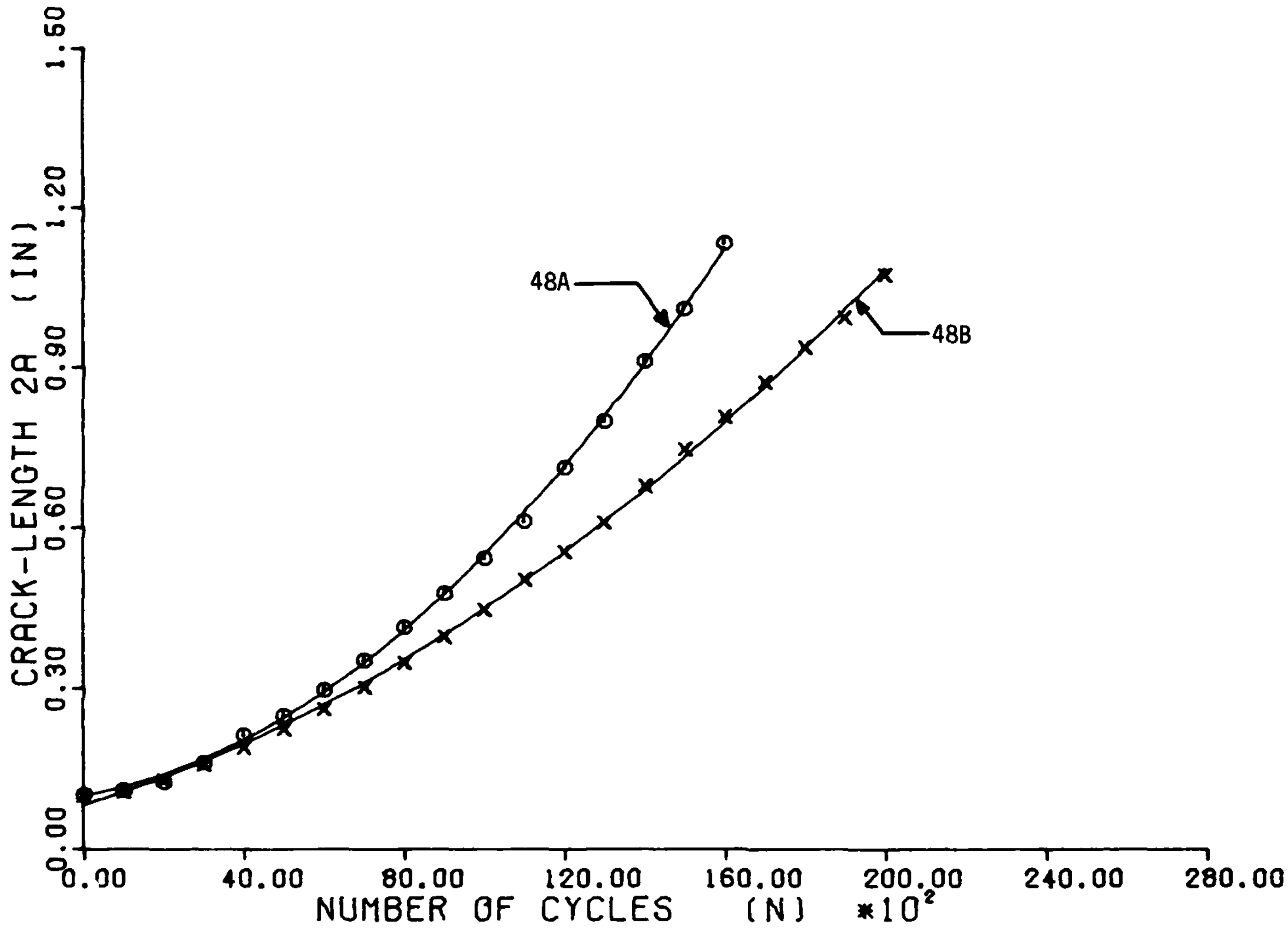



Figure C-9. Constant Amplitude Tests of Crack Growth Gages 48A and 48B

TABLE C-10 CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES 32A AND 32B

| | | | |
|---|---|---|---|
| GAGE SIZE | NORMAL (W/O TABS) | $P_{MAX}$ | 28120 LBS |
| ATTACHMENT | FM-73 | $P_{MIN}$ | 0 LBS |
| ENVIRONMENT | LAB AIR | CYCLIC RATE | 0.5 Hz |

| CRACK GROWTH GAGE 32A | | CRACK GROWTH GAGE 32B | |
|---|---|---|---|
| CYCLES N | CRACK LENGTH 2a (INCHES) | CYCLES N | CRACK LENGTH 2a (INCHES) |
| EDM | 0.103 | EDM | 0.104 |
| PRECRACK | 0.150 | PRECRACK | 0.159 |
| 300 | 0.191 | 300 | 0.200 |
| 1400 | 0.251 | 1400 | 0.253 |
| 2430 | 0.292 | 2430 | 0.302 |
| 3430 | 0.333 | 3430 | 0.305 |
| 4630 | 0.383 | 4630 | 0.402 |
| 5655 | 0.433 | 5655 | 0.449 |
| 6615 | 0.470 | 6615 | 0.500 |
| 7515 | 0.526 | 7515 | 0.556 |
| 8425 | 0.574 | 8425 | 0.604 |
| 9225 | 0.619 | 9225 | 0.656 |
| 9925 | 0.657 | 9925 | 0.699 |
| 10625 | 0.700 | 10625 | 0.748 |
| 11375 | 0.757 | 11375 | 0.799 |
| 12050 | 0.798 | 12050 | 0.852 |
| 12750 | 0.839 | 12750 | 0.901 |
| 13375 | 0.885 | 13375 | 0.950 |
| 13875 | 0.909 | 13875 | 0.998 |
| 14550 | 0.955 | 14550 | 1.051 |
| 15160 | 0.999 | 15160 | 1.099 |
| 15760 | 1.046 | 15760 | 1.150 |
| 16310 | 1.090 | 16310 | 1.210 |
| 17010 | 1.150 | 17010 | 1.276 |
| 17585 | 1.207 | 17585 | 1.358 |

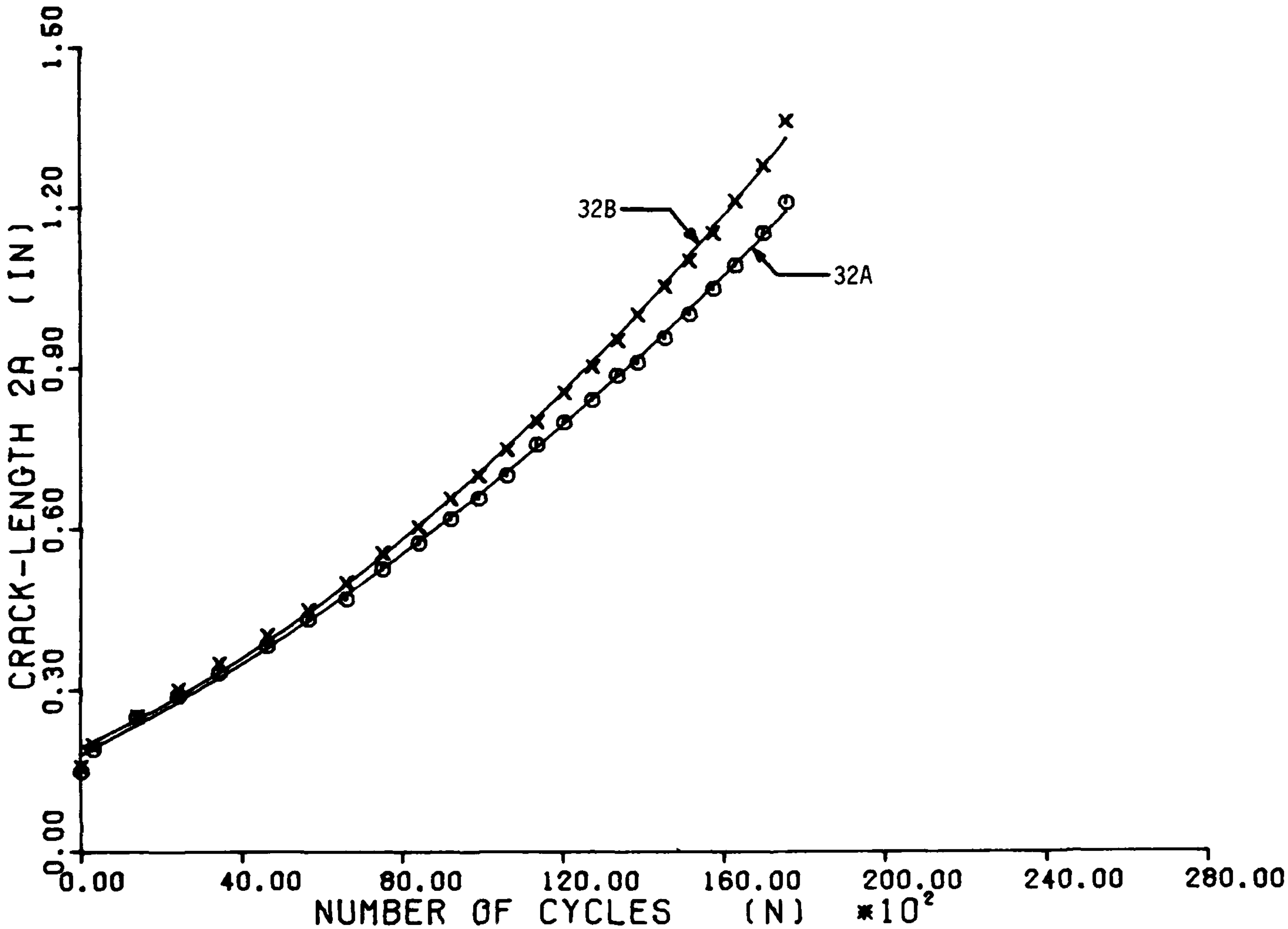



Figure C-10. Constant Amplitude Tests of Crack Growth Gages 32A and 32B

TABLE C-11 CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES 118A AND 118B

| | | | |
|---|---|---|---|
| GAGE SIZE | NORMAL (W/O TABS) | $P_{MAX}$ | 28120 LBS |
| ATTACHMENT | EA 9309] | $P_{MIN}$ | 0 LBS |
| ENVIRONMENT | LAB AIR | CYCLIC RATE | 0.5 Hz |

| CRACK GROWTH GAGE 118A | | CRACK GROWTH GAGE 118B | |
|---|---|---|---|
| CYCLES N | CRACK LENGTH 2a (INCHES) | CYCLES N | CRACK LENGTH 2a (INCHES) |
| EDM | 0.105 | EDM | 0.105 |
| 2000 | .133 | 2000 | .121 |
| 3000 | .155 | 3000 | .140 |
| 4000 | .182 | 4000 | .159 |
| 5000 | .211 | 5000 | .190 |
| 6000 | .246 | 6000 | .208 |
| 7000 | .282 | 7000 | .239 |
| 8000 | .321 | 8000 | .262 |
| 9000 | .366 | 9000 | .302 |
| 10000 | .423 | 10000 | .329 |
| 11000 | .445 | 11000 | .364 |
| 12000 | .507 | 12000 | .403 |
| 13000 | .565 | 13000 | .443 |
| 14000 | .614 | 14000 | .479 |
| 15000 | .679 | 15000 | .513 |
| 16000 | .751 | 16000 | .553 |
| 17000 | .822 | 17000 | .603 |
| 18000 | .902 | 18000 | .649 |
| 19000 | .983 | 19000 | .696 |
| 20000 | 1.090 | 20000 | .736 |
| 21000 | | 21000 | .789 |
| 22000 | | 22000 | .836 |
| 23000 | | 23000 | .885 |
| 24000 | | 24000 | .939 |
| 25000 | | 25000 | 1.006 |
| 26000 | | 26000 | 1.035 |
| 27000 | | 27000 | 1.092 |

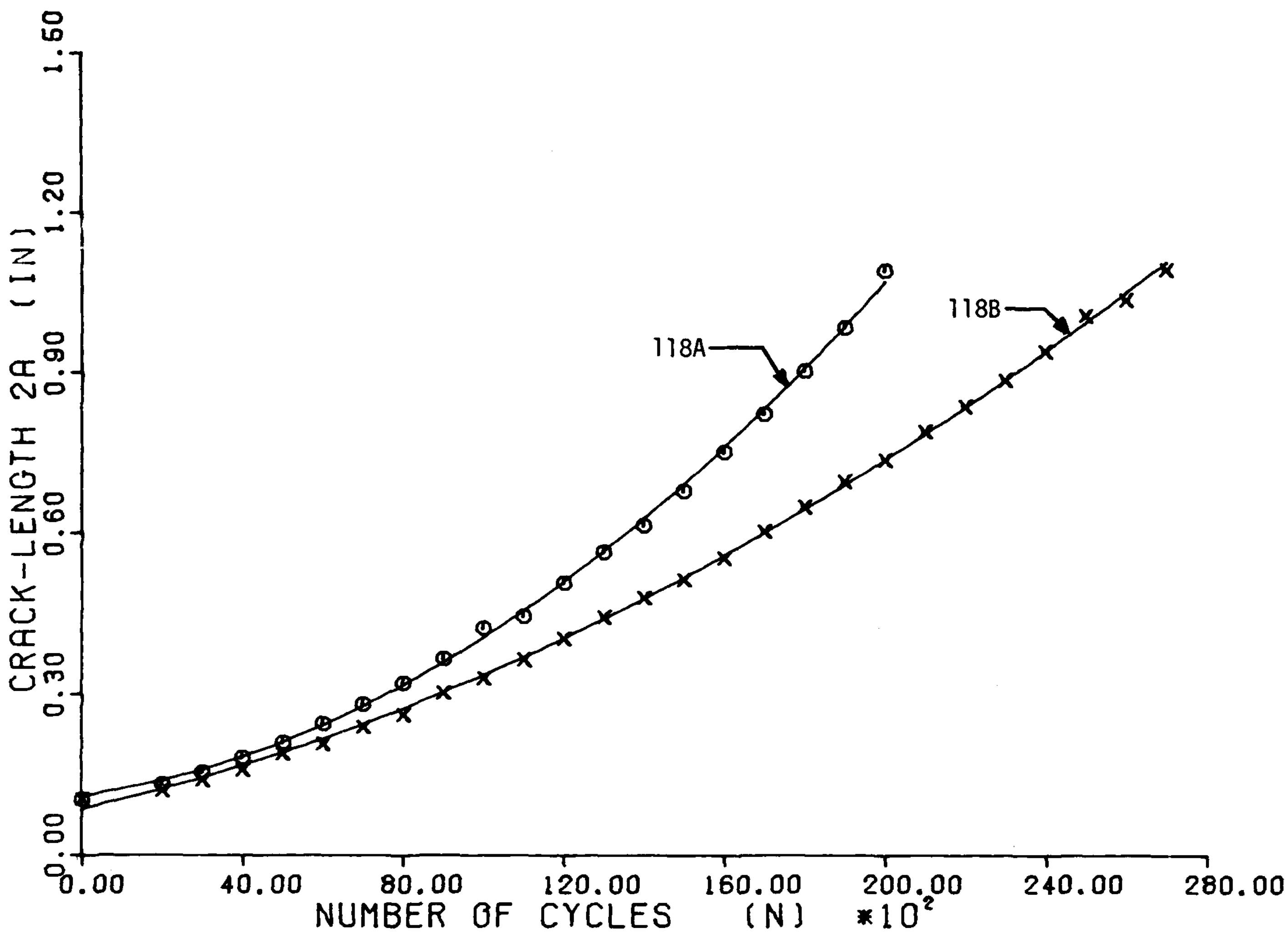



Figure C-11. Constant Amplitude Tests of Crack Growth Gages 118A and 118B

TABLE C-12 CRACK PROPAGATION DATA FOR CRACK GROWTH GAGES 110A AND 110B

| | | | |
|---|---|---|---|
| GAGE SIZE | LONG (WITH TABS) | $P_{MAX}$ | 28120 LBS |
| ATTACHMENT | EA 939091 | $P_{MIN}$ | 0 LBS |
| ENVIRONMENT | LAB AIR | CYCLIC RATE | 0.5 Hz |
| CRACK GROWTH GAGE 110A | | CRACK GROWTH GAGE 110B | |
| CYCLES N | CRACK LENGTH 2a (INCHES) | CYCLES N | CRACK LENGTH 2a (INCHES) |
| EDM | 0.103 | EDM | 0.103 |
| 2000 | .125 | 2000 | .119 |
| 3000 | .144 | 3000 | .157 |
| 4000 | .172 | 4000 | .185 |
| 5000 | .199 | 5000 | .223 |
| 6000 | .229 | 6000 | .263 |
| 7000 | .271 | 7000 | .312 |
| 8000 | .312 | 8000 | .366 |
| 9000 | .352 | 9000 | .425 |
| 10000 | .398 | 10000 | .491 |
| 11000 | .434 | 11000 | .567 |
| 12000 | .483 | 12000 | .656 |
| 13000 | .546 | 13000 | .745 |
| 14000 | .600 | 14000 | .835 |
| 15000 | .659 | 15000 | .942 |
| 16000 | .718 | 16000 | 1.050 |
| 17000 | .785 | | |
| 18000 | .855 | | |
| 19000 | .908 | | |

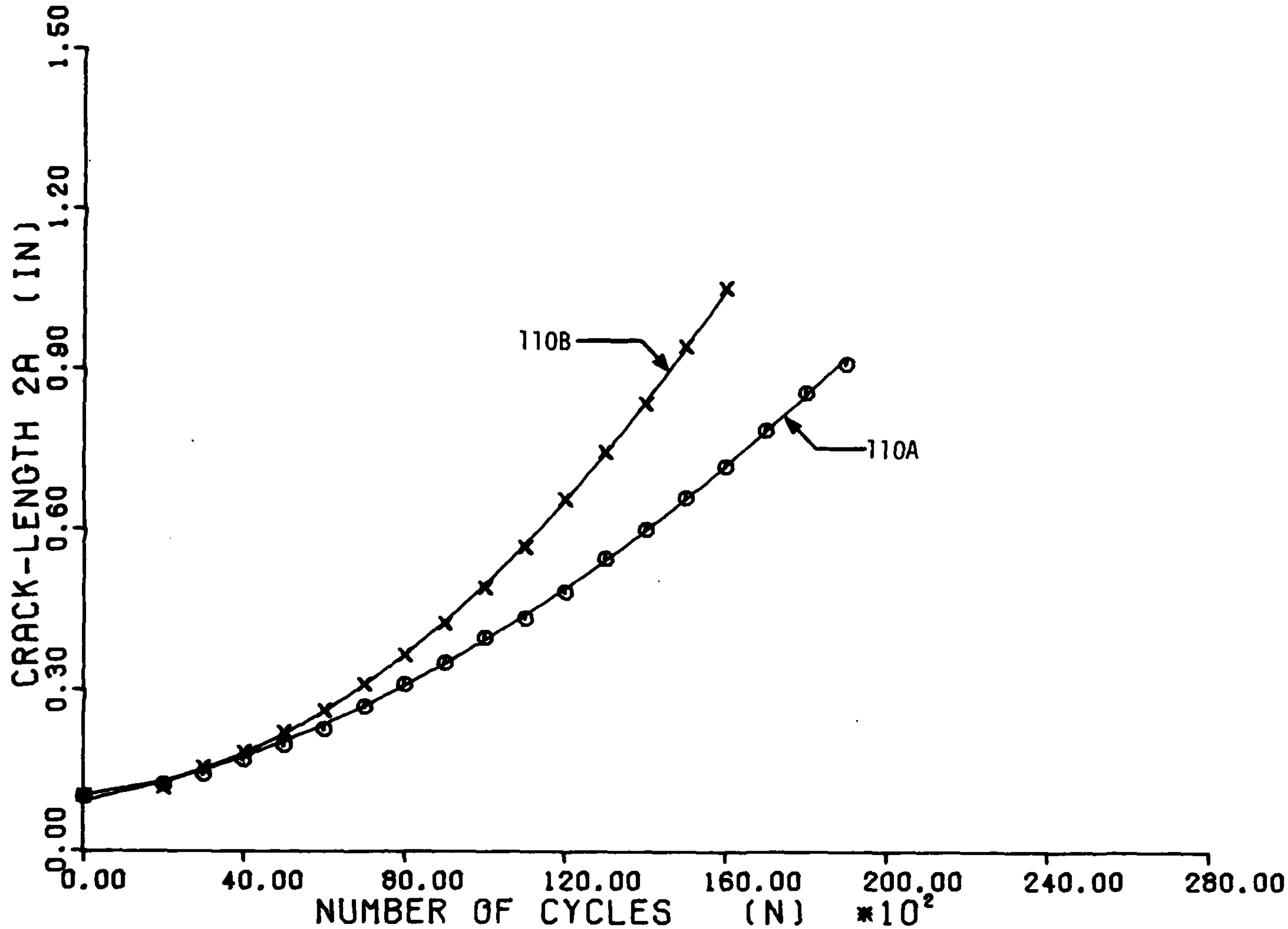



Figure C-12. Constant Amplitude Tests of Crack Growth Gages 110A and 110B

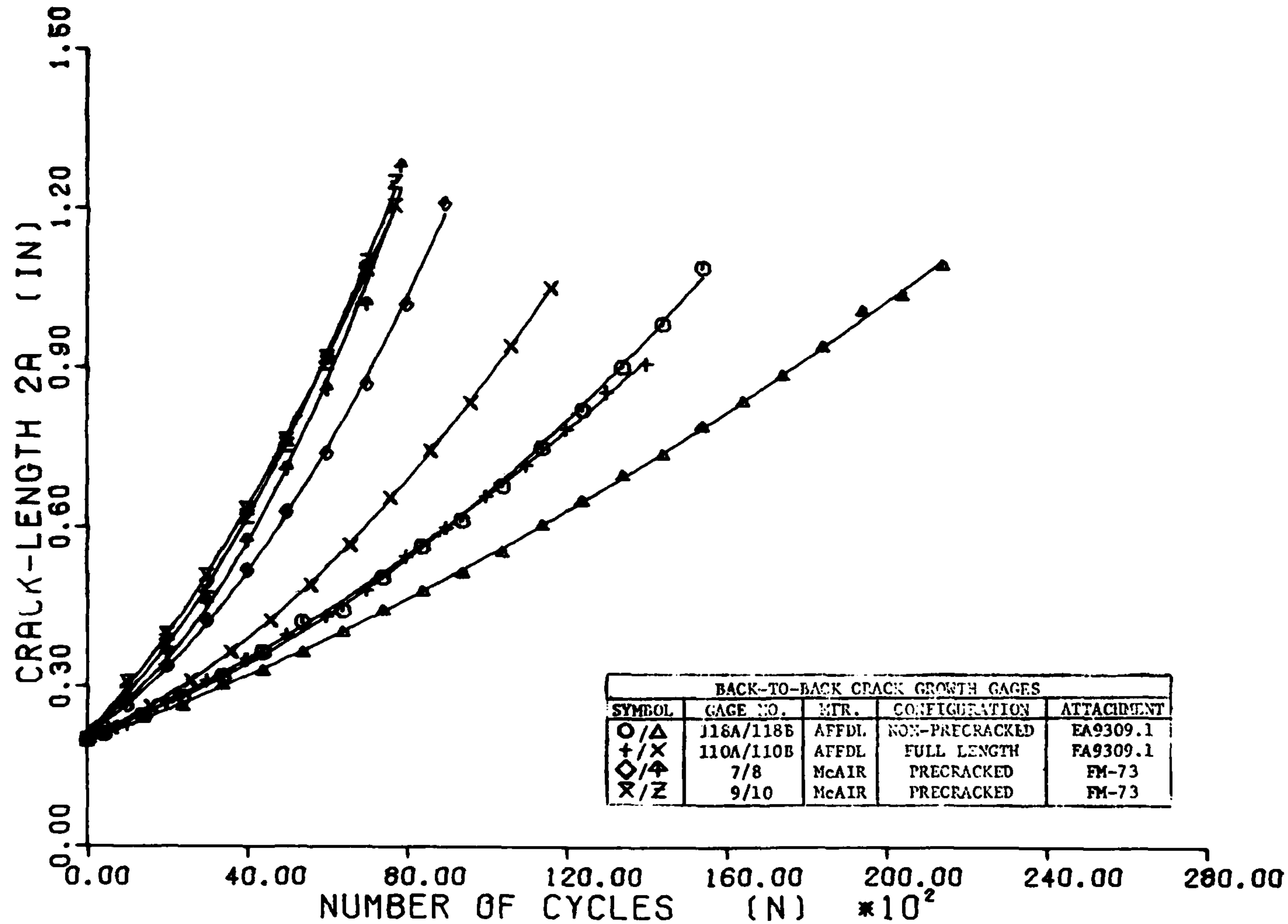



Figure C-13. Constant Amplitude Tests - AFFDL Tests of AFFDL Gages (Bonded with EA9309.1 Adhesive) Compared with McAir Tests of McAir Gages (Bonded with FM-73 Adhesive)

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