

AD-A189 553

THERMAL-MECHANICAL FATIGUE TESTING OF A
TITANIUM-ALUMINIDE ALLOY(U) AIR FORCE INST OF TECH
WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING

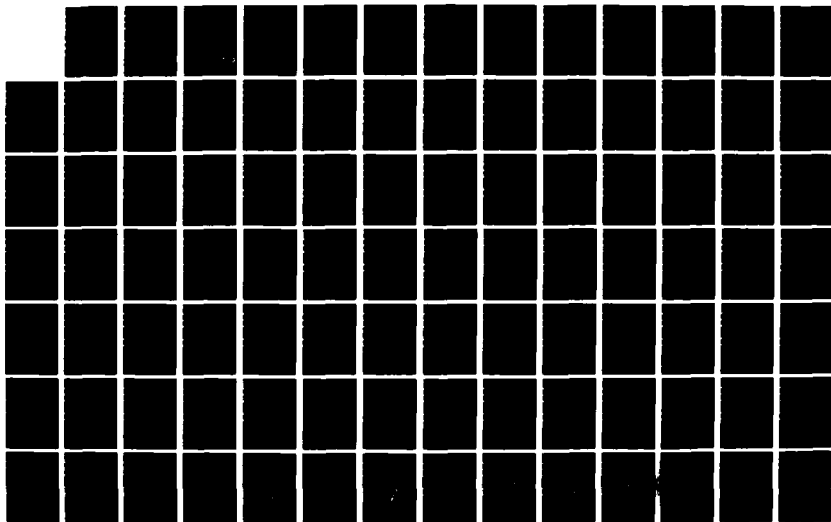
1/2

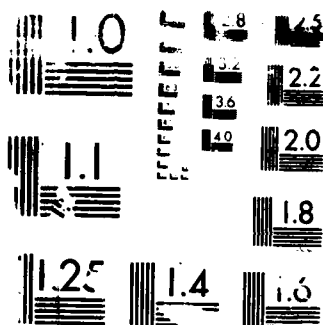
UNCLASSIFIED

J J PERNOTE DEC 87 AFIT/GAE/AA/87D-18

F/G 11/6 1

NL

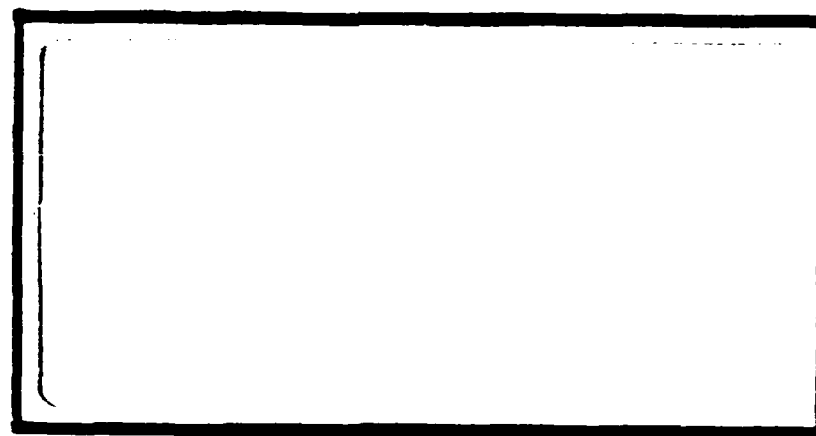




RESOLUTION TEST CHART

DTIC FILE COPY

AD-A189 555



DTIC

MAR 03 1988

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

DISTRIBUTION STATEMENT A

Approved for public release;

AFIT/GAE/AA/87D-18

THERMAL-MECHANICAL FATIGUE TESTING
OF A TITANIUM-ALUMINIDE ALLOY
THESIS

John J. Pernot
Second Lieutenant, USAF

AFIT/GAE/AA/87D-18

DTIC
ELECTE
MAR 03 1988
S a H D

Approved for public release; distribution unlimited

AFIT/GAE/AA/87D-18

**THERMAL-MECHANICAL FATIGUE TESTING
OF A TITANIUM-ALUMINIDE ALLOY**

THESIS

**Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology**

Air University

**In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Aeronautical Engineering**

John J. Pernot

Second Lieutenant, USAF

December 1987

Approved for public release; distribution unlimited

Preface

The major purpose of this thesis was to develop a Thermal-Mechanical Fatigue (TMF) testing system for titanium-aluminide compact tension specimens. I could not have accomplished this without the help of Jay Anderson. Jay helped with the connections of all major components, the writing of the computer software, and the trouble-shooting of the equipment.

I would like to thank Dr. Theodore Nicholas of the Materials Laboratory Metals Behavior Branch for sponsoring this work and my thesis advisor, Dr. Shankar Mall, for all the help he has given me during the equipment development, TMF experimentation, and results analysis.

Most of all, I wish to thank my wife, Donna, for her patience and understanding during the past 18 months, and especially for her assistance in typing and editing this work.



Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	☐
By _____	
Distribution/	
Availability Codes	
Avail and/or	
Dist	Special
A-1	

Table of Contents

	Page
Preface	ii
List of Figures	iv
List of Tables.	vii
Abstract.	viii
I. Introduction.	1
II. Thermal-Mechanical Fatigue.	6
Thermal-Mechanical Fatigue Background . . .	6
TMF Testing Equipment	8
TMF Life Prediction Methods	13
Titanium Aluminides	20
III. Experimental Equipment.	21
Test System	21
Mechanical Loading System	23
Temperature Control System.	30
Crack Length Measurement Devices.	42
Computer Control of Equipment	49
IV. Experimental Procedure.	54
Specimen Details.	54
Precracking of Specimens.	56
Isothermal Testing.	59
TMF Testing	61
V. Results and Discussions	67
Crack Length Analysis	67
Crack Growth Analysis	75
Fracture Surfaces	88
VI. Conclusions and Recommendations	92
Appendix A: Software Written for Computer Control and Data Aquisition for IP TMF Test. . .	95
Appendix B: Modifications of CCADA Software for Isothermal and OP TMF Tests.	118
Bibliography.	120
Vita.	123

List of Figures

Figure	Page
1. Temperature and Load Limit Profiles of Turbine Disk During Typical Flight Cycle . . .	2
2. Isothermal Temperature and Load Profile. . . .	8
3. TMF Temperature and Load Profiles.	9
4. Effect of Frequency on Crack Growth Rate . . .	14
5. Typical Crack Growth Relation.	16
6. Definition of Parameters on da/dN Curve. . . .	19
7. Block Diagram of Testing System.	22
8. Mechanical Loading System.	24
9. Modified Grip for EP Current Leads	26
10. Grips Designed for TMF	27
11. Spacer Placement Between Specimen and Grips. .	28
12. Cooling Basket for Load Cell	29
13. Temperature Control System	31
14. Top View of Mounting Assembly for Heating Lamps.	33
15. Quartz Lamps Heating Areas	34
16. Compressed Air Cooling Jets.	35
17. Primary and Secondary Air Flow to Cooling Jets	36
18. Thermocouple Locations on the CT Specimen. . .	36
19. PID Control in the Micricon 82300.	38
20. Water Cooling System	42
21. Protective Relay System.	43
22. Crack Length Measuring Devices	44
23. DC Current and Pickup Positions.	46

24.	Block Diagram of the TMF CCADA Program	51
25.	Compact Tension Specimen Dimensions.	56
26.	Load Reduction Scheme Used to Pecrack Specimens.	58
27.	1200°F Isothermal Visual Crack Growth Measurements	60
28.	1200°F Isothermal EP Measurements.	62
29.	IP TMF Temperature Profile	63
30.	IP TMF Visual Crack Growth Measurements. . . .	65
31.	IP TMF EP Measurements	66
32.	1200°F Isothermal Test Calibration Curve . . .	68
33.	IP TMF Calibration Curve	70
34.	Isothermal and IP TMF Calibration Curves . . .	71
35.	1200°F Isothermal Calculated Crack Length. . .	73
36.	IP TMF Calculated Crack Length	74
37.	Crack Growth Relation Using Seven-Point Method for 1200°F Isothermal Test.	77
38.	Crack Growth Relation Using 15-Point Method for 1200°F Isothermal Test.	78
39.	Crack Growth Relations Using Seven- and 15- Point Methods for 1200°F Isothermal Test . . .	79
40.	Crack Growth Relations Using Seven- Point Method for 600°F to 1200°F IP TMF Test	81
41.	Crack Growth Relations Using 15-Point Method for 600°F to 1200°F IP TMF Test	82
42.	Crack Growth Relations Using Seven- and 15-Point Methods for 600°F to 1200°F IP TMF Test.	83
43.	Crack Growth Relations for 1200°F Isothermal and 600°F to 1200°F Tests Using 15-Point Method	85
44.	1200 F Isothermal and 600°F to 1200°F IP TMF Fracture Surfaces.	89

45.	1200°F Isothermal Test Fractured Specimen. . .	90
46.	600°F to 1200°F IP TMF Test Fractured Specimen	91
47.	Block Diagram of the TMF CCADA Program	98
48.	Flow Chart for Main Program of CCADA.	99

List of Tables

Table		Page
1.	Accuracy of Wavetek Model 278	25
2.	PI Control Parameters and Their Effects . .	39
3.	Accuracy of the Power Supply and Voltmeter	47
4.	Composition of the Ti_3Al Alloy.	54
5.	Heat Treatment of the Ti_3Al Alloy	54
6.	Tensile Properties for Ti_3Al	55
7.	Output Device Numbers	97
8.	IEEE-488 Address Numbers and Device Names. .	97.

Abstract

There is a continuing need to study the affect of combined thermal and mechanical cycling of materials. This combined cycling is referred to as thermal-mechanical fatigue (TMF) cycling. This study emphasizes the development of a computer-controlled testing system that can mechanically fatigue a specimen under a variety of thermal conditions. These conditions include isothermal temperatures, as well as cyclic temperatures in phase (IP) or out of phase (OP) with the load.

To demonstrate the capability of this system, both a 1200°F isothermal load fatigue test and a 600°F to 1200°F IP TMF test were carried out on a titanium-aluminide alloy, Ti₃Al. Crack growth relations were established for both cases by plotting the da/dN versus ΔK data on log-log axis and fitting the power law relations, $da/dN = C (\Delta K)^n$ to the data. The results show the crack growth rate for the isothermal test is slightly higher than the growth rate for the IP TMF test at a given value of stress intensity range, ΔK . The crack surfaces were very rough and crack growth was not along the mid-plane of the specimen.

Further TMF study is required particularly for other loading frequencies and other load-temperature phase differences. After these studies are complete, models can be developed to characterize the crack growth behavior of this titanium-aluminide alloy.

THERMAL-MECHANICAL FATIGUE TESTING OF A TITANIUM-ALUMINIDE ALLOY

I. Introduction

Most modern, high-performance aircraft use the gas turbine engine for propulsion. The engine generates high temperature gas that is expanded and accelerated through a nozzle to develop thrust (1:139). Components of the gas turbine must meet design requirements based on temperature, stress, and the environment. Durability and cost are usually two of the most important factors considered when selecting materials for such components (2:1).

The continuing desire to increase thrust and improve fuel efficiency results in higher component temperatures and rotational speeds (3:1; 4:3). In the burner and afterburner, temperatures can be over 2000°C (3632°F), but material temperatures can be reduced with liner cooling. In the turbine rotor, stresses result from high gas temperatures and pressure, as well as rotation and vibration. Turbine entry temperatures (TET) for the F100 engine used in F15 and F16 aircraft is 1425°C (2597°F). At the hottest part of the turbine blade, stresses can be about 200 MN/m² (29.0 ksi), but at the root of the blade, they can exceed 500 MN/m² (72.5 ksi) (2:1-4). Along with increasing the gas turbine

engine's overall performance, there is the concern of durability to result in longer lasting equipment (3:1; 4:3).

Complex thermal and mechanical cycles caused during flight create thermal and mechanical stresses that can lead to fatigue damage, and finally failure of the component (5:2). Turbine disk temperature and load limit profiles experienced during a typical flight cycle are shown in Figure 1.

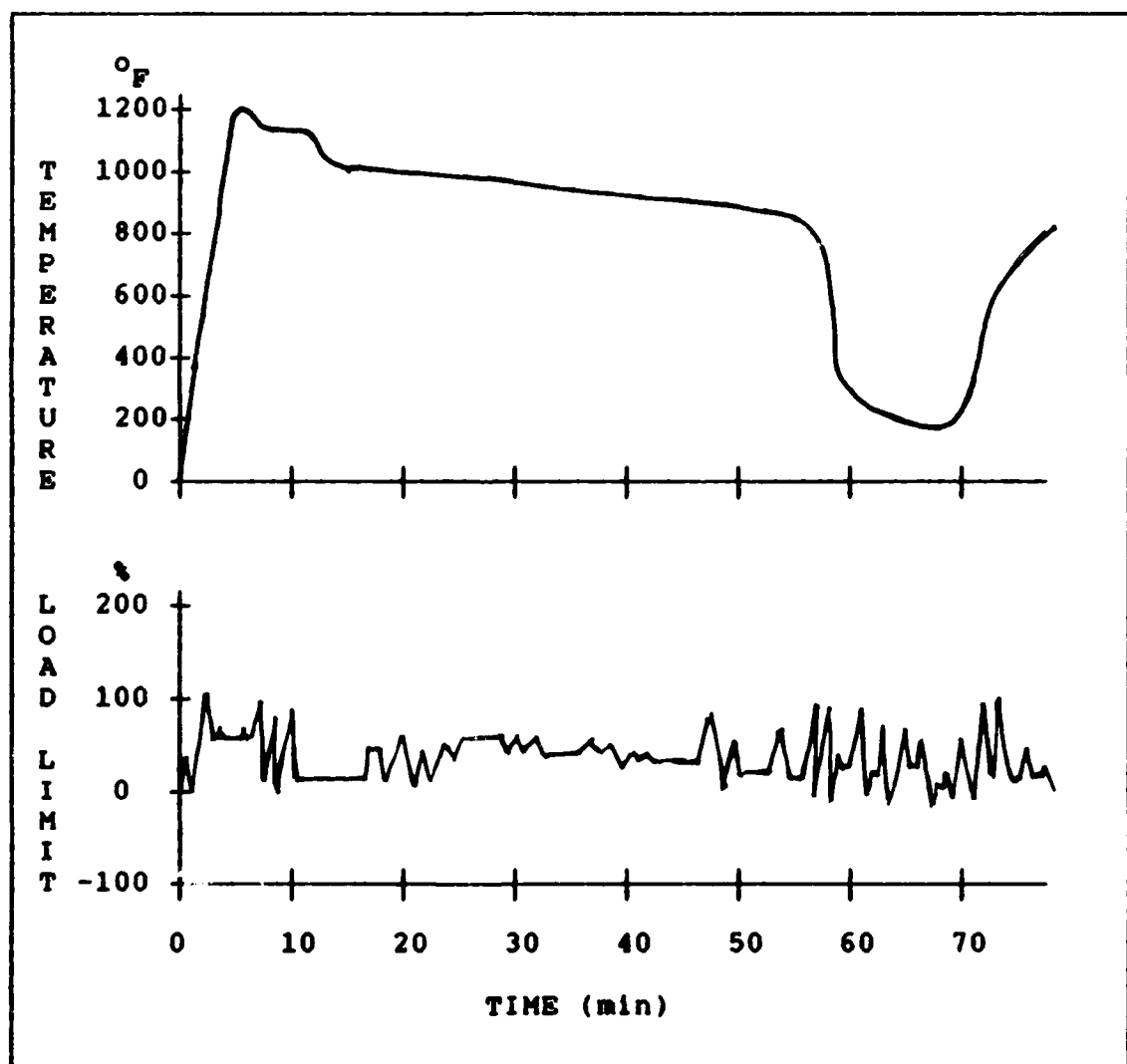


Figure 1 Temperature and Load Limit Profiles of Turbine Disk During Typical Flight Cycle

In high temperature aircraft components such as turbine blades and vanes, a critical failure mode is low-cycle thermal fatigue (LCTF). Thermal fatigue refers to the condition of stresses and strains imposed by thermal expansion due to temperature (3:1-3). In all the previously mentioned high temperature components, mechanical and thermal loading occurs simultaneously. The superposition of mechanical fatigue with cyclic temperature loading is referred to as thermal-mechanical fatigue (TMF).

Until the mid-1970s useful life estimates of gas turbine engine components have been very conservative. As an example, the total fatigue life of turbine disks had been statistically determined based on a critical crack occurring in one out of every 1000 disks. With a relatively new philosophy referred to as Retirement for Cause (RFC), the components with remaining useful life would be inspected and put back into service. In 1975 the Air Force Wright Aeronautical Laboratories (AFWAL) examined the technology involved in implementing RFC (6:1). To implement such a philosophy, fracture mechanics must be applied to estimate crack growth and determine an interval to inspect a component for critical cracks.

Emphasis is now being placed on high temperature fracture mechanics in the research and development of new materials for gas turbine engines. The approach emphasizes crack nucleation and propagation at elevated temperatures, including TMF analysis (7:1). The continued interest in this

area resulted in the establishment of the Air Force Engine Structural Integrity Program (ENSIP). The ENSIP requires the testing of components to establish crack growth rates in order to ensure that initial detectable flaws will not grow to a critical size over the life of the engine. Such testing will also determine an inspection interval for all components of the engine (8:1-2).

Continued research in TMF is necessary to develop models to characterize specific materials. According to Halford (3:38-40), the accuracy of predicting TMF behavior based on isothermal data is very poor. Most often, due to economic constraints, estimates of TMF behavior must be made solely on isothermal tests. Attempts are continually being made to develop isothermal-based models for TMF. Bill (9:2-3) reviewed a variety of TMF life prediction methods emphasizing steels and nickel-base superalloys. There is a great need to develop a method that will apply to a larger variety of materials at different temperatures and cycle frequencies (5:5). The need for a more flexible model intensifies when the material of interest is very expensive and/or available in limited quantities. Such is the case for the titanium-aluminide alloys.

The titanium-aluminide alloys are high temperature intermetallic compounds that are currently under development. These new, low density alloys have high specific strength and high temperature capability. These characteristics are similar to those of the nickel-base superalloys, but the

maximum operating temperature of current titanium aluminide alloys is approximately 649°C (1200°F). The most impressive feature of the titanium-aluminide alloy is the possibility of component weight reduction with equal strength (10:1.1).

The overall goal of this effort was to develop a TMF testing system for the titanium aluminide alloys. As mentioned earlier, these materials are expensive; therefore, test specimens must be very small. This equipment features the capability of testing such small specimens. There is also a current need for an apparatus to test material in a safe and relatively inexpensive manner. In recent years, much of the TMF testing done has used high electric current to heat specimens. The limitations of this heating method, as well as possible alternatives are discussed in this thesis.

A TMF testing system that uses quartz lamps to heat the specimen and electric potential to measure crack length is explained in detail. The system was successfully used in isothermal and TMF testing of Ti_3Al . Results for an isothermal 649°C (1200°F) fatigue test and a 315°C (600°F) to 649°C (1200°F) in-phase TMF test are included and discussed in this study. Because of the high cost and low availability of the material, the compact tension (CT) specimen was used exclusively for these tests, but the testing apparatus can easily be modified for any specimen geometry.

II. Thermal-Mechanical Fatigue

Thermal-Mechanical Fatigue Background

Fatigue refers to a material's deterioration caused by repeated loading. Components can be stressed beyond their elastic limits, as in the case of those subjected to thermal stresses induced by temperature oscillations. Fatigue life in the low cycle, plastic region historically has been related to the plastic strain by

$$N \epsilon_p^2 = C \quad (1)$$

where N , ϵ_p , and C are the number of fatigue cycles, plastic strain, and the material constant respectively (11:5.9-5.10).

To make life predictions for structural components, the crack growth rate must be known. After the nucleation of a crack, linear elastic fracture mechanics (LEFM) can be used to determine the rate of crack growth, da/dN , as long as the plastic region near the crack tip is small. The growth rate can be expressed as a function of the stress intensity range, ΔK , and sometimes the maximum stress intensity, K_{max} . In some cases a simple power relation is used, such as

$$da/dN = C (\Delta K)^n \quad (2)$$

where C and n are material constants. Numerous attempts have been made to develop more accurate expressions, but they cannot be generalized to apply in all cases (12:261-266).

Life prediction becomes more complex as a component is subjected to simultaneous temperature and mechanical loading, resulting in a state of thermal-mechanical fatigue (TMF). The validity of LEFM in TMF analysis is often debated since high temperature fatigue is most often associated with plastic deformation. In the past, two simple approaches for life predictions have been based on isothermal data. The first uses the maximum temperature isothermal life as the predicted life, and the other uses the minimum isothermal life experienced over the range of operating temperatures (3:2). These methods are not always conservative, and in some cases they are too conservative, resulting in the discarding of components with useful life. Halford (3:30) carried out an extensive study of the comparison between isothermal and TMF life. In most cases, both lives were nearly the same. In 40 percent of the materials studied, TMF reduced life, and in only 7 percent TMF increased life. Russel (5:3) showed the phase difference between temperature and mechanical loads can result in longer or shorter life, depending on certain material properties. In general, he found in-phase (IP) TMF loading of low strength, ductile materials and out-of-phase (OP) TMF loading of high strength, low ductile materials resulted in longer component life.

TMF Testing Equipment

TMF testing equipment requires a mechanical loading device and a temperature controlling system. They must be capable of in-phase (IP) and out-of-phase (OP) testing. IP refers to a condition where the maximum (peak) load occurs at the maximum temperature and an OP condition results from a time difference between peaks. A 180° OP test requires the maximum load to occur at the minimum temperature. Other cycle combinations have been studied, but in this study only the IP and 180° OP cases are considered. Throughout this report, OP will refer to the 180° OP condition. Since most TMF data is compared to the results of isothermal tests, the test equipment should be capable of creating isothermal as well as TMF loading conditions. Temperature and load profiles for the isothermal and TMF tests are shown in Figures 3 and 4 respectively.

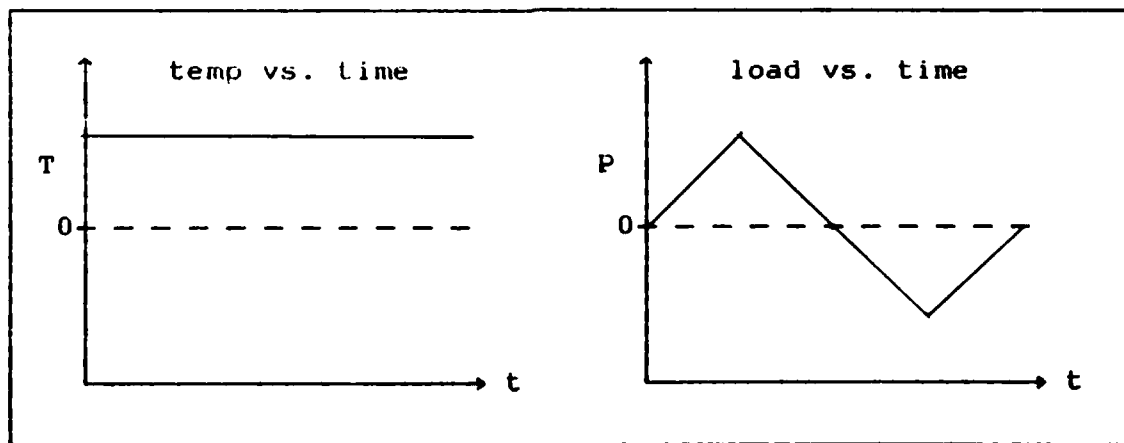


Figure 2 Isothermal Temperature and Load Profile

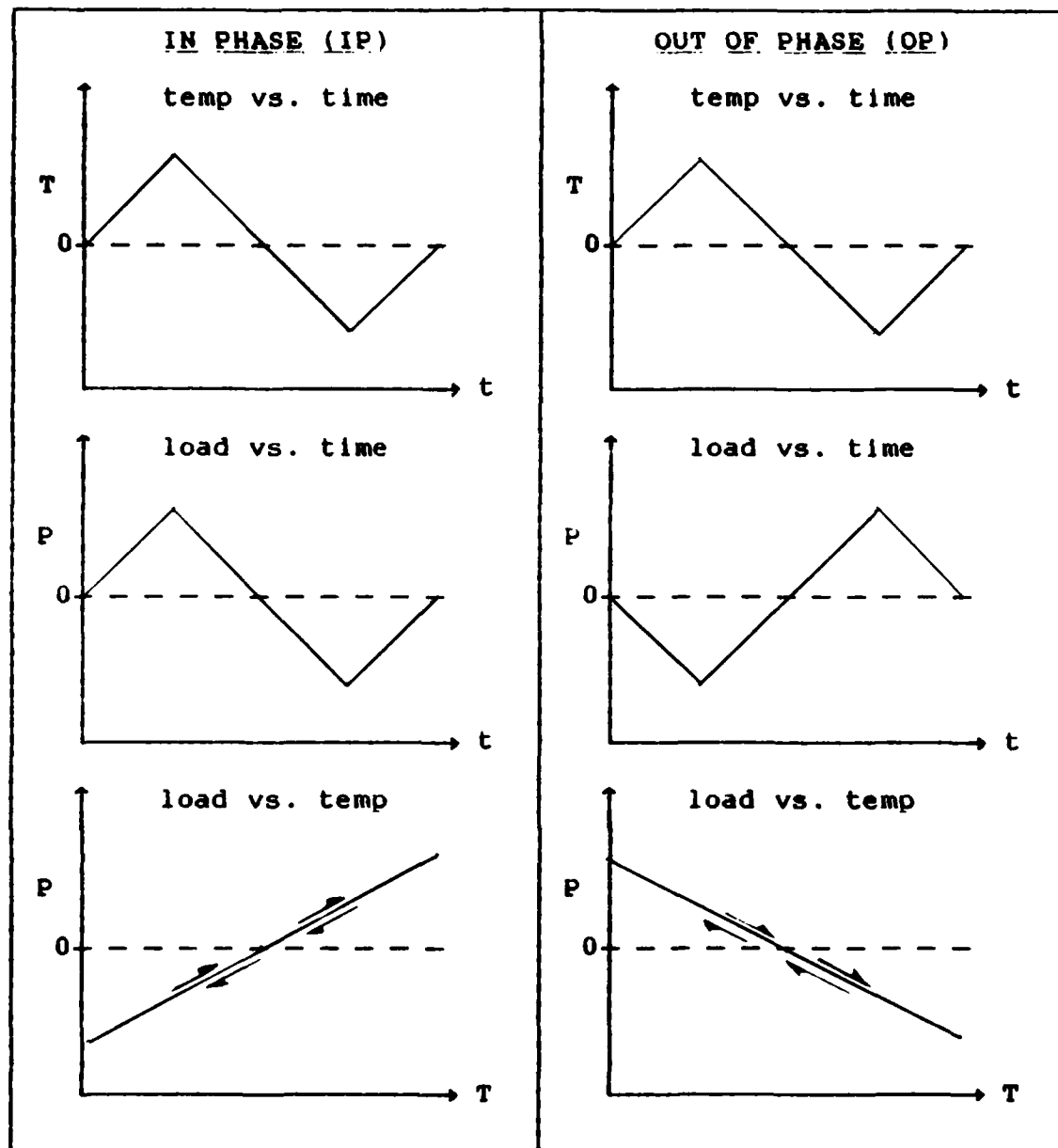


Figure 3 TMF Temperature and Load Profiles

Most equipment used for thermal fatigue testing consists of closed-loop temperature and load controlled systems. The equipment usually includes a mechanical loading device that has been modified by some means to heat the specimen. A

specimen can be heated by immersing it in a bed of hot fluid or passing high current through it. Other methods include the use of radiation or radio frequencies for heating (3:24).

The hot fluid bed method can be used to heat specimens at a very high rate. The major limitation of the method is the inability to thermally or mechanically cycle the material. The bed is normally used for the heat treatment of specimens or generation of thermal stresses.

Passing high current through a specimen can also result in high heating rates, but with a great amount of control, unlike the previous method. Wilson and Warren (6:3) of Pratt & Whitney used current up to 1200 amps between 0 and 3 volts AC to achieve heating rates of 56°C per second ($100^{\circ}\text{F}/\text{sec}$) using closed-loop control. Temperatures of the center crack tension (CCT) specimens ranged from 93°C (200°F) to 538°C (1000°F). The temperature cycles were limited to 0.5 cycles per minute to allow for proper cooling. Deluca and Cowles (13:106) applied this technique to CCT specimens to establish heating profiles of 427°C (800°F) to 982°C (1800°F). This method was also used for the initial testing of Ti_3Al at Pratt & Whitney. For these titanium-aluminide tests, an infrared pyrometer was used for control and measurement of temperature (10,2.44). This heating method can be dangerous, since high current is constantly applied to the specimen. A major disadvantage of this method is that it creates a non-uniform temperature field around the crack tip. If the

electric field is uniform in an uncracked specimen, a crack will disturb the field and create a localized hot spot at the crack tip. Griffin and Cunningham (14:1) have found that thermal stresses caused by electrical heating must be considered when calculating stress intensities, adding considerable complications to the analysis.

Radiation heating lamps can be used for thermal testing applications. This method is chosen by some researchers since it is clean and relatively easy to control. Heil (8:20,23) has used four quartz lamp heaters to perform TMF tests on Inconel 718 CCT specimens. Heating and cooling rates of 8°C per second (14.4°F/sec) were used to cycle temperatures between 427°C (800°F) and 649°C (1200°F). He welded type-K thermocouple wire to the specimens for feedback and control.

Oleinik, Pogrebnyak, and Zmil (15:321-323) have designed a device that uses radiation heating to achieve specimen temperatures up to 1800°C (3272°F) for fatigue tests. The heating is produced by passing high current through a 6 mm (0.24 in.) diameter molybdenum rod wound in a four-loop spiral around a cylindrical test specimen. Specimen temperature is measured by platinum/rhodium-platinum/rhodium (type PR-30/6) thermocouples welded along the working zone. The temperature variation in this zone is 2 percent, but a high frequency regulator can control temperatures to within 2°C (3.6°F). This device is limited to a heating rate of 40°C/min (72°F/min).

Pelloux and Marchand (16:A4) have used the radio frequency heating technique for TMF tests of nickel-base superalloys. They have found that low frequency heaters produce lower wall thickness gradients and have fewer grounding problems than the high frequency heaters. They used thermocouples for temperature measurement and feedback, and a thermistor for a stable cold junction required for control of the system.

Crack length measurements are usually made with a traveling microscope or other visual measurement device. According to ASTM Standard E647 (17:708), measurements for constant load-amplitude fatigue crack growth tests should be made no less than every 0.25 mm (0.01 in.) or ten times the precision of the measurement instrument. Some researchers have used an electrical potential (EP) drop method to measure cracks. To use this method, constant current is applied to the specimen. Voltage drop measurements are made across the crack at specific increments of load cycles. With periodic visual measurements to develop voltage versus crack length calibration data, crack length measurements are established. The EP drop method is explained in the paper by Hartman and Johnson (18:106-112). They have elaborated on thermal EMF, crack closure, and other complicating factors that are involved when using this method. Heil (8:23) successfully used this method to measure crack length in CCT specimens. Wright, Jang, and Popp of the General Electric Company used

EP to measure cracks in single edge notch geometry. They adopted a technique from Gangloff who measured surface flaws in round test bars with resolution of 2.5 μm (0.1 mil) (4:16).

TMF Life Prediction Models

Attempts are continually being made to apply fracture mechanics to high temperature crack growth. Linear elastic fracture mechanics (LEFM) is valid only if the plastic yielding zone is small compared to the crack length. In many cases LEFM is assumed valid in high temperature crack growth, but plasticity due to creep can occur resulting in the use of other methods to account for plastic yielding, such as the J integral or crack opening displacement (COD). Sadananda and Shahinian (19:685-703) have reviewed studies regarding high temperature crack growth. They have determined that there are time-dependent and cycle-dependent regions of crack growth as shown in Figure 4.

In general, crack growth can be a function of load ratio (R), temperature (T), test frequency (ν), and time. Since tests cannot be carried out under each possible condition, models must interpolate crack growth based on known behavior. Heil (8:29-30) has used a linear summation of each region shown in Figure 4 to obtain the total crack growth rate:

$$\left. \frac{da}{dN} \right]_{\text{total}} = \left. \frac{da}{dN} \right]_{\text{time-dependent}} + \left. \frac{da}{dN} \right]_{\text{mixed-mode}} + \left. \frac{da}{dN} \right]_{\text{cycle-dependent}} \quad (3)$$

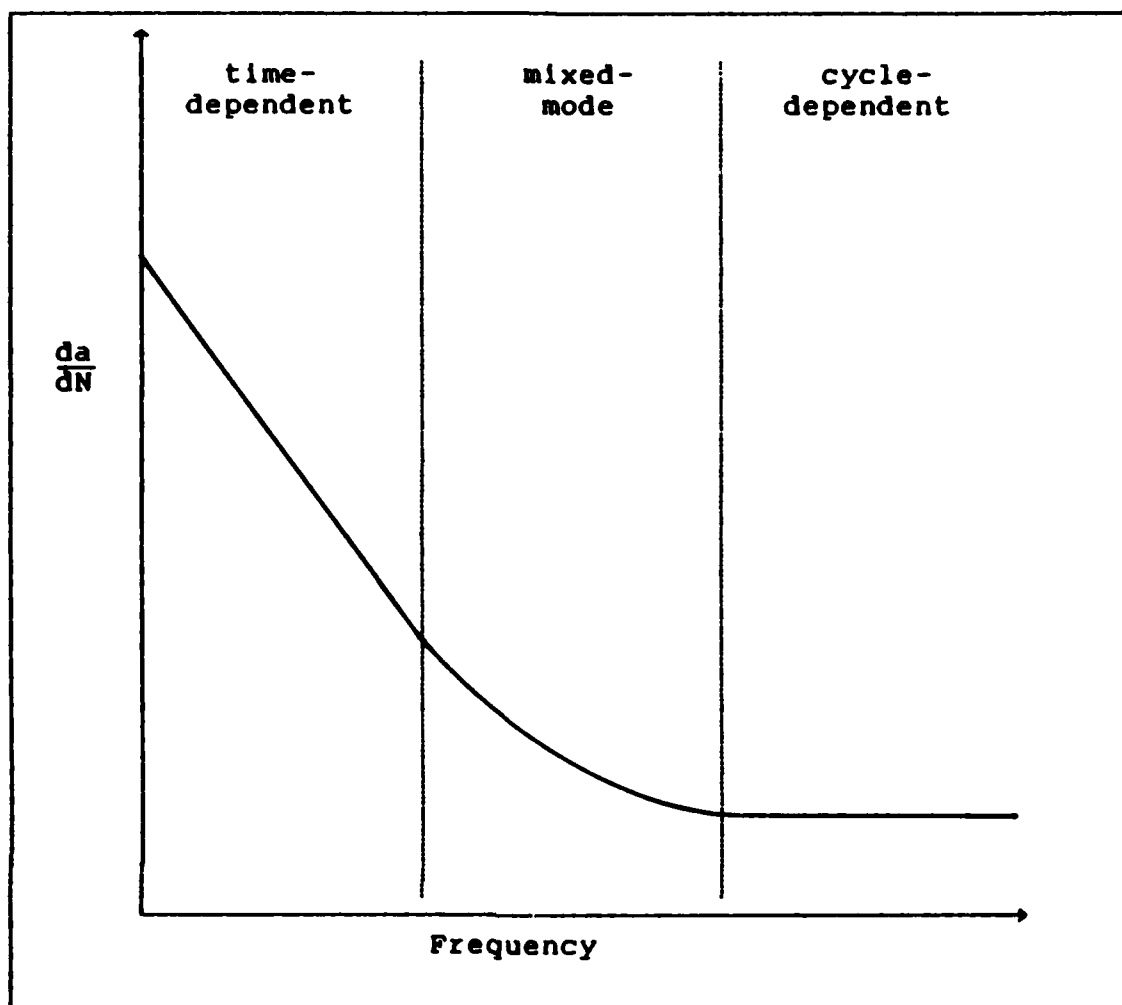


Figure 4 Effect of Frequency on Crack Growth Rate

The individual terms of Eq (3) could be developed using data obtained from each distinct region. Heil (8:30-31) has developed equations describing the time and cycle dependent regions, but found the mixed-mode region to be very difficult to define.

Hyperbolic Sine (SINH) and the Modified Sigmoidal Equation (MSE) equations have been used to describe high

temperature crack growth. These models define isothermal crack growth in terms of stress intensity factor, stress ratio, hold time, and frequency (7:3). Crack growth at various conditions can be interpolated from test data using the two equations.

The SINH model, developed by Pratt & Whitney, has been used extensively to predict isothermal crack growth, and is being extended to TMF conditions. The model fits a hyperbolic sine equation to crack growth rate (da/dN) versus stress intensity range (ΔK) data (6:8-9):

$$\log (da/dN) = C_1 \sinh [C_2(\log \Delta K + C_3)] + C_4 \quad (4)$$

where

C_1 = material constant

and C_2 , C_3 , and C_4 are independent functions of ν , R , and T .

$C_2 = f_2(\nu, R, T)$

$C_3 = f_3(\nu, R, T)$

$C_4 = f_4(\nu, R, T)$

A plot of $\log (da/dN)$ versus $\log (\Delta K)$ is shown in figure 5.

The constants for the SINH equation are determined using an interpolation algorithm. The procedure used to fit crack growth data is outlined by Wilson and Warren (8:8-11). This model has also been used to describe crack growth data obtained in the preliminary studies of Ti_3Al (10:2.26-2.33).

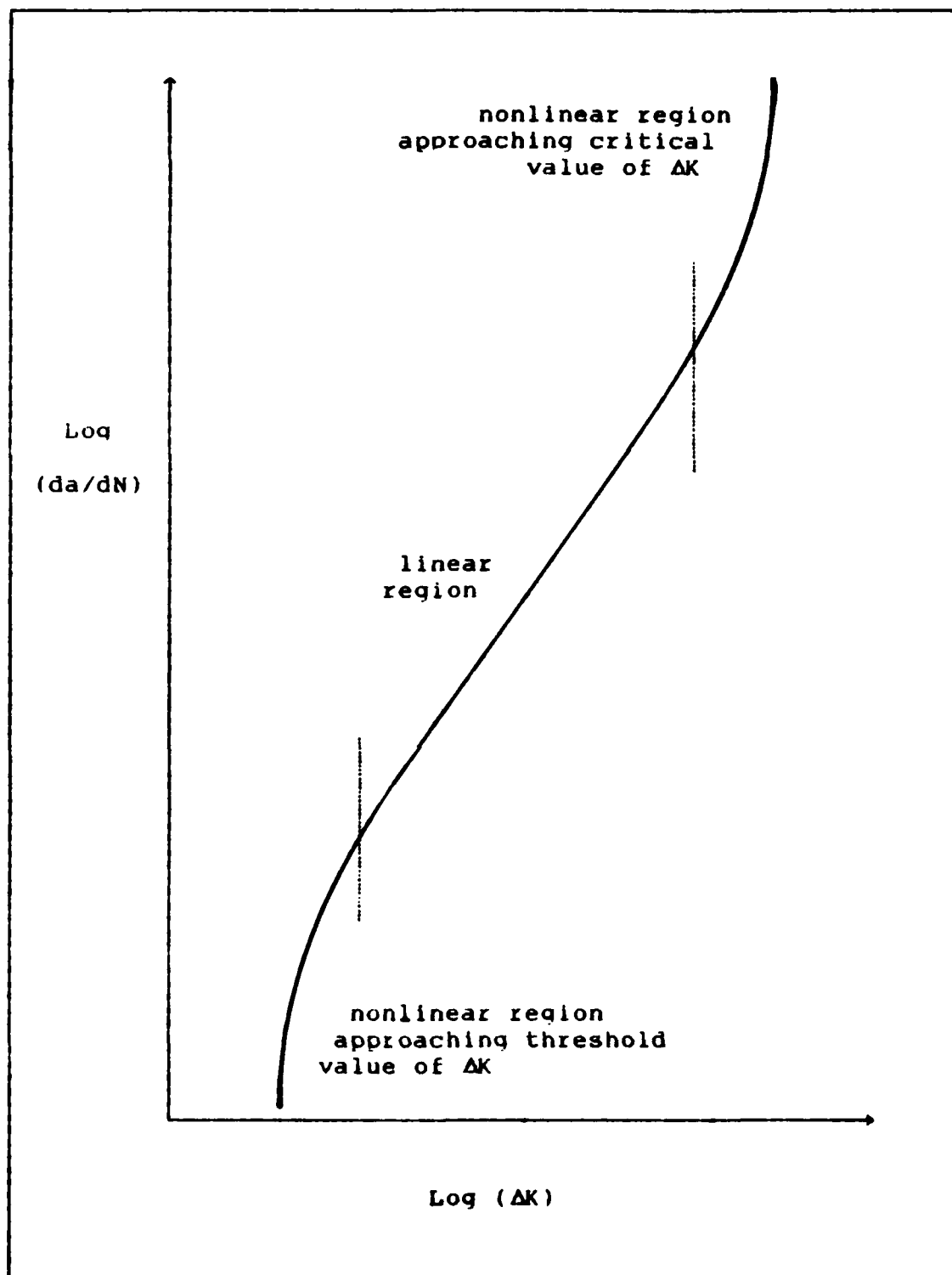


Figure 5 Typical Crack Growth Relation

The MSE model has successfully been used to fit high temperature crack growth data. The MSE uses a six-coefficient, modified, sigmoidal equation to fit the data shown previously in Figure 5. The MSE is not only a function of ν , R , and T , but also of the hold time (t_H) (8:33-41). The basic equation is of the form:

$$da/dN = \exp \left\{ B \left[\frac{\Delta K}{\Delta K^*} \right]^P \right\} \left\{ \ln \left[\frac{\Delta K}{\Delta K^*} \right] \right\}^Q \left\{ \ln \left[\frac{\Delta K_C}{\Delta K} \right] \right\}^D \quad (5)$$

where

ΔK^* represents the threshold value of ΔK (ΔK required to initiate a crack)

ΔK_C is the critical value of ΔK (ΔK causing failure)

B , P , Q , and D describe the slope, position,
and shape of the curve (20:9.1).

B , P , and ΔK^* define the location of the inflection point. Because of the three term dependence, it is very difficult to determine the values of the coefficients from the test data. Some simplifications can be made in the analysis.

Heil (8:33-53) has used the MSE to predict crack growth in Inconel 718 under a variety of test conditions, including isothermal load fatigue, in-phase TMF, and out-of-phase TMF. He used the following modified sigmoidal equation:

$$da/dN = \exp \left\{ B' \left[\frac{\Delta K}{\Delta K_1} \right]^P \right\} \left\{ \ln \left[\frac{\Delta K}{\Delta K^*} \right] \right\}^Q \left\{ \ln \left[\frac{\Delta K_c}{\Delta K} \right] \right\}^D \quad (6)$$

where

$$D = - \left[\frac{Q^{1/2} \ln (\Delta K_1 / \Delta K_c)}{\ln (\Delta K_1 / \Delta K^*)} \right]^2 \quad (7)$$

$$P = \left[\frac{da}{dN_1} \right]' - \left[\frac{Q}{\ln (\Delta K_1 / \Delta K^*)} \right] + \left[\frac{D}{\ln (\Delta K_c / \Delta K_1)} \right] \quad (8)$$

$$B' = \ln \left[\frac{da}{dN_1} \right] - Q \ln \left\{ \ln \left[\frac{\Delta K_1}{\Delta K^*} \right] \right\} - D \ln \left\{ \ln \left[\frac{\Delta K_c}{\Delta K_1} \right] \right\} \quad (9)$$

The parameters are shown in Figure 6. Heil then made the curve symmetric about the inflection point, setting Q equal to -D. The symmetry allows ΔK to be expressed as a function of ΔK_1 and ΔK^* ; therefore, the number of parameters is reduced to five (8:33-36).

A number of other models have been used successfully to characterize the high temperature crack growth behavior of materials. Halford (3:38-48) has reviewed many of these techniques, including the Manson-Coffin, Ostergen, and Total Strain Range (TSR) approaches.

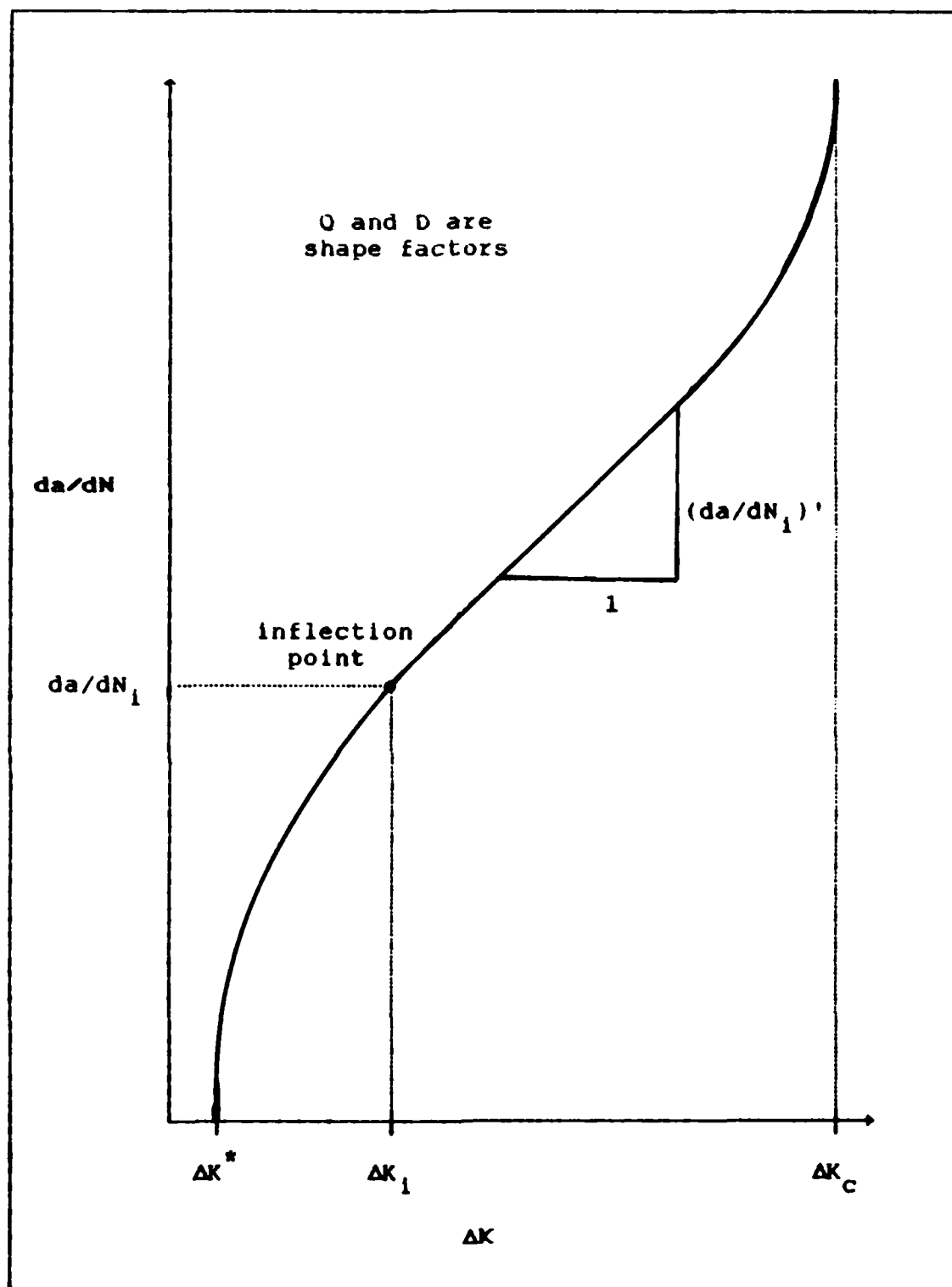


Figure 6 Definition of Parameters on da/dN Curve

Titanium Aluminides

Titanium (Ti) and Aluminum (Al) have many attractive characteristics that allow them to be considered for many applications, but most importantly, for high temperature aircraft structural components (21:1721). Compounds of Ti and Al take advantage of the unique properties of each, resulting in the titanium aluminides, Ti_3Al , $TiAl$, and $TiAl_3$.

Titanium-aluminide alloys feature high specific strength and low density. The alloys maintain their strength and stiffness up to $650^{\circ}C$ ($1200^{\circ}F$), and are much more fire resistant than titanium, permitting their use in higher temperature environments, such as those of gas turbine engines. These alloys can dramatically reduce weight and increase thrust, resulting in higher performance engines (10:1.1).

The Ti_3Al alloy is stronger, more dense, and more ductile than the other titanium aluminide alloys; therefore, it was chosen for this study. The fatigue characteristics of titanium-aluminides over a wide range of temperatures is not known. The TMF analysis of the material is required before it can be used in the components previously mentioned.

III. Experimental Equipment

The objective of the present study, as previously mentioned, was to develop a thermal-mechanical fatigue (TMF) testing system to study the titanium-aluminide alloys. The capability of the system was demonstrated by performing isothermal as well as TMF tests on the titanium-aluminide, Ti_3Al . The testing system is described here.

Test System

The test system required for TMF studies consists of a mechanical loading device, thermal control unit, and crack growth measurement instruments. A main computer is used to control each component of the system and acquire all the load, temperature, and crack length data. Figure 7 shows a block diagram of the entire system. The mechanical loading is produced by a closed loop MTS servohydraulic loading and control system. Temperature is maintained by heating and cooling the specimen. The heating is provided by four quartz lamp heaters controlled by a microprocessor that uses thermocouples for feedback. The specimen is cooled by jets of compressed air regulated by both mechanical and computer-controlled electric valves. The crack length is measured using an electrical potential drop technique and a traveling telemicroscope with digital position readout. Although this system was designed for testing compact tension (CT)

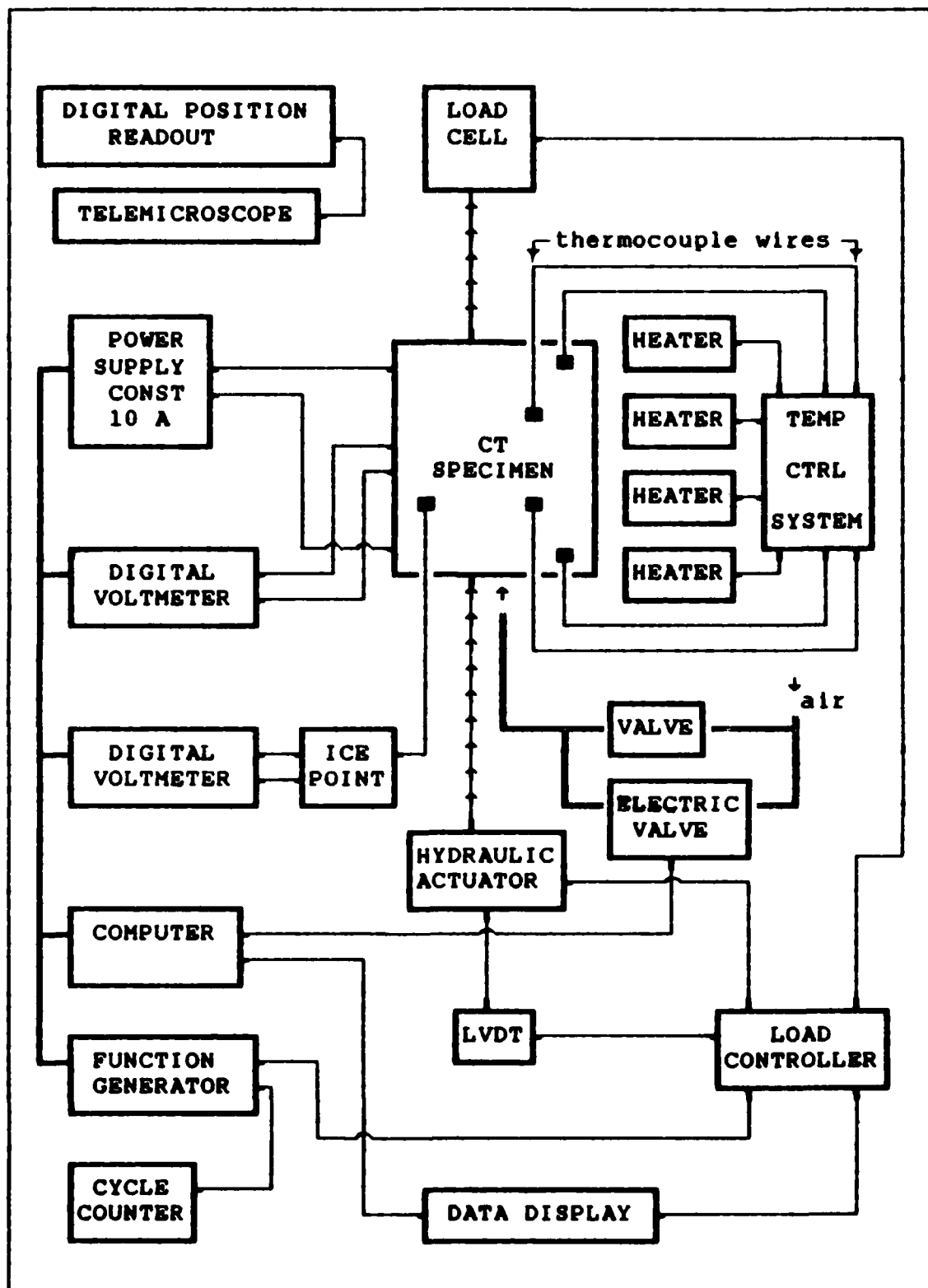


Figure 7 Block Diagram of Testing System

specimens, it can easily be modified for use with other specimen geometries as well. All components of the testing system will be described in detail.

Mechanical Loading System

The major components of the system that mechanically loads the specimen are shown in Figure 8. They include:

- 1) 10 kip Material Testing System (MTS)
servohydraulic machine
- 2) Zenith 248 computer used for control
and data acquisition
- 3) Wavetek function generator
- 4) MTS controller and data display
- 5) Cooling cylinders and basket
- 6) High temperature grips

The 10 kip MTS loading machine was operated in the 10 percent (maximum possible load is 1000 lbs.) load-control range using the load cell for feedback. The computer was programmed to send the function generator values of frequency, amplitude, offset, and wave shape. The function generator has two outputs. The first sends a signal to the cycle counter (sync) and the second sends loading signals to the servohydraulic controller (func), which in turn loads the specimen. The data display reads load and displacement from the controller and sends it to the computer whenever the data is requested.

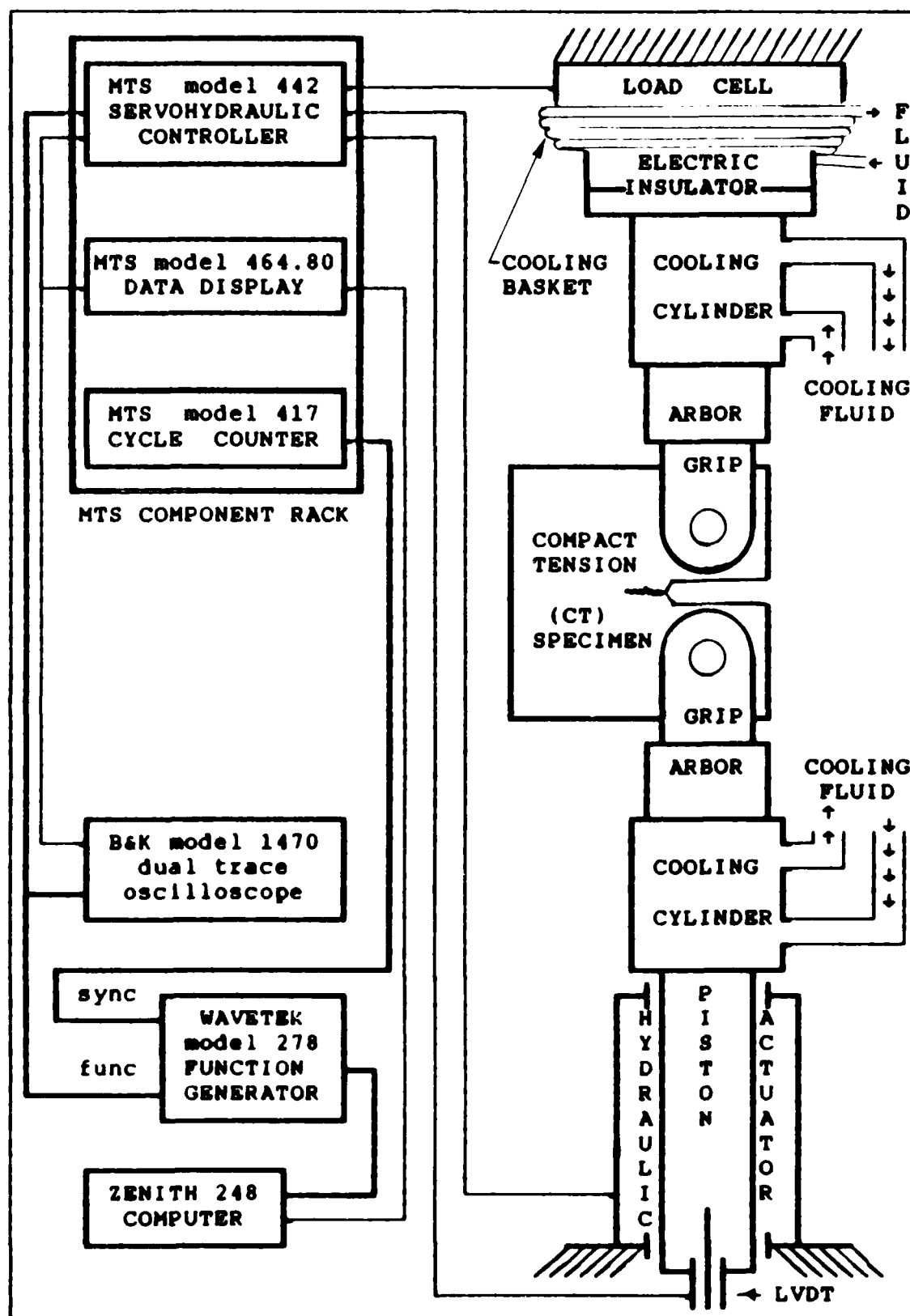


Figure 8 Mechanical Loading System

The load cell was calibrated to within 0.5 percent for the 1000 lb. load range setting. The function generator used for the system was a Wavetek model 278 programmable synthesized function generator. The Zenith 248 computer sent data to the function generator using a IEEE-488 (GPIB) data bus. For the tests considered in this study, triangular waveforms were generated by the Wavetek 278 and sent to the MTS 442 servohydraulic controller. The accuracy of this function generator is described in Table 1 (22:1.1-1.3).

Table 1 Accuracy of Wavetek Model 278

MODE	ACCURACY
FREQUENCY	2.0%
AMPLITUDE	2.0% of programmed value
OFFSET	40.0mV in dc function
WAVEFORM	triangular linearity of 99%

Modifications made to the MTS load frame for high temperature testing were high temperature grips, cooling cylinders, and a cooling basket. An electrical insulator was connected between the load cell and cooling cylinder to electrically isolate the upper portion of the specimen for electric potential (EP) crack length measurements. This method of crack length measurement will be discussed later.

Initially two grips were manufactured according to the ASTM standard E 647 (17:712) using Rene 41, a high temperature

nickel-base alloy. The slot was then widened to allow for connection of the electric current leads that are used in the EP measurement of crack growth. The modified grip dimensions are shown in Figure 9.

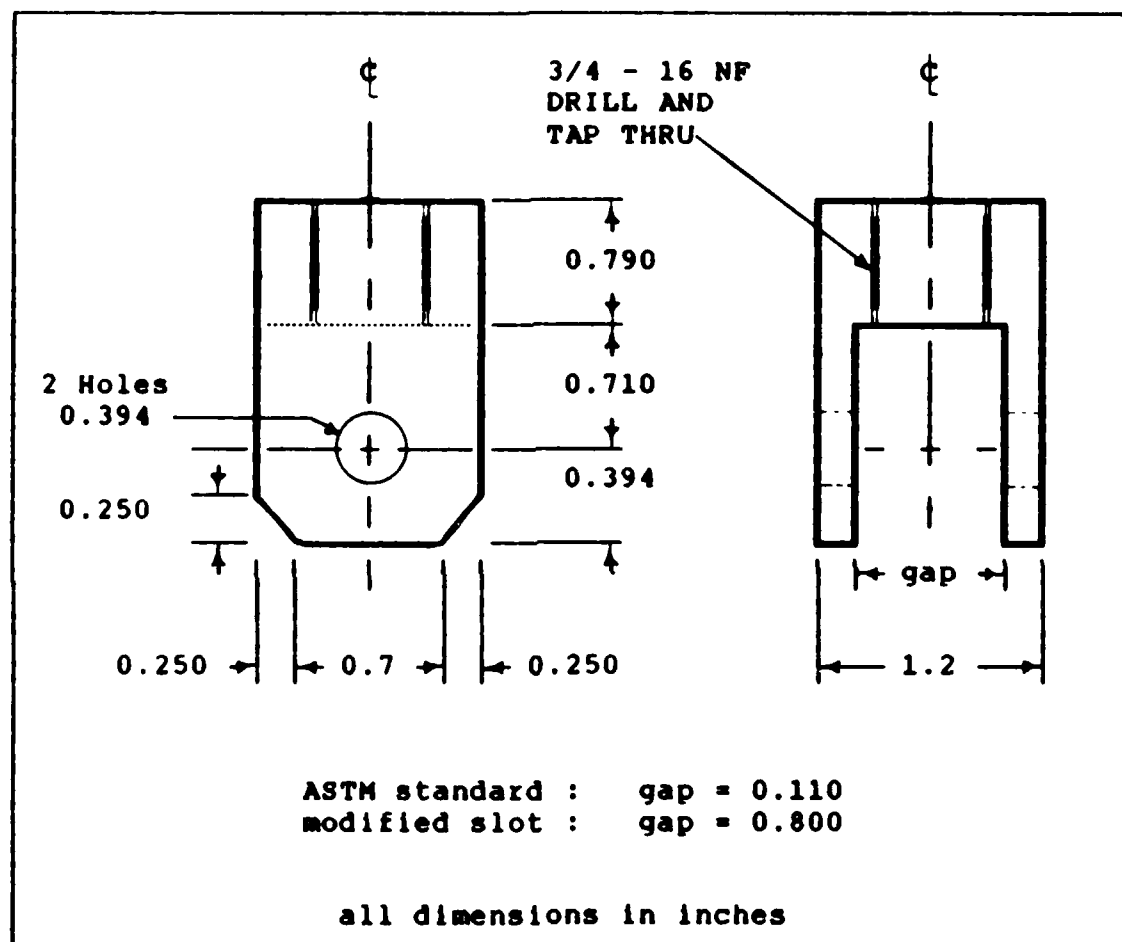


Figure 9 Modified Grip for EP Current Leads

During preliminary experiments involving thermal cycling of the specimen, the grips, even with the slot modification, inhibited proper heating and cooling of the specimen. The temperature of the specimen region that is enclosed by the

grip was too low during heating and high during cooling. The slot in the grips was not wide enough to allow the lamps to adequately cover the specimen or to allow enough air from the cooling jets to pass over the specimen. A new grip design was used to improve the temperature profile across the specimen. The slot of the new grip is 0.4 inch wider and 1.29 inches longer than the old grips. Figure 10 shows the new grip design.

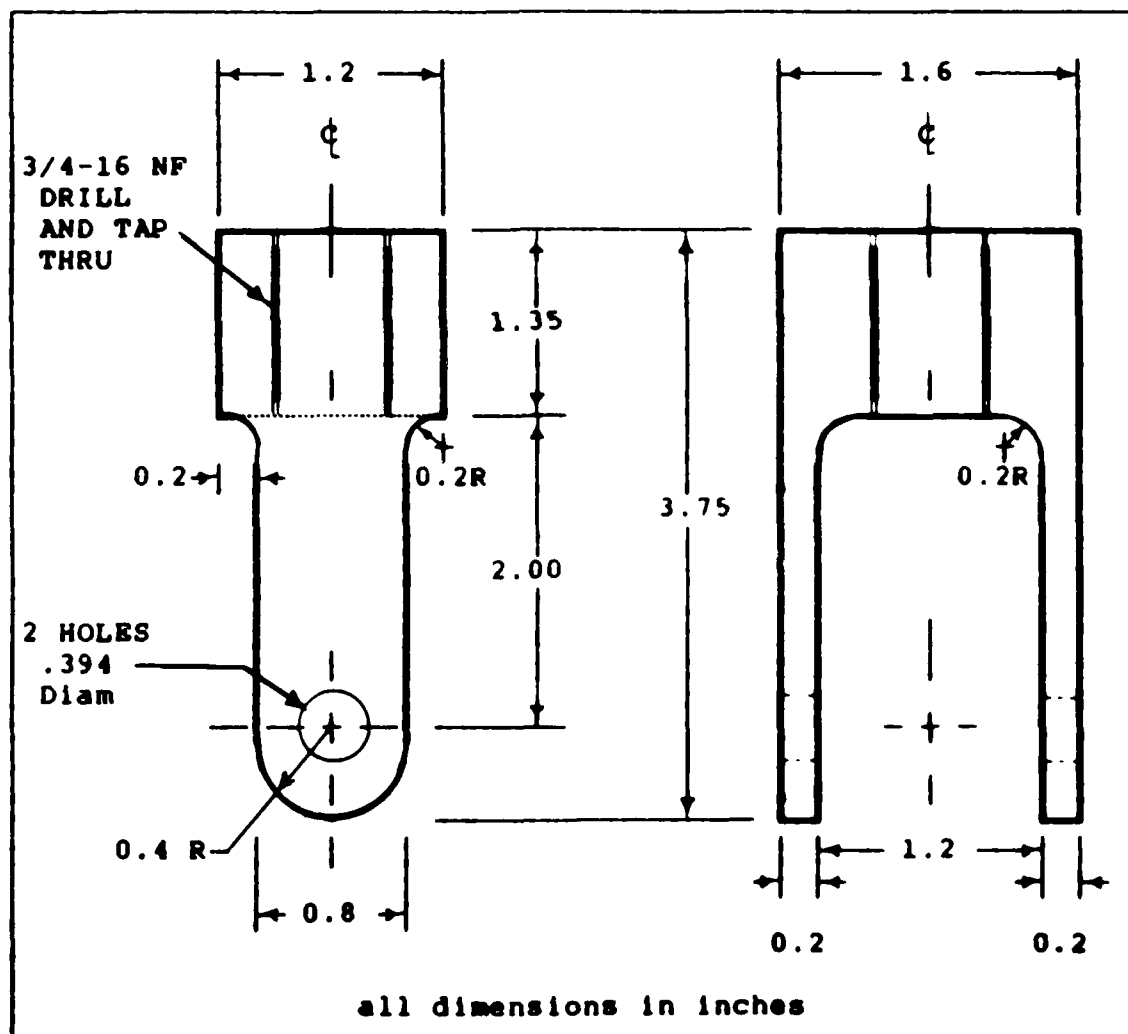


Figure 10 Grips Designed for TMF

To reduce heating of the pins, ceramic insulators were placed around them as shown in Figure 11. This prevents the lamp's direct heat from hitting the pins. The insulators also act as spacers that keep the specimen centered in the slot. Maintaining specimen alignment with the applied load prevents any pin bending from creating transverse loads on the specimen.

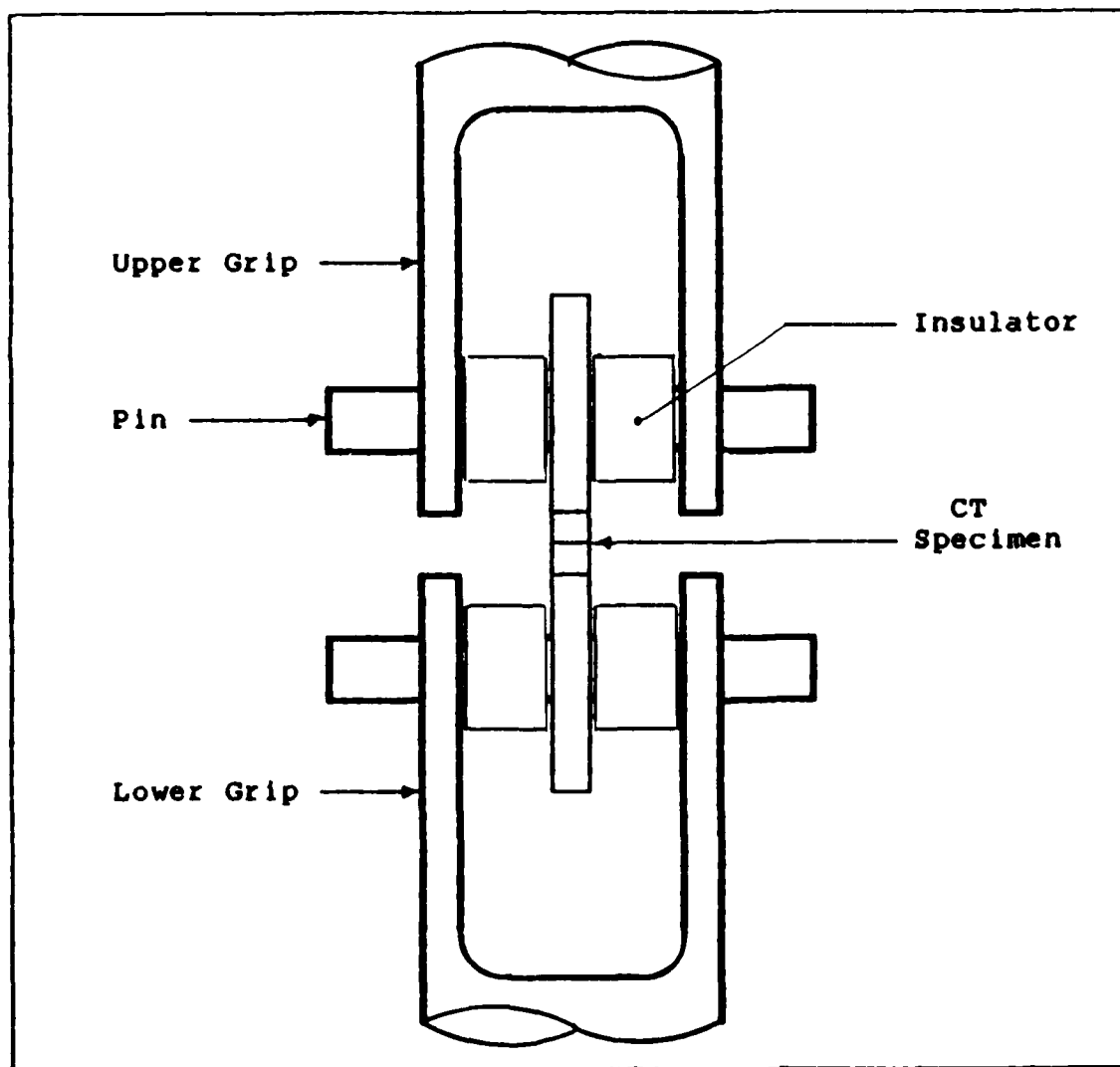


Figure 11 Spacer Placement Between Specimen and Grips

To eliminate the heating of load cell and actuator piston, a cooling basket and cooling cylinders were installed in the loading system. The cooling basket was made from 1/4 inch copper tubing wound in a 10-loop, cone-shaped spiral. The basket is shown in Figure 12. The cooling cylinders were

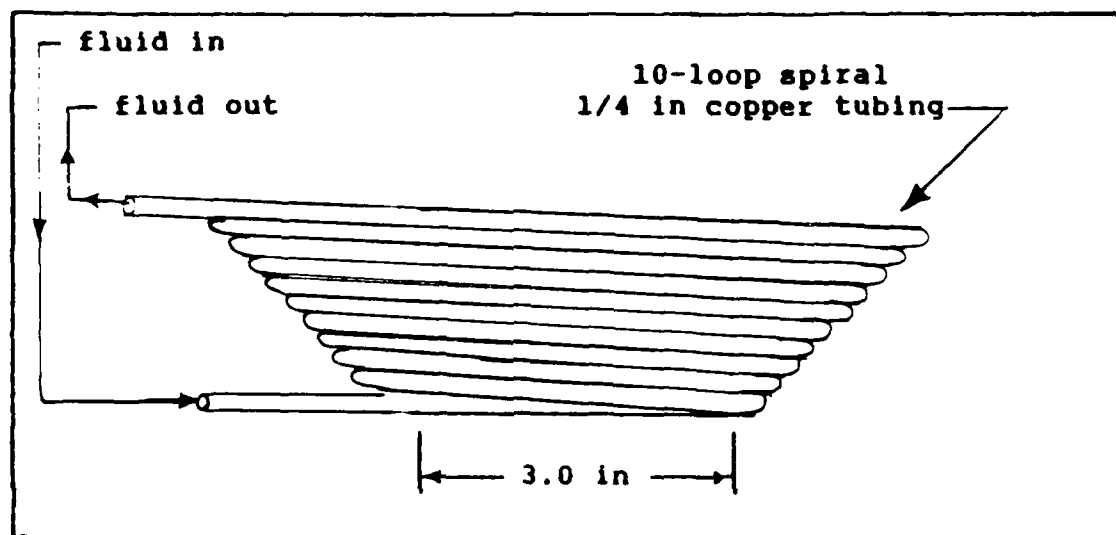


Figure 12 Cooling Basket for Load Cell

machined from a 2.75 inch outside diameter stainless steel tube. They are 12 inches long and sealed with end caps. There is a water inlet at the bottom and a outlet at the top of each as previously shown in Figure 8. These allow for the circulation of cooling fluid through them. Distilled water was pumped through the basket and cylinders and constantly cooled to room temperature with a water conditioning unit. The basket encloses the load cell to prevent convective heating, and the cylinders are in the line of loading to prevent conductive heating of both the load cell and piston.

Temperature Control System

The components used for temperature control of the specimen are shown in Figure 13. The major components of the system are:

- 1) Micricon 82300 process control system
- 2) Four quartz lamp heaters
- 3) HP 3456A digital voltmeter
- 4) Zenith 248 computer
- 5) Computer and manually controlled
cooling air system
- 6) Cooling water arrangement

The specimen is heated with four quartz lamp heaters. During preliminary experiments, the lamp heaters used were the parabolic strip type. The heaters use 1000 watt tungsten-filament quartz lamps that reflect radiant energy off a parabolic surface and onto the specimen. The specimen absorbs the infrared radiant energy and converts it to heat energy. A major advantage of this heating method is that the energy passes through the air without heating it; therefore, most of the energy is transmitted to the specimen. A disadvantage of this method is that to operate most efficiently, a specimen should be dark and nonreflective to absorb more energy, but specimens need to be polished in order to make clear crack length measurements with a traveling telemicroscope.(23:3.1-3.2) This method of crack length measurement will be discussed in a following section.

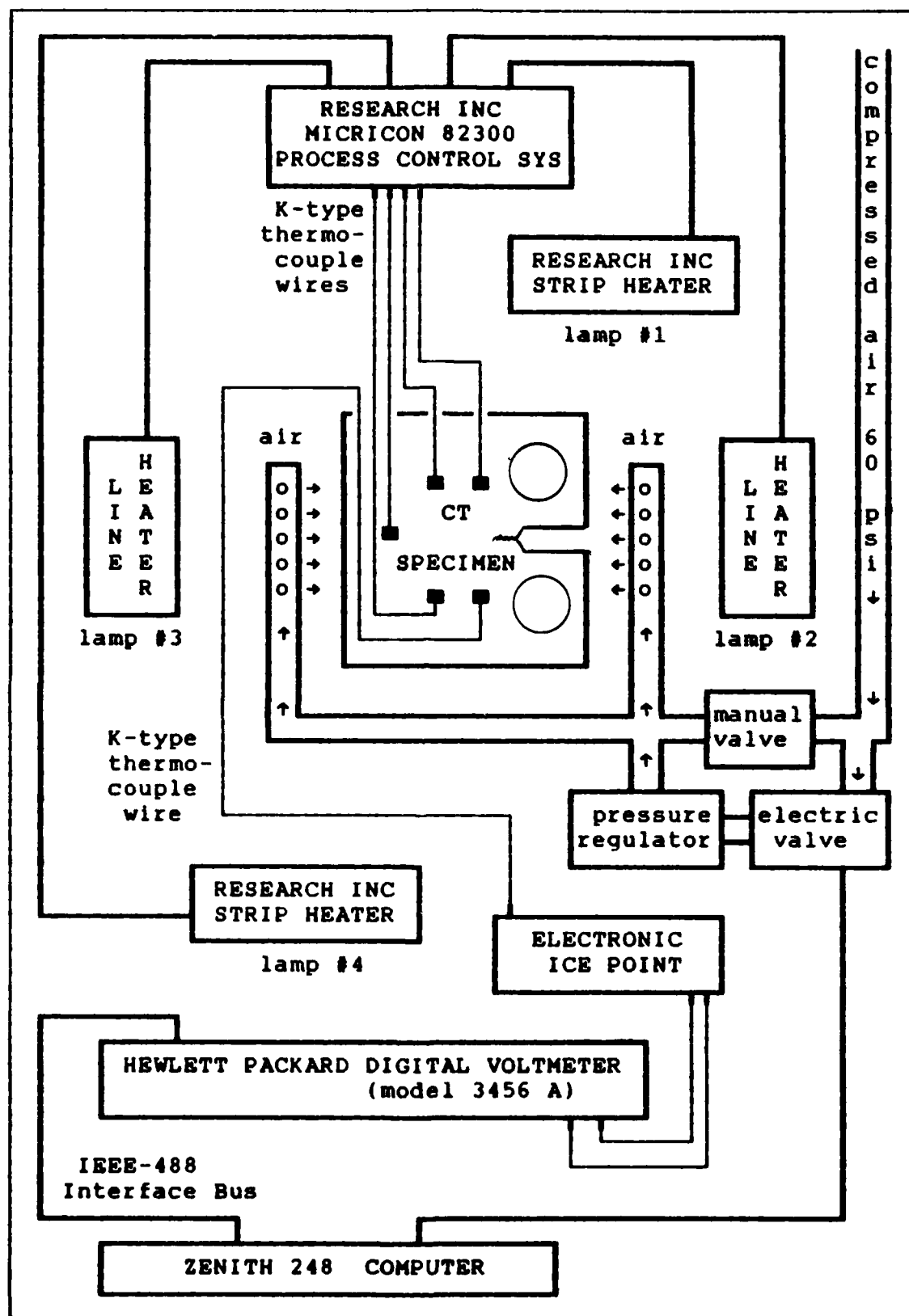


Figure 13 Temperature Control System

The heaters are mounted on aluminum brackets and connected to the MTS loading frame with a rod and knuckle arrangement as shown in Figure 14. The main mounting bracket is attached to the main support of the MTS loading frame, and the mounting knuckle is allowed to rotate in order to swing the lamps away from the specimen when required. The rods and knuckles can rotate and translate as shown in order to position the lamps to obtain the proper heating coverage of the specimen. This arrangement provided the flexibility to heat a small CT specimen. When the lamps are in a position that provides a uniform temperature distribution across the specimen, the adjustment screws can be tightened to prevent further movement.

Lamps number one and four were positioned in front of the specimen and two and three were placed behind. The two front lamps heated horizontally and the two rear lamps heated vertically. The areas of the specimen that are heated by each lamp are shown in Figure 15. The areas slightly overlapped in the center for complete coverage. Heil (8:21) used similar lamp configurations to heat center crack tension specimens. During temperature cycling he was able to maintain temperature variations of 5°C (9°F) or less. As previously mentioned the CT specimen is being considered here, and for this specimen, the four strip heaters were not adequate. Large temperature gradients existed near the notch and edge of the specimen. To compensate for heat losses in these two regions, line heaters were used to heat areas two

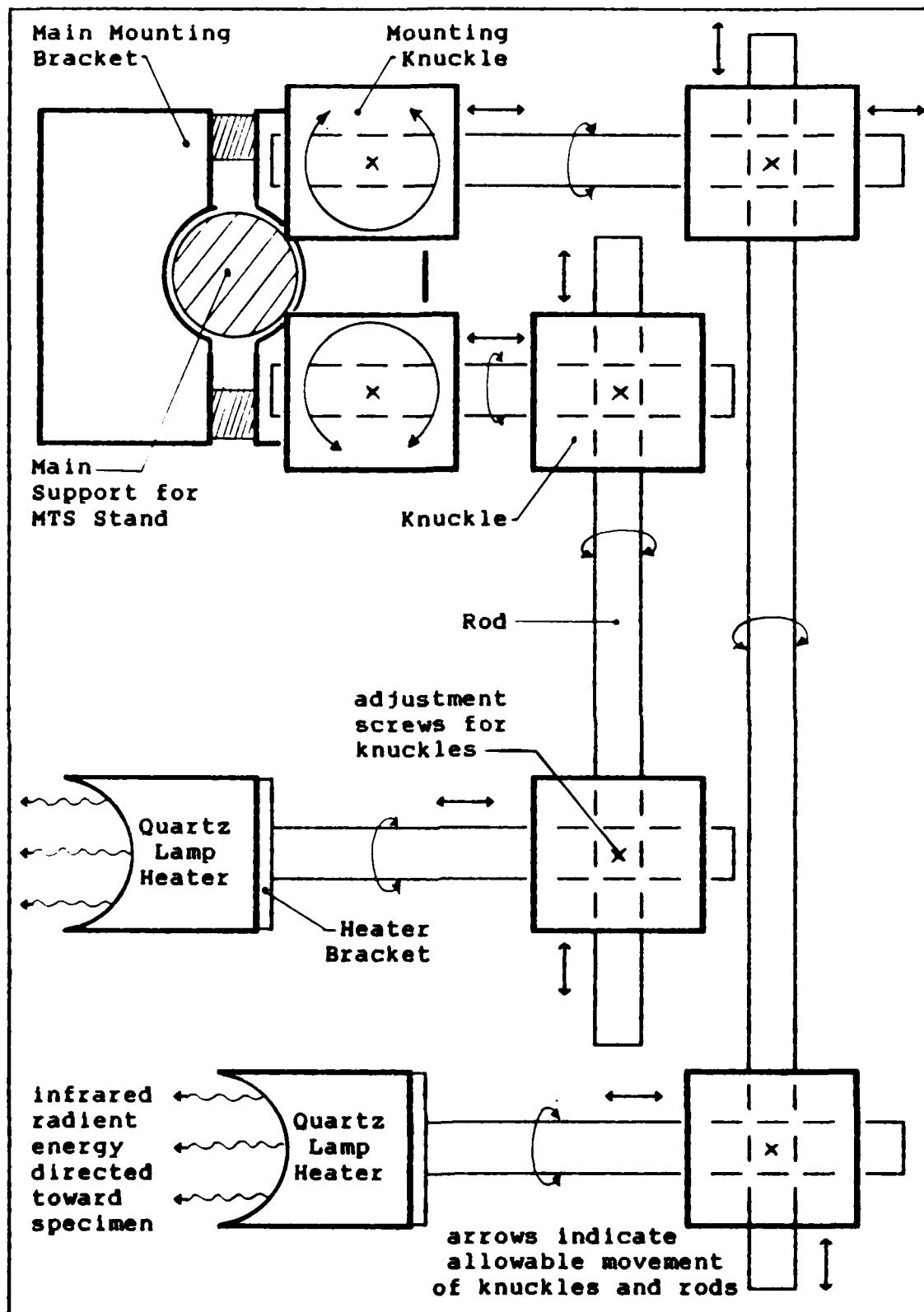


Figure 14 Top View of Mounting Assembly for Heating Lamps

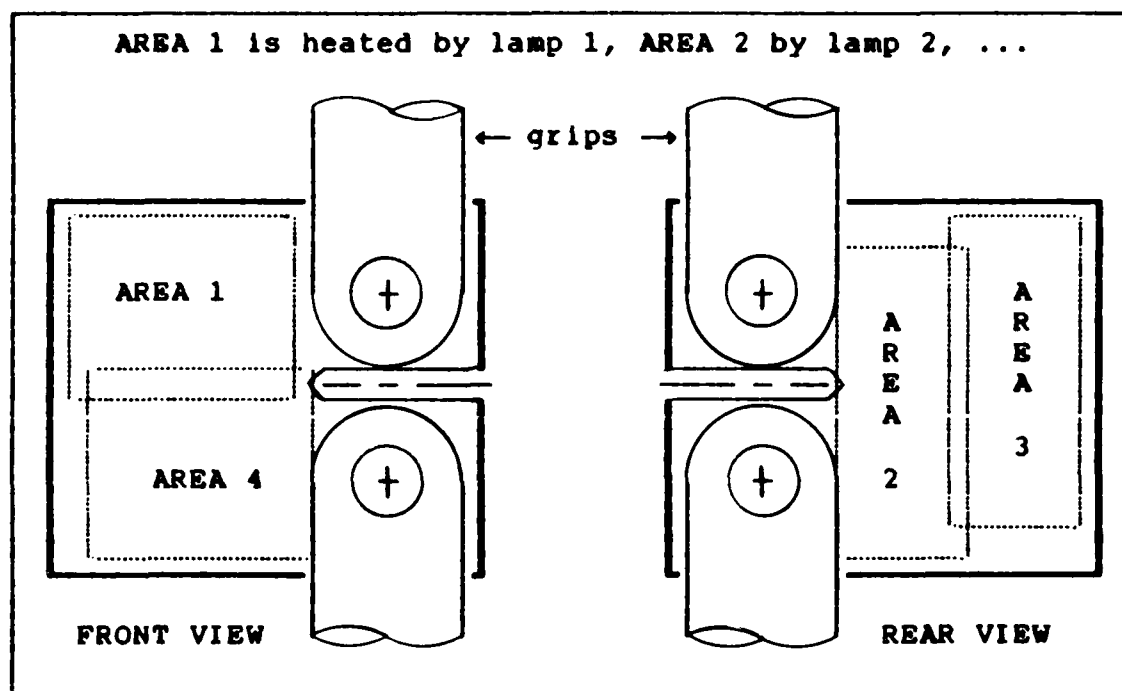


Figure 15 Quartz Lamps Heating Areas

and three (the two areas that are heated from the rear). These heaters can concentrate heat flux at a focus line (24:1.1). When these heaters were brought slightly out of focus, they were able to provide the coverage required as shown in Figure 15 and maintain the desired temperature.

During temperature cycling, forced convective cooling was required to reduce specimen temperatures in the desired time. Jets of air were blown across the front and back of specimen as illustrated in Figure 16. To maximize cooling rates, the air was also used to cool the grips. During the heating portion of the cycle, the grips act as a heat sink, and during the cooling portion, transfer heat to the specimen.

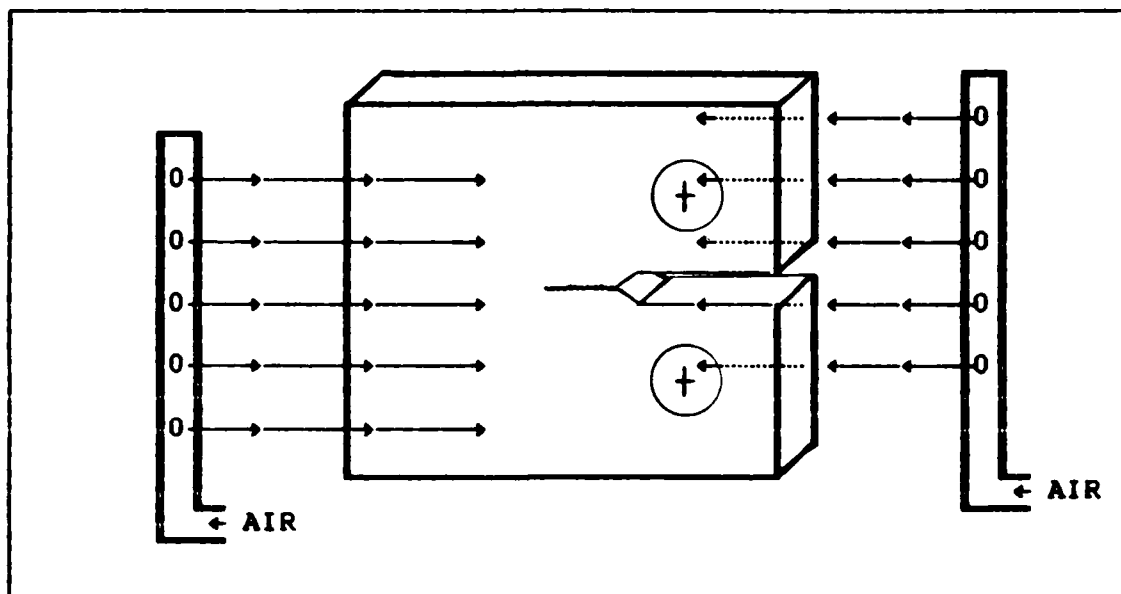


Figure 16 Compressed Air Cooling Jets

Initial experimentation showed that low levels of air flow used during heating, resulted in less temperature variation across the specimen. This brought about a need for two levels of air flow, one for use during heating of the specimen and the other for cooling. The two levels of air flow are described in Figure 17. The manual valve is adjusted to achieve the desired level of air flow for the heating portion of the cycle. During cooling, the electric valve opens, allowing secondary air flow to pass over the specimen. To regulate the secondary air flow, a pressure regulator was placed in the flow between the electric valve and cooling jets. With this two-level cooling process, heating and cooling rates of 12.5°F per second were achieved (600°F to 1200°F cycles in 96 second periods).

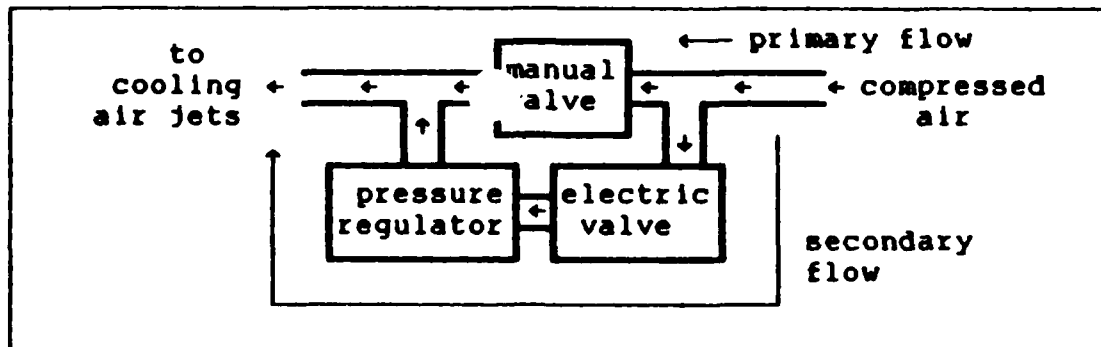


Figure 17 Primary and Secondary Air Flow to Cooling Jets

A Micricon 82300 process control system was used to power the heating lamps and Chromel-Alumel (type-K) thermocouples were used for feedback. Eight sets of thermocouple wires were welded to the specimen at the four locations shown in Figure 18. These positions were chosen

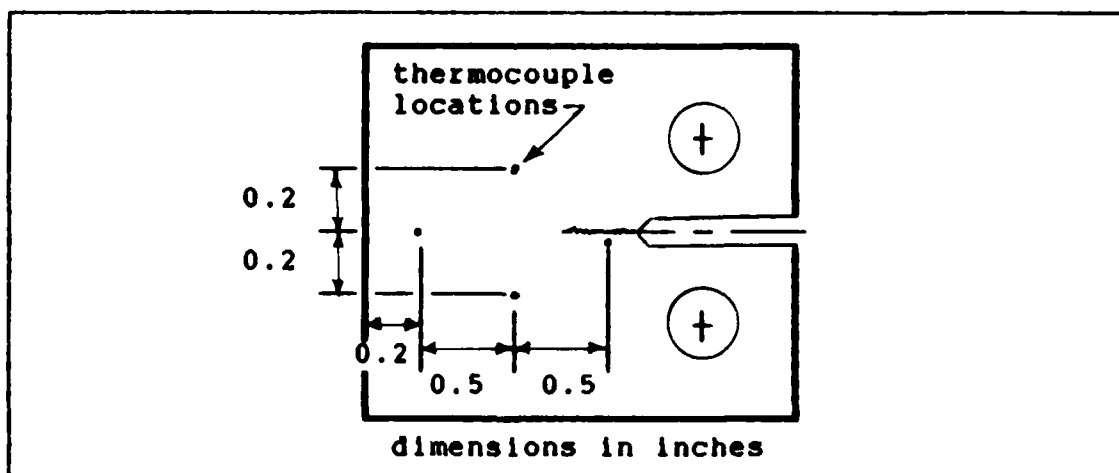


Figure 18 Thermocouple Locations on the CT Specimen

after trying various locations. The upper and lower thermocouples were welded as much as 0.5 inches above and

below the center line extending from the notch tip. At these locations, the temperature deviations across the specimen were as high as 16 percent. At the 0.2 inch locations temperature deviation was reduced to approximately 1 percent during temperature cycling tests between 600°F and 1200°F and less than 1 percent during isothermal tests. If the thermocouple farthest away from the notch tip is closer than 0.2 inches from the edge of the specimen, lamp number three operates at too high an output level and the lamp life is reduced considerably. A 1.0 inch separation between the two thermocouples that lie along the specimen center line was chosen in order to control the temperature near the crack while providing enough heat to compensate for the heat sink effect of the grips and the convective losses at the edge of the specimen.

The Micricon 82300 uses three-mode (proportional, integral, and derivative or PID) control. PID control in the Micricon is described in Figure 19. The proportional factor, or gain, determines how the output of the controller will vary with a change in the error signal. The gain setting can be adjusted between 0.0 and 128.0. (25:1.4,2.9) During preliminary experiments with the Micricon, gain settings between 30.0 and 60.0 were used to create cyclic temperature profiles of 600°F to 1200°F with a period of four minutes.

Integral, or reset, adds to or subtracts from the gain to determine the final output. Reset is used to correct the steady state error (offset) when using PID control (26:7).

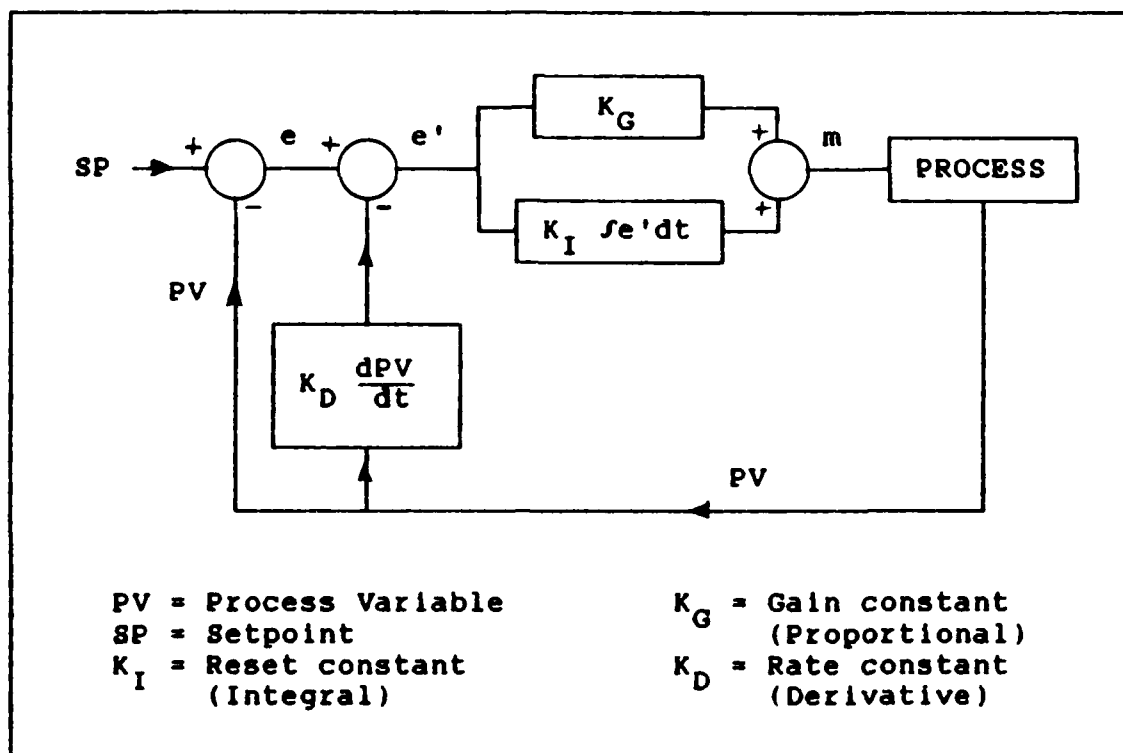


Figure 19 PID Control in the Micricon 82300

The reset control for the Micricon can be set between 0.0 and 60.23 repeats per minute to correct the offset in the maximum (peak) temperature (25:2.9).

The derivative factor, or rate, takes into account the time lag in the system (26:11). Rate values ranging from 0.0 to 8.5 minutes can be set.

Research Inc., manufacturers of the Micricon, (27:5) suggest that gain and rate be set first, simultaneously. The gain should be set as high as possible without creating large oscillations of the lamp output. Preliminary tests showed that an increase in output resulted in an instantaneous increase in temperature; therefore, rate was not required for

control of the lamps. After the gain was set, the reset was used to eliminate the offset. According to Research Inc. (26:9), reset values that are too large cause oscillations of the output as in the case of too much gain. However, oscillations of the lamp output did not occur for any value of reset used. A summary of the control parameters and their effects on the temperature profile is shown in Table 2. Rate is not included in this table since only proportional and integral (PI) control was required for the quartz lamp heaters.

Table 2 PI Control Parameters and Their Effects

GAIN	RESET	EFFECT
45.0	30.0	did not achieve peak setpoint (SP); peak occurred 10 sec. after peak SP
55.0	30.0	did not reach SP but achieved a 40°F increase from the previous case peak occurred 6 sec. after peak SP
65.0	30.0	peak value was 5°F less than previous case, but occurred at peak SP
30.0	30.0	low peak value in temperature cycling worked well for isothermal tests
30.0	60.0	worked well for cycling between 600°F and 1200°F in 96 sec. period
45.0	60.0	created small oscillations after peak SP was achieved

Gain values of 30.0 worked well for both isothermal and temperature cycling tests. This prevented oscillations of lamp output. These oscillations must be avoided since they

drastically reduce the life of a tungsten-filament lamp. As seen from the table with gain settings of 30.0, reset values of 30.0 and 60.0 worked well for the isothermal and cycling temperature tests respectively.

The minimum (LO LMT) and maximum (HI LMT) output sent to the lamps can be controlled by the Micricon 82300. LO LMT and HI LMT values of 5.0 percent and 60.0 percent were used during cycling tests to extend the bulb's life. During these tests the lamps will operate over their entire output range unlike the isothermal tests, when lamp output does not exceed 40.0 percent. Using the LO LMT and HI LMT setting prevents large jumps in current output to the lamps.

As previously mentioned, eight thermocouples were welded to the specimen. Four were required for feedback to the Micricon controller and the others served two purposes. First, through-the-thickness temperature variations were investigated. A type-K thermocouple thermometer (Omega Model 650) and the Micricon 82300 were used to measure these temperatures. With the 0.1 inch-thick Ti_3Al specimens, no variations were detected. Second, the thermocouple voltage was recorded through a voltmeter and converted to temperature using the relation obtained from the thermocouple manufacturer, Omega Engineering Inc. (28:T.12):

$$T(^{\circ}C) = C_0 + C_1x + C_2x^2 + \dots + C_8x^8 \quad (10)$$

where the constants are defined as:

$$C_0 = 0.226584602$$

$$C_1 = 24152.109$$

$$C_2 = 67233.4248$$

$$C_3 = 2210340.682$$

$$C_4 = -860963914.9$$

$$C_5 = 4.83506 \times 10^{10}$$

$$C_6 = -1.18452 \times 10^{12}$$

$$C_7 = 1.38690 \times 10^{13}$$

$$C_8 = -6.33708 \times 10^{13}$$

and:

x = voltage read by the voltmeter in volts

Temperature is converted to $^{\circ}\text{F}$ by:

$$T(^{\circ}\text{F}) = 32.2 + (9/5) T(^{\circ}\text{C}). \quad (11)$$

The recorded temperature was used by the computer to:

- 1) generate temperature versus time plots
- 2) trigger the frequency generator to keep the load in or out of phase with the temperature
- 3) open and close the electric valve

The final component of the temperature control system is the water cooling arrangement. The cooling basket, cooling cylinders, and quartz lamps all require coolant, in this case distilled water, to be pumped through them. Distilled water was used to prevent corrosion of the components. A water conditioner reduces the water temperature after it circulates through all the components and returns to the holding tank. Figure 20 shows the closed-loop water cooling system.

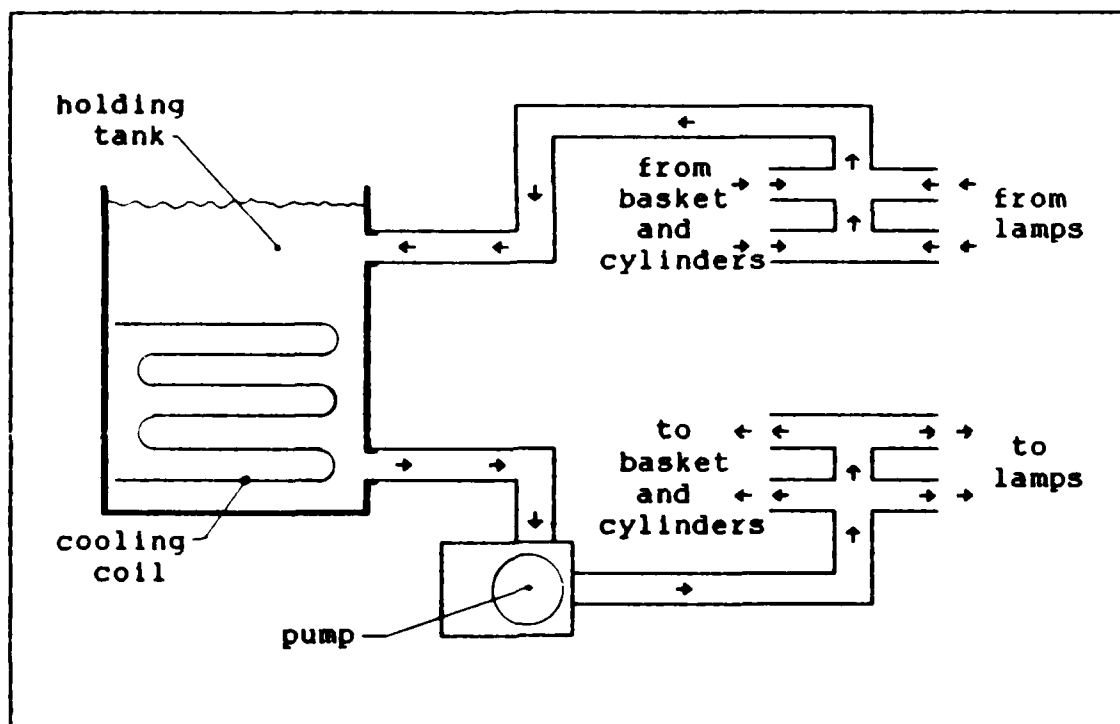


Figure 20 Water Cooling System

If leaks occur in the system and a large quantity of coolant is lost, severe damage can be done to the lamps and pump. To protect these components, a relay system was developed to shut down the pump and Micricon control unit if the water in the tank dropped below a specified level. This system uses a cork float attached to a microswitch that closes under the float's weight when the tank water level drops. A diagram of this relay system is shown in Figure 21.

Crack Length Measurement Devices

Crack length was measured with both optical and electrical potential (EP) methods. The devices used for crack length measurement are shown in Figure 22.

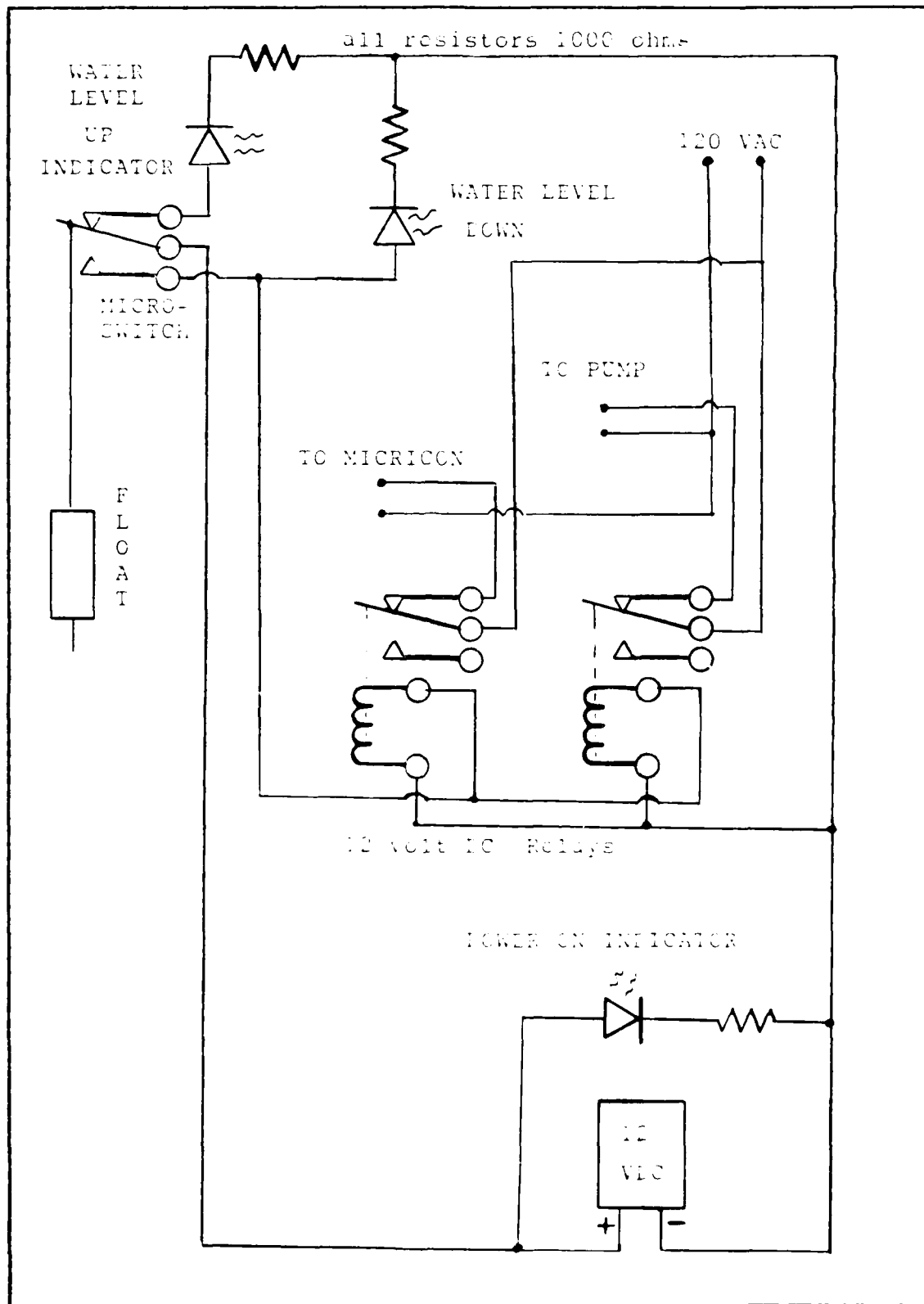


Figure 21 Protective Relay System

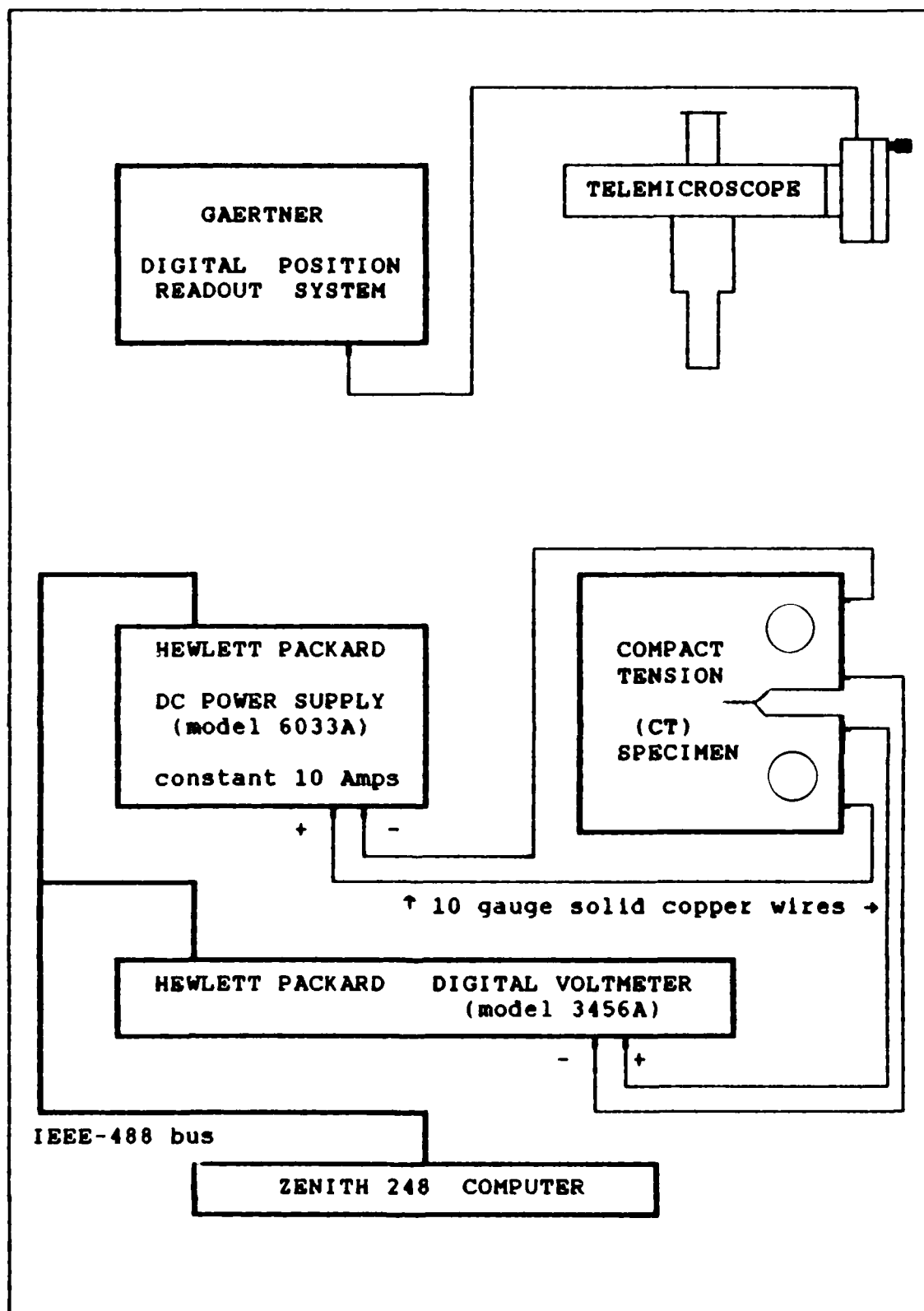


Figure 22 Crack Length Measuring Devices

The components used in the measuring system are:

- 1) Traveling telemicroscope with digital readout
- 2) HP 6033A DC power supply to apply constant 10 Amps through specimen
- 3) HP 3456A digital voltmeter to measure voltage drop across specimen
- 4) Zenith 248 computer used to control current and read voltage data

Optical measurements are made with 0.00005 inch resolution using a Gaertner telemicroscope and digital position readout system. Reference marks were inscribed behind the notch to get consistent crack length readings. A high intensity lamp was used to illuminate the surface during thermal cycles when the four heating lamps could not provide the proper light angle to clearly see the crack.

Electrical potential (EP) drop across CCT test specimens has been used successfully to measure crack growth (8:23,16:9) as mentioned earlier. During isothermal conditions this method works well; however, a problem arises when the temperature varies, since the potential drop is dependent on temperature. Voltage measurements must be taken at the same temperature to obtain consistent results.

For the CT specimen employed in this study, two main current leads were bolted behind the crack at the corners, as illustrated in Figure 23. To minimize current losses, 10 gauge

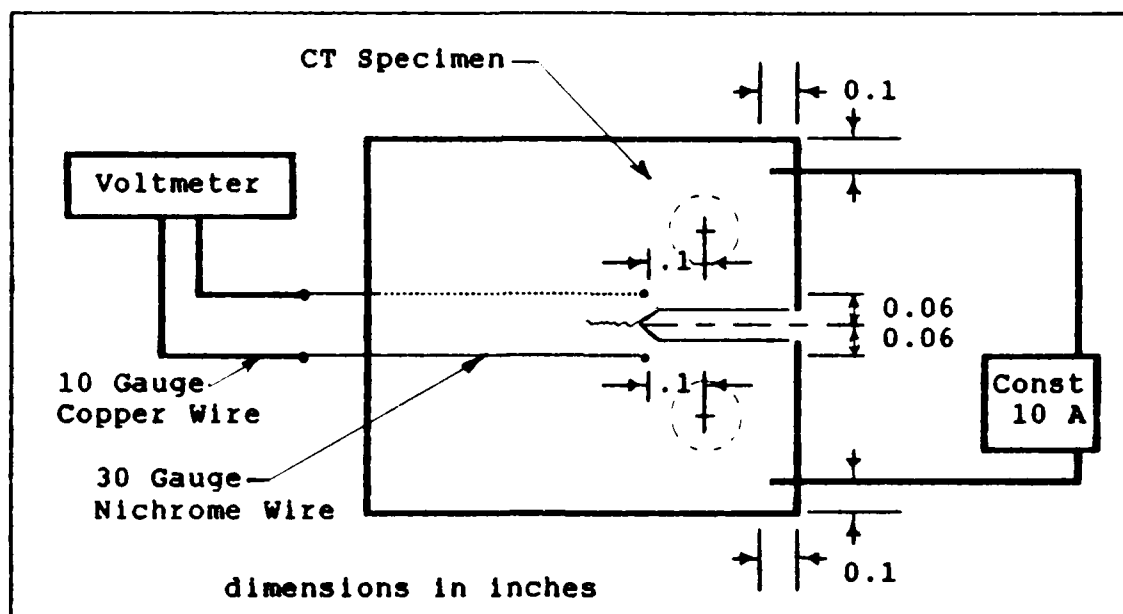


Figure 23 DC Current and Pickup Positions

solid copper wires connect the power supply directly to the CT specimen. The two test leads that measure voltage drop across the crack were welded close behind the initial crack at the notch, the upper lead in front, and the lower lead in back. To minimize the errors in the voltage measurement, 10 gauge solid copper wires connect the voltmeter to the test leads. This reduces the length of the test leads to 12 inches. Nichrome wire had been used successfully as test leads by Hartman and Johnson (18:108) while testing IN 718. Nichrome was chosen to minimize the thermoelectric effect and was also used for studying Ti_3Al .

The power supply used in these tests was a Hewlett Packard HP6033A system DC power supply and the voltmeter was a Hewlett Packard 3456A digital voltmeter. Both used the IEEE-488 (HP-IB) bus for data transfer to and from the main

computer, the Zenith 248. The accuracy of both components is described in Table 3 (29:1.5,30:29).

Table 3 Accuracy of the Power Supply and Voltmeter

DEVICE	RESOLUTION	ACCURACY
HP6033A DC power supply	0.01 Amps	0.3 %
3456A digital voltmeter	0.001×10^{-3} volts	< 0.001 %

To take consistent EP measurements, the readings always were taken at the same temperature, and to prevent the effect of crack closure on the measured voltage, readings were always taken at maximum load. To obtain a more accurate voltage reading, 25 readings were taken in one second and averaged. Using the method described by Hartman and Johnson (18:107), thermal EMF is subtracted from the EP measurements to reduce the error associated with EMF. Since thermal EMF remains when there is no current flowing through the specimen, the EMF can be measured easily. The voltage then used for crack length analysis is:

$$V = V_{EP} - V_{EMF} \quad (12)$$

where:

V_{EP} is the voltage taken with the current turned on

V_{EMF} is the voltage taken with the current turned off

The method used to take electric potential (EP) crack growth readings involved the following steps:

- 1) Temperature was monitored to determine when the EP readings would be taken. (For isothermal tests, the program monitored the load only to find the maximum value, assuming that the temperature was constant.) For in-phase tests, readings were taken at maximum temperature, and for out-of-phase tests, they were taken at minimum. This was to allow all readings to be taken at the maximum load.
- 2) At the peak load, a set of 25 voltage readings was taken with the current off and averaged. The current was then turned up to 10 Amps and allowed an entire cycle to stabilize.
- 3) Another set of readings was taken at the next consecutive peak and averaged. The current was then turned back down to 0 Amps.
- 4) A third set of voltage readings was then taken at the next peak and averaged.
- 5) The first and third readings were averaged to obtain a value of V_{EMF} . V_{EMF} was then subtracted from V_{EP} , the average value of the second set of readings, to yield the corrected value, V .

This method generated corrected potential readings, V , taken at specific cycle numbers, N . Taking visual crack length measurements, a_m , at specific cycle numbers, N ,

allowed the voltage measurements to be converted to crack length. With these two groups of data, a calibration curve relating a_m to V was created. The benefit of using this method is that the calibration equation is valid for the other test specimens as long as the initial voltage, V_o , is known and readings are taken at the same temperature. An example of a calibration equation is:

$$a = A_o + A_1 V + A_2 V^2 + A_3 V^3 + A_4 V^4 \quad (13)$$

where:

V = electric potential across specimen

a = crack length

A_o = offset value

A_n = constants to be evaluated, $n = 1, \dots, 4$

A_o in Eq (13) will vary between tests, but if the values of A_1 , A_2 , A_3 and A_4 remain constant, A_o can be related to V_o by the equation:

$$A_o = a_o - A_1 V_o - A_2 V_o^2 - A_3 V_o^3 - A_4 V_o^4 \quad (14)$$

Computer Control of Equipment

All the electronic components previously described were controlled by a Zenith 248 computer. The computer was programmed to trigger the function generator, read data from the voltmeters and data display, control the output of the

power supply, and also activate the electric valve controlling the cooling air.

Figure 7 shows the complete arrangement of the computer and all the electronic components. The voltmeters, power supply, and function generator were all connected to the computer by a IEEE-488 (GPIB) data bus. A Qua Tech Inc. MXI-241 multifunction board was installed in the Zenith 248 to provide an interface with all GPIB-compatible components. The data display used a RS-232 port, and the electric valve was connected to an internal digital to analog (D/A) board. The D/A board used was a Qua Tech Inc. DM12-10 12-bit D/A board. Since the maximum output of the D/A board is only 22 milliamps, the board activated a relay that opened the valve.

The computer software to control all the electronic equipment and acquire data is given in Appendix A. This particular version was used for the in-phase TMF tests, but with minor modifications was used for the isothermal and out-of-phase tests. These modifications are described in Appendix B. The program shown in Appendix A reads the maximum and minimum loads, the maximum and minimum temperatures, the number of cycles, and electrical potential crack length measurements, while opening and closing the electric air valve at peaks and valleys in the temperature cycle. The program also reads temperature for one complete cycle to obtain a temperature-versus-time plot to establish the correct settings on the Micricon 82300 process control system. Setup of the Micricon process control variables has

been discussed previously. A block diagram of the TMF testing Computer Control and Data Acquisition (CCADA) program is shown in Figure 24.

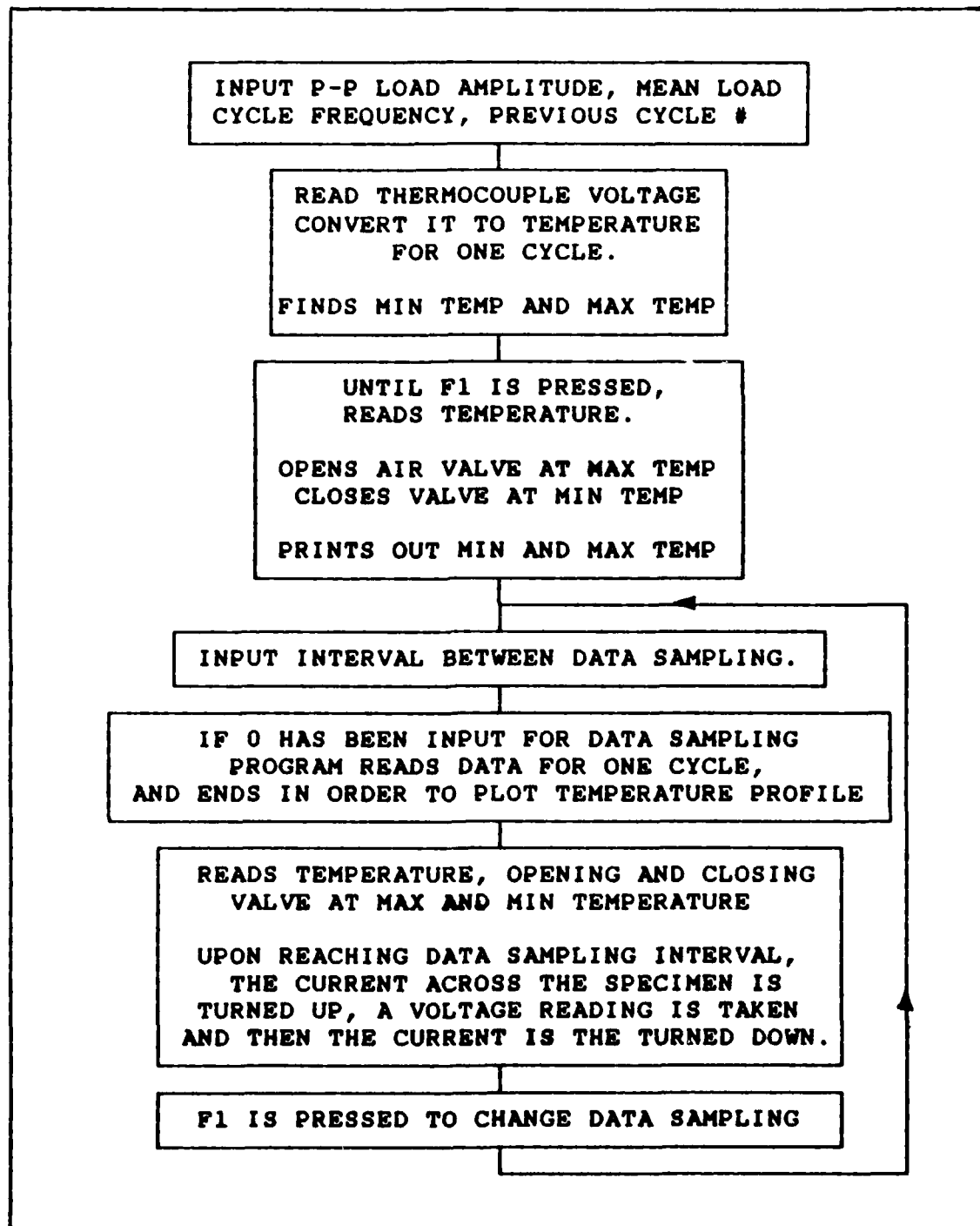


Figure 24 Block Diagram of the TMF CCADA Program

Initially, values of frequency, load amplitude, load offset, and previous cycle count were input to the computer. Then the program sent the load values to the frequency generator. The program then applied the offset load, read temperature for a complete cycle, and started into a setup mode. In this mode, the program continued to read temperature and displayed the minimum, T_{min} , and maximum, T_{max} , temperature values while opening and closing the valve. During this period, adjustments of the valve and regulator, as well as settings of the Micricon 82300 were made to achieve the desired T_{min} and T_{max} . After proper adjustments and settings were made, the temperature profile (temperature versus time) was plotted.

After the desired temperature profile was obtained, the program moved from setup to the testing mode. The data acquisition interval was input into the computer and program triggered the load, in or out of phase with the temperature, whatever was desired. During further operations of the program the electrically controlled air valve was opened and closed during each cycle. Upon reaching the preset interval of cycles, the program began reading data. This includes taking a voltage potential reading across the specimen, turning up the power supply to a constant 10 Amps, taking another voltage reading, turning down the power supply, and taking a third voltage reading. After the third reading was complete, the computer read the minimum and maximum load (P_{min} and P_{max}) from the data display, and cleared the memory

for the next cycle interval. The number of cycles was calculated by counting the number of temperature peaks. (During isothermal tests, the number of cycles was obtained by multiplying the time by frequency.) $T_{\min}$ and $T_{\max}$ over the cycle interval were determined and reset for the next cycle interval. Thereafter, all data was printed on disk, screen, and printer. At any time, function key F1 could be triggered to change the interval between data samplings. When exiting the program, first the amplitude, and then the offset were reduced to take the complete load off the specimen.

IV. Experimental Procedure

Specimen Details

The specimen employed in this investigation was the compact tension (CT) machined from Ti_3Al . The composition of the alloy studied in atomic percent is Ti-24Al-11Nb. The weight composition and the heat treatment of this alloy are given in Tables 4 and 5 respectively.

Table 4 Composition of the Ti_3Al Alloy

Element	Ti	Al	Nb	Fe	O	N
Weight %	Bal	13.50	21.40	0.080	0.084	0.003

Table 5 Heat Treatment of the Ti_3Al Alloy

- 1) 2100°F for one hour in vacuum
- 2) Fan-forced Argon cooled (3°F per second)
- 3) Age harden at 1400°F for one hour in vacuum
- 4) Air cool to room temperature

Values of strength and elongation for titanium-aluminide, Ti_3Al , are given in Table 6.

Table 6 Tensile Properties for Ti_3Al

	RT	500°F	1200°F
UTS	131 ksi	128 ksi	76 ksi
0.2% YS	108 ksi	94 ksi	46 ksi
Elong (%)	2.3	8.4	4.4

Dimensions for the specimen employed in this study are shown in Figure 25. The crack length, a , is measured from the pin center to the crack tip. Standards for the notch and all machining tolerances followed the ASTM standard E 647 (16,709-714) for constant- load-amplitude fatigue crack growth rates above 10^{-8} m/cycle.

To prepare for testing, the specimens were first polished. Second, holes were drilled in the corners to allow for connection of the current leads used for electric potential (EP) crack measurement. Third, the thermocouple wires and electric potential pickup lead wires were welded to the specimens. Welding of Chromel, Alumel, or Nichrome wire to the Ti_3Al alloy is very difficult; therefore, two to five Nichrome wire straps were welded across each thermocouple and test lead to prevent the connection from loosening during fatigue testing. The slightest movement of the specimen

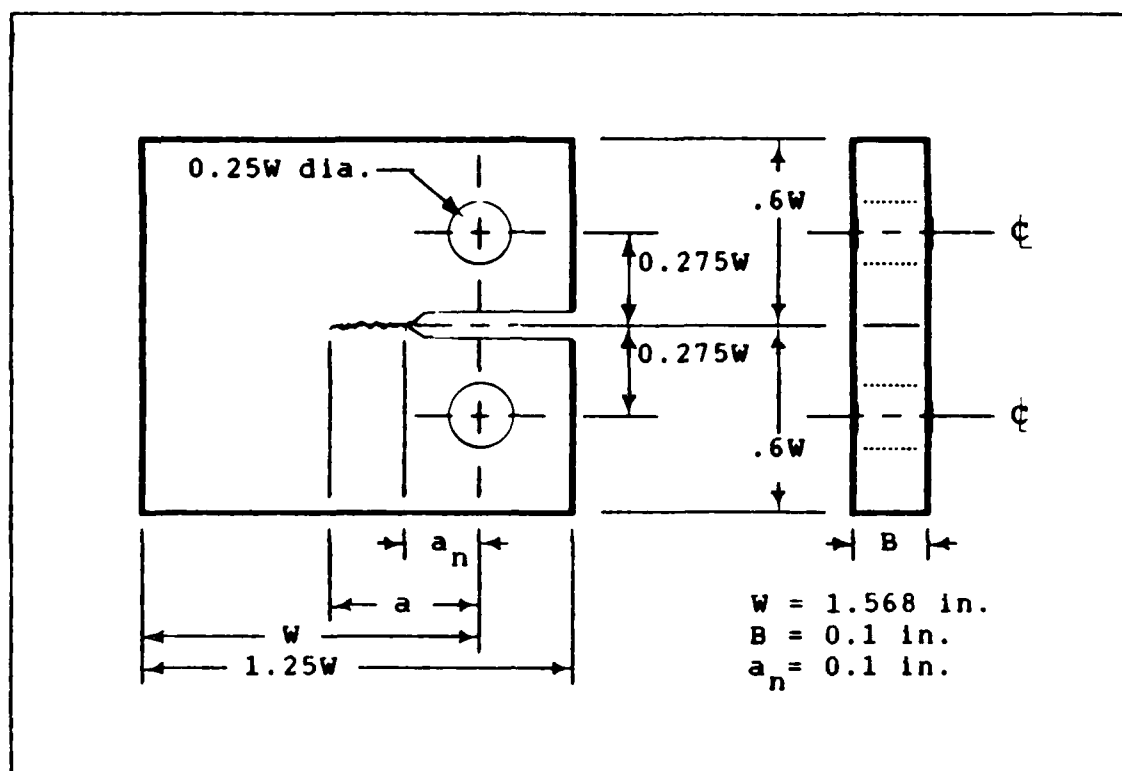


Figure 25 Compact Tension Specimen Dimensions

caused breaking of welds without extra support. During precracking of the specimens, the high frequency (10 Hz) fatigue loading caused excessive movement of the wires. This movement separated some of the strap welds, but posed no problems because multiple straps were used.

Precracking of Specimens

The specimens were precracked according to the ASTM standard E 647 (16,714). The minimum fatigue precrack must be the larger of either $0.1B$ or h , where B is the specimen thickness and h is the width of the notch. The precrack is defined as $a_o - a_n$ where a_o is the initial crack length and a_n

is the notch length. For the specimens used in this study, B was 0.1 inch and h was 0.08 inch; therefore, a precrack equal to h was required. The initial stress intensity created by the load must be large enough to create a crack, but as soon as the crack begins to grow, the load must decrease to prevent unstable crack growth or large plastic zone from occurring. While increasing crack length, a, the value of the stress intensity ratio, ΔK , must be decreased to a starting value of ΔK for the actual fatigue test. Initial values of ΔK were determined from preliminary studies by the Materials Laboratory at WPAFB. Initial values of ΔK used for precracking was $24.0 \text{ ksi}\sqrt{\text{in.}}$ and upon reaching an initial crack length of h, ΔK had to be reduced to a value of approximately $7 \text{ ksi}\sqrt{\text{in.}}$ To establish the loads required for these values of ΔK , the following relation obtained from the ASTM standard E 647 (17:709) was used:

$$\Delta P = \Delta K B \sqrt{W} \frac{(1 - \alpha)^{3/2}}{(2 + \alpha)} (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4)^{-1} \quad (15)$$

where

$$\Delta P = P_{\max} - P_{\min}$$

$$\Delta K = K_{\max} - K_{\min}$$

$$\alpha = a/W$$

Figure 26 shows the employed load reduction scheme to decrease ΔK as the crack length increased during precracking of the specimens.

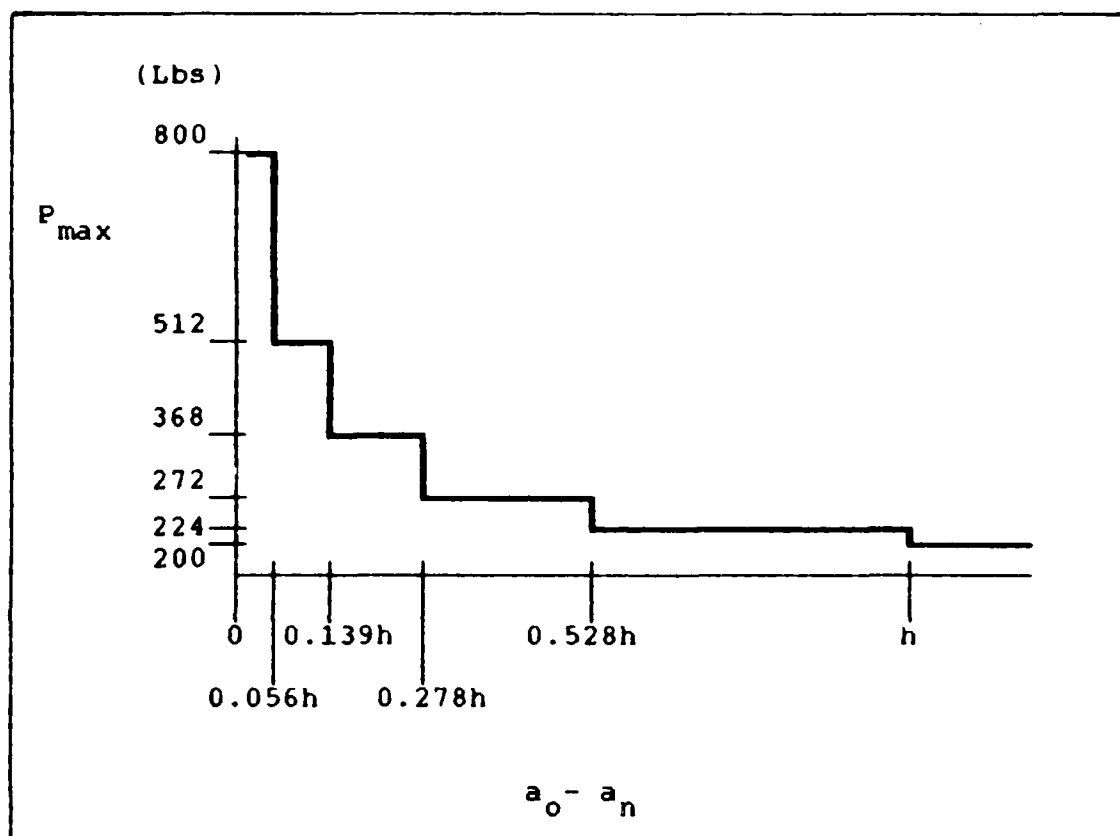


Figure 26 Load Reduction Scheme Used to Precrack Specimens

Although testing of the specimens was carried out by computer-controlled techniques, the load reduction during precracking was done manually. The current always was flowing through the specimen and the voltage drop was monitored to detect the slightest crack extension. As soon as the voltage across the specimen began to increase, the crack would be monitored visually to begin load reduction as

described in Figure 26. When the precracking was completed, the last load level was maintained for the actual fatigue test. At this instant, the computer controls all aspects of the test, including acquiring data at desired cycle intervals. In the fatigue tests considered here, loading of $P_{\max} = 200$ lbs. and stress ratio, $R, = 0.1$ was used.

Isothermal Testing

A maximum testing temperature of 1200°F was chosen for this study since the titanium-aluminide alloy Ti_3Al maintains its properties up to this value. For the isothermal test, the CCADA program was modified as described in Appendix B.

Crack length measurements should be made at intervals that evenly distribute da/dN versus ΔK data. The ASTM standard E 647 (16:708,709) recommends intervals of measurement as:

$$\Delta a \leq 0.02 W \quad \text{for} \quad 0.25 \leq a/W \leq 0.60$$

$$\Delta a \leq 0.01 W \quad \text{for} \quad a/W > 0.60$$

The electrical measurements were made more often than this but visual measurements at these intervals were taken to establish a calibration relationship for the electric potential (EP) crack measurement. Figure 27 shows the crack growth data obtained from the visual method. The crack lengths were measured from an inscribed reference mark. The crack length is then calculated from:

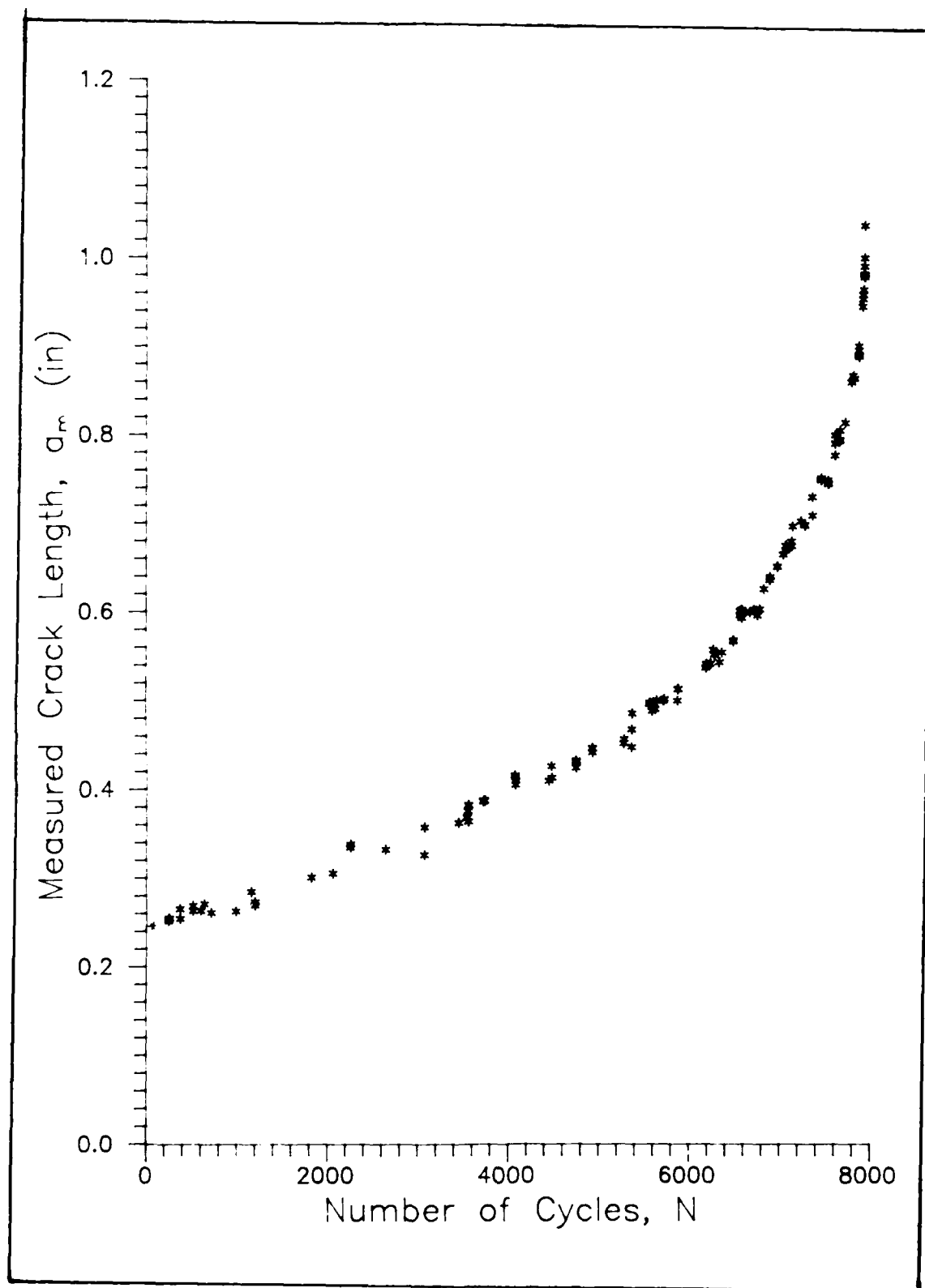


Figure 27 1200°F Isothermal Visual Crack Growth Measurements

$$a = a_m + a_r \quad (16)$$

where

a_m is the measured crack length and
 a_r is the reference mark distance

The corresponding EP measurements for the 1200° F isothermal test are shown in Figure 28.

TMF Testing

For the in-phase (IP) TMF test, the CCADA program was used as shown in Appendix A. The temperature was cycled between 600°F and 1200°F for this test. A maximum temperature, T_{max} , of 1200°F was chosen in order to compare the crack growth relations to the isothermal T_{max} test. The minimum temperature, T_{min} , that this system was able to achieve in a 100 second cycle (the limitation of the function generator) was 600°F. An actual period of 96 seconds (1.6 minutes) was used since the Micricon 82300 is programed in minutes. The temperature profile (solid line) established for this test is shown in Figure 29. The temperature differs from the programmed value (dashed line) by a maximum of 12°F (approximately one percent deviation). Variations were observed mainly when the cooling air valve opened and closed (approximately one second after T_{max} and T_{min} were reached).

The procedure for measuring crack length was similar to that used for the isothermal case, except the EP measurements were always taken at T_{max} to obtain consistent results. For

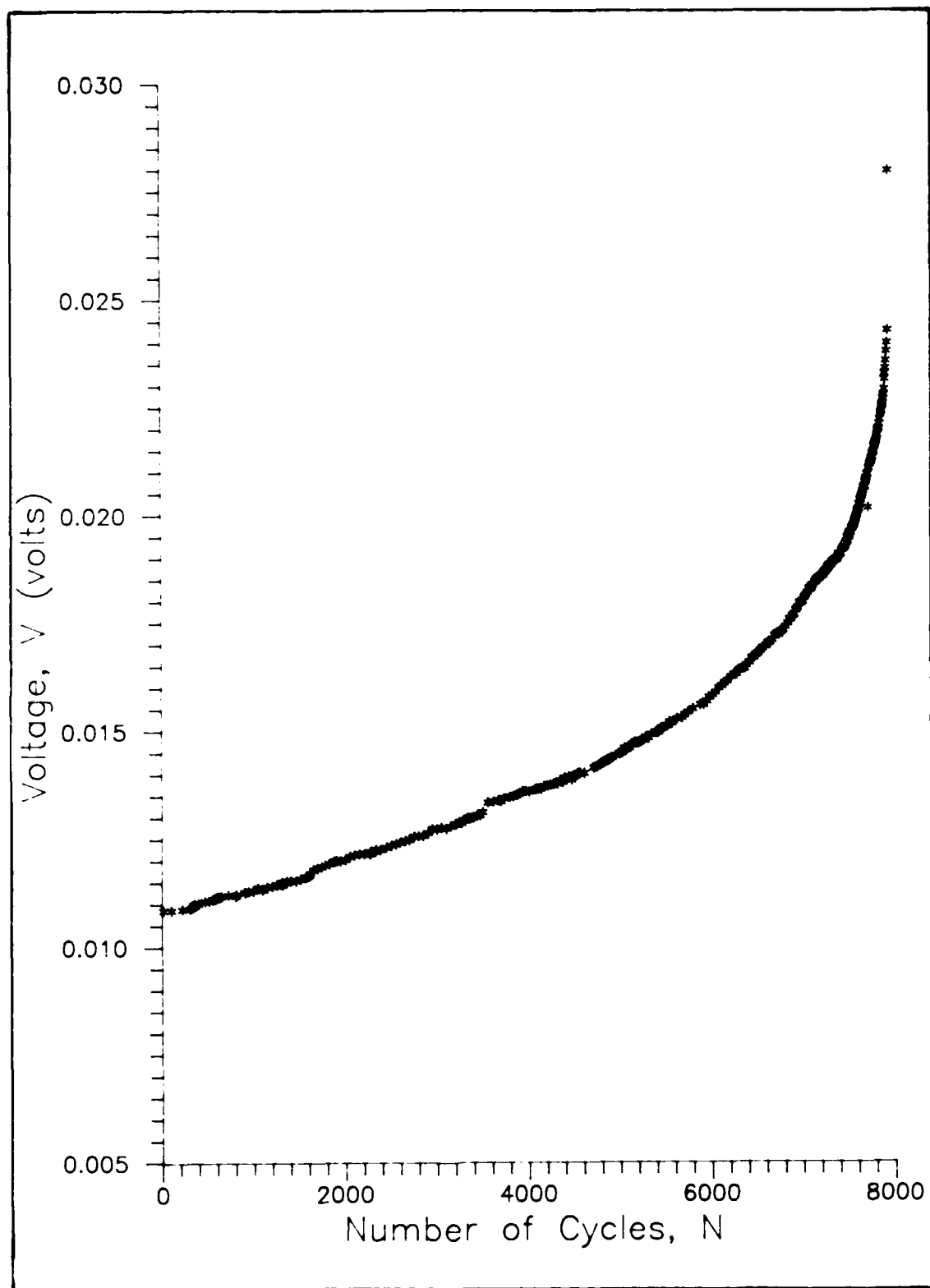


Figure 28 1200°F Isothermal EP Measurements

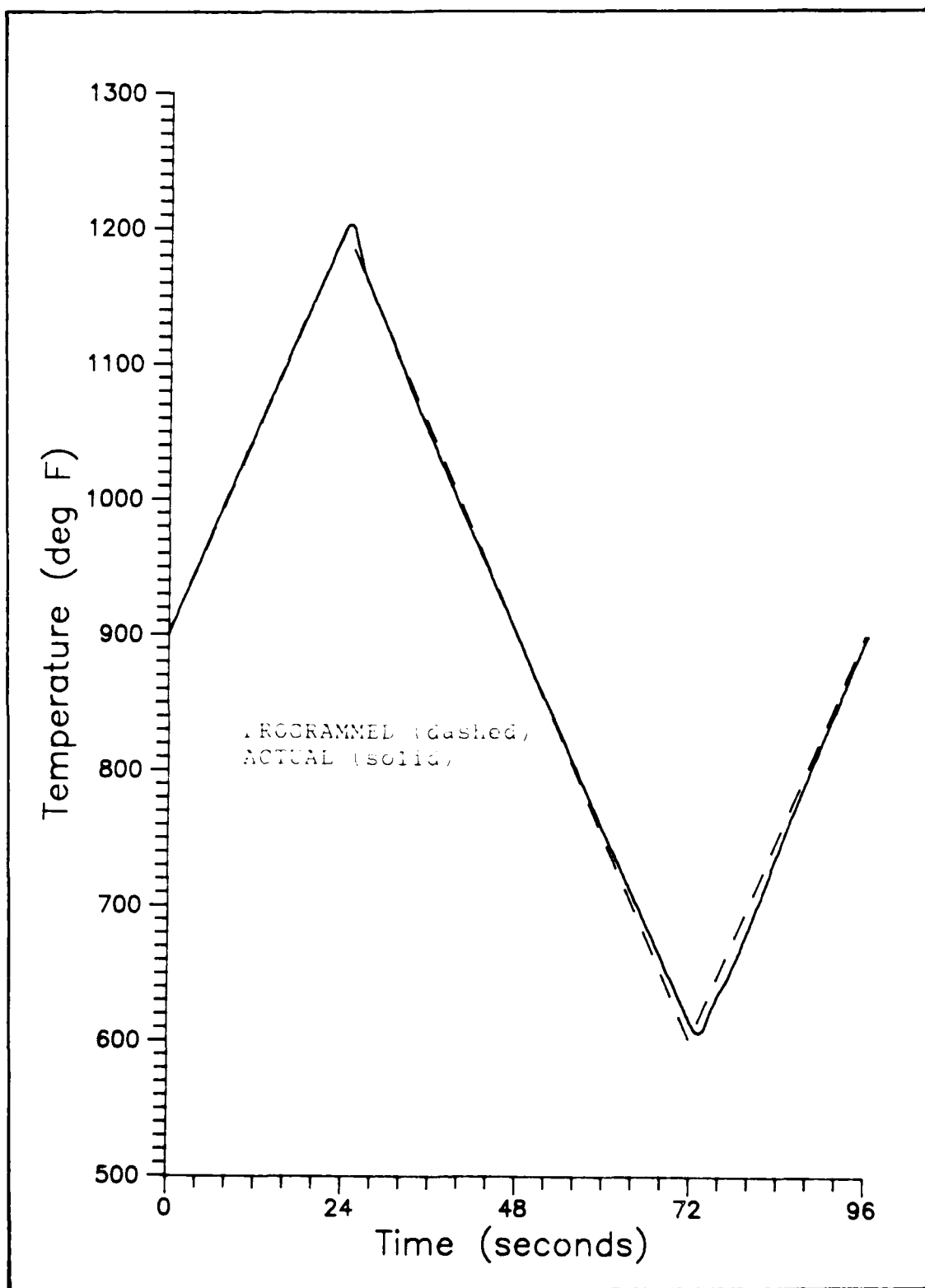


Figure 29 IP TMF Temperature Profile

the IP TMF conditions, $T_{\max}$ occurs at the maximum load, $P_{\max}$. As noted earlier, EP measurements should always be taken at $P_{\max}$, regardless of the temperature-load phase used for the test. Fewer visual measurements were taken since the calibration data from the isothermal case could be used in this case also. Since all measurements for the isothermal and IP TMF tests were taken at 1200°F, only the offset value, A_o , needed to be established. This will be explained in the next chapter. Visual crack length and electrical potential drop data are plotted in Figures 30 and 31 respectively.

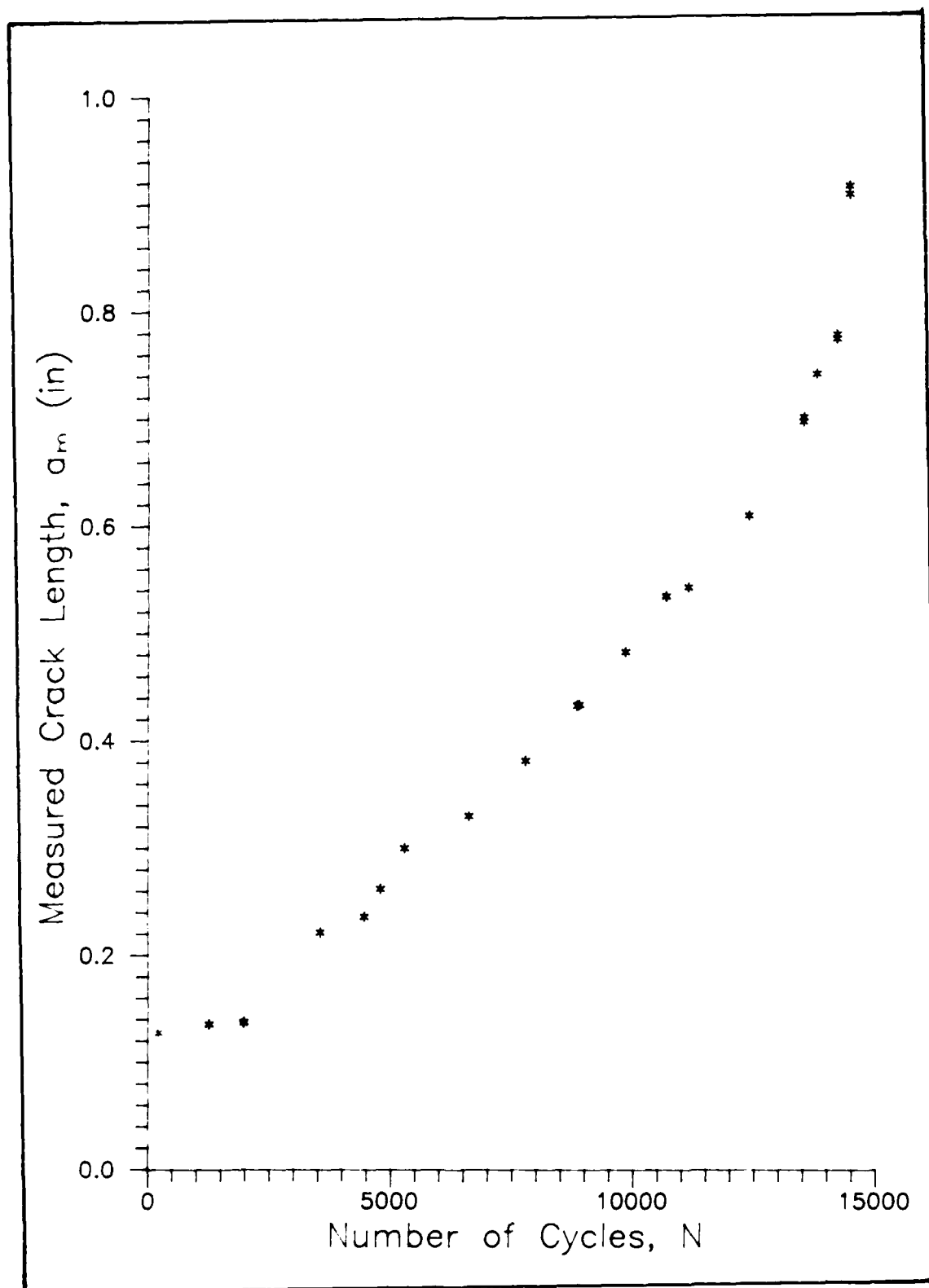


Figure 30 IP TMF Visual Crack Growth Measurements

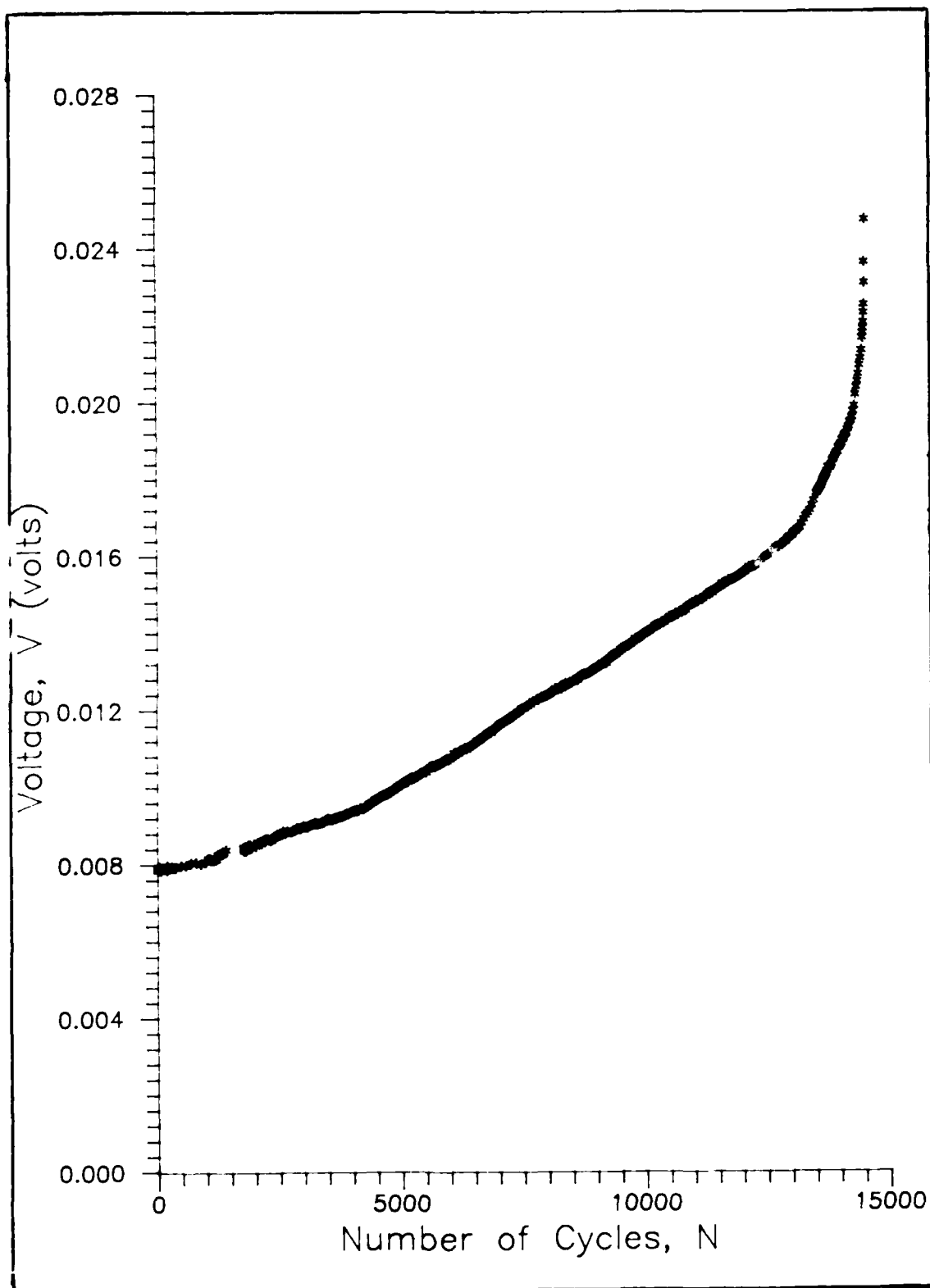


Figure 31 IP TMF EP Measurements

V. Results and Discussions

Crack Length Analysis

As previously mentioned, crack length was measured both visually and electrically. Plots of crack length versus number of cycles and voltage versus number of cycles for both the isothermal and TMF conditions were shown in Chapter IV. The crack length in these plots is the visually measured length, a_m . To establish crack length versus number of cycle plots for the electrical potential (EP) method, a conversion must be made between voltage and crack length. To establish such a relation, measured crack length was first plotted as a function of voltage at specific increments of fatigue cycles. This plot of data taken during the 1200°F isothermal fatigue test is shown in Figure 32. A calibration equation was established to fit this data. The relation was found to be a linear one, and is given below:

$$a_m = A_0 + A_1 V \quad (17)$$

where

$$A_0 = -0.38468 \text{ in.}$$

$$A_1 = 57.8773 \text{ in./volt}$$

In this equation, a_m is used and not the physical crack length, a , because the equation is relating voltage to measured crack length. The relation between physical crack length and

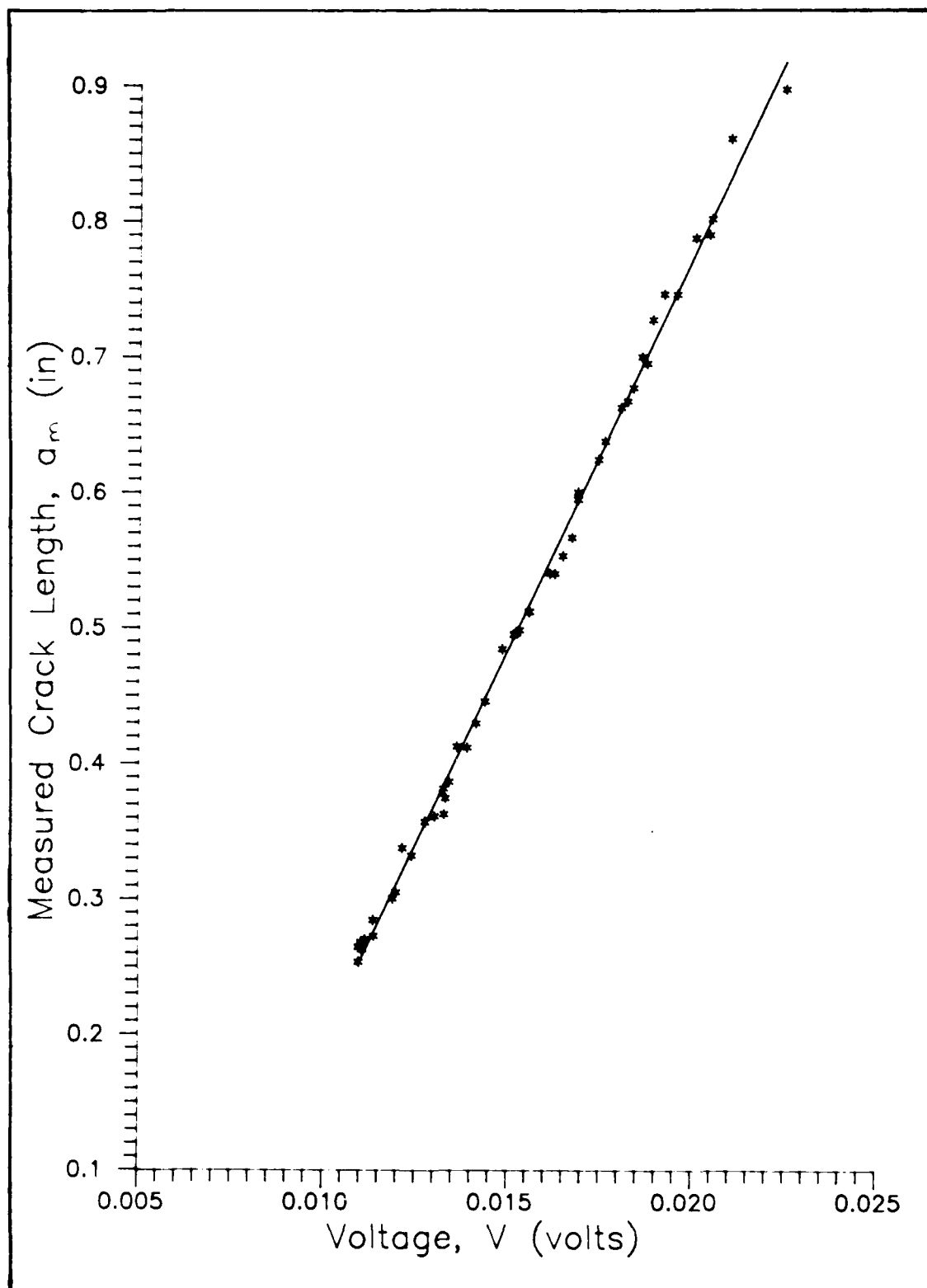


Figure 32 1200°F Isothermal Test Calibration Curve

measured crack length is provided in Eq (16). It can be seen from the plot that the linear calibration relation agrees well with the measured data. The maximum deviation of the actual data from this calibration line is 0.02 inch.

The calibration data for the in phase TMF test is shown in Figure 33. A calibration equation was established for this test in the same way as for the isothermal case. Here, the constants A_0 and A_1 for Eq (17) are -0.32386 in. and 58.0125 in./volt respectively. The deviation for this case was as much as 0.06 inch. The larger deviation can be attributed to the temperature cycling, and also the loss of a lamp, which occurred three times during the experiment.

The slope of calibration equations for the isothermal and TMF tests differ by only 0.23 percent. This was expected since both sets of electrical potential data were taken from the same specimen geometry machined from the same material. Further, both sets of data were taken at the same temperature; however, there was a slight variation in the temperature during the TMF tests. Both calibration curves are compared on the same set of axes in Figure 34. This shows that both have nearly identical values of slope, A_1 , and different y axis intercept, A_0 . This difference in intercept can be attributed to the initial conditions, such as the length of the Nichrome wire used for voltage measurements and precise location of the weld.

To apply this approach to other temperature and load cycle tests, the offset, A_0 , needs to be established. As

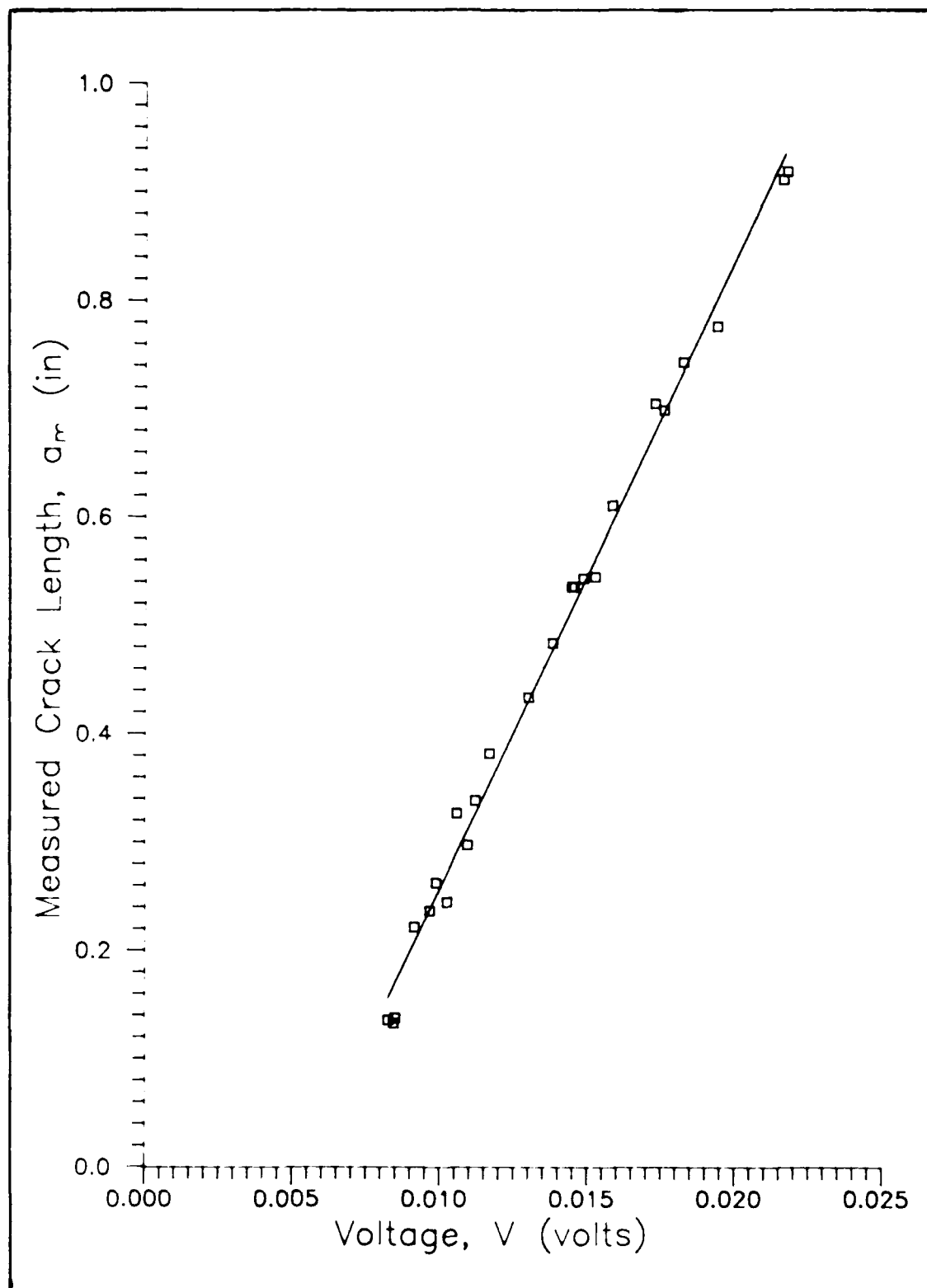


Figure 33 IP TMF Calibration Curve

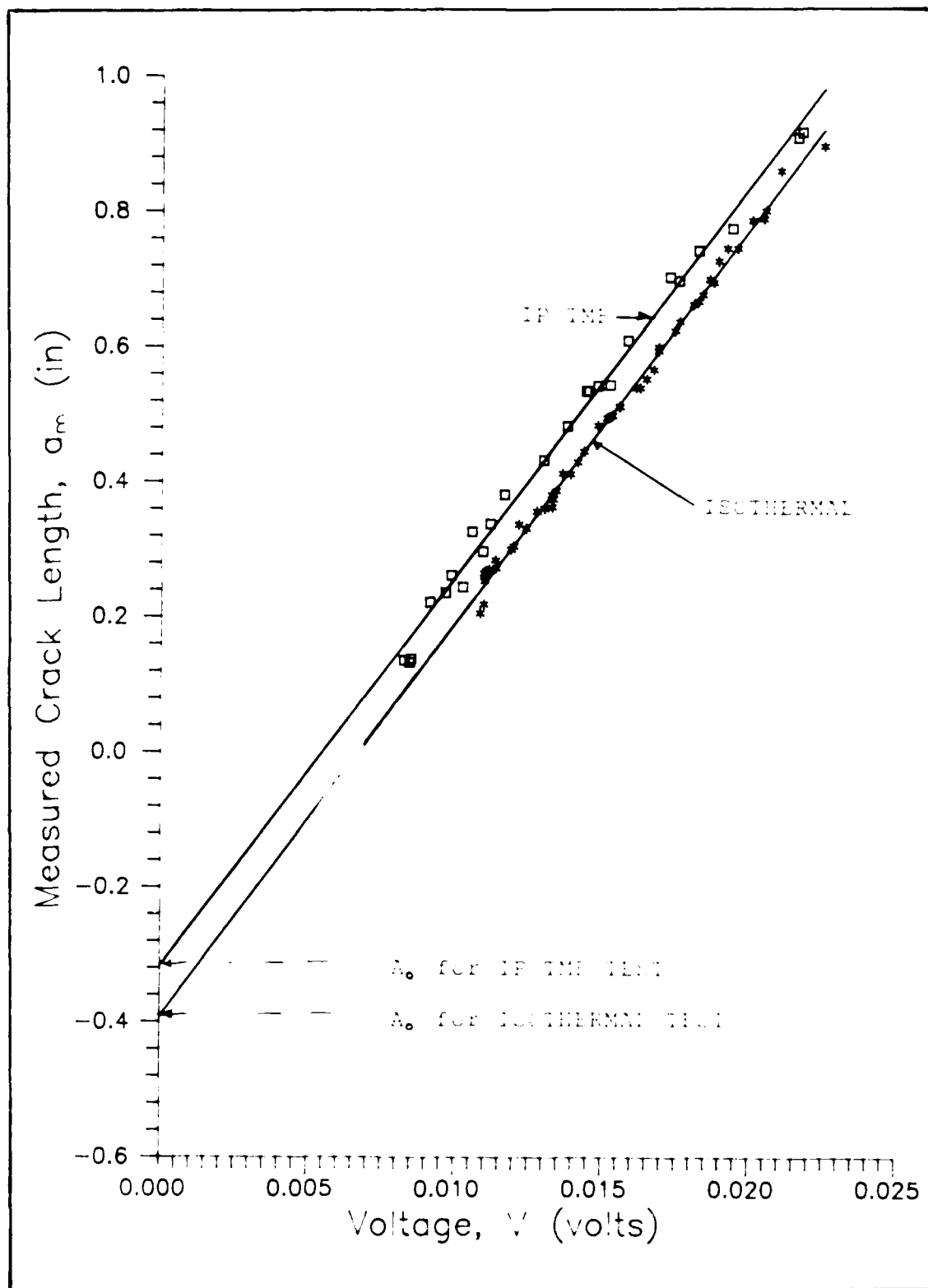


Figure 34 Isothermal and IP TMF Calibration Curves

seen from the TMF case, about 30 visual measurements are sufficient to obtain the coefficients of Eq (17). The slope, A_1 , should not change between tests as shown by the comparison of both calibration curves in Figure 34.

After establishing the calibration equations:

$$a_m = (57.8773 \text{ in./volt}) V - 0.38468 \text{ in.} \quad (18)$$

for the isothermal test and

$$a_m = (58.0125 \text{ in./volt}) V - 0.32386 \text{ in.} \quad (19)$$

for the IP TMF test, the recorded voltage from the EP method was converted to crack length. Figures 35 and 36 show the calculated crack length, a_{ep} , as a function of fatigue cycles for the 1200°F isothermal and 600°F to 1200°F IP TMF tests respectively. As mentioned previously, a lamp failed three times during the IP TMF test. Only one of these failures drastically changed the temperature distribution across the specimen; therefore, the data obtained during this condition was eliminated from the analysis. This occurred at approximately the 1500th fatigue cycle and a gap in the data can be seen in Figure 36.

The crack length data plotted in Figures 35 and 36 were used to compute crack growth rates, which will be discussed in the next section.

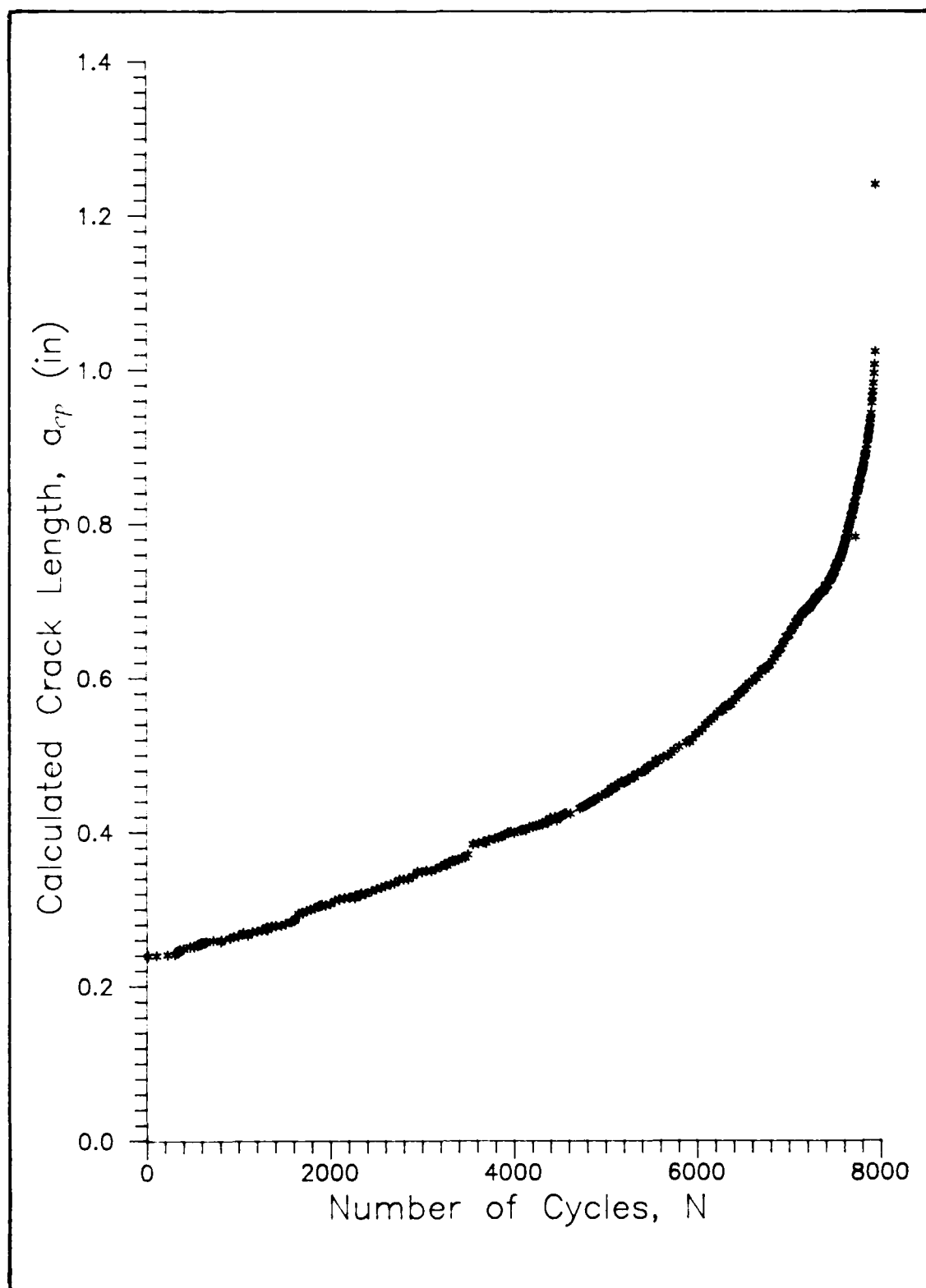


Figure 35 1200°F Isothermal Calculated Crack Length

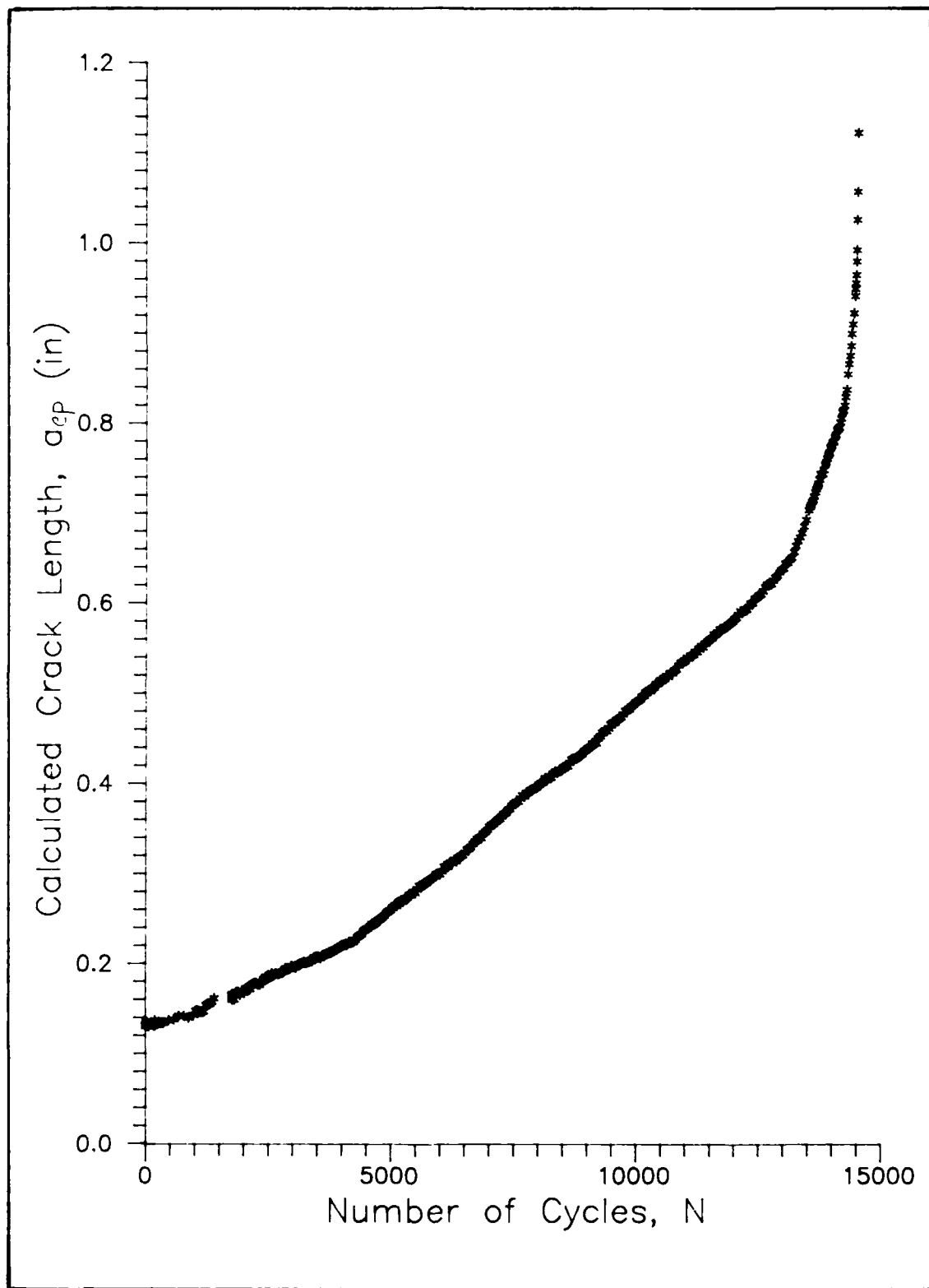


Figure 36 IP TMP Calculated Crack Length

Crack Growth Analysis

Crack growth rates, da/dN , were obtained from crack length versus number of cycle data by fitting third, seventh and 15th order polynomials to successive data points. These polynomial curve-fit methods will be referred to as three-, seven-, and 15-point methods respectively. These methods are similar to those recommended in ASTM E 647 (17:715). The stress intensity range, ΔK , was calculated using the equation for standard compact type specimens (17:709):

$$\Delta K = \frac{\Delta P}{B \sqrt{W}} \frac{(2 + \alpha)}{(1 - \alpha)^{3/2}} (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \quad (20)$$

where

$$\Delta P = P_{\max} - P_{\min}$$

$$\Delta K = K_{\max} - K_{\min}$$

$$\alpha = a/W$$

The physical crack length, a , is required for calculating ΔK ; therefore, the calculated crack length, a_{ep} , was converted to " a " using the relation:

$$a = a_{ep} + a_r \quad (21)$$

where

a_r is the reference mark distance.

Plots of da/dN versus ΔK now could be developed using all three methods for both the isothermal and TMF cases. Data obtained using the three-point method showed a very wide scatter on the plot and therefore was eliminated from this discussion. The large scatter could be attributed to the deviations in the a_{ep} data. Since nearly 1000 data points were used in the analysis, more consecutive points (seven points or 15 points) should be used to approximate the slope. The other two methods reduced the data reasonably well, and log-log plots of da/dN versus ΔK for both isothermal and IP TMF cases were developed. Figure 37 shows the results from the isothermal test using the seven-point method and Figure 38 shows the 15-point results.

After taking Log_{10} of both the da/dN and ΔK data, a linear regression analysis was used to obtain a best-fit straight line. The equation found using the seven-point method is:

$$\text{Log}_{10}(da/dN) = 2.2797 \text{ Log}_{10}(\Delta K) - 13.380 \quad (22)$$

and using the 15-point method:

$$\text{Log}_{10}(da/dN) = 2.4198 \text{ Log}_{10}(\Delta K) - 13.954 \quad (23)$$

Results from both methods are compared in Figure 39. As can be seen from the plot, both methods yielded, in general, the same fatigue crack relationship.

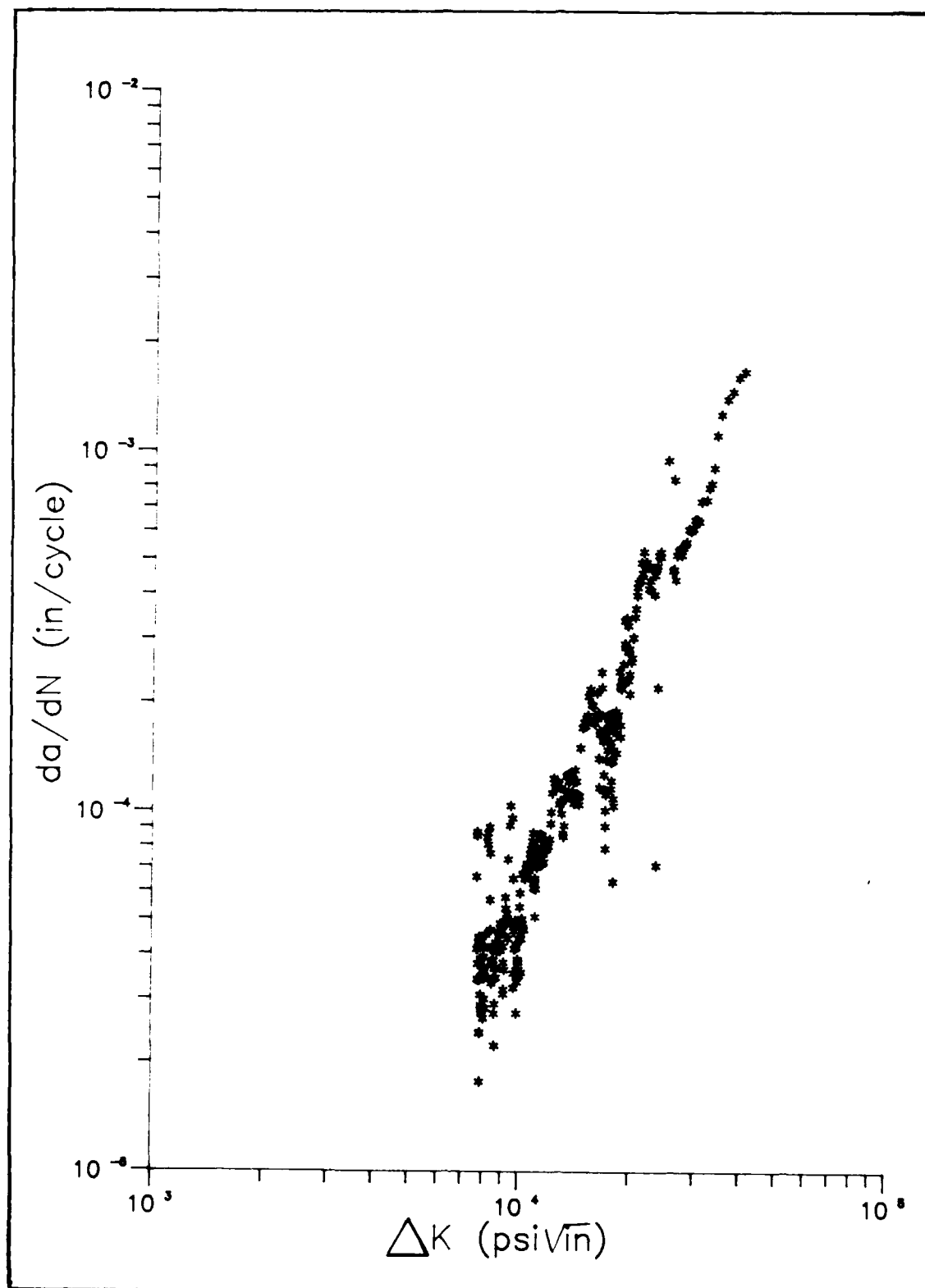


Figure 37 Crack Growth Relation Using Seven-Point Method for 1200°F Isothermal Test

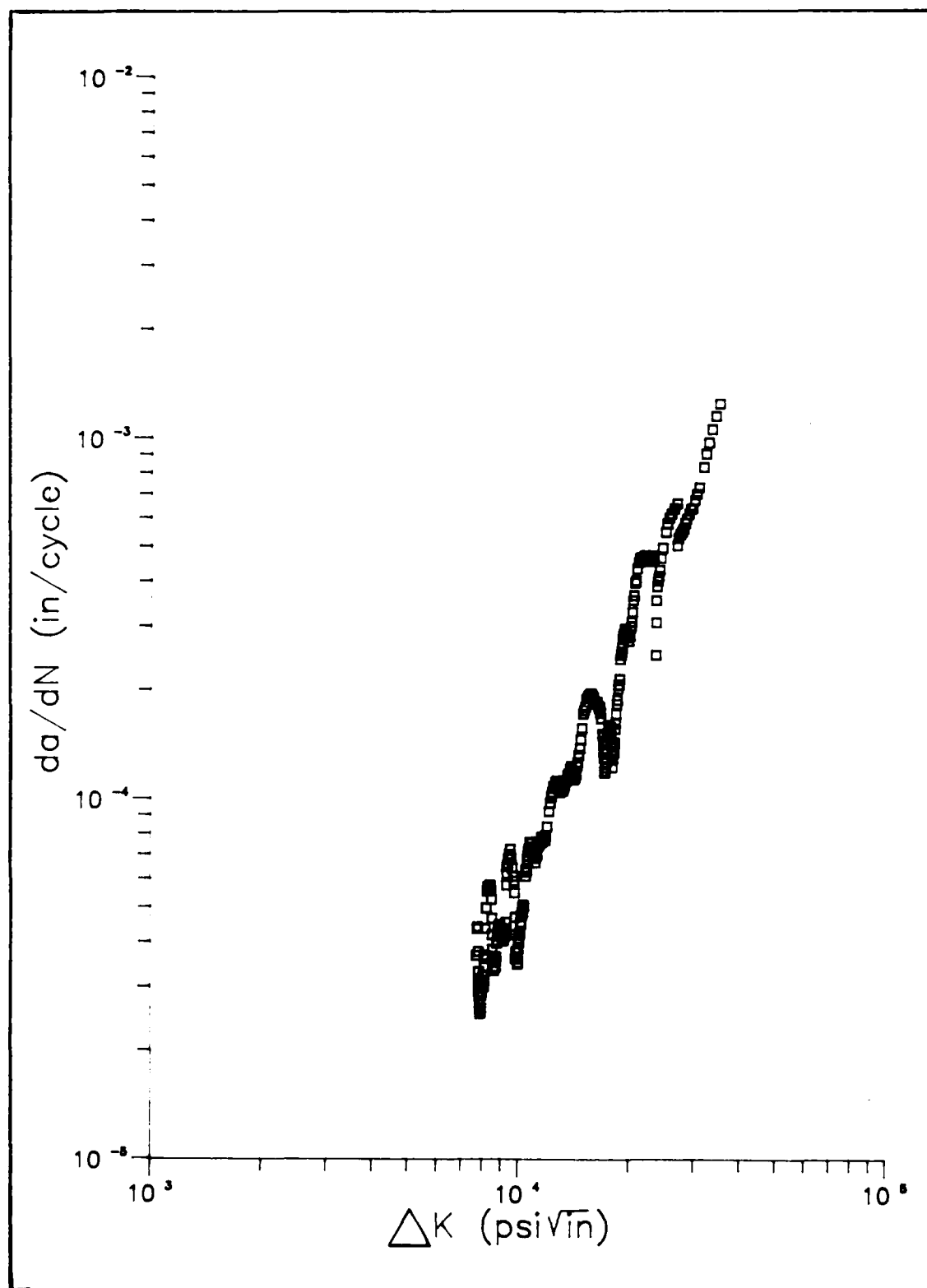


Figure 38 Crack Growth Relation Using 15-Point Method for 1200°F Isothermal Test

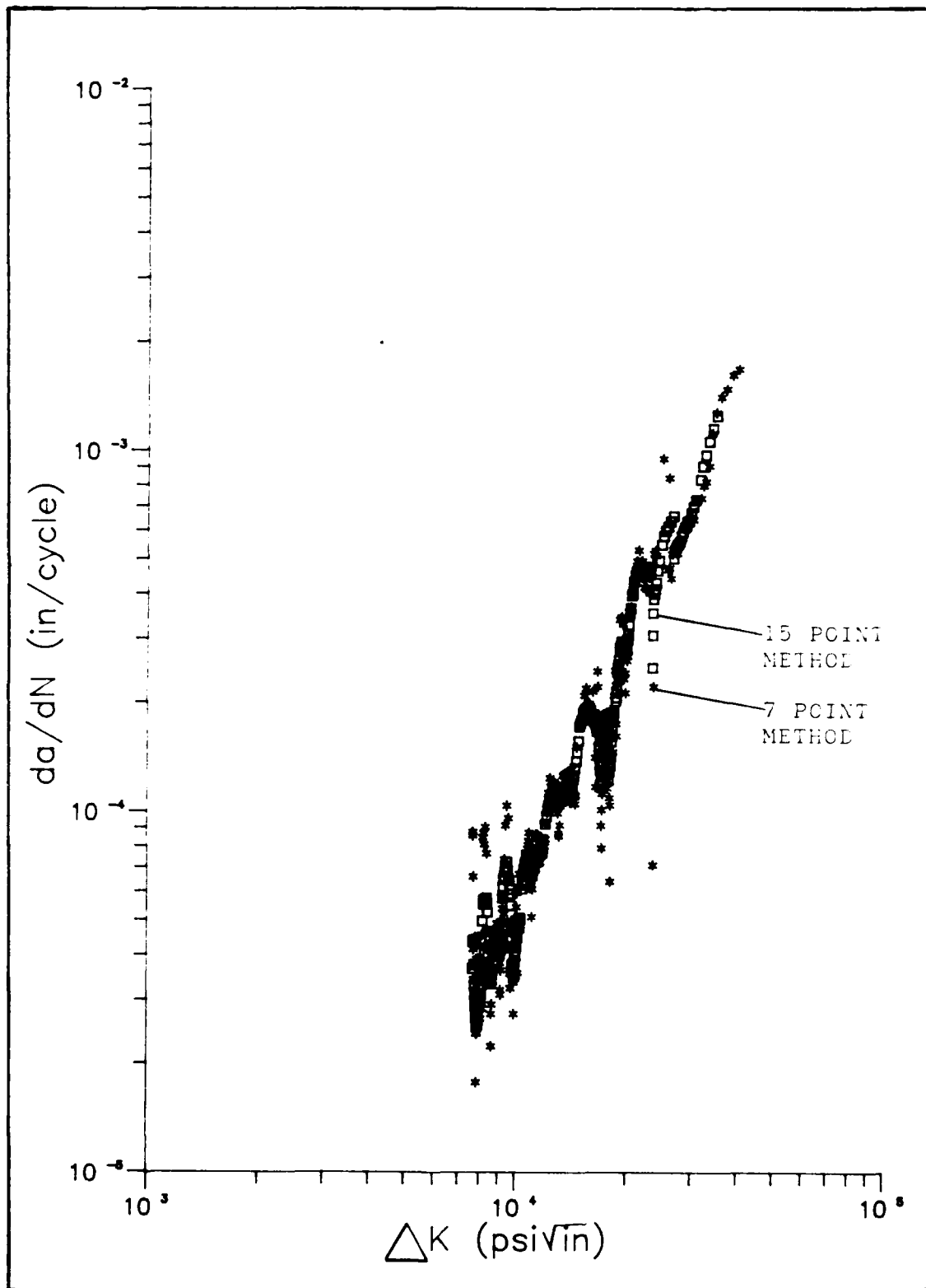


Figure 39 Crack Growth Relations Using Seven- and 15-Point Methods for 1200°F Isothermal Test

There is a considerable amount of scatter in da/dN versus ΔK data as shown in Figures 37 and 38. It should be noted that this data was established from one specimen. Such scatter is not commonly observed in fatigue crack growth studies at room temperature; however, scatter has been observed in similar studies at elevated temperatures. For example, Heil (8:117) observed a scatter in da/dN by a factor of 2 to 4 at a given level of ΔK during his TMF investigation with IN 718. The data of this present investigation shows a scatter in da/dN by a factor between 6 and 10 at a given level of ΔK . This can be attributed to various factors. The crack growth was nonlinear, and will be discussed later with the crack surfaces. The material is still under development, hence this batch of material is not completely homogeneous. However, these factors should be investigated before making any conclusive comments.

The TMF test was analyzed in the same way as the isothermal test. Seven-point and 15-point results are shown in Figures 40 and 41. The equations for the best-fit lines of both graphs are:

$$\text{Log}_{10}(da/dN) = 1.8951 \text{ Log}_{10}(\Delta K) - 11.910 \quad (24)$$

and

$$\text{LOG}_{10}(da/dN) = 1.9520 \text{ Log}_{10}(\Delta K) - 12.153 \quad (25)$$

for the seven- and 15-point graphs respectively. Figure 42 compares the data obtained from both methods. In general,

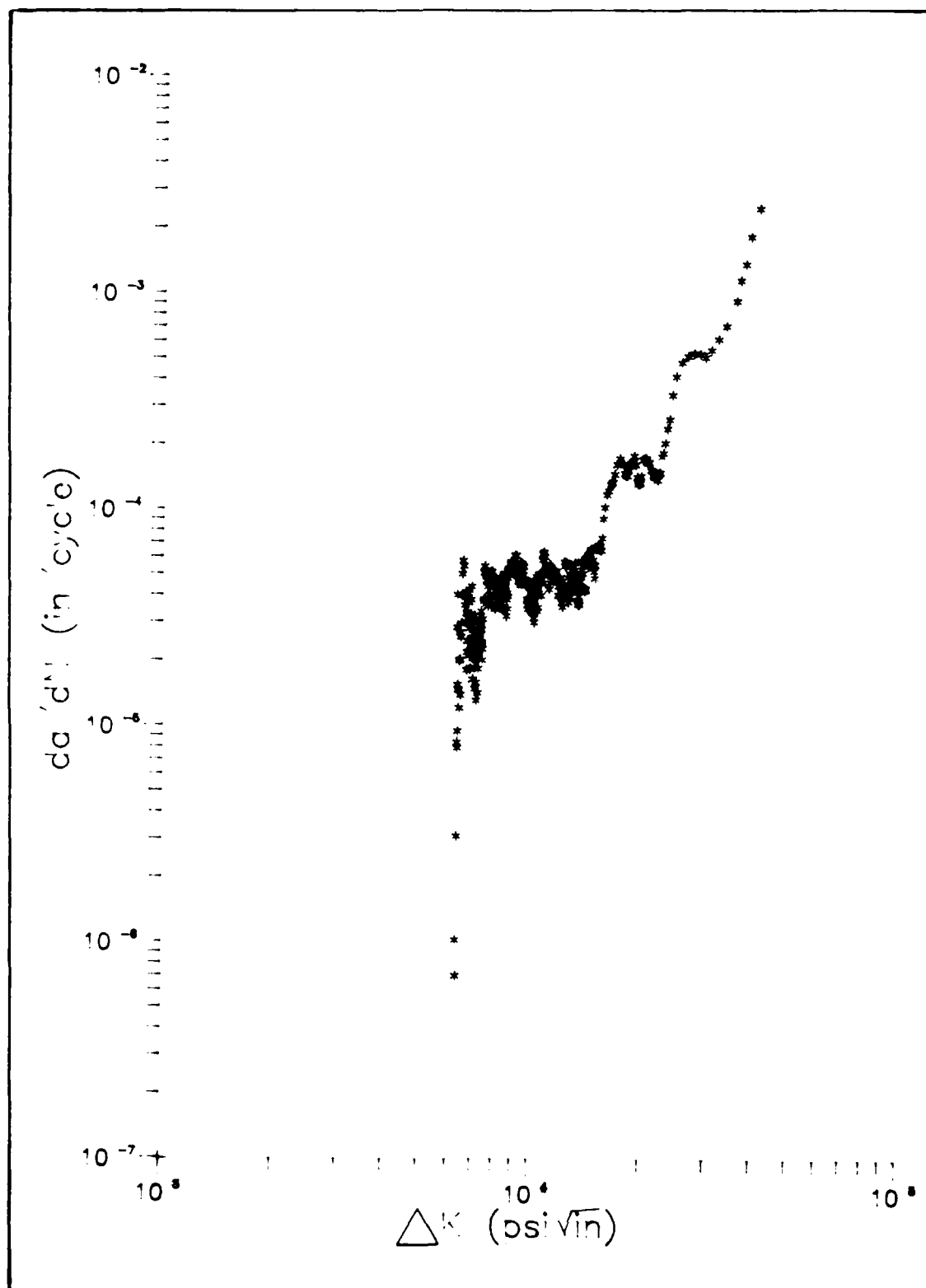


Figure 40 Crack Growth Relations Using Seven-Point Method for 600 F to 1200 F IP TMF Test

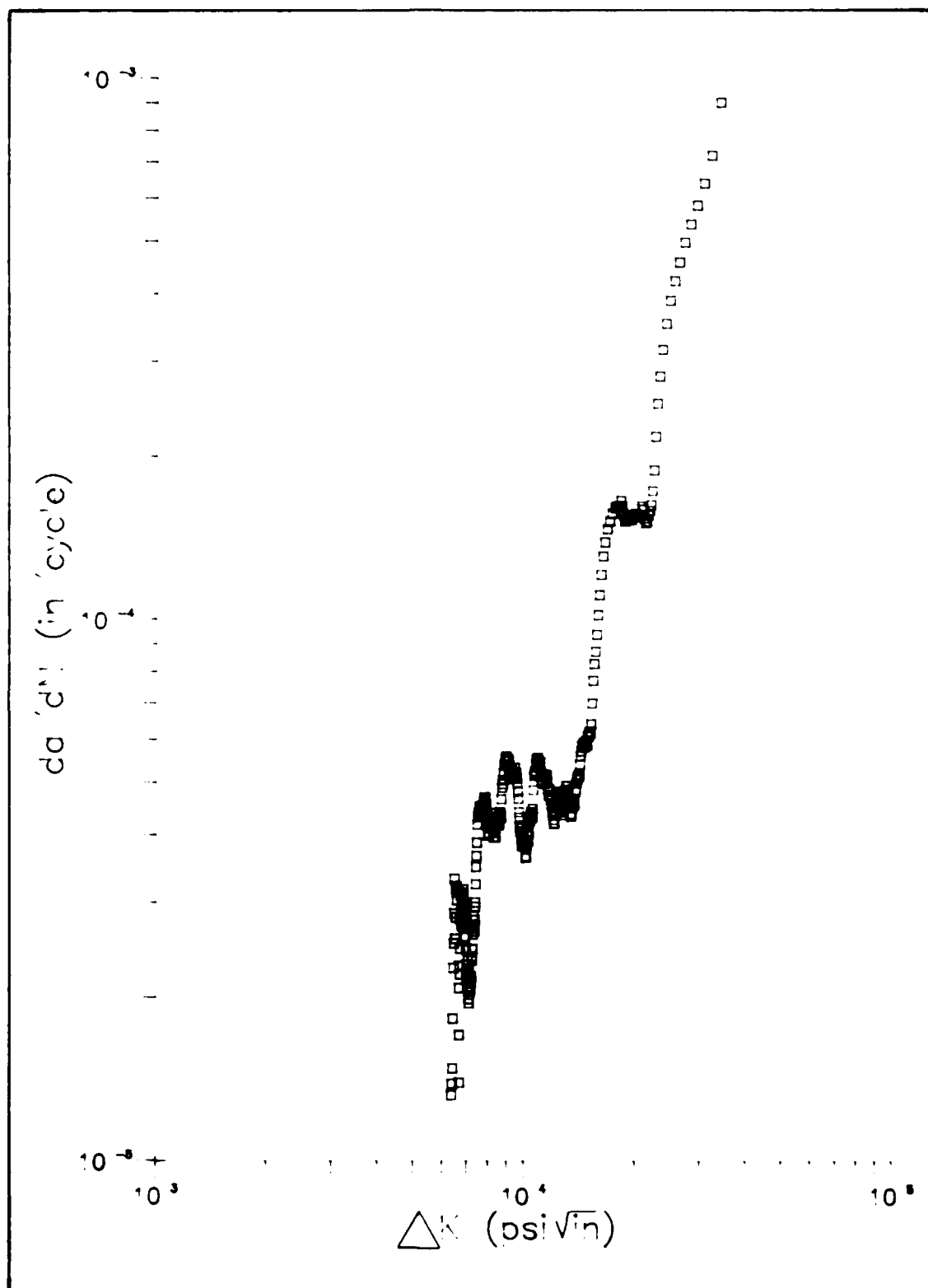


Figure 41 Crack Growth Relations Using 15-Point Method for 600°F to 1200°F IP TMF Test

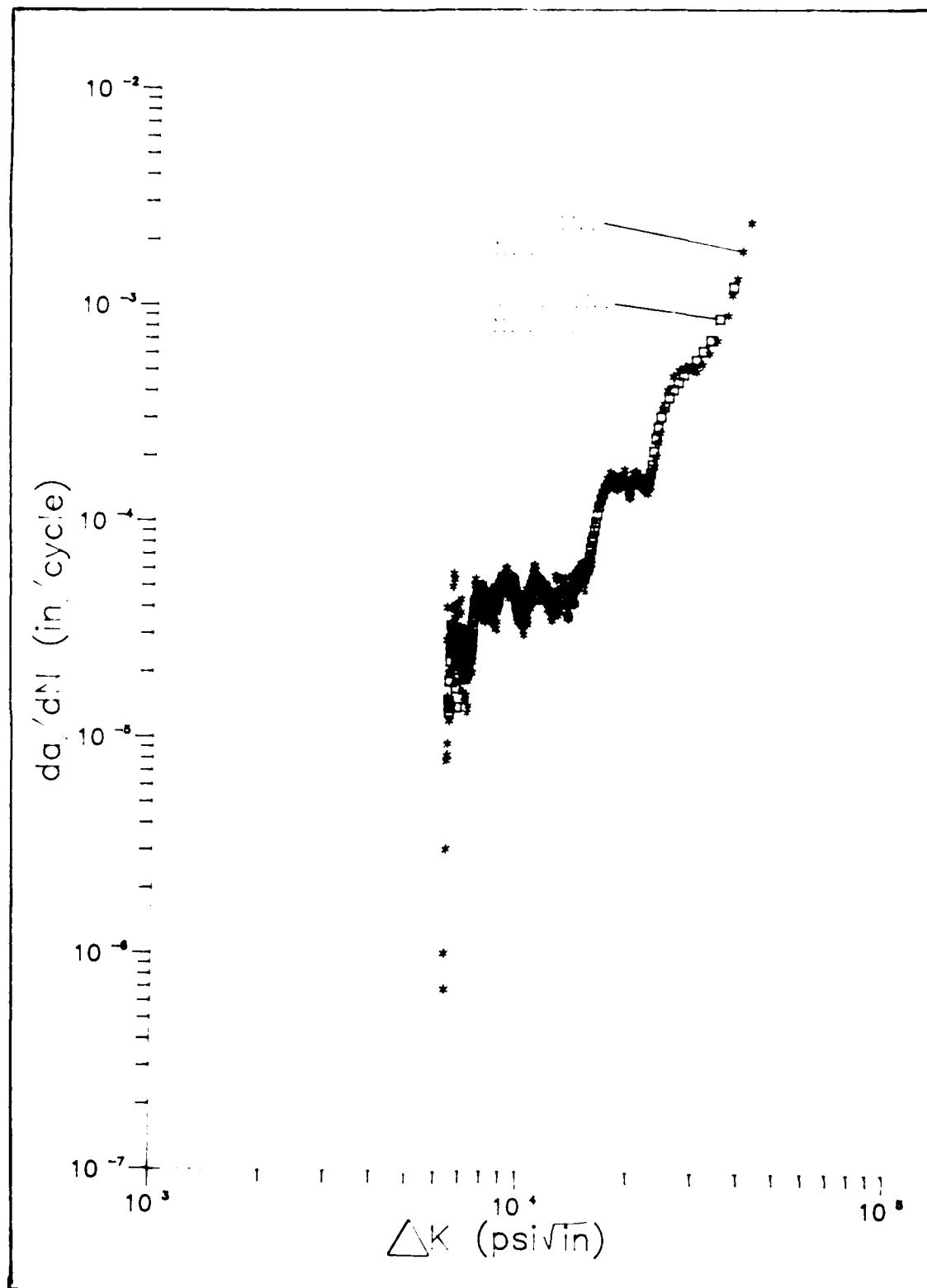


Figure 42 Crack Growth Relations Using Seven- and 15-Point Methods for 600 F to 1200 F IP TMF Test

most data obtained from one method agrees with the other, as in the case of the 1200°F isothermal results.

In the ΔK region between $8 \times 10^3 \text{ psi}\sqrt{\text{in.}}$ and $2 \times 10^4 \text{ psi}\sqrt{\text{in.}}$, da/dN is nearly constant value, resulting from a linear portion of the crack length versus fatigue cycles data, which can be seen in Figure 36. This linear behavior can also be seen in the visual crack length data shown in Figure 31. This behavior only occurred during the IP TMF test, and since only two specimens are considered in this test, no conclusive explanations can be made.

The scatter in the IP TMF da/dN versus ΔK results is similar to that found in the previous test. In addition to the previously mentioned reasons for this scatter, the temperature is constantly cycling during the test. The crack length measurements used to compute crack growth may have been taken at slightly different temperatures, resulting in variations in temperature affect.

Using the 15th-order polynomial fit of the data, the isothermal crack growth rates were compared to IP TMF. A plot of these growth rates is shown in Figure 43. Eqs (23) and (25) define the data as straight lines and are in the standard slope y-intercept form:

$$Y = m X + b \quad (23)$$

where

$$Y = \text{Log}(da/dN)$$

$$X = \text{Log}(\Delta K)$$

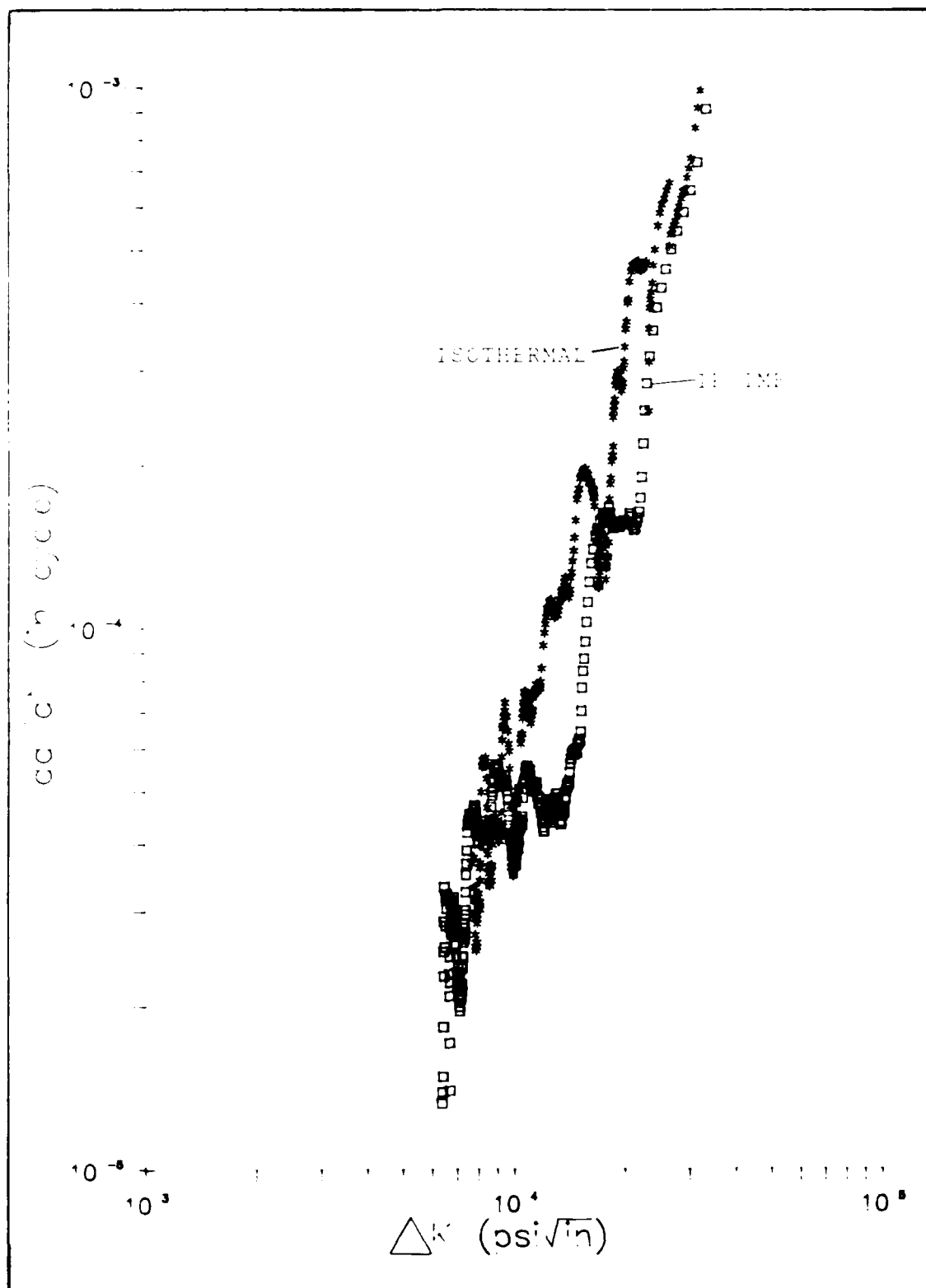


Figure 43 Crack Growth Relations for 1200°F Isothermal and 600°F to 1200°F Tests Using 15-Point Method

Basic laws of logarithms were used to get the equations in a more standard form. Eq (26) can be written:

$$\text{Log}(da/dN) = m \text{Log}(\Delta K) + \text{Log}(10^b) \quad (27)$$

and using the laws of logarithms, Eq (27) becomes:

$$\text{Log}(da/dN) = \text{Log}(\Delta K)^m + \text{Log}(10^b) \quad (28)$$

$$\text{Log}(da/dN) = \text{Log}\{(\Delta K)^m(10^b)\} \quad (29)$$

Therefore, Eq (29) can be written in the form:

$$(da/dN) = (10^b)(\Delta K)^m \quad (30)$$

or redefining 10^b as C and redefining m as n results in the more common expression previously shown in Chapter II:

$$da/dN = C (\Delta K)^n \quad (2)$$

Eq (2) was used to define both sets of data shown in Figure 43. For the isothermal case, n equals 2.4198 and C equals 1.1117×10^{-14} ; for the IP TMF case, n equals 1.445 and C equals 7.0307×10^{-13} . As seen in Figure 43, at lower values of ΔK , crack growth rates are slightly larger for the isothermal condition than for that of IP TMF. The point at which the lines intersect is the point at which the crack growth rates are equal. At this intersection, da/dN for both cases were equal.

AD-A189 555

THERMAL-MECHANICAL FATIGUE TESTING OF A
TITANIUM-ALUMINIDE ALLOY(U) AIR FORCE INST OF TECH
WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING

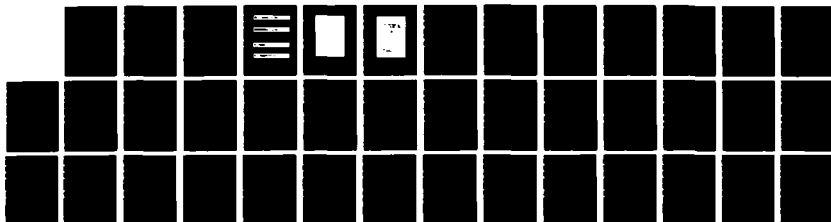
2/2

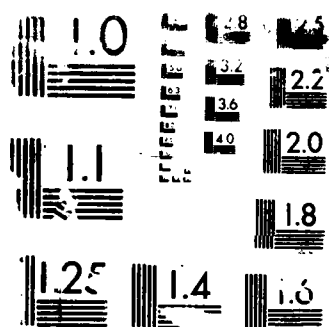
UNCLASSIFIED

J J PERNOTE DEC 87 AFIT/GAE/AA/87D-18

F/G 11/6 1

NL





RESOLUTION TEST CHART

$$[da/dN]_{iso} = [da/dN]_{IP\ TMF} \quad (31)$$

Substituting for the growth rates:

$$(1.1117 \times 10^{-14}) \Delta K^{2.4198} = (7.0307 \times 10^{-13}) \Delta K^{1.9520} \quad (32)$$

Taking the logarithm of both sides and solving:

$$2.4198 \log_{10}(\Delta K) - 13.954 = 1.9520 \log_{10}(\Delta K) - 12.153 \quad (33)$$

$$0.4678 \log_{10}(\Delta K) = 1.8010 \quad (34)$$

$$\Delta K = 7.0784 \times 10^3 \text{ psi}\sqrt{\text{in.}} \quad (35)$$

Substituting back into Eq (2) yields da/dN .

$$da/dN = 2.3018 \times 10^{-5} \text{ in/cycle} \quad (36)$$

At a value of ΔK equal to 7078.4 $\text{psi}\sqrt{\text{in.}}$, both curves yield the same growth rate. As mentioned in Chapter IV, the fatigue tests were started at approximately 7 $\text{ksi}\sqrt{\text{in.}}$; therefore, the overall trend of the data obtained during these tests shows that the IP TMF crack growth rate was less than the 1200°F isothermal growth rate for a given ΔK . This can be attributed to the fact that during TMF conditions, the material is subjected to the maximum temperature only at maximum load. For the isothermal test, the specimen is always held at the maximum temperature and may contribute to the reduction in life.

Fracture Surfaces

The fracture surfaces of both specimens investigated are shown in Figures 44, 45, and 46. In general, crack growth for both tests was irregular. This was observed physically during the tests and this feature is shown in the measured crack length versus fatigue cycle data, particularly for the IP TMF test (Figure 30). Such irregular crack growth behavior was more prominent during the earlier part of the tests as shown in the results of Figure 30. This irregular behavior could be attributed to the fact that this material is an intermetallic compound still under development. Kernas (21:1721,1722) has studied fatigue characteristics of Ti_3Al . He has found that, at elevated temperatures, scattered intergranular fracture occurs resulting from a limited number of slip systems. He also has observed a decreased planarity of the fracture surfaces. It should also be noted that, in the specimens considered here, the cracks did not always grow along the mid-plane of the specimen as shown in Figures 45 and 46. These growth irregularities must be studied further to totally understand the fracture behavior of this material.

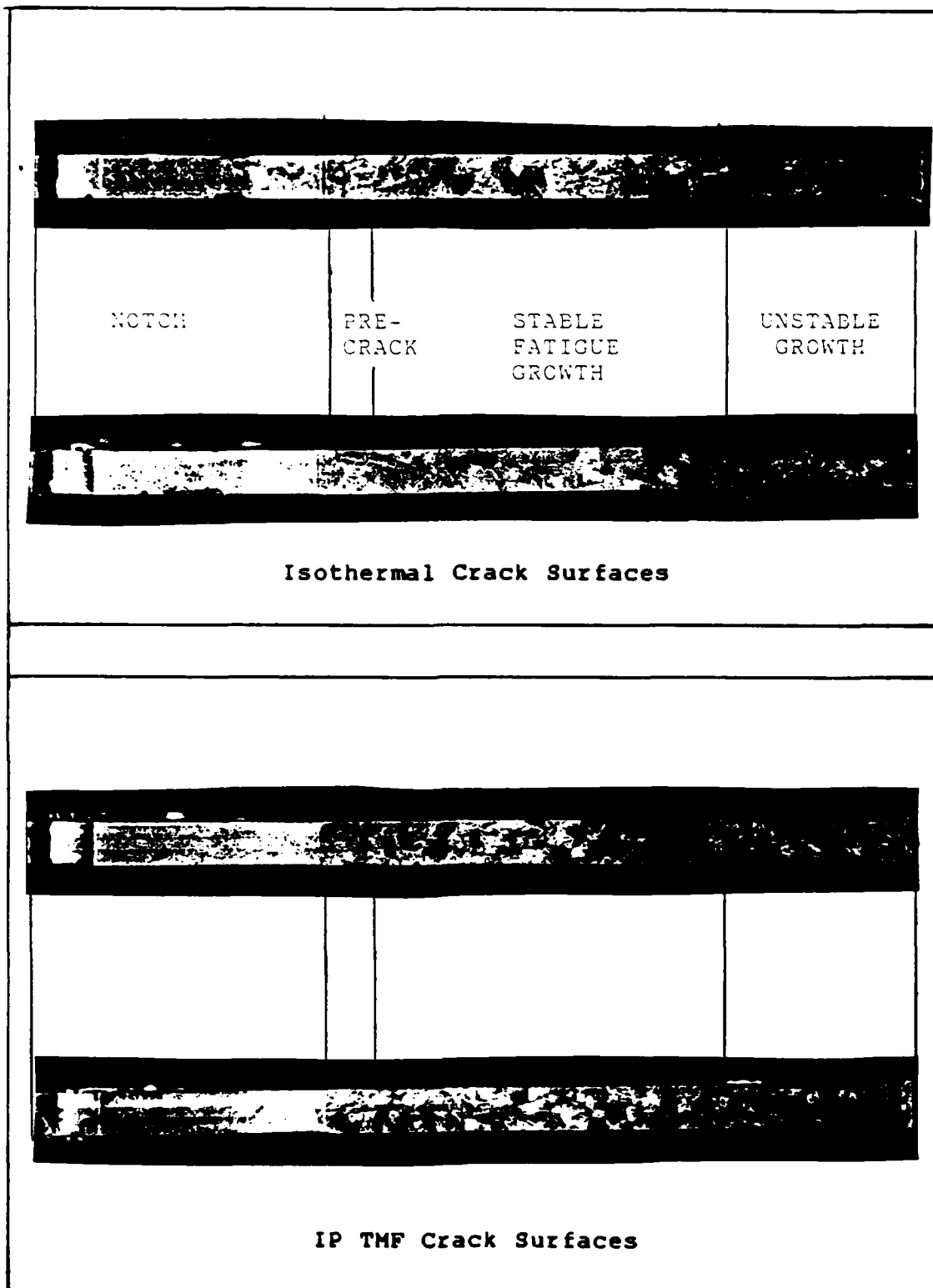


Figure 44. 1200°F Isothermal and 600°F to 1200°F IP TMF Fracture Surfaces

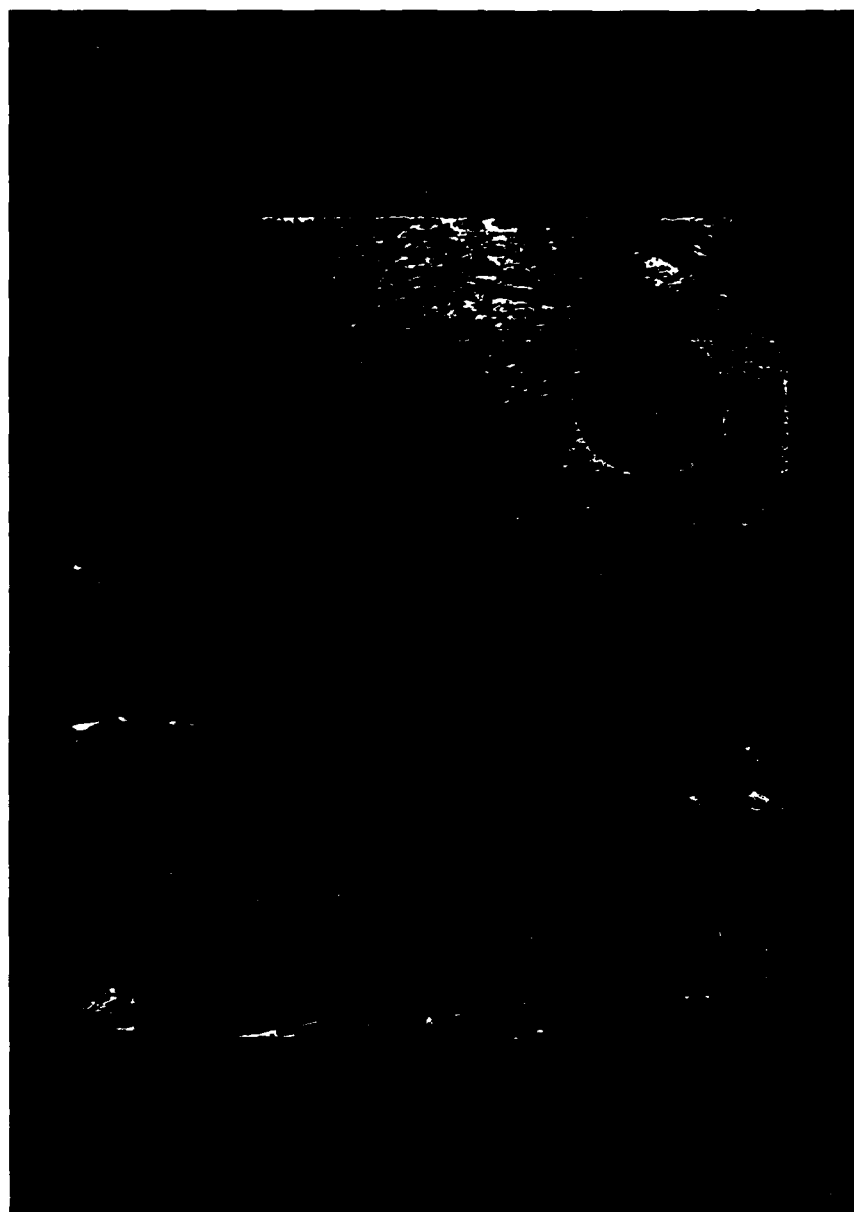


Figure 45 1200^oF Isothermal Test Fractured Specimen

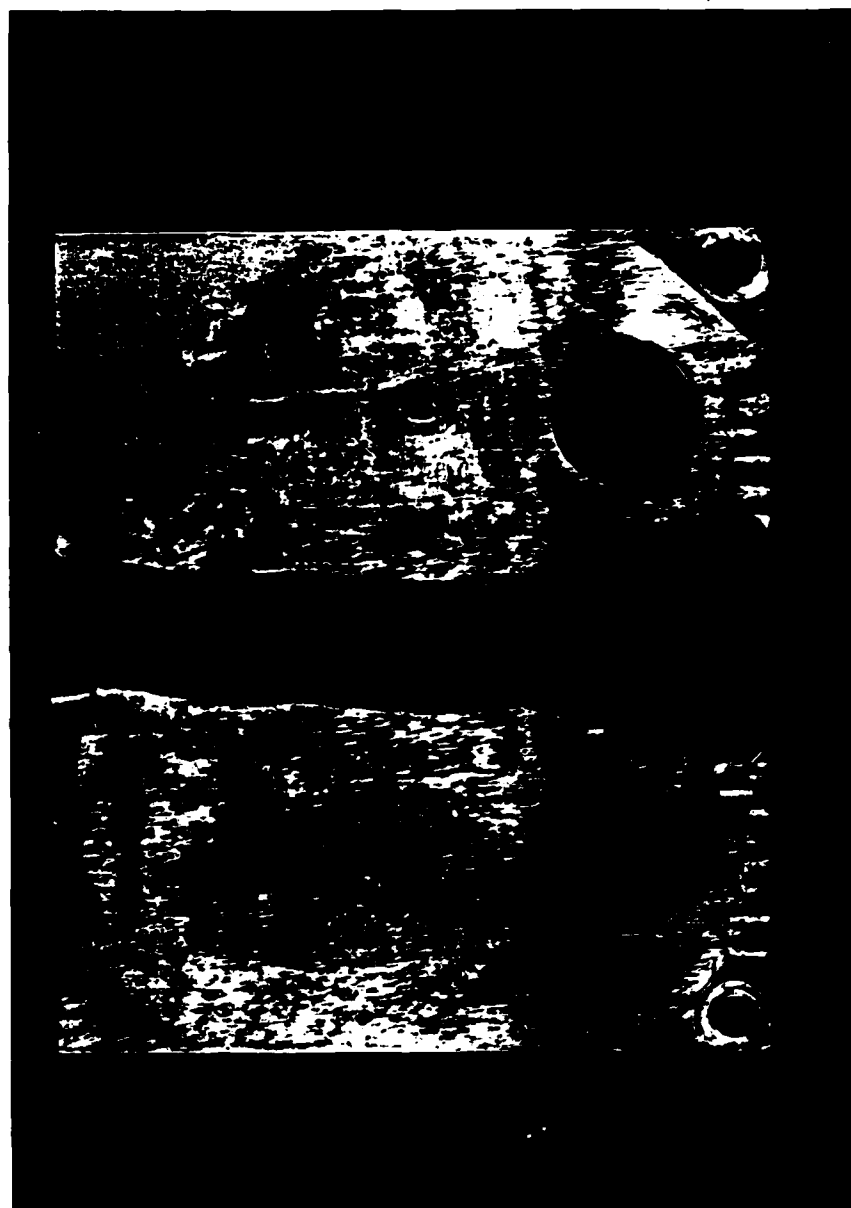


Figure 46 600°F to 1200°F IP TMF Test Fractured Specimen

Conclusions and Recommendations

This study discussed, in detail, the development of a setup for thermal-mechanical fatigue (TMF) testing of materials. The setup consists of a MTS servohydraulic loading machine modified to thermally load a specimen with a variety of temperature profiles. This setup utilizes an electric potential (EP) drop technique to measure crack length. A computer program for control of the entire system as well as the acquisition of data has been developed for in-phase (IP) TMF testing. The modifications that can be made to this program for isothermal and out-of-phase (OP) TMF testing have also been discussed.

To demonstrate the use of the computer-controlled testing system, isothermal and IP TMF tests have been carried out on compact tension (CT) specimens machined from the titanium aluminide Ti_3Al . The results of these tests have been presented in this study.

The conclusions drawn from this study can be summarized as follows:

- 1) Equipment was developed for:
 - i) isothermal testing
 - ii) IP and OP TMF testing
- 2) The equipment used an EP drop technique to measure crack length. This crack length was used to establish crack

growth relations.

3) The equipment was able to control temperature to within 2 percent of the programmed value during temperature cycling between 600°F and 1200°F. Heating and cooling rates of 12.5°F/sec. were established on a small CT specimen.

4) The capability of this system was demonstrated by performing 1200°F isothermal and 600°F to 1200°F IP TMF tests on the titanium-aluminide, Ti₃Al.

5) Results from both tests have been discussed. For the ΔK region studied, isothermal crack growth rates were slightly higher than the IP TMF growth rates for a given value of ΔK.

6) The fracture surfaces of both test specimens were very rough and irregular.

Recommendations can be summarized as:

1) The Micricon 82300 should be computer controlled. This is required to make adjustments of control parameters directly from the computer. The Micricon is computer adaptable, but the software could not have been written in the time required to complete this thesis.

2) Temperatures should be read directly from the Micricon, resulting in four temperature readings corresponding to the four quartz-lamp-heated areas. This also requires the computer connections and software previously described. The system developed here reads the voltage in a type-K thermocouple and converts it to

temperature, but could read the voltage from only one thermocouple (corresponding to one area) at a time.

3) After computer connections of the Micricon are made, the valve controlling the cooling air should trigger from the programmed (setpoint) value of temperature. Doing so would allow the valve to open and close at the maximum and minimum setpoint, resulting in better control of the maximum and minimum temperatures.

4) The OP test described in this thesis needs to be completed.

5) Isothermal, IP TMF, and OP TMF tests need to be completed at lower values of ΔK , and at other frequencies of temperature and load.

6) After all testing is complete, a model must be developed to characterize the TMF behavior of this material.

Appendix A

Software Written for Computer Control and
Data Acquisition (CCADA) of an In-Phase (IP)
Thermal-Mechanical Fatigue (TMF) Test

The computer program that is shown in this appendix was written to control an in-phase (IP) thermal-mechanical fatigue (TMF) test using the equipment described in this thesis. The program was developed to:

- 1) Monitor a temperature cycle produced by the Micricon 82300 process controller and trigger a mechanical loading cycle in phase with it.
- 2) Control an electric valve to allow cool air to flow across the specimen.
- 3) Measure and record crack growth using the electric potential method.
- 4) Record the minimum and maximum load between data samplings.
- 5) Record the minimum and maximum temperature between data samplings.
- 6) Record the cycle count at data samplings.

The output devices and their corresponding numbers used throughout the program are shown in Table 7. The IEEE-488 address numbers and their corresponding device names are shown in Table 8. A block diagram that describes the operations of the program is shown in Figure 47. The variables used in the program are defined in lines 520 through 690 of the program. A flow chart of the main program is shown in Figure 48.

Table 7 Output Device Numbers

OUTPUT NUMBER	OUTPUT DEVICE NAME
1	com port 2 used for data display
2	data file (disk or hard drive)
3	temperature profile data file

Table 8 IEEE-488 Address Numbers and Device Names

ADDRESS NUMBER	DEVICE NAME
9	Wavetek Function Generator
6	Voltmeter used to determine temperature
22	Voltmeter used for EP crack measurement
5	Power Supply used for EP method

NOTE: The CCADA program uses many examples and programming advice included in references 29 through 32.

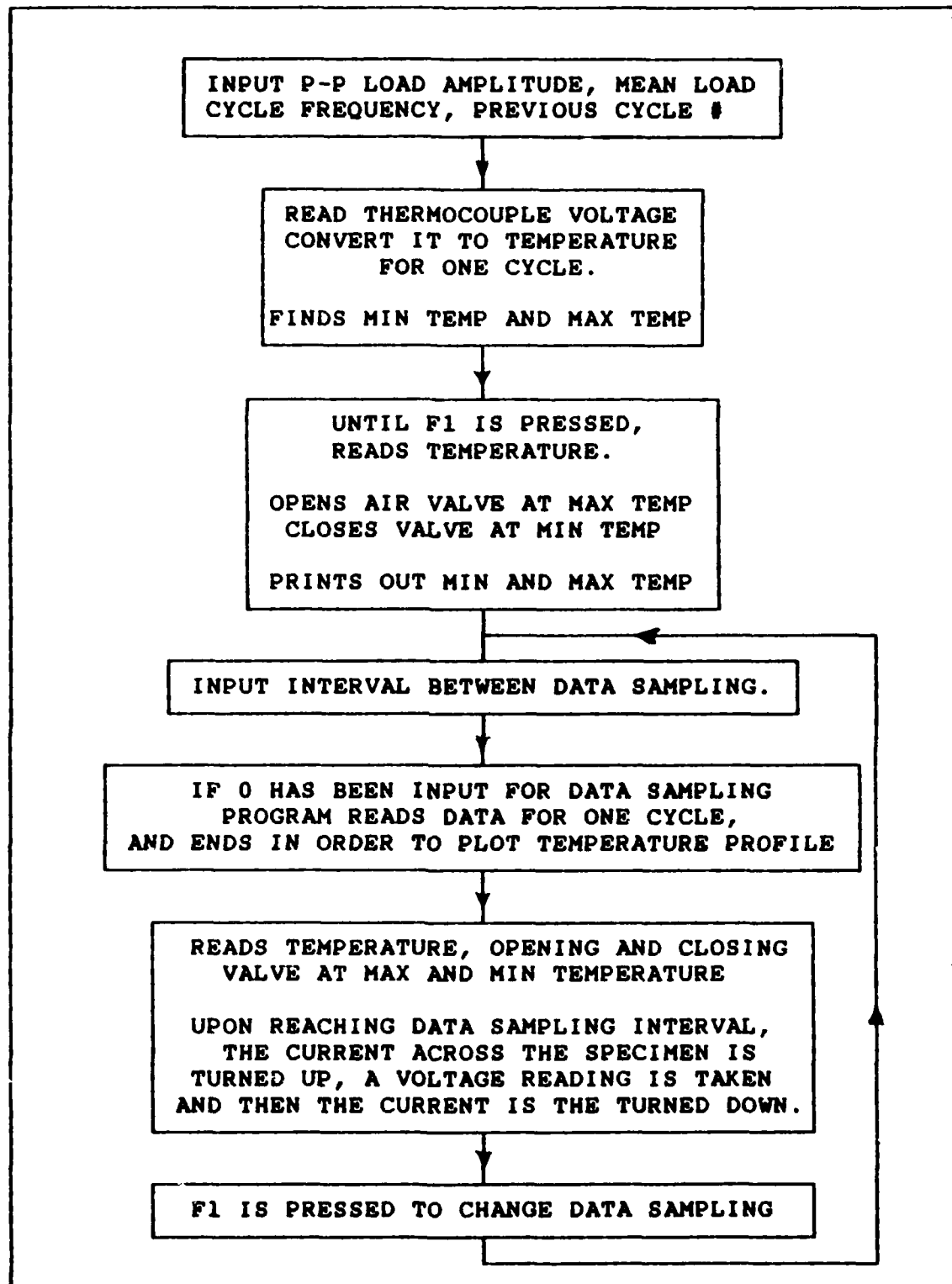


Figure 47 Block Diagram of the TMF CCADA Program

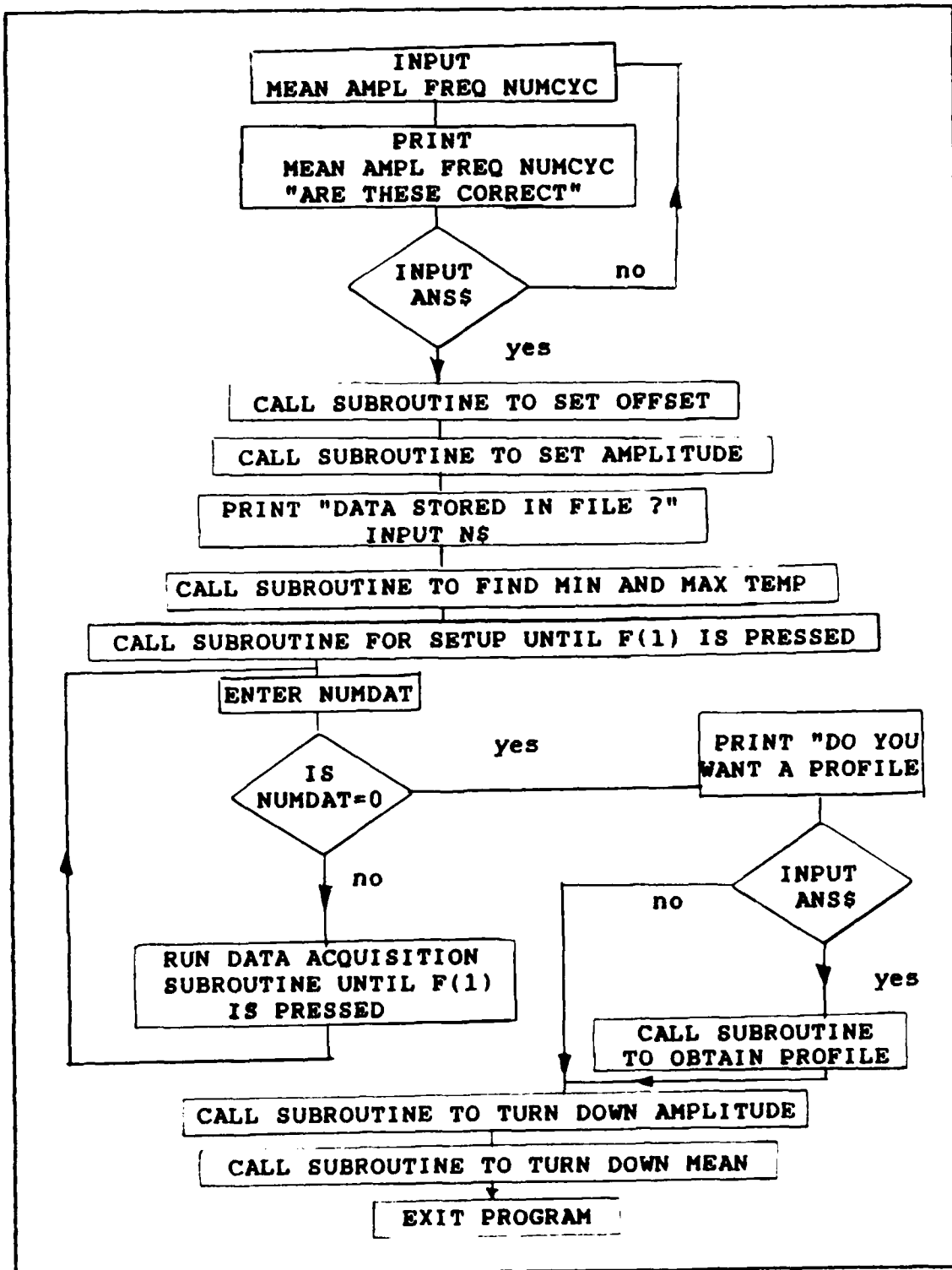


Figure 48 Flow Chart for Main Program of CCADA

```

10 REM computer control and data acquisition (CCADA) program
20 REM for in phase (IP) thermal mechanical fatigue (TMF)
30 REM material testing
40 REM
50 REM opens com 2 port as #1
60 REM initializes data display
70 REM
80 PRINT "IT DID NOT WORK IF IT LOCKED UP, HIT <CTRL>C AND
RUN AGAIN"
90 OPEN"COM2:2400,E,7,1,CS,DS" AS #1
100 PRINT #1,CHR$(2); 'data disp
remote
110 IF LOC(1)<3 THEN 110 'checks
que
120 PRINT #1,CHR$(77),CHR$(51),CHR$(13); 'mode 3 for
min-max
130 IF LOC(1)<6 THEN 130
140 DIM C(500)
150 DIM A(500)
160 KEY OFF
170 CLS
180 PRINT
"*****"
190 PRINT "** CONTROL AND DATA ACQUISITION PROGRAM FOR THE
MTS LOADING *"
200 PRINT "** MACHINE MODIFIED FOR THERMAL- MECHANICAL
FATIGUE TESTING *"
210 PRINT
"*****"
220 PRINT "** THE PROGRAM WAS DEVELOPED TO:
*"
230 PRINT "**
*"
240 PRINT "** 1) Monitor a thermal cycle created by the
Micricon 82300 *"
250 PRINT "** and trigger a mechanical cycle in-phase
with it. *"
260 PRINT "** 2) Record the number of cycles
*"
270 PRINT "** 3) Measure and record crack growth using a
DC potential *"
280 PRINT "** drop method. Measurements are taken at
constant 10 A *"
290 PRINT "** and also at 0 A.
*"
300 PRINT "** 4) Open an electrically controlled valve to
allow cool *"
310 PRINT "** air to flow over the specimen for the
second half of *"
320 PRINT "** the cycle.

```

```

**
330 PRINT "**      5) Record the minimum and maximum values of
temperature      *"
340 PRINT "**      and load between data samplings.
**
350 PRINT "**
**
360 PRINT
"*****"
*****"
370 PRINT "**
**
380 PRINT "**      The program was written by John J. Pernot and
Jay Anderson      *"
390 PRINT "**
**
400 PRINT
"*****"
*****"
410 REM
420 REM      program continues with carriage return
430 REM
440 INPUT "-----HIT <RETURN> TO
CONTINUE-----",ANS$
450 REM
460 REM
470 CLS
480 PRINT
"*****"
*****"
490 PRINT "**      THE VARIABLES USED IN THE PROGRAM ARE
DEFINED AS :      *"
500 PRINT
"*****"
*****"
510 PRINT
"*****"
*****"
520 PRINT "**      MEAN....MEAN VALUE OF THE LOAD (VOLTS)
**
530 PRINT "**      AMPL....PEAK-PEAK AMPLITUDE OF THE LOAD (VOLTS)
**
540 PRINT "**      FREQ....FREQUENCY OF THE CYCLE (HERTZ)
**
550 PRINT "**      NUMCYC..NUMBER OF THE PRESENT CYCLE
**
560 PRINT "**      NUMDAT..NUMBER OF CYCLES BETWEEN DATA SAMPLING
**
570 PRINT "**      NUMPREV.PREVIOUS CYCLE NUMBER
**
580 PRINT "**      ANS$....ANSWER TO INTERACTIVE QUESTIONS
**

```

```

590 PRINT "**      N$......NAME OF DATA FILE
*"
600 PRINT "**      TMIN....MINIMUM TEMPERATURE BETWEEN DATA
SAMPLINGS      *"
610 PRINT "**      TMAX....MAXIMUM TEMPERATURE BETWEEN DATA
SAMPLINGS      *"
620 PRINT "**      TTMIN...MINIMUM TEMPERATURE OF EACH CYCLE
*"
630 PRINT "**      TTMAX...MAXIMUM TEMPERATURE OF EACH CYCLE
*"
640 PRINT "**      TPREV...PREVIOUS TEMPERATURE READING
*"
650 PRINT "**      TMEAN...MEAN TEMPERATURE
*"
660 PRINT "**      NUMCHK..VALUE USED TO CHECK IF F(1) HAS BEEN
PRESSED      *"
670 PRINT "**      NUMTRG..VALUE USED TO DETERMINE WHEN TO
TRIGGER LOAD  *"
680 PRINT "**      X.....VALUE USED AS A VARIABLE AND COUNTER
*"
690 PRINT "**      K,I.....USED FOR DELAY TIMERS
*"
700 PRINT
*****
*****"
710 REM          program continues with carriage return
720 REM
730 INPUT "-----HIT <RETURN> TO
CONTINUE-----",ANS$
740 REM
750 CLS
760 PRINT
*****
*****"
770 PRINT "**
*"
780 PRINT "**          Computer Control and
*"
790 PRINT "**          Data Acquisition (CCADA)
*"
800 PRINT "**          Program
*"
810 PRINT "**
*"
820 PRINT "**          for
*"
830 PRINT "**          In Phase (IP) Thermal Mechanical
*"
840 PRINT "**          Fatigue (TMF) Testing of Materials
*"
850 PRINT "**
*"

```

```

860 PRINT
*****
870 PRINT "*"
880 PRINT "*"
890 PRINT "*"
900 PRINT "          NOTE: SPECIMEN MUST BE THERMALLY
          "
910 PRINT "          CYCLED BEFORE RUNNING PROGRAM..."
920 PRINT "*"
930 PRINT "          IF SPECIMEN IS NOT BEING CYCLE,
          "
940 PRINT "          ANSWER NO TO THE FOLLOWING QUESTION
          "
950 PRINT "*"
960 PRINT "          AND   EXIT   PROGRAM !
          "
970 PRINT "*"
980 PRINT
*****
990 REM
1000 REM          program asks is you wish to continue
1010 REM
1020 INPUT "DO YOU WISH TO CONTINUE ? ",ANS$
1030 IF ANS$="y" OR ANS$="Y" OR ANS$="yes" OR ANS$="YES" THEN
1070
1040 CLS
1050 KEY ON
1060 END
1070 REM          program clears screen and sends IEEE-488 and
LABSTAR commands
1080 REM          the software commands for LABSTAR follow
1090 REM
1100 CLS
1110
ADC.SETUP=&H8F3:ALTOUT12.B=&H718:ALTOUT12.BT=&H777:ALTOUT12.R
=&H7D9
1120
ALTOUT12.RT=&H83A:ALTOUT12.S=&H6C9:ALTOUT12.ST=&H6EF:ALTOUT8.
B=&H2A1
1130
ALTOUT8.BT=&H32B:ALTOUT8.R=&H3BB:ALTOUT8.RT=&H44B:ALTOUT8.S=&
H21C
1140

```

```

ALTOUT8.ST=&H25C:DAC.SETUP=&H1A:INADC12.B=&HD20:INADC12.BT=&H
DB1
1150
INADC12.EXTCLOCK=&HE52:INADC12.S=&HCAB:INADC12.ST=&HCDA:INADC
8.B=&H997
1160
INADC8.BT=&HA03:INADC8.EXTCLOCK=&HA72:INADC8.S=&H916:INADC8.S
T=&H94A
1170
OUTDAC12.B=&H53C:OUTDAC12.BT=&H59F:OUTDAC12.R=&H605:OUTDAC12.
RT=&H65C
1180
OUTDAC12.S=&H4E1:OUTDAC12.ST=&H50D:OUTDAC8.B=&H8E:OUTDAC8.BT=
&HEF
1190
OUTDAC8.R=&H153:OUTDAC8.RT=&H1B6:OUTDAC8.S=&H3F:OUTDAC8.ST=&H
65
1200
SCAN12.B=&HFB5:SCAN12.BT=&H104B:SCAN12.S=&HEFF:SCAN12.ST=&HF5
1
1210
SCAN8.B=&HB87:SCAN8.BT=&HC16:SCAN8.S=&HACD:SCAN8.ST=&HB20
1220 DEF SEG=0
1230 CSEG0=(256*PEEK(&H3C9))+PEEK(&H3C8)
1240 DEF SEG=CSEG0
1250 REM
1260 REM
1270 REM          IEEE-488 software commands follow
1280 REM
1290 OI=0!
1300 BUSSTA=&H4C5:CLR=&HA71:DCL=&H3A8:EOI=&H2BE
1310 GTL=&H4A2:GTS=&H2AE:IFC=&H2D2
1320 IFC3=&H315:INIT=&H321:LISTEN=&H6F5:LLO=&H3C8
1330 LON=&H2C2:PASSCONT=&H609:PPDS=&H4D7:PPEN=&H3F8
1340 PPOL=&H59C:PPU=&H3D8:READS=&H7FC:READB=&H7DE
1350 RECECONT=&H645:REMOTE=&H6CE :SDC=&H3B8:SETTIMER=&HAA4
1360 SPOL=&H4F9:TALK=&H7A3:TCA=&H24E:TCS=&H29E
1370 TON=&H2CA:TRIG=&H4B3:ULON=&H2C6:UNL=&H36D
1380 UNT=&H398:UTON=&H2CE:WRITES=&H8CB:WRITEB=&H8BB
1390 XFER=&H99B
1400 DEF SEG = 0
1410 CSEG1=(256*PEEK(&H3C7))+PEEK(&H3C6)
1420 DEF SEG=CSEG1
1430 REM
1440 CLS
1450 INPUT "ENTER THE MEAN VALUE FOR THIS RUN:  ";MEAN!
1460 CLS
1470 INPUT "ENTER THE P-P AMPLITUDE FOR THIS RUN:  ";AMPL!
1480 CLS
1490 INPUT "ENTER THE FREQUENCY FOR THIS RUN:  ";FREQ!
1500 CLS
1510 INPUT "ENTER THE PREVIOUS CYCLE NUMBER      :  ";NUMCYC

```

```

1520 CLS
1530 PRINT "ARE THESE THE CORRECT VALUES FOR THIS RUN"
1540 PRINT "MEAN" : "MEAN!"
1550 PRINT "AMPLITUDE" : "AMPL!"
1560 PRINT "FREQUENCY" : "FREQ!"
1570 PRINT "PREVIOUS NUMBER OF CYCLES: " NUMCYC
1580 Numprev=NUMCYC
1590 NX=0
1600 INPUT "Y/N: ";ANS$
1610 N$="N"
1620 IF ANS$=N$ THEN 1450
1630 CLS
1640 REM
1650 GOSUB 1930 'sets offset
1660 GOSUB 2410 'sets amplitude
1670 INPUT "NAME OF THIS TEST RUN: EXP. A:CK001.ASC";N$
1680 LPRINT "The data is stored in file: ",N$
1690 REM
1700 OPEN N$ FOR OUTPUT AS #2
1710 GOSUB 2840 'finds max and min
1720 GOSUB 3460 'starts at min, turns
valve on and
1730 'off, prints min and
max for setup
1740 NUMTRG=0
1750 PRINT "NUMBER OF CYCLES BETWEEN EACH DATA SAMPLING:"
1760 INPUT "ENTER 0 TO QUIT please do it
quick!!!!:";NUMDAT
1770 IF NUMDAT>0 THEN 1870
1780 INPUT "do you want to have a profile";ANS$
1790 IF ANS$="n" OR ANS$="N" OR ANS$="no" OR ANS$="NO" THEN
1810
1800 GOSUB 3970 'obtains temperature
profile
1810 GOSUB 2510 'turns amplitude down
to 0
1820 GOSUB 2170 'turns mean down to 0
1830 CLS
1840 SYSTEM
1850 END
1860 REM
1870 Numprev=NUMCYC
1880 GOSUB 4770 'starts data
acquisition
1890 GOTO 1750 'returns to change
data sampling
1900 REM
1910 END
1920
REM-----
-----
1930 REM this subprogram will set the mean value

```

```

1940
REM-----
-----
1950 DEF SEG=CSEG1
1960 SYSCON% = 1          'MAKES Z-248 SYSTEM CONTROLLER
1970 I488ADDR% = &H318    'INITIALIZES THE CONTROLLER ADD.
1980 DEVADDR% = 1         'SETS BOARD ADD.
1990 CALL INIT(SYSCON%,I488ADDR%,DEVADDR%)
2000 CALL REMOTE          'SET DEVICES TO REMOTE
2010 CALL LLO             'DISABLES FRONT PANELS
2020 COMMS$ = "B1C1F99P1I" 'WAVETEK REMOTE,SINGLE CYCLE,FUNC
TRIANGLE,OUTPUT 1
2030 LISTEN$ = "9"        'WAVETEK ADDRESS
2040 EOIS$ = ""           'END OF DATA
2050 CALL WRITES(LISTEN$,EOIS$,COMMS$) 'PERFORMS THE ABOVE
2060 CALL REMOTE
2070 OI= OI +.01          ' INCREASES MEAN BY .1 VOLT
2080 FOR I = 1 TO 100
2090 NEXT I
2100 COMMS$ = "D" + STR$(OI) + "I"
2110 LISTEN$ = "9"
2120 EOIS$ = ""
2130 CALL WRITES(LISTEN$,EOIS$,COMMS$)
2140 REM
2150 IF OI < MEAN! -.01 THEN 2070 'LOOP BACK TO INCREASE THE
MEAN
2160 RETURN
2170
REM-----
-----
2180 REM          this subprogram turns the mean value back to 0
2190
REM-----
-----
2200 DEF SEG=CSEG1
2210 OI=MEAN!
2220 OI= OI -.01          ' decreases MEAN BY .1 VOLT
2230 FOR I = 1 TO 100
2240 NEXT I
2250 COMMS$ = "D" + STR$(OI) + "I"
2260 LISTEN$ = "9"
2270 EOIS$ = ""
2280 CALL WRITES(LISTEN$,EOIS$,COMMS$)
2290 IF OI > .01 THEN 2220 'LOOP BACK TO decrease THE MEAN
2300 RETURN
2310
REM-----
-----
2320 REM  this subprogram sets the load frequency and
triggers it
2330
REM-----

```

```

-----
2340 DEF SEG=CSEG1
2350 COMMS$ = "F" + STR$(FREQ!) + "IJ"      'SETS THE FREQUENCY
2360 LISTEN$ = "9"                          'SETS THE WAVETEK
2370 EOIS$ = ""
2380 CALL WRITES(LISTEN$,EOIS$,COMMS)        'PERFORMS THE ABOVE
2390 RETURN
2400
REM-----
-----
2410 REM      this subprogram sets the amplitude of the test
run
2420
REM-----
-----
2430 DEF SEG=CSEG1
2440 AMP! = AMPL!                          'SETS THE AMPL
2450 COMMS$ = "A" + STR$(AMP!) + "I"
2460 LISTEN$ = "9"
2470 EOIS$ = ""
2480 CALL WRITES(LISTEN$,EOIS$,COMMS)
2490 RETURN
2500
REM-----
-----
2510 REM      this subprogram turns the amplitude down to .1
2520
REM-----
-----
2530 DEF SEG=CSEG1
2540 AMP! = AMPL!                          'SETS THE AMPL
2550 COMMS$ = "A" + STR$(AMP!) + "I"
2560 AMP!=AMP!-.1
2570 FOR I=1 TO 500
2580 NEXT I
2590 LISTEN$ = "9"
2600 EOIS$ = ""
2610 CALL WRITES(LISTEN$,EOIS$,COMMS)
2620 IF AMP!>0! THEN 2550
2630 RETURN
2640
REM-----
-----
2650 REM      this subprogram turns the cooling air on
2660
REM-----
-----
2670 DEF SEG=CSEG0
2680 ADDRESS%=&H310                        'address of d/a
converter module
2690 CALL DAC.SETUP(ADDRESS%)              'set up of the
address

```

```

2700 CHANNEL%=0                                ' 0 value
corresponds to +10 v
2710 VALUE%=4095                              '4095 value
corresponds to 0 v
2720 CALL OUTDAC12.S(CHANNEL%,VALUE%)          'sends out a point
2730 RETURN
2740
REM-----
-----
2750 REM          this subprogram turns the cooling air off
2760
REM-----
-----
2770 DEF SEG=CSEG0
2780 ADDRESS%=&H310                            'address of d/a
converter module
2790 CALL DAC.SETUP(ADDRESS%)                  'set up of the
address
2800 CHANNEL%=0                                '0 corresponds to
+10 v
2810 VALUE%=0                                  '4095 corresponds to
0 v
2820 CALL OUTDAC12.S(CHANNEL%,VALUE%)          'sends out a point
2830 RETURN
2840
REM-----
-----
2850 REM          this subprogram reads voltage from the HP3456
2860 REM          voltmeter and converts it to temperature
2870 REM          the subprogram also searches for the min and
2880 REM          max temp
2890
REM-----
-----
2900 DEF SEG=CSEG1
2910 DIM TF(5000)
2920 I=0                                        'initialize i =0
2930 CHECKT = TIMER
2940 REM          the loop that takes temperature readings
begins here
2950 I=I+1 :CLS :PRINT "tmax=",TMAX,"tmin=",TMIN
2960 FOR K=1 TO 500                            'delay timer for
reading next temp
2970 NEXT K
2980 RDATA$="+015.4660E-3"
2990 SYSCON%=1                                'IBM PC as system
controller
3000 I488ADDR%=&H318                            '488 controller
physical address
3010 DEVADDR%=1                                '488 controller
device address
3020 CALL INIT(SYSCON%,I488ADDR%,DEVADDR%)      'initialize

```

```

the system
3030 CALL REMOTE
3040 CALL LLO
3050 COMMS=" F1 R2 0.1STI T3"           'puts the HP3456 into
dc range                                '100mv 10 samples/s
3060
single trigger
3070 LISTEN$="6"                         'address 6
3080 EOIS=""                             'device
3090 CALL WRITES(LISTEN$,EOIS,COMMS)     'sends command to
HP3456
3100 TALK$="6"
3110 LISTEN$=""
3120 CALL READS(TALK$,LISTEN$,EOIS,RDATA$,STATUS%)
3130 IF STATUS% = 1 THEN 3120             'if no reading taken,
tries again
3140 X=VAL(RDATA$)                       'x = value of the
reading
3150 REM constants for the temperature polynomial
3160 A0=.226584602#
3170 A1=24152.109#
3180 A2=67233.4248#
3190 A3=2210340.682#
3200 A4=-860963914.9#
3210 A5=4.83506*10^10
3220 A6=-1.18452*10^12
3230 A7=1.3869*10^13
3240 A8=-6.33708*10^13
3250 REM temperature in degrees C
3260
TC=A0+X*(A1+X*(A2+X*(A3+X*(A4+X*(A5+X*(A6+X*(A7+A8*X))))))
3270 REM temperature in degrees F
3280 TF(I)=TC*9/5+32.2
3290 IF TF(I)<40! THEN 2960
3300 IF I>1 THEN 3340
3310 TMIN=TF(I)
3320 TMAX=TF(I)
3330 IF I=1 THEN 2950
3340 IF TF(I)<TMAX THEN 3360
3350 TMAX=TF(I)
3360 IF TF(I)>TMIN THEN 3380
3370 TMIN=TF(I)
3380 TMEAN = (TMIN+TMAX)/2
3390 IF (TIMER-CHECKT)<((1/FREQ!)+2!) THEN 2950
3400 IF (TF(I)-TF(I-1))<0! THEN 2950      'must satisfy
these 3 conditions
3410 IF TF(I)>TMEAN THEN 2950
3420 PRINT "max temp =",TMAX,"min temp =",TMIN
3430 TF=TF(I)
3440 RETURN
3450
REM-----

```

```

-----
3460 REM          the subprogram searches for the min and
3470 REM          max temp and turns the cooling air off and
on
3480
REM-----
-----
3490 KV=0
3500 PRINT "PRESS F1 TO EXIT LOOP"
3510 NUMCHK = 0
3520 ON KEY(1) GOSUB 4700          'sets function key F1
3530 KEY(1) ON
3540     REM          start the subprogram
3550 DEF SEG=CSEG1
3560     REM
3570 TPREV=TF
3580 FOR K=1 TO 1000
3590 NEXT K
3600 RDATA$="+013.0630E-3"
3610 SYSCON%=1                    'IBM PC as system
controller
3620 I488ADDR%=&H318              '488 controller
physical address
3630 DEVADDR%=1                  '488 controller
device address
3640 CALL INIT(SYSCON%,I488ADDR%,DEVADDR%) 'initialize
the system
3650 CALL REMOTE
3660 CALL LLO
3670 COMMS$=" F1 R2 0.1STI T3"   'puts the HP3456 into
dc range
3680                              '100mv 10 samples/s
single trigger
3690 LISTEN$="6"                 'address 6
3700 EOIS$=""                    'device
3710 CALL WRITES(LISTEN$,EOIS$,COMMS) 'sends command to
HP3456
3720 TALK$="6"
3730 LISTEN$=""
3740 CALL READS(TALK$,LISTEN$,EOIS$,RDATA$,STATUS%)
3750 IF STATUS% = 1 THEN 3740     'if no reading taken,
tries again
3760 X=VAL(RDATA$)               'makes voltage array
3770
TC=A0+X*(A1+X*(A2+X*(A3+X*(A4+X*(A5+X*(A6+X*(A7+A8*X))))))
3780 TF=TC*9/5+32.2
3790 IF TF<40! THEN 3580
3800 IF KV=0 AND (TF-TPREV)>0 THEN 3540
3810 IF KV=1 AND (TF-TPREV)<0 THEN 3540
3820 IF KV=0 THEN 3890
3830 GOSUB 2740
3840 KV=0

```

```

3850 TMIN=TPREV
3860 PRINT "MAX TEMP IS ";TMAX,"AND MIN TEMP IS";TMIN
3870 IF NUMCHK = 1 THEN 3920
3880 GOTO 3540
3890 GOSUB 2640
3900 TMAX=TPREV
3910 KV=1 : GOTO 3540
3920 TMEAN = (TMIN+TMAX)/2
3930 TMIN=TMEAN
3940 TMAX=TMEAN
3950 RETURN
3960
REM-----
-----
3970 REM          this subprogram reads voltage from the HP3456
3980 REM          voltmeter and converts it to temperature
3990 REM
4000 REM          obtains temperature profile for one cycle
4010
REM-----
-----
4020 NNS="a:profile.asc"
4030 LPRINT "PROFILE DATA STORED IN FILE: " NNS
4040 OPEN NNS FOR OUTPUT AS #3
4050 DIM X(1000)
4060 DIM AT(1000)
4070 REM
4080 I=0                                'sets up parameters
4090 TIMEI=TIMER
4100 KV=0                                'valve is initially
closed
4110 DEF SEG=CSEG1
4120 I=I+1
4130 IF TIMER>(TIMEI+(1.3/FREQ!)) THEN 4480
4140 FOR K=1 TO 100
4150 NEXT K
4160 RDATA$="+000.8990E-3"
4170 SYSCON%=1                            'IBM PC as system
controller
4180 I488ADDR%=&H318                      '488 controller
physical address
4190 I488ADDR%=&H318                      '488 controller
physical address
4200 DEVADDR%=1                          '488 controller device
address
4210 CALL INIT(SYSCON%,I488ADDR%,DEVADDR%) 'initialize
the system
4220 CALL REMOTE
4230 CALL LLO
4240 COMM$=" F1 R2 0.1STI T3"
4250 LISTEN$="6"
4260 EOI$=""

```

```

4270 CALL WRITES(LISTENS$,EOIS$,COMMS$)
4280 TALK$="6"
4290 LISTENS$=""
4300 CALL READS(TALK$,LISTENS$,EOIS$,RDATAS$,STATUS%)
4310 IF STATUS% = 1 THEN 4300
4320 X=VAL(RDATAS$)
4330 IF X<.001 THEN 4160
4340 AT(I)=TIMER
4350 X(I)=X
4360 IF I<5 THEN 4120
4370 IF KV=1 THEN 4430
4380 IF X(I)>X(I-4) THEN 4120
4390 GOSUB 2650                                     'opens valve
4400 KV=1
4410 REM
4420 GOTO 4110
4430 REM
4440 IF X(I)<X(I-4) THEN 4120
4450 GOSUB 2750
4460 KV=0
4470 GOTO 4110
4480 FOR J=1 TO I
4490 X = X(J)
4500 A0=.226584602#
4510 A1=24152.109#
4520 A2=67233.4248#
4530 A3=2210340.682#
4540 A4=-860963914.9#
4550 A5=4.83506*10^10
4560 A6=-1.18452*10^12
4570 A7=1.3869*10^13
4580 A8=-6.33708*10^13
4590
TC=A0+X*(A1+X*(A2+X*(A3+X*(A4+X*(A5+X*(A6+X*(A7+A8*X))))))
4600 TF(J)=TC*9/5+32.2
4610 NEXT J
4620 ATT=AT(1)
4630 K=I-1
4640 FOR J=1 TO K
4650 AT(J)=AT(J)-ATT
4660 PRINT #3, AT(J);TF(J)
4670 NEXT J
4680 RETURN
4690
REM-----
-----
4700 REM          this subprogram changes the value of NUMCHK
4710 REM          when F1 is pressed during a process
4720
REM-----
-----
4730      NUMCHK = 1

```

```

4740 PRINT "WAITING UNTIL END OF LOOP BEFORE EXITING"
4750 RETURN
4760
REM-----
-----
4770 REM          the subprogram runs the data acquisition
process
4780 REM          and also turns the cooling air off and on
and
4790 REM          counts the number of cycles
4800
REM-----
-----
4810 KV=0
4820 PRINT "PRESS F1 TO EXIT LOOP"
4830 NUMCHK = 0
4840 ON KEY(1) GOSUB 4700          'sets function key F1
4850 KEY(1) ON
4860 REM          start the subprogram
4870 DEF SEG=CSEG1
4880 REM
4890 TPREV=TF
4900 FOR K=1 TO 1000
4910 NEXT K
4920 RDATA$="+014.0910E-3"
4930 SYSCON%=1                    'IBM PC as system
controller
4940 I488ADDR%=&H318              '488 controller
physical address
4950 DEVADDR%=1                  '488 controller
device address
4960 CALL INIT(SYSCON%,I488ADDR%,DEVADDR%) 'initialize
the system
4970 CALL REMOTE
4980 CALL LLO
4990 COMMS$=" F1 R2 0.1STI T3"   'puts the HP3456 into
dc range
5000                             '100mv 10 samples/s
single trigger
5010 LISTEN$="6"                 'address 6
5020 EOIS$=""                    'device
5030 CALL WRITES(LISTEN$,EOIS$,COMMS) 'sends command to
HP3456
5040 TALK$="6"
5050 LISTEN$=""
5060 CALL READS(TALK$,LISTEN$,EOIS$,RDATA$,STATUS%)
5070 'PRINT STATUS% ;
5080 IF STATUS% = 1 THEN 5060     'if no reading taken,
tries again
5090 X=VAL(RDATA$)               'makes voltage array
5100
TC=A0+X*(A1+X*(A2+X*(A3+X*(A4+X*(A5+X*(A6+X*(A7+A8*X))))))

```

```

5110 TF=TC*9/5+32.2
5120 IF TF<40! THEN 4900
5130 IF NUMTRG=1 THEN 5170
5140 IF TF<TMEAN THEN 5170
5150 GOSUB 2320
5160 NUMTRG=1
5170 IF KV=0 AND (TF-TPREV)>0 THEN 4860
5180 IF KV=1 AND (TF-TPREV)<0 THEN 4860
5190 IF KV=0 THEN 5300
5200 GOSUB 2740 'turns air off
5210 NUMCYC=NUMCYC+1
5220 KV=0
5230 TTMIN=TPREV
5240 IF TTMIN>TMIN THEN 5260
5250 TMIN=TTMIN
5260 TMEAN=(TMAX+TMIN)/2
5270 NUMTRG=0
5280 IF (NUMCHK = 1) AND (NX=0) THEN 5380
5290 GOTO 4860
5300 GOSUB 2640 'turns air on
5310 KV=1
5320 TTMAX=TPREV
5330 IF TTMAX<TMAX THEN 5350
5340 TMAX=TTMAX
5350 IF NUMCYC<(NUMPREV+NUMDAT) THEN 5370
5360 GOSUB 5740
5370 GOTO 4860
5380 RETURN
5390
REM-----
-----
5400 REM          this subprogram reads the minimum and maximum
load
5410 REM
5420 REM
5430
REM-----
-----
5440 DEF SEG=CSEG1
5450 MAX = 0
5460 MAX1 = 0
5470 REM
5480 TT=TIMER
5490 REM
5500 REM
5510 REM
5520 PRINT #1,CHR$(76),CHR$(13); 'data disp
sends min-max
5530 IF LOC(1)<23 THEN 5530
5540 P = 0
5550 WHILE LOC(1)<>1
5560 P = P + 1

```

```

5570 FOR I = 1 TO 10
5580 NEXT I
5590 INPUT #1,C(P)
5600 'PRINT C(P)
5610 WEND
min and max
5620 FOR I = 1 TO 100
data aquired
5630 IF C(I) = 4 THEN 5650
5640 NEXT
5650 I = I + 2
5660 MAX = C(I)
5670 I = I + 1
5680 MIN = C(I)
5690 PRINT #1,CHR$(82),CHR$(13);
5700 IF LOC(1) <3 THEN 5700
5710 RETURN
5720 REM
5730
REM-----
5740 REM          this subroutine reads the voltage from the
HP3456
5750 REM          used for determining voltage drop across the
crack
5760 REM
5770
REM-----
5780      DEF SEG=CSEG1
5790 N=30
5800 RDATA$=SPACE$(N)
5810 SYSCON%=1
controller
5820 I488ADDR%=&H318
physical address
5830 I488ADDR%=&H318
physical address
5840 DEVADDR%=1
address
5850 CALL INIT(SYSCON%,I488ADDR%,DEVADDR%)
the system
5860 CALL REMOTE
5870 CALL LLO
5880 COMMS$="F1 R1 25STN .01ST1 M2 T3"
5890 LISTEN$="22"
5900 EOI$=""
5910 CALL WRITES(LISTEN$,EOI$,COMMS)
5920 FOR I = 1 TO 1000
5930 NEXT I
5940 COMMS$="REM"
5950 LISTEN$="22"

```

'pulls the
'out of the
'
'
'

'IBM PC as system
'488 controller
'488 controller
'488 controller device
'initialize

```

5960 EOI$=""
5970 CALL WRITES(LISTEN$,EOI$,COMMS)
5980 TALK$="22"
5990 LISTEN$=""
6000 CALL READS(TALK$,LISTEN$,EOI$,RDATA$,STATUS%)
6010 LISTEN$="22"
6020 CALL LISTEN(LISTEN$)
6030 CALL GTL
6040 CALL SDC
6050 CALL REMOTE
6060 CALL LLO
6070 COMMS$="OUT 1"
6080 LISTEN$="5"
6090 EOI$=""
6100 CALL WRITES(LISTEN$,EOI$,COMMS)
6110 CALL REMOTE
6120 CALL LLO
6130 COMMS$="VSET 1.0"
6140 LISTEN$="5"
6150 EOI$=""
6160 CALL WRITES(LISTEN$,EOI$,COMMS)
6170 PRINT #2,VAL(RDATA$);
6180 PRINT VAL(RDATA$);
6190 LPRINT VAL(RDATA$);
6200 IF NX=2 THEN 6250
6210 IF NX = 1 THEN GOSUB 6580
6220 IF NX = 0 THEN GOSUB 6390
6230 IF NX<3 THEN 6360
6240 REM
6250 GOSUB 5440
6260 PRINT #2,NUMCYC;MIN;MAX;TMIN;TMAX
6270 PRINT NUMCYC;MIN;MAX;TMIN;TMAX
6280 LPRINT NUMCYC;MIN;MAX;TMIN;TMAX
6290 TMEAN=(TMIN+TMAX)/2
6300 TMAX=TMEAN
6310 TMIN=TMEAN
6320 REM
6330 REM
6340 NUMPREV = NUMCYC
6350 NX=0
6360 RETURN
6370 REM
6380
REM-----
-----
6390 REM          turns power supply up to const 10 Amps
6400 REM
6410
REM-----
-----
6420 DEF SEG=CSEG1
6430 IHPP! = .2

```

```

6440 CALL REMOTE
6450 CALL LLO
6460 FOR I = 1 TO 250
6470 NEXT I
6480 COMM$= "ISET" + STR$(IHPP!)
6490 IHPP!= IHPP! + .2
6500 LISTEN$="5"
6510 EOI$=""
6520 CALL WRITES(LISTEN$,EOI$,COMM$)
6530 IF IHPP!= 10! THEN 6550
6540 IF IHPP! < 10! THEN 6440
6550 NX = NX+1
6560 RETURN
6570

```

```

REM-----

```

```

6580 REM          turns power supply down to 0 Amps
6590 REM
6600

```

```

REM-----

```

```

6610 DEF SEG=CSEG1
6620 IHPP! = 10!
6630 TTT = TIMER
6640 CALL REMOTE
6650 CALL LLO
6660 FOR I = 1 TO 250
6670 NEXT I
6680 COMM$= "ISET" + STR$(IHPP!)
6690 IHPP!= IHPP! - .2
6700 LISTEN$="5"
6710 EOI$=""
6720 CALL WRITES(LISTEN$,EOI$,COMM$)
6730 IF IHPP!= 0! THEN 6750
6740 IF IHPP! > 0! THEN 6640
6750 NX = NX+1
6760 RETURN
6770

```

```

REM-----

```

```

6780 REM
6790 REM          end of program
6800 REM
6810

```

```

REM-----

```

Appendix B

Modifications of the CCADA Software
Required for Isothermal and
Out-of-Phase (OP) Thermal-Mechanical
Fatigue (TMF) Testing

To run isothermal fatigue tests using the CCADA program, the following modifications must be made:

- 1) Delete lines 2640 through 5390.
- 2) A data acquisition subprogram similar to the subprogram starting at line 4770 must be written and added to the program. This program must monitor the load from the data display to trigger the data acquisition process at maximum load. References 29, 30, and 31 contain examples of programs to control devices similar to those used here.
- 3) Cycle count can either be read directly from the data display or calculated from :

$$\text{NUMCYC} = \text{TIME} * \text{FREQ} \quad (37)$$

NUMCYC, TIME, and FREQ are defined in Appendix A.

The only variation between the in-phase (IP) and out-of-phase (OP) programs is that the IP program triggers the load when the mean temperature is reached during heating, and the OP program triggers the load when the mean temperature is reached during cooling. The modifications for the OP condition are:

- 1) Change line 1470 to read NUMTRG = 1
- 2) Change line 5140 to read IF TF>TMEAN THEN 4250
- 3) Delete line 5270
- 4) Add line 5345; NUMTRG = 0

Bibliography

1. Hill, Philip G. and Peterson, Carl R. Mechanics and Thermodynamics of Propulsion. Reading Massachusetts: Addison-Wesley Publishing Company, 1970.
2. Mom, A. J. A. Operating Conditions and Materials Selection and Development in Gas Turbines. National Aerospace Laboratory (NLR) Amsterdam. The Netherlands, 17 MAR 1981.
3. Halford, Gary R. Low-Cycle Thermal Fatigue. Lewis Research Center, Cleveland OH, February 1986.
4. Wright, P.K. and others. Fatigue and Fracture of Advanced Blade Materials. General Electric Company, Cincinnati OH, February 1985.
5. Russell, E.S. Practical Life Prediction Methods for Thermal-Mechanical Fatigue of Gas Turbine Buckets. General Electric Company, Schenectady NY, August 1985.
6. Wilson, D. A. and Warren, J. R. Thermal Mechanical Fatigue Crack Growth. Pratt & Whitney, West Palm Beach Florida, March 1985.
7. Nagar A. and Mall S. A Review of High Temperature Fracture Mechanics for Hypervelocity Vehicle Applications. Submitted for Presentation at the 29th Structures, Structural Dynamics and Materials Conference, Williamsburg VA, April 1988.
8. Heil, Major Michael L. Crack Growth in Alloy 718 Under Thermal-Mechanical Cycling. PhD dissertation. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, November 1986.
9. Bill, Robert C. Micromechanisms of Thermomechanical Fatigue--A Comparison With Isothermal Fatigue. U.S. Army Aviation Research and Technology Activity--AVSCOM, Lewis Research Center, Cleveland OH, June 1986.
10. Aeronautical Systems Division, Air Force Systems Command Fatigue and Fracture of Titanium Aluminides. Wright-Patterson AFB OH, February 1985.
11. Baumeister, T. and others. Mark's Standard Handbook for Mechanical Engineers. New York: McGraw-Hill Publishing Company, 1979.

12. Broek, David. Elementary Engineering Fracture Mechanics. Netherlands: Martinus Nijhoff Publishers, 1986.
13. DeLuca, D.P. and Cowles, B.A. Fatigue and Fracture of Advanced Blade Materials. Pratt & Whitney, West Palm Beach FL, February 1985.
14. Griffin, J.H. and Cunningham, S. The Influence of Electric Current on Crack Propagation in Thermal Fatigue Tests. Department of Mechanical Engineering, Carnegie-Mellon University, Pittsburgh PA, February 1986.
15. Oleinik, A.S. and others. Heating Device For Rigs Used in Fatigue Testing of Specimens at Temperatures Up To 1800°C. Academy of Sciences of the Ukraine SSR, March 1983.
16. Pelloux, R.M. and Marchand, N. Thermal-Mechanical Fatigue Behavior of Nickel-Base Superalloys. Massachusetts Institute of Technology, Cambridge MS, March 1986.
17. ASTM. 1979 Annual Book of ASTM Standards. American Society for Testing and Materials, Philadelphia PA, 1979.
18. Hartman, G.A. and Johnson, D.A. "D-C Electric-Potential Method Applied to Thermal/Mechanical Fatigue Crack Growth," Experimental Mechanics: 106-112 (March 1987).
19. Sadananda, K. and Shahinian, P. Application of Fracture Mechanics Techniques to High Temperature Crack Growth. Thermostructural Materials Branch, Naval Research Laboratory, Washington D.C., 1978.
20. Larsen, James J. and Nicholas, Theodore. Cummulative Damage Modeling of Fatigue Crack Growth. U.S. Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB OH, undated.
21. Kerans, R.J. "Deformation in Ti Al Fatigued at Room and Elevated Temperatures," Metallurgical Transaction A, 15A: 1721-1729 (September 1984)
22. Model 248 12 MHz Programmable Synthesized Function Generator Instruction Manual. Wavetek, San Diego CA, 1983.

23. Model 5305 Parabolic Strip Heater Rev B. Research Inc., Minneapolis MN, December 1985.
24. Model 5193 Line Heater. Research Inc., Minneapolis MN, July 1984.
25. Micricon Users Manual. Research Inc., Minneapolis MN, 1986.
26. Fundamentals of Process Control. Research Inc., Minneapolis MN, May 1981.
27. Micricon Control PID Adjustments. Research Inc., Minneapolis MN, 1981.
28. Complete Temperature Measurement Handbook and Encyclopedia. Omega Engineering Inc., Stamford CT, 1986.
29. HP6033A System DC Power Supply Operating and Service Manual. Hewlett Packard, December 1983.
30. 3456A Introductory User's Guide. Hewlett Packard, 1980.
31. IEEE 488 GPIB Controller Instruction Manual. Qua Tech Inc., Akron OH, undated.
32. DM12-10 12-Bit Digital to Analog Converter Module Instruction Manual. Qua Tech Inc., Akron OH, undated.

VITA

Lieutenant John J. Pernot was born on 23 June 1963 in Pittston, Pennsylvania. He graduated from the Pittston Area High School in 1981 and attended The Pennsylvania State University, from which he received the degree of Bachelor of Science in Mechanical Engineering. Upon graduation in May 1986, he received a commission in the USAF, and entered the School of Engineering, Air Force Institute of Technology.

Permanent address: 115 Hillcrest Drive
Duryea, PA 18642

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1. REPORT SECURITY CLASSIFICATION UNCLASSIFIED		1b. RESTRICTIVE MARKINGS													
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.													
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE															
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/CAE/AA/87D-18		5. MONITORING ORGANIZATION REPORT NUMBER(S)													
6a. NAME OF PERFORMING ORGANIZATION School of Engineering	6b. OFFICE SYMBOL (If applicable) AFIT/ENY	7a. NAME OF MONITORING ORGANIZATION													
6c. ADDRESS (City, State and ZIP Code) Air Force Institute of Technology Wright-Patterson AFB OH 45433-6583		7b. ADDRESS (City, State and ZIP Code)													
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Materials Lab, Ceramic and Metals Division	8b. OFFICE SYMBOL (If applicable) AFWAL/MLLN	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER													
8c. ADDRESS (City, State and ZIP Code) AFWAL/MLLN Wright-Patterson AFB OH 45433-6583		10. SOURCE OF FUNDING NOS. <table border="1"><tr><td>PROGRAM ELEMENT NO</td><td>PROJECT NO.</td><td>TASK NO.</td><td>WORK UNIT NO</td></tr></table>		PROGRAM ELEMENT NO	PROJECT NO.	TASK NO.	WORK UNIT NO								
PROGRAM ELEMENT NO	PROJECT NO.	TASK NO.	WORK UNIT NO												
11. TITLE (Include Security Classification) SEE BOX 19															
12. PERSONAL AUTHOR(S) John C. Pernot, 2nd Lt, USAF															
13a. TYPE OF REPORT MS Thesis	13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Yr., Mo., Day) 1987 December	15. PAGE COUNT 134												
16. SUPPLEMENTARY NOTATION															
17. COSATI CODES <table border="1"><tr><td>FIELD</td><td>GROUP</td><td>SUB GR</td></tr><tr><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td></tr></table>		FIELD	GROUP	SUB GR										18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Thermal Fatigue, Heating, Cracks, Temperature, Test Methods, Fatigue Tests	
FIELD	GROUP	SUB GR													
19. ABSTRACT (Continue on reverse if necessary and identify by block number) Title: THERMAL-MECHANICAL FATIGUE TESTING OF A TITANIUM-ALUMINIDE ALLOY Thesis Chairman: Shankar Mall Professor of Aeronautics and Astronautics <i>Approved for public release: 12W AFR 190-1</i> <i>John C. Pernot</i> 31 Dec 87 Deputy for Research and Professional Development Air Force Institute of Technology (AFIT) Wright-Patterson AFB OH 45433															
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐		21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED													
22a. NAME OF RESPONSIBLE INDIVIDUAL Shankar Mall		22b. TELEPHONE NUMBER (Include Area Code) (513) 255-5533	22c. OFFICE SYMBOL AFIT/ENY												

DD FORM 1473, 83 APR

EDITION OF 1 JAN 73 IS OBSOLETE.

SECURITY CLASSIFICATION OF THIS PAGE

There is a continuing need to study the affect of combined thermal and mechanical cycling of materials. This combined cycling is referred to as thermal-mechanical fatigue (TMF) cycling. This study emphasizes the development of a computer-controlled testing system that can mechanically fatigue a specimen under a variety of thermal conditions. These conditions include isothermal temperatures, as well as cyclic temperatures in phase and out of phase with the load.

To demonstrate the capability of this system, both a 1200°F isothermal load fatigue test and a 600°F to 1200°F in-phase TMF test were carried out on a titanium-aluminide alloy, Ti₃Al. Crack growth relations were established for both cases by plotting the da/dN versus ΔK data on log-log axis and fitting the power law relations, $da/dN = C (\Delta K)^n$ to the data. The results show the crack growth rate for the isothermal test is slightly higher than the growth rate for the in-phase TMF test at a given value of stress intensity range, ΔK . The crack surfaces were very rough and crack growth was not along the mid-plane of the specimen.

Further TMF study is required, particularly for other loading frequencies and other load-temperature phase differences. After these studies are complete, models can be developed to characterize the crack growth behavior of this titanium-aluminide alloy.

EMD
DATE
FILMED
3-1988
DTIC