

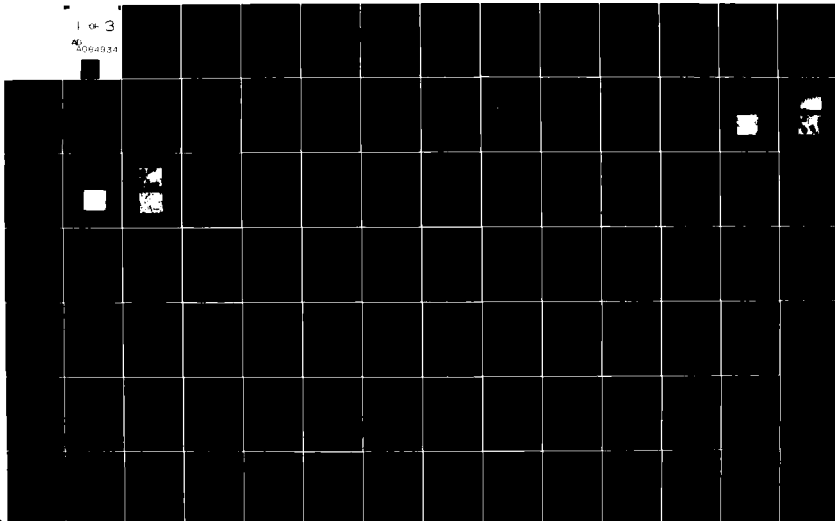
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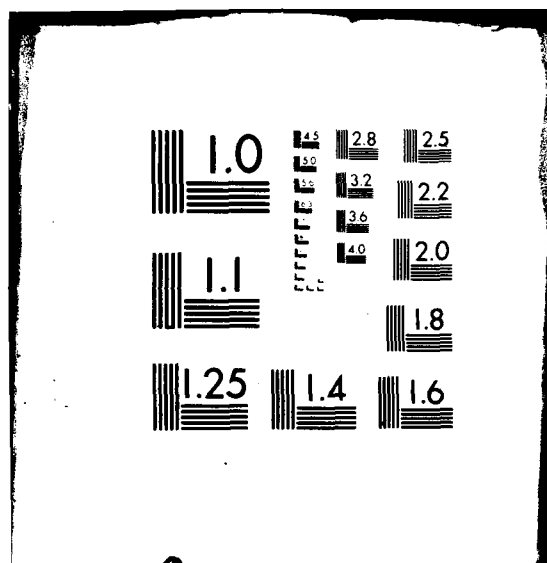
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CUMULATIVE DAMAGE FRACTURE MECHANICS UNDER ENGINE SPECTRA

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AIR FORCE SYSTEMS COMMAND
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SUMMARY

Cumulative damage fracture mechanics at elevated temperatures is particularly complex, requiring a basic understanding of the variables affecting crack growth and an ability to model material behavior. The synergistic effects of varying load and load sequencing on crack propagation in engine disk materials preclude the use of conventional linear damage accumulation techniques (e.g., Miner's Rule) for accurate life predictions. Failure to consider interaction effects may lead to significant errors in predicted crack growth behavior and in the resulting life prediction. In most cases, the result is an underestimation of propagation life and the concomitant economic penalties of premature removal. Also to be considered is any overestimate of life and the serious implications concerning component safety.

The objective of this contract was to develop and demonstrate an empirically based mathematical model and computer code capable of predicting cumulative damage effects on fatigue crack growth in gas turbine engine disks.

Since the technical approach was empirical in nature, no attempt was made to isolate and describe individual microscopic events associated with propagation interrupted by overloads and/or dwells, but rather synergism resulting from various combinations of these was empirically described using an interpolative mathematical model. The resulting descriptions of generic elemental cumulative damage events could then be used to analyze specific complex mission spectra, and the life under such a mission could then be computed by simple numerical integration of segregated elements. A three-step process of mission segregation, crack growth rate interpolation, and calculation of fatigue crack propagation life was established. This computerized model performs Mission Analysis and Prediction (MAP) of crack growth in gas turbine engine disks subject to complex mission loading.

Development of the MAP computing software was based on an analysis of representative missions for TF30 and F100 engines employing Waspaloy and IN100 turbine disks. Such mission usage is composed of a variety of operational activities including aircraft takeoff, ferry and refueling, terrain-following radar (TFR), bombing runs, and combat under subsonic and supersonic conditions.

Analysis of the turbine disk missions revealed that these low-cycle fatigue loading sequences differ significantly from the high-cycle loading spectra typically experienced by airframe components. The load sequence effects observed in turbine disk operation are characterized by a high occurrence frequency of major throttle excursions (overloads). As a result, immediate post-overload load sequence behavior is of increased significance, while the long-term effects of an overload on crack growth are truncated by the frequently repeated overload. The instantaneous behavior of a crack propagating under fatigue interrupted by frequently occurring overloads was shown to be dominated by delayed retardation. That is, both Waspaloy and IN100 exhibit continuous post-overload deceleration in crack growth until the recurrence of an overload truncates and restarts the load interaction process. This behavior is not effectively described by conventional models of load sequence effects. However, the methodology employed in the MAP system was developed specifically for prediction of mission crack growth with frequently occurring overloads.

Development of the Mission Analysis and Prediction system was based on the P&WA philosophy of empirical synergistic modeling. This philosophy states that any complex mission spectrum can be segregated into elemental damage events that can be quantitatively described. The crack propagation life expected under such a spectrum can then be computed as the linear addition of the damage associated with properly segregated events.

Mission segregation is accomplished by the first of three MAP algorithms: the segregation, interpolation, and computation algorithms. These are described below.

The set of rules by which a mission profile is separated (segregated) into its elemental cumulative damage events constitutes the segregation algorithm. As formulated, the segregation algorithm translates an input isothermal stress-time profile into a parametric, cycle-by-cycle description of the loading sequence. This segregated mission definition provides input compatible with the interpolation algorithm.

The fundamental strength of the MAP system is the interpolative capability provided by the hyperbolic sine model. The application of this procedure is executed by the interpolation algorithm. As formulated, this algorithm performs a complex interpolation to obtain a crack growth rate curve (da/dN vs ΔK) as a function of the operating parameters (e.g., stress ratio, temperature, cyclic frequency, and load sequence parameters). These interpolated curves are subsequently used in the computation algorithm to obtain a fatigue crack life calculation.

A cycle-by-cycle integration of the collection of interpolated crack growth curves is performed by the computation algorithm. The resulting life calculation is a prediction of crack propagation resulting from the input mission usage profile.

The accuracy of the cumulative damage fracture mechanics system was evaluated by conducting a number of model demonstration tests simulating engine usage. Using the MAP system, specimen life calculations were obtained for the simulated missions. Subsequently, fatigue crack propagation tests were conducted to evaluate the model accuracy.

The results of the complete model demonstration program established the utility of the MAP system and illustrated the importance of accurate assessment of the cumulative damage fatigue crack growth which results from mission usage of a military gas turbine engine.

PREFACE

The major portion of this work was performed under Air Force Materials Laboratory Contract F33615-77-C-5153, "Cumulative Damage Fracture Mechanics Under Engine Spectra." The project engineer was D. E. Macha, reporting to Dr. W. H. Reimann, AFML/LLN. This program was conducted in the Materials and Mechanics Laboratories of Pratt & Whitney Aircraft Government Products Division, West Palm Beach, Florida. The responsible engineer was J. M. Larsen, assisted by B. J. Schwartz and the Program Manager was C. G. Annis, Jr., Group Leader, Fracture Mechanics and Component Life Analysis, reporting to M. C. VanWanderham, General Supervisor, Mechanics of Materials and Structures.

The authors wish to acknowledge D. W. Ogden who directed the material testing, T. Watkins and V. De La Torre, who aided in data analysis, and R. N. Green and Dr. J. H. Griffin for their participation in development of the mission segregation algorithm.

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SECTION I INTRODUCTION

Cumulative damage fracture mechanics at elevated temperatures is particularly complex, requiring a basic understanding of the variables affecting crack growth and an ability to model material behavior. The synergistic effects of varying load and load sequencing on crack propagation in engine disk materials preclude the use of conventional linear damage accumulation techniques (e.g., Miner's Rule) for accurate life predictions. Failure to consider interaction effects may lead to significant errors in predicted crack growth behavior and in the resulting life prediction. In most cases, the result is an underestimation of propagation life and the concomitant economic penalties of premature removal. Also to be considered is any overestimate of life and the serious implications concerning component safety. The desirability of an accurate crack propagation prediction methodology is clearly evident.

The objective of this program was to develop and demonstrate an empirically based mathematical model and computer code, capable of predicting cumulative damage effects on fatigue crack growth in engine disks.

Pratt & Whitney Aircraft Group, under the AFML sponsorship, recently developed an efficient and accurate empirical method for analyzing synergism in crack propagation at elevated temperatures (References 1, 2, and 3). No attempt was made to isolate and describe individual microscopic events associated with propagation interrupted by overloads and/or dwells, but rather synergism resulting from various combinations of these was empirically described using an interpolative mathematical model. The resulting descriptions of generic elemental cumulative damage events were then used to analyze specific complex mission spectra. The life under such a mission was then computed by simple numerical integration of segregated elements. This proven method formed the basis of our technical approach to cumulative damage fracture mechanics.

The program consisted of a 24-month, four-phase technical effort. Phase I, Mission Definition, defined representative composite missions for two advanced Air Force fighter engines that employ Waspaloy and IN100 turbine disks. These results provided the foundation for test matrix formulation. Phase II, Mission Segmentation, defined, segregated, and quantified elemental cumulative damage events. Phase III, Mathematical Model Development, evaluated the data generated in Phase II, integrated these results with relevant pre-existing data, and translated the resulting model into a computer code. Phase IV was Model Demonstration. The Air Force Project Engineer provided two representative mission profiles, upon which life history (a, N) predictions were made. These were recorded with the Air Force Project Engineer prior to demonstration testing. Fatigue crack propagation (FCP) tests on the two materials, IN100 and Waspaloy, addressing the two profiles, and using both compact and surface flaw specimens, were performed to verify the model experimentally. A flow chart of the program operating plan is shown in Figure 1.

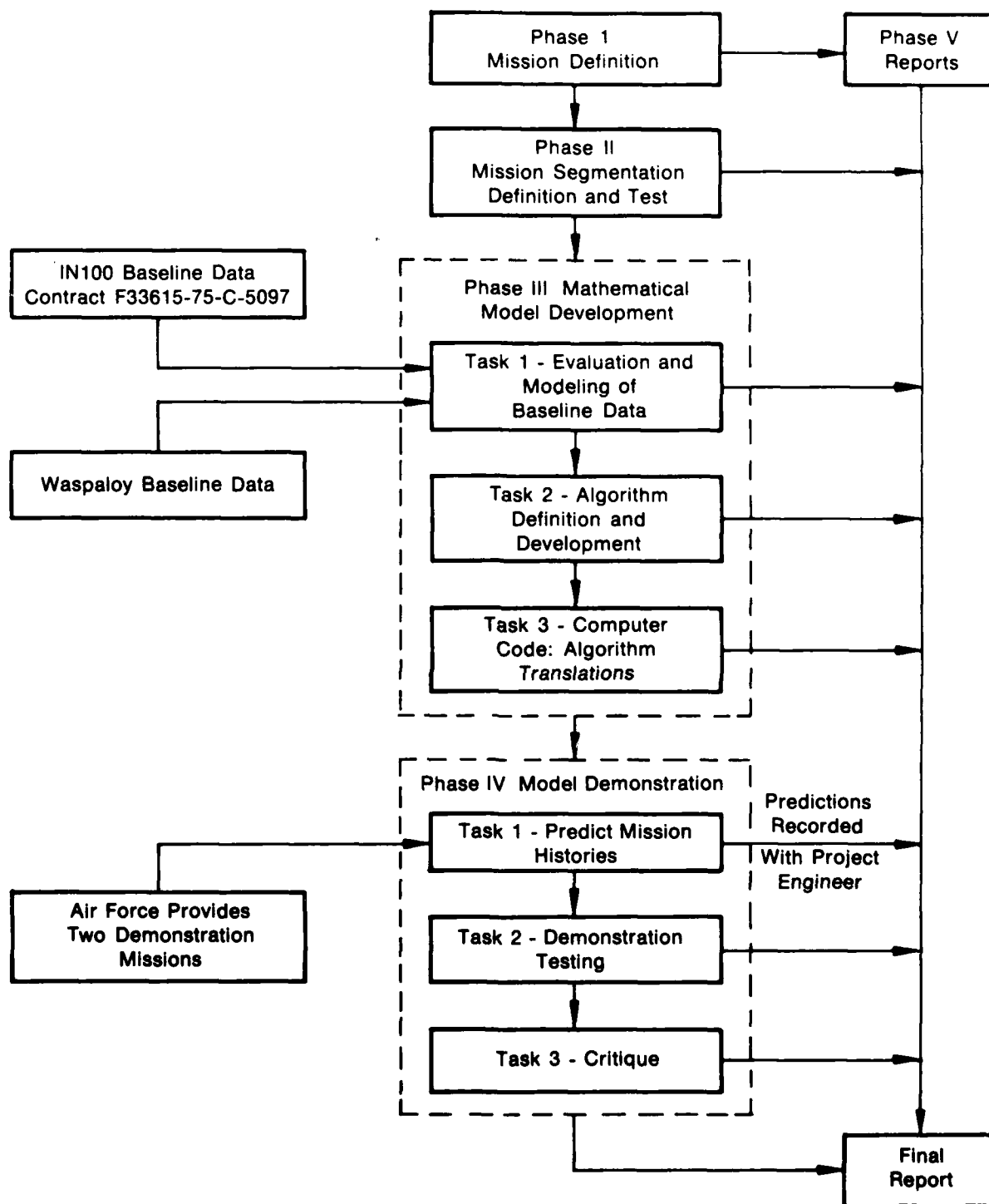


Figure 1. Flow Chart of Program Operating Plan

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SECTION II TECHNICAL PROGRAM AND ACCOMPLISHMENTS

A. PHASE I - MISSION DEFINITION

1. Mission Operating Profile

The objective of the analysis of mission usage data, the Phase I activity, was to provide a basis for formulation of a test and evaluation program for optimum model applicability. Mission usage field data for military aircraft was generally obtained from pilot interviews and event history recorders (EHR) which have been installed on advanced Air Force fighters to acquire real-time engine operating parameters. The compilation and characterization of these raw data define representative engine usage for a variety of operational activities including aircraft takeoff, ferry and refueling, terrain following radar (TFR), bombing runs, and combat under subsonic and supersonic conditions.

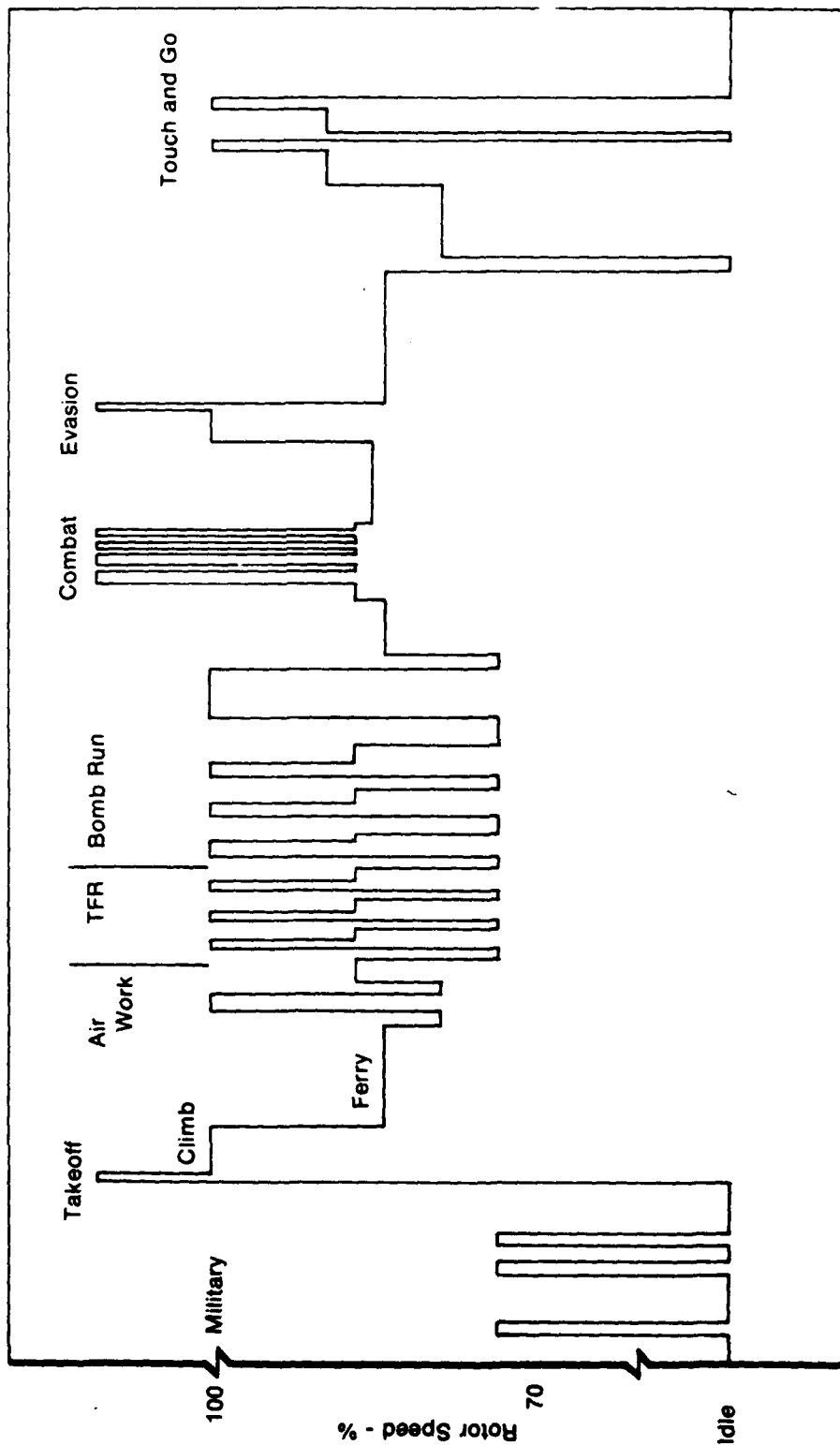
Representative missions were analyzed for two advanced Air Force fighter engines employing Waspaloy and IN100 turbine disks. For Waspaloy, a composite mission has been prepared to reflect the broad range of operating conditions imposed on this disk. This composite, presented in Figure 2, illustrates the representative duty cycles in terms of rotor speed for the collection of individual mission usages. Figure 3 shows a similar mission for a second engine which employs turbine disks fabricated from IN100. This operating history, given in terms of maximum stress, is based on a Tactical Air Command (TAC) composite mission supplied by the Air Force Materials Laboratory in 1974. This mission has excluded load sequences corresponding to operation of TFR, since this is not a characteristic operating activity for this engine. The two flight missions presented are currently used as the basis for field life predictions for Waspaloy and IN100 disks.

Cumulative damage element event definition, required specimen testing, and model development were based on these two missions.

2. Mission Stress Analysis

A generalized fracture mechanics residual life prediction system capable of addressing crack propagation in disks under mission loading must consider all fracture critical locations in the disk. These include: (1) bore (internal defects), (2) rim (cooling holes, attachments), and (3) web (boltholes). Bore problems are usually associated with inclusions or other intrinsic, subsurface defects where crack propagation is not affected by the surrounding environment. Alternatively, the fracture behavior of surface cracks in wrought nickel-base superalloys may be influenced by strong environmental effects (e.g., oxidation, sulfidation). This program addressed the propagation of surface cracks in air; the propagation of internal defects, or of surface cracks subjected to extremes in environment, was not considered.

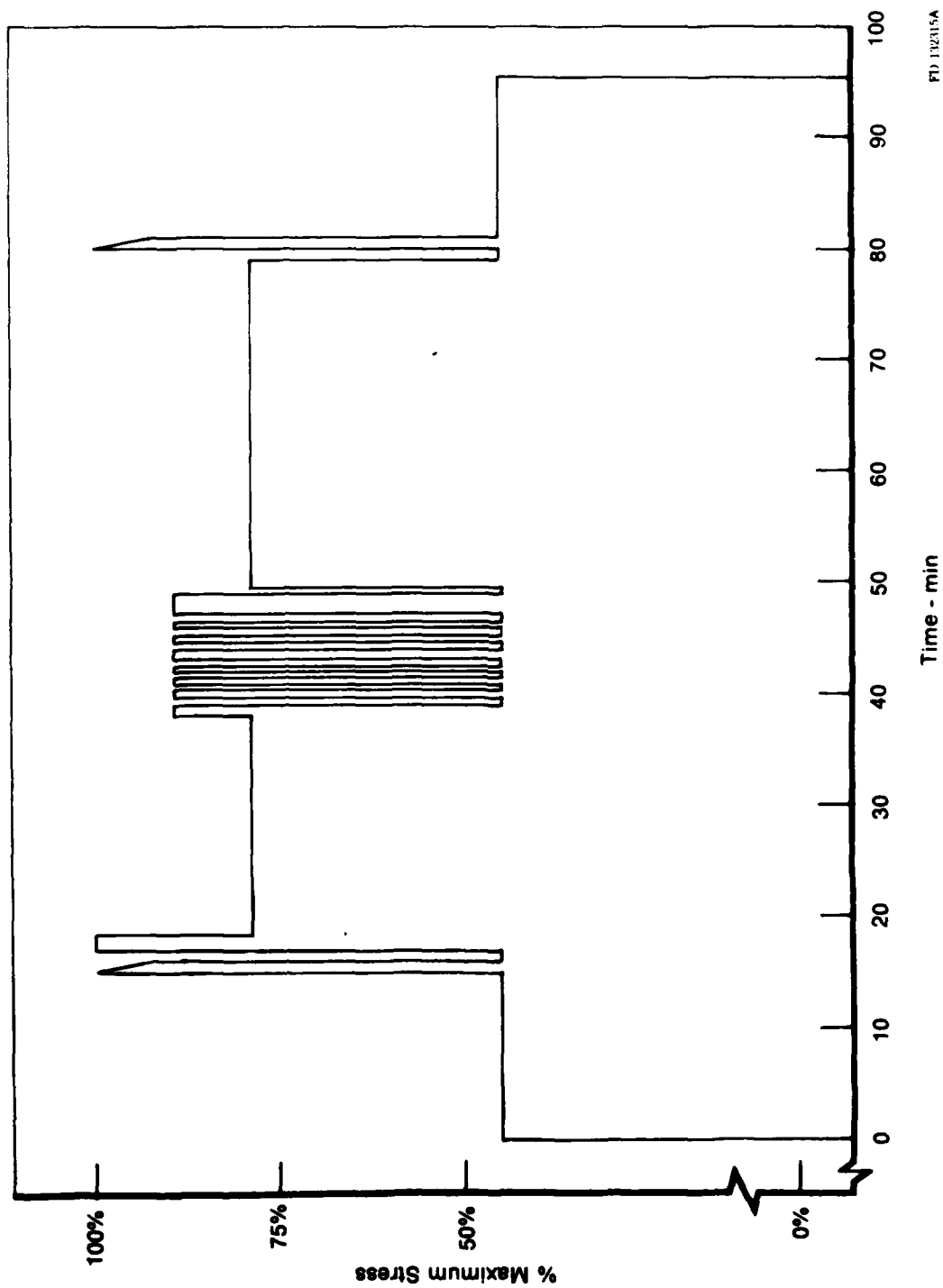
The stress analysis of fracture critical disk locations concentrated on boltholes and cooled and uncooled rims of turbine disks. At these locations, stress histories depend on the operating mission profile (Figures 2 and 3), transient thermal gradients, and the geometrical stress concentration. Under a program for the Air Force Aero Propulsion Laboratory, "Structural Life Prediction and Analysis," (Reference 4) a survey was made of estimated bolthole stresses in the two advanced Air Force fighter engines considered in the present contract. The results of the bolthole stress survey were examined as part of the cumulative damage stress analysis performed under the current contract. In addition, bore, bolthole, and rim stress-temperature-time profiles for both Air Force and Navy turbine disks were reviewed.



Time

Figure 2. Representative Mission for Waspaloy Disks

FD-1000



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Figure 3. Representative Mission for IN100 Disks

There are as many different stress-temperature-time profiles as there are fracture critical locations on individual disks. Some of these are particularly complex. Figure 4 presents the operational conditions at the fracture critical location for a cooled turbine rim (radial cooling hole) in a Waspaloy disk. Figure 5 presents the stress-temperature-time response for a bolthole in another Waspaloy disk. The stress-temperature-time response of a bolthole in an IN100 disk subjected to a simplified subsonic combat mission is given in Figure 6.

The ultimate objective of this contract was to produce results having general applicability to the analysis of surface cracks in Waspaloy and IN100 turbine disks. Crack propagation data were generated from laboratory specimens having well-defined stress intensity solutions and thickness representative of disk operation. These data represent crack growth in a uniform stress field; the influence of aberrations in the elastic stress field, such as caused by notches, is excluded from the actual test data. The problem of predicting fatigue crack propagation (FCP) in large stress gradients may be solved analytically using advanced crack tip stress intensity solutions such as K developed by P&WA.

B. PHASE II - MISSION SEGMENTATION AND TESTING

1. Philosophy

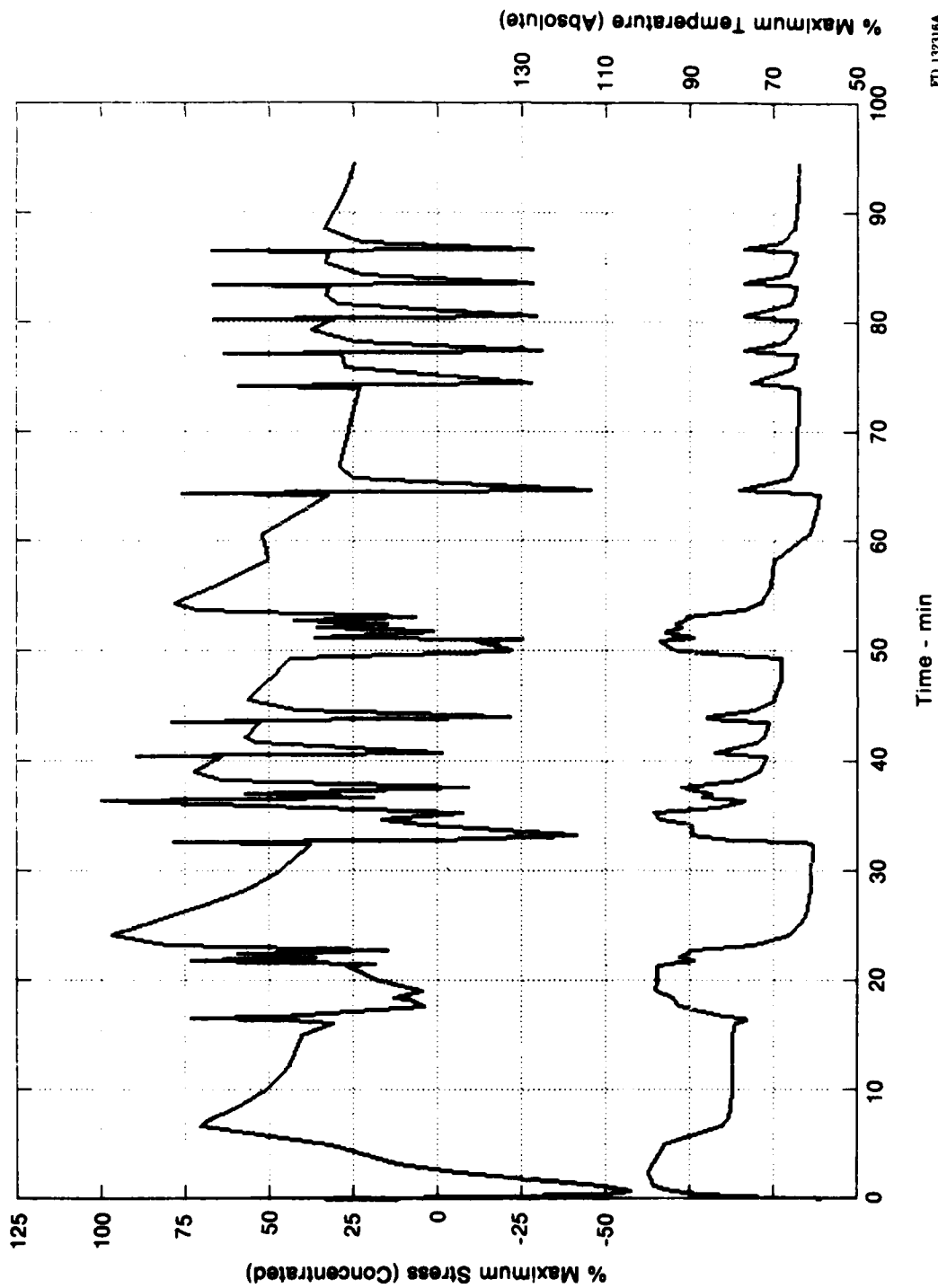
A thorough understanding of fatigue crack propagation under complex cycling is fundamental to both damage-tolerant-design and retirement-for-cause methodologies. Previous investigations have considered certain aspects of FCP under stress-temperature-time and geometry (thickness) conditions representative of turbine airfoil operation; however, additional study of crack propagation under stress-temperature-time conditions characteristic of turbine disk operation was needed.

The goal of Phase II of this contract was to develop an understanding of cumulative damage FCP suitable for development of an empirical model capable of accurately predicting crack growth for typical USAF turbine disk stress-temperature-time profiles. The approach was to employ a new experimental methodology which examines the macroscopic effects of realistic service loading on FCP. This approach, first demonstrated in AFML contract F33615-75-C-5057 "Applications of Fracture Mechanics at Elevated Temperatures" (Reference 1, 2, and 3), has been extended and optimized for cumulative damage crack growth.

The P&WA philosophy of empirical synergistic modeling is that any complex mission spectrum can be segregated into elemental damage events which can be quantitatively described. The crack propagation life expected under such a spectrum can then be computed as the linear addition of the damage associated with properly segregated events. The following definition is fundamental to understanding this approach:

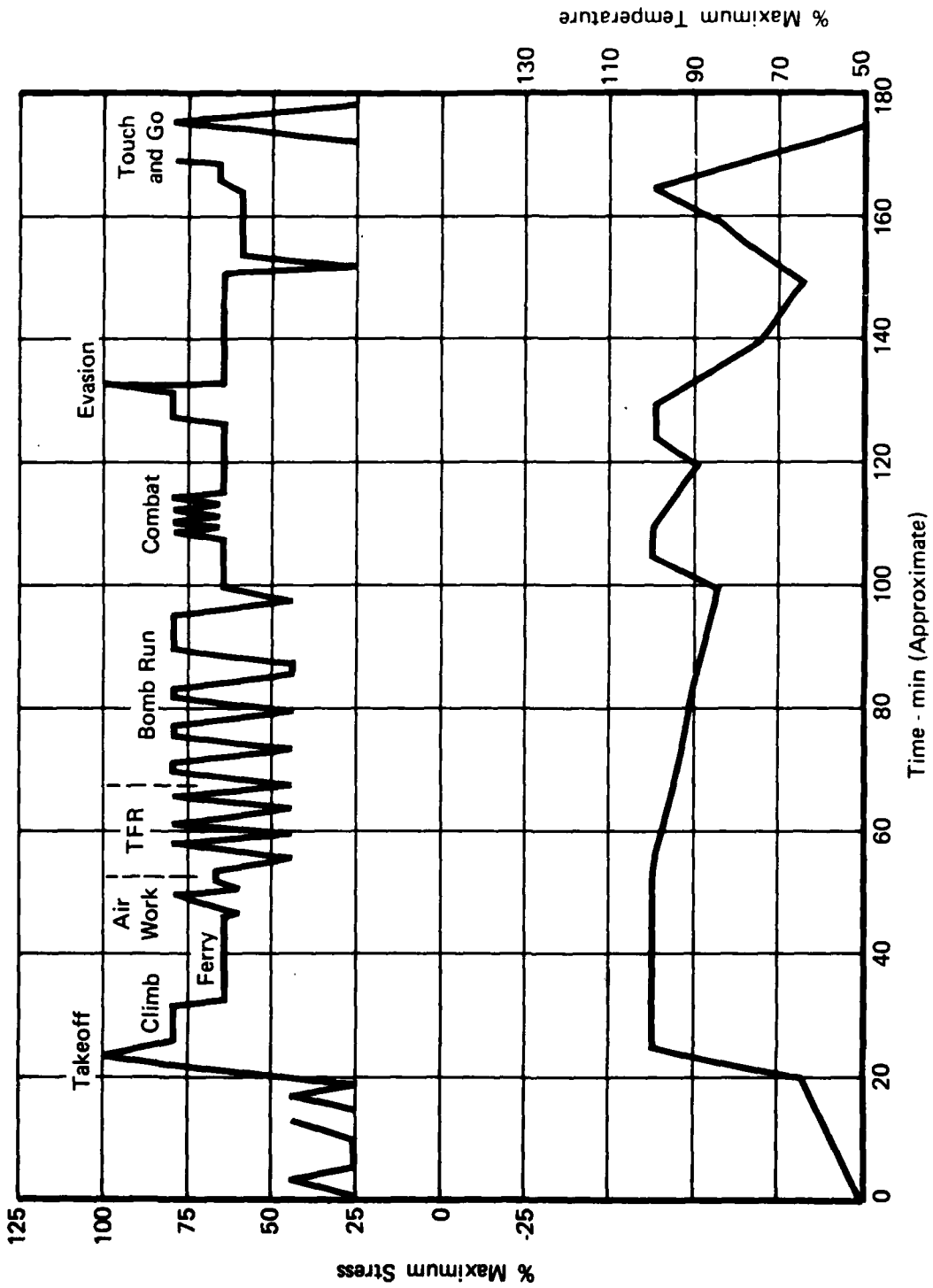
- An elemental damage event is the smallest repeating load-time sequence which results in FCP not predictable by linear damage accumulation alone.

An analysis of the missions currently used for field life predictions of two advanced USAF fighter engines established cumulative damage elemental events. These events are defined as: (1) constant load amplitude cycling, including dwells, (2) sustained load crack growth, and (3) overload(s)/LCF cycling.



FD 13216A

Figure 4. Operational Conditions for a Cooled Turbine Disk Rim (Waspaloy)



FD 177401

Figure 5. Operational Conditions for a Turbine Disk Web (Waspaloy)

9

2. Metallurgical Analysis

a. Waspaloy (PWA 1007)

Three Waspaloy forgings were obtained from Reisner Metals, Inc. The forgings were fabricated from Teledyne Allvac billet, heat No. L568, code WAH. The forgings were 457 mm (18 in.) OD by 40.6 mm (1.6 in.) thick. The chemical composition of Waspaloy (PWA 1007) met or exceeded the specifications shown in Table 1, and the results of mechanical property tests, also given in the table, satisfied material specifications. Typical microstructure of the Waspaloy forgings is shown in Figure 7, and thin foil electron micrographs of representative structure are presented in Figure 8.

b. GATORIZED® IN100 (PWA 1073)

Two IN100 forgings were GATORIZED at P&WA/Florida. Material source was Udimet Powder Division of Special Metals Corporation, heat codes F822, B1 and B2. The mechanical properties and chemical composition of the IN100 (PWA 1073) met or exceeded specifications shown in Table 2. Typical microstructure of the IN100 is given in Figure 9. Note the small grain size, ASTM 12-14. Thin-foil transmission electron micrographs of representative dislocation substructure are given in Figure 10.

3. Experimental Program

a. Applicability of Linear Elastic Fracture Mechanics

A fundamental assumption implicit in the development of the cumulative damage crack propagation model is the applicability of linear elastic fracture mechanics (LEFM) for Waspaloy and IN100. An examination of this assumption is discussed below. Consideration of nonlinear fracture mechanics concepts is beyond the scope of this contract.

The presence of a crack in a stressed component necessitates redistribution of stresses around the crack. The stress intensity factor is a parameter that reflects this redistribution and is a function of nominal stress, crack size, and specimen and crack geometries. The concept of stress intensity factor was originally defined for an infinitely sharp elastic crack tip, and it is this deformation that gives the material resistance to crack propagation.

The degree of brittleness of a material (and the limit to the applicability of linear elastic fracture mechanics) is directly related to the type of stress redistribution process that occurs at the crack tip. In the high temperature fatigue process, this redistribution of stress is expected to depend on the relative degree of elastic, plastic, creep, and chemical work expended at the crack. In a completely brittle material, relaxation of the crack tip stress field is negligible, and simple reinitiation of a stopped crack is sufficient to promote complete fracture. The absolute limit to the applicability of fracture mechanics is general yielding.

The usefulness of LEFM depends on a uniparametrical relationship between crack growth rate and the stress intensity factor. Crack tip inelasticity, due to material response at elevated temperatures, can preclude general utility of K as the correlative parameter.

The following provides our approach to the development of a system of empirical models for accurate predictions of surface crack growth in Waspaloy in IN100 turbine disks.

Tests are conducted to ensure that the crack tip experiences sufficient geometric constraint and/or environment embrittlement as to render crack growth rate — ΔK relationships independent of component geometry (e.g., thickness).

TABLE 1
CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF WASPALOY
(PWA 1007)

	<u>Chemical Composition (%)</u>	
	<u>Minimum</u>	<u>Maximum</u>
Carbon	0.02	0.10
Manganese	—	0.75
Sulfur	—	0.020
Silicon	—	0.75
Chromium	18.00	21.00
Colbalt	12.00	15.00
Molybdenum	3.50	5.00
Titanium	2.75	3.25
Aluminum	1.20	1.60
Zirconium	0.02	0.12
Boron	0.003	0.010
Iron	—	2.00
Copper	—	0.10
Bismuth	—	0.00005 (0.5 ppm)
Lead	—	0.0010 (10 ppm)
Nickel	remainder	

Mechanical Properties

Tensile

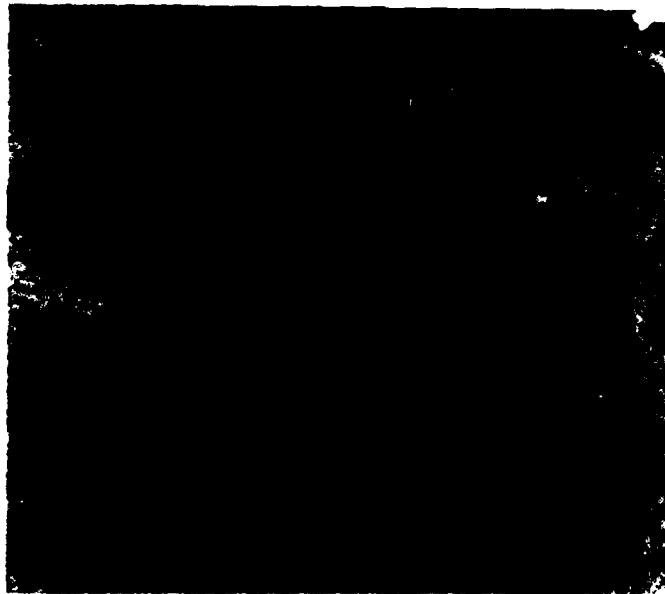
<u>Temperature</u>		<u>0.2% Yield Strength</u>		<u>Ultimate Strength</u>		<u>Elongation</u>	<u>Reduction in Area</u>
<u>(°C)</u>	<u>(°F)</u>	<u>(MPa)</u>	<u>(ksi)</u>	<u>(MPa)</u>	<u>(ksi)</u>	<u>(%)</u>	<u>(%)</u>
Room Temp		1062	(154.0)	1373	(199.2)	24.5	37.2
538	(1000)	949	(137.7)	1251	(181.4)	17.0	31.2

Stress Rupture

<u>Temperature</u>		<u>Applied Stress</u>		<u>Time to Failure</u>	<u>Elongation</u>
<u>(°C)</u>	<u>(°F)</u>	<u>(MPa)</u>	<u>(ksi)</u>	<u>(hr)</u>	<u>(%)</u>
732	(1350)	552	(80.0)	56.7	28.5
816	(1500)	310	(45.0)	67.7	27.0



Mag: 100X



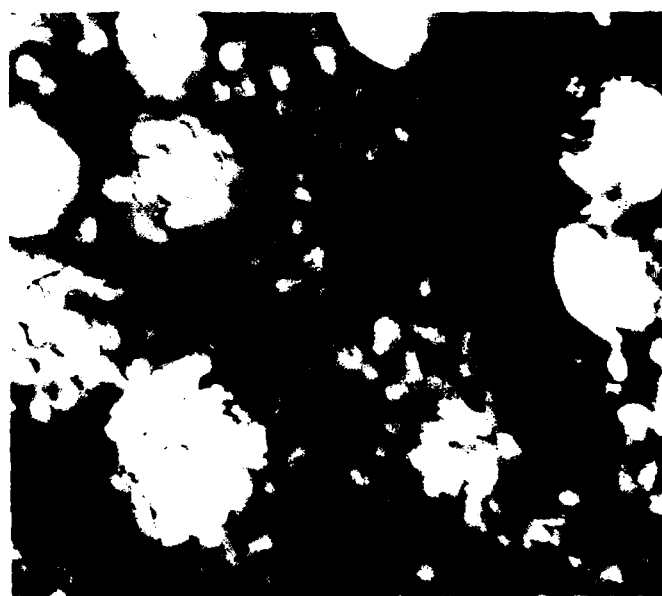
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Figure 7. Typical Microstructure of Waspaloy (PWA 1007) (ASTM Grain Size 3 to 5)



Mag: 10,000X



Mag: 70,000X

FD 13220

Figure 8. Thin Foil Transmission Electron Micrographs of Representative Structure from a Waspaloy (PWA 1007) Pancake Forging

TABLE 2
CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF GATORIZED®
IN100 (PWA 1073)

	<i>Chemical Composition (%)</i>	
	<i>Minimum</i>	<i>Maximum</i>
Carbon	0.05	0.09
Manganese	—	0.020
Sulfur	—	0.010
Phosphorus	—	0.010
Silicon	—	0.010
Chromium	11.90	12.90
Cobalt	18.00	19.00
Molybdenum	2.80	3.60
Titanium	4.15	4.50
Aluminum	4.80	5.15
Vanadium	0.58	0.98
Boron	0.016	0.024
Zirconium	0.04	0.08
Tungsten	—	0.05
Iron	—	0.30
Copper	—	0.07
Columbium and Tantalum	—	0.04
Lead*	—	0.0002 (2 ppm)
Bismuth*	—	0.00005 (0.5 ppm)
Oxygen	—	0.010 (100 ppm)
Nickel	remainder	

*If determined

Mechanical Properties

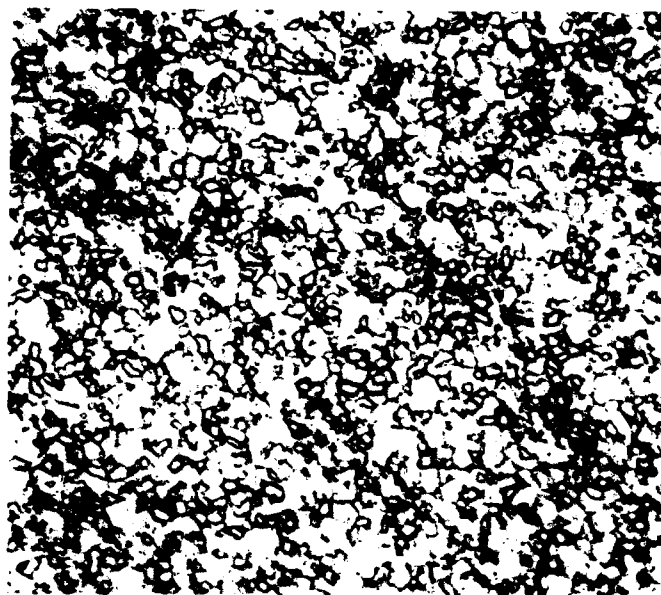
		<u>Tensile</u>		<i>Elongation</i> <i>(%)</i>	<i>Reduction in Area</i> <i>(%)</i>
<i>Temperature</i> <i>(°C)</i>	<i>(°F)</i>	<i>0.2 % Yield Strength</i> <i>(MPa)</i>	<i>Ultimate Strength</i> <i>(ksi)</i>		
Room Temp		1166 (169.1)	1631 (236.5)	16.5	29.3
704	(1300)	1113 (161.4)	1241 (180.0)	22.0	27.0

Stress Rupture

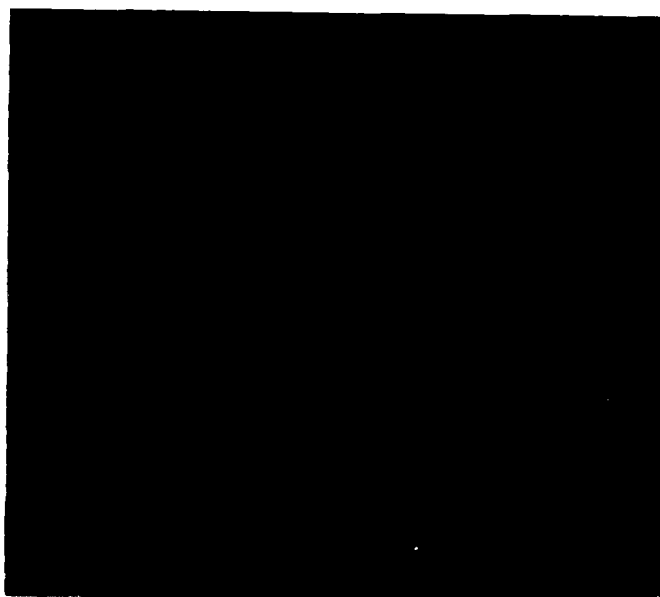
<i>Temperature</i> <i>(°C)</i>	<i>(°F)</i>	<i>Applied Stress</i> <i>(MPa)</i>	<i>(ksi)</i>	<i>Time to Failure</i> <i>(hr)</i>	<i>Elongation</i> <i>(%)</i>	<i>Reduction in Area</i> <i>(%)</i>
732	(1350)	655	(95.0)	22.1	7.5	15.6
732	(1350)	655	(95.0)	29.0	15.0	25.3
732	(1350)	655	(95.0)	27.4	16.7	24.1

Creep

<i>Temperature</i> <i>(°C)</i>	<i>(°F)</i>	<i>Applied Stress</i> <i>(MPa)</i>	<i>(ksi)</i>	<i>Time to Failure</i> <i>(hr)</i>	<i>Hours to Creep</i> <i>(1%)</i>	<i>(2%)</i>
704	(1300)	551.6	(80.0)	161.0	127.1	161.0



Mag: 1,000X



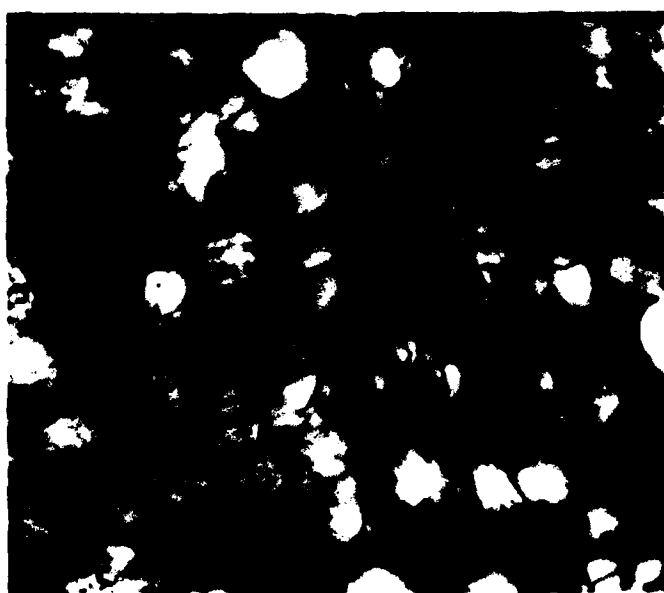
Mag: 10,000X

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*Figure 9. Typical Microstructure of GATORIZED[®] IN100 (PWA 1073)
(ASTM Grain Size 12 to 14)*



Mag: 10,000X



Mag: 70,000X

FD 132322

Figure 10. Thin Foil Transmission Electron Micrographs of Representative Structure from a GATORIZED® IN100 Pancake Forging

While it is known that crack growth rate is related to stress intensity factor for specific conditions, tests are performed to study the generality of the K concept. In one series of tests, crack growth data are obtained in a previously investigated range, but the specimen net section stress is allowed to approach and exceed yield conditions, and deviation from elastic conditions is quantified. Specimen geometry (through-thickness center crack (Figure 11a) and compact specimen (Figure 11b)) and thickness are varied to test the uniqueness of da/dN vs ΔK relationship at a given operating condition.

Those geometries and thickness are used where da/dN vs ΔK is generally unique for a given operating condition. Well-documented (Reference 5) specimens are used to avoid uncertainties concerning K-calibration. Thicknesses are representative of turbine disks so as to avoid potential mixed-mode crack growth sometimes observed in thin sections.

b. Test Procedure

Test specimens were precracked using procedures outlined in ASTM E-399. Precracking was performed at room temperature at a cyclic frequency of 10 or 20 Hz; anomalous precracking effects were easily recognizable.

Crack propagation testing was conducted on closed-loop servocontrolled equipment operated under load control. Cyclic tests were performed using isosceles triangular load waveforms, and specimen heating was provided by resistance, clamshell furnaces having windows to allow observation of crack growth at the test temperature.

Crack lengths were measured on both surfaces of the propagation specimen using a traveling microscope. This was facilitated by interrupting the cyclic loading and applying the mean test load. This procedure held the specimen rigid while increasing crack tip visibility. A high intensity light was used to provide oblique illumination to the crack and further increase crack visibility. In general, crack length measurements were taken at increments no larger than 0.50 mm (0.020 in.). Crack length measurements are considered to be accurate to within ± 0.025 mm (0.001 in.).

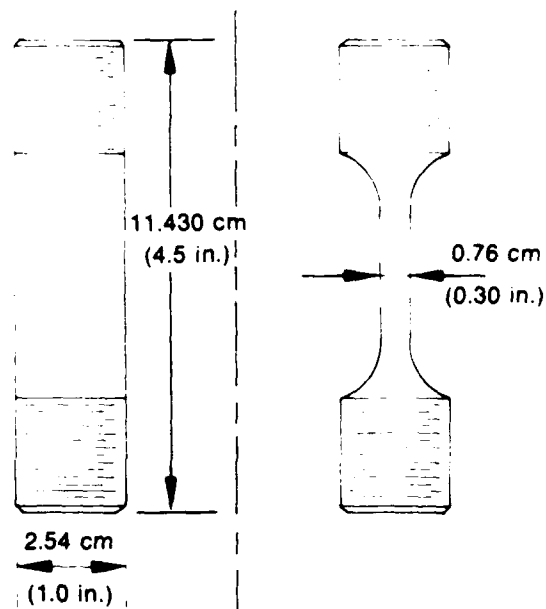
c. Test Program

(1) Constant Load Amplitude Cycling

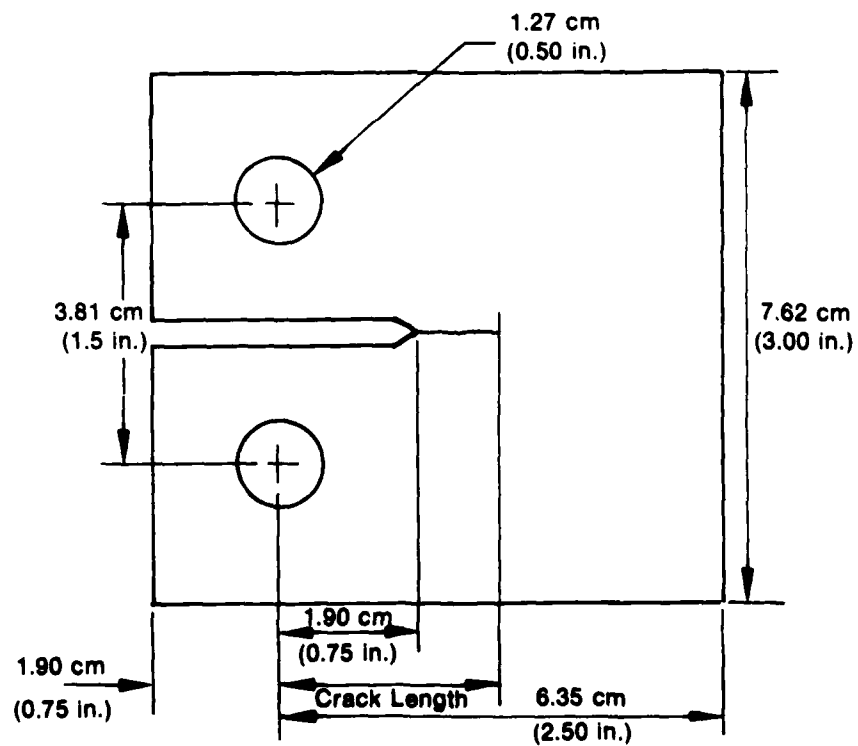
Crack propagation under constant amplitude loading conditions is known to be a function of the applied stress intensity range (within the limits of linear elastic fracture mechanics). This stress intensity range, ΔK , may be viewed as the driving force for crack propagation. Many relationships have been developed to correlate observed crack growth rate and the stress intensity factor. Paris and Erdogan presented the simple relationship:

$$\frac{da}{dN} = C(\Delta K)^n \quad (1)$$

where C and n are material constants. A major drawback to equations similar to (1) is that they do not account for the effects of load sequence. Additionally, dependencies of crack growth on temperature and loading frequency make the general application of equations such as (1) more difficult.



a. Through-Thickness Center Crack Tension Specimen



b. Compact Specimen

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Figure 11. Test Specimens Have Documented Fracture Mechanics Analysis

A specific goal of the constant load amplitude testing was to describe the effects of temperature, stress ratio and loading frequency on crack propagation of Waspaloy (PWA 1007) and IN100 (PWA 1073). The fundamental tool used to achieve this objective was developed by P&WA under a separate AFML contract and has been optimized under the current program. The model, which provides an interpolative capability for crack growth rate as a function of several operating parameters (e.g. temperature, stress ratio, frequency), will be presented at length in a later section.

The following tasks were performed in order to provide a basis for an accurate, interpolative model for constant load amplitude FCP; the matrix of these basic propagation tests is given in Table 3. All tests employed saw tooth, constant load amplitude cycling.

(a) Heat-to-Heat Variation

With few exceptions, specimens tested in this program were taken from the same heats of material (Waspaloy and IN100) and were different from those of existing data. The heats of material for this program met P&WA specifications, and tests were performed to ensure compatibility with existing data. In order to determine and quantify any significant variations from heat-to-heat, test conditions were selected to overlap preexisting data.

No significant variations in crack propagation behavior were found among available heats of material. The extremely rigid controls of alloy chemistry imposed on both IN100 and Waspaloy ensure consistent composition. Processing and heat treatment specifications, supported by a quality control inspection of microstructure and mechanical properties, also limit the performance variability of each alloy. As was shown in Figure 9, the characteristic microstructure of GATORIZED® IN100 (PWA 1073) is extremely uniform, having a very small grain size (ASTM 12 to 14). The crack growth behavior of this material is correspondingly well behaved. The microstructure of conventionally forged Waspaloy (PWA 1007), Figure 8, possesses a much larger characteristic grain size (ASTM 3 to 5), and the allowable variability in grain size is generally ASTM 2 to 7. While the heats of Waspaloy evaluated under this contract did not display significant heat-to-heat variability, the potential for limited variation in the elevated temperature cracking behavior of this alloy exists as a result of grain size flexibility.

(b) Effect of Loading Rate (Frequency)

Tests to determine the influence of cyclic frequency on elevated temperature crack propagation in Waspaloy were performed under the current program, and similar data has been generated for IN100 (References 1, 2, and 3). The range of frequencies examined (0.00833 Hz (0.5 cpm) to 20 Hz) was chosen so as to reflect actual loading of a turbine disk as defined in Phase I.

(c) Effect of Stress Ratio

An investigation of the effect of stress ratio ($R = \sigma_{\max}/\sigma_{\min}$) on crack growth was conducted over the range of $0.1 \leq R \leq 0.8$ for a broad range of temperatures. The influence of negative stress ratios was examined under an auxiliary investigation to be discussed later.

(d) Effect of Temperature

The effect of operating temperature on subcritical crack growth was investigated for Waspaloy under the test program of this contract. The effect of temperature for IN100 had been previously characterized (Reference 2). For both materials, the range of interest was 427 to 732°C (800 to 1350°F), and the environment was laboratory air.

TABLE 3
BASIC PROPAGATION TEST MATRIX

Stress Ratio	Frequency (Hz)	Thickness (mm)	Thickness (in.)	Temperature				Number of Tests	
				°C (°F)	°C (°F)	°C (°F)	°C (°F)	Waspaloy	IN100
0.05	0.167	2.54	(0.1)	X*	X*	X*	3	0	
0.05	0.167	7.62	(0.3)	XX†	X†	X†	4	0	
0.05	0.167	12.70	(0.5)	X†	X*		2	0	
0.10	0.167	7.60	(0.3)		XX‡		1	2	
0.10	20 Hz	7.62	(0.3)	X†	XX†		3	0	
0.10	120 sec dwell	7.62	(0.3)			X*	1	0	
0.10	600 sec dwell	7.62	(0.3)			X	1	0	
0.10	0.00833	7.62	(0.3)		X	X†	1	2	
0.50	0.167	7.62	(0.3)	X†	X°		2	0	
0.80	0.167	7.62	(0.3)	X†	X		2	1	
0.80	20	7.62	(0.3)		X†		1	0	
Sustained Load (da/dt)		7.62	(0.3)		X*		9	0	
							30	5	

°R = 0.55
‡IN100 only
†Waspaloy only
*Existing data for IN00

°R = 0.55

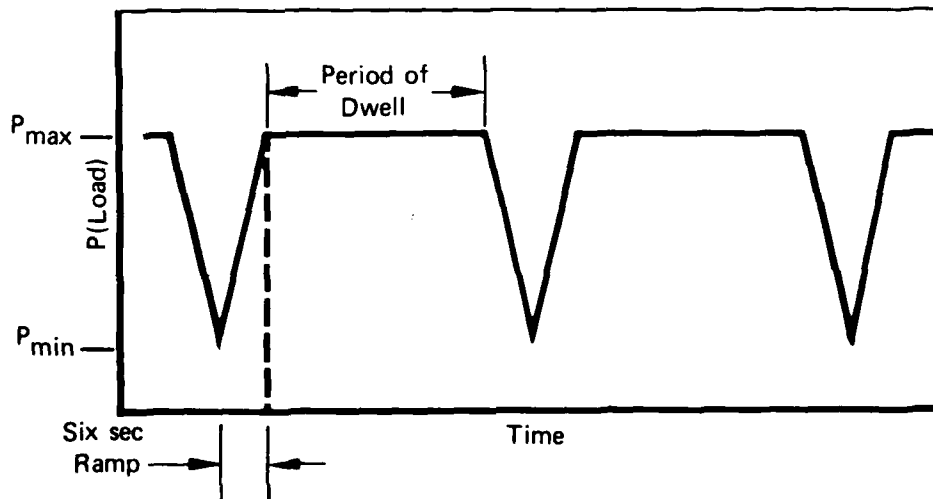
‡IN100 only

†Waspaloy only

*Existing data for IN00

(2) Crack Propagation Under Periodic Load Dwell

This task examined the crack propagation of Waspaloy and IN100 under fatigue cycling with a dwell at maximum load, Figure 12. The testing, outlined in Table 3, was conducted to characterize the effect of period of load dwell and operating temperature on subcritical crack growth.



FD 164828

Figure 12. Loading Waveform for Periodic Load Dwell Testing

(3) Sustained Load Crack Growth

The methodology used to determine sustained load crack growth relationship for Waspaloy and IN100 was developed by P&WA under an AFML contract, and is described in Reference 2. The test effort employed compact specimens and examined creep crack growth over the range of 649 to 732°C (1200 to 1350°F). This work, discussed in detail in a later section, resulted in an interpolative model of sustained load crack growth as a function of temperature. The test matrix for this task is included in Table 3.

(4) Synergistic Crack Propagation

The majority of the crack growth studies outlined thus far employ constant load amplitude fatigue cycling. These tests, while necessary, are not completely representative of component operating conditions. As discussed under Phase I, Mission Definition, gas turbine components experience complex load and temperature histories. Crack growth relationships are complicated by load sequence effects, and the influence of elevated temperature operation on load interaction phenomena is unclear.

The objective of the testing in this task was to establish possible synergistic effects among secondary parameters affecting crack propagation. Testing was designed to investigate the effects of low cycle fatigue (LCF) — dwell interactions at constant peak load, interactions of major load excursions (overloads) with less severe cycling with variable stress ratio, and interactions of high amplitude sustained load on LCF.

The generated data provided a basis for development of a mathematical model capable of predicting cumulative crack growth during a complex stress-temperature-time spectrum for typical Waspaloy and IN100 turbine disks.

A typical operating mission consists of a complex thermal-mechanical stress history such as that shown in Figure 4. Our approach is to separate and isolate those stress-time histories most suspected of having synergistic effects on crack growth in Waspaloy and IN100. This approach to model development calls for isothermal testing only, thus minimizing complicated and costly thermal mechanical testing.

For each test performed under the current task, crack propagation data was obtained using procedures described earlier, and crack length (a) vs cumulative cycles (N) data was generated. See Appendix C. The actual test performed, defined in the following tasks, was composed of repetitive segments containing an isolated load sequence (elemental damage event).

(a) *Task 1 — LCF-Dwell Interaction at Constant Peak Stress*

The purpose of Task 1 was to investigate possible synergistic effects of combined LCF and dwell. All tests were performed with constant peak stress (load), and two temperatures were investigated, 649 and 732°C (1200 and 1350°F). A schematic of the stress-time history is given in Figure 13. The test matrix is presented in Table 4.

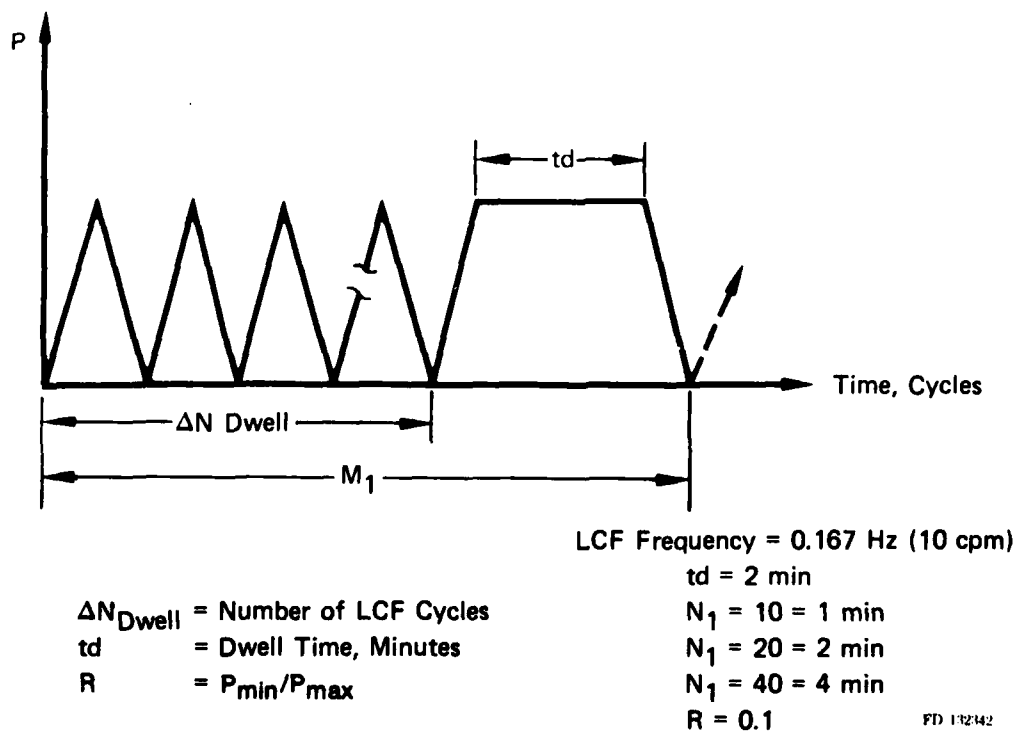


Figure 13. Low Cycle Fatigue-Dwell Interaction at Constant Peak Stress

TABLE 4
SYNERGISTIC FCP TEST MATRIX

SYNERGISTIC FCP TEST MATRIX										
Test Description	Dwell Time (min)	Cycles Between Overloads	Overload Ratio	Temperature = 649°C (1200°F)		Temperature = 732°C (1350°F)		Number of Tests Required		
				Stress Ratio		Stress Ratio		Waspaloy IN100		
				0.1	0.5	0.1	0.5	Waspaloy	IN100	
LCF-Overload	0	40	1.5	X*	X*			1	0	
		20		X*	XX*	X	X*	6	1	
		5			X*			1	0	
		40	1.25		X*			1	0	
		20		X*	X*	X	X*	4	1	
		5			X*			1	0	
LCF-dwell	2	40	1.0	X*		X*		2	0	
		20		X*	X*	X*	X*	4	0	
		10		X*		X*		2	0	
	Total								24	2

Specimen Thickness = 7.62 mm (0.3 in.)

*Existing data for IN100

Specimen Thickness = 7.62 mm (0.3 in.)

*Existing data for IN100

A Task 1 mission, M_1 , was defined as ΔN_{Dwell} LCF cycles plus a 2-min dwell. As the test matrix defines, ΔN_{Dwell} varied so that the total time for LCF cyclic crack growth was less than, equal to, and greater than the dwell period. The tests investigated the interaction as a function of the ratio of LCF to sustained load crack growth within a single mission.

Crack growth relations, da/dN vs ΔK , were obtained for each of the test conditions using procedures described later. The relations defining crack growth will also be discussed in a later section.

(b) Task 2 — Variable Stress Ratio Interaction with Major Load (LCF — Overload)

The purpose of Task 2 was to investigate possible synergistic effects of major load excursions on LCF crack growth in Waspaloy and IN100. The test temperatures were 649 and 732°C (1200 and 1350°F). A schematic of the stress-time history is given in Figure 14 and the test matrix for Task 2 is presented in Table 4.

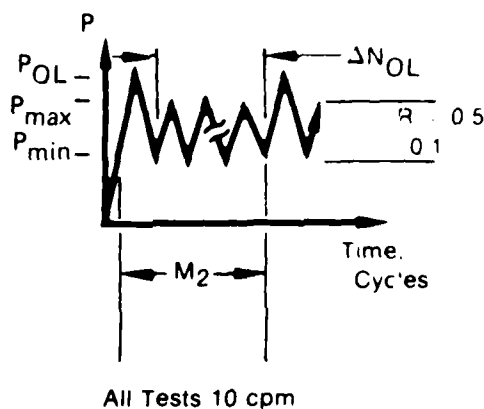
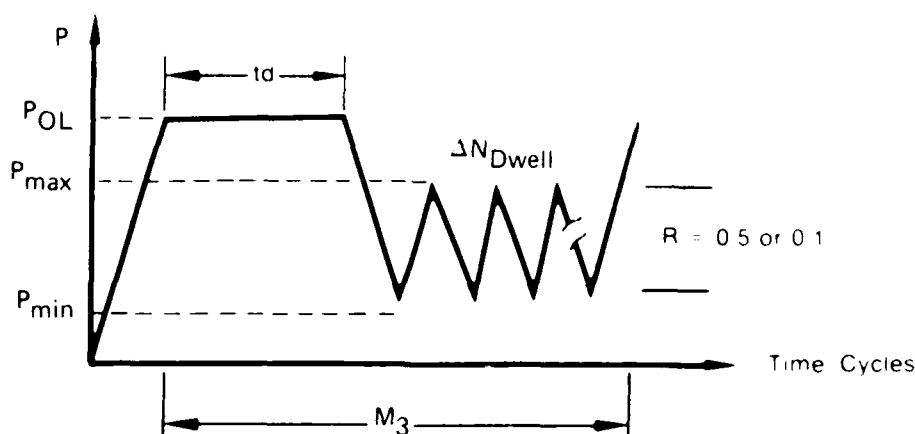


Figure 14. Variable Stress Ratio With Major Load Excursions

(c) Task 3 — Interaction of High Amplitude Sustained Load with LCF

The purpose of Task 3 was to investigate the possible synergistic effects of high amplitude sustained loads on LCF of Waspaloy and IN100. However, initial construction of the test matrix was accomplished without complete knowledge of the form of typical mission profiles giving stress and temperature as a function of time. The missions (Figures 2 through 6), defined under Phase I of this contract, represent the results of the most current engine usage and analyses conducted and describe conditions encountered by a disk operated in a military gas turbine engine. A review of these profiles shed question on the ultimate value the overload dwell-LCF tests proposed under this task. The form of these tests is illustrated in Figure 15.

The testing was designed to measure the effect of a dwell at overload upon subsequent FCP; however, no such overload dwells were observed in the mission profiles. Since all other load sequences were addressed in testing and modeling, the tests of this task were replaced with other, more pertinent, tests. These include the auxiliary negative stress ratio tests as well as selected tests designed to complement and extend the original matrix.



t_d = Dwell Time, min
 N = Number of Cycles

Figure 15. Interaction of Sustained High Load With LCF

(5) Auxiliary Investigations

The testing described in the following sections was conducted to supplement the data generated for use in model development. The results of these investigations provide insight into the nature of crack propagation under a variety of test conditions which are beyond the scope of the model development for this program. While not actually used in crack propagation modeling, the auxiliary data provide a means to assess the limits of applicability of the model.

(a) Effect of Negative Stress Ratio

Fatigue cycling which is characterized by tension-compression loading ($R < 0$) may occur in turbine disks under some circumstances. For example, thermally and mechanically induced strain gradients may produce local compressive stresses in a disk under mission operation, Figure 4. The negative R tests of Table 5 were conducted in order to evaluate this effect on crack propagation in Waspaloy and IN100.

(b) Effect of Net Section Stress

The through-thickness center flaw crack propagation specimen (shown in Figure 11a) was used to determine the effect of stress levels greater than 0.8 times the yield strength of Waspaloy. Similar tests were performed on IN100 previously. This specimen was selected due to the small initial crack size (approximately 0.762 mm (0.030 in.)) obtainable. The small crack provides the capability to obtain the necessary high net section stress with corresponding stress intensities (ΔK approximately 55 MPa $\sim$ (50 ksi in.)) that are comparable to existing linear elastic crack propagation curves.

TABLE 5
AUXILIARY INVESTIGATIONS

Test Description	Stress Ratio	Frequency (Hz)	Thickness (mm)	Temperature			Number of Tests Waspaloy IN100
				°C 427	(°F) 800	(°C) 649	
1 $\sigma_{op} > 0.8 \sigma_y$	0.1	0.167	7.62 (0.3)				2
2 Prior Plastic Deformation	0.1	0.167	7.62 (0.3)		X		2
3 Negative Stress Ratio	-0.5	0.167	7.62 (0.3)		X		2
	-1.0	0.167	7.62 (0.3)		X		2
4 Thermal Mechanical Fatigue	0.05	0.0167	7.62 (0.3)		800 1300F		1
5 Overload-Underload-LCF	0.5	0.167	7.62 (0.3)				1
Total							10
							5

*Existing data for IN100

+Waspaloy only.

(c) Effect of Prior Plastic Deformation

The purpose of this task was to investigate the influence of prior plastic cycling on subsequent crack propagation. Crack growth in material which has previously been yielded is representative of the initial stages of propagation of a flaw which initiated in the region of a stress concentrator. These tests are outlined in Table 5.

(d) Effect of Overload-Underload-LCF Sequencing

The crack propagation testing upon which the cumulative damage modeling was based is isothermal in nature. It was assumed that a nonisothermal mission may be suitably represented by a series of isothermal segments. The purpose of this investigation was a brief examination of crack propagation of Waspaloy (PWA 1007) subject to thermal-mechanical fatigue (Table 5).

(e) Thermal-Mechanical Fatigue

The crack propagation testing upon which the cumulative damage modeling was based is isothermal in nature. It was assumed that a nonisothermal mission may be suitably represented by a series of isothermal segments. The purpose of this investigation was a brief examination of crack propagation of Waspaloy (PWA 1007) subject to thermal-mechanical fatigue (Table 5).

(f) Effect of Thickness

The goal of this task was to investigate the effect of specimen thickness on crack propagation in Waspaloy (PWA 1007). Of specific concern was the qualification of crack propagation data as thickness independent (i.e., representative of the most severe geometric constraint).

C. PHASE III — MATHEMATICAL MODEL DEVELOPMENT

1. Model Description

To analyze a complex mission spectrum in terms of consistently accurate cumulative damage accounting requires two basic tools: (1) a mathematical model describing crack propagation at frequencies, temperatures, and stress ratios representative of turbine disk operation, and (2) a model which describes cumulative damage synergistic effects such as:

- Overloads of varying degree and occurrence frequency
- Dwells of varying duration
- Combinations of these with simple cyclic crack growth behavior.

The requisite tool is the Interpolative Synergistic Hyperbolic Sine Model, SINH.

a. Mathematical Formulation

The model is based on the hyperbolic sine equation,

$$\log (da/dN) = C_1 \sinh (C_2 (\log (\Delta K) + C_3)) + C_4 \quad (2)$$

where the coefficients have been shown (References 1, 2, and 3) to be functions of test frequency, stress ratio, and temperature:

$$\begin{aligned} C_1 &= \text{material constant} \\ C_2 &= f_2(v, R, T) \\ C_3 &= f_3(v, R, T) \\ C_4 &= f_4(v, R, T) \end{aligned}$$

Additionally, Equation 2 may also be used to describe crack propagation data as a function of load sequence parameters.

Descriptions of the mathematical model (SINH) and the hyperbolic sine function ($\sinh$) on which it is based are provided in the following paragraphs.

b. Characteristics of the $\sinh$

The hyperbolic sine is defined as

$$y = \sinh x = \frac{e^x - e^{-x}}{2} \quad (3)$$

and when presented on Cartesian coordinates it appears as shown in Figure 16. The function is zero at $x = 0$ and has its inflection there.

The introduction of the four regression coefficients, C_1 through C_4 , permits relocation of the point of inflection and scaling of both axes. In the equation

$$(y - C_4) = \sinh (x + C_3), \quad (4)$$

C_3 establishes the horizontal location of the hyperbolic sine point of inflection and C_4 locates its vertical position.

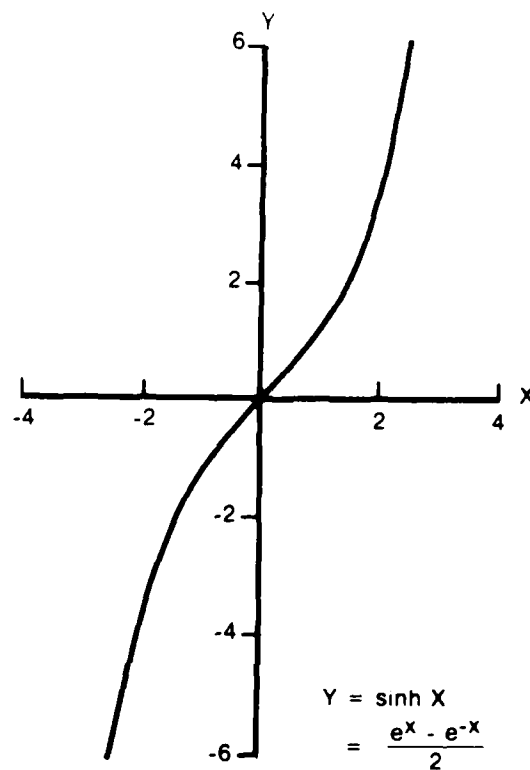
To scale the axes, C_1 and C_2 are introduced

$$\frac{(y - C_4)}{C_1} = \sinh (C_2(x + C_3)) \quad (5)$$

which can be rewritten as

$$y = C_1 \sinh (C_2 (x + C_3)) + C_4 \quad (6)$$

of which Equation 2 is a special case where $y = \log (da/dN)$ and $x = \log (\Delta K)$. Note that C_3 has units of $\log (\Delta K)$ and C_4 has units of $\log (da/dN)$; C_1 and C_2 are dimensionless and can be conceptualized as stretching the curve vertically and horizontally, respectively. Experience indicates that, for a given material, C_1 can be fixed without adversely affecting model flexibility.



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Figure 16. Hyperbolic Sine on Cartesian Coordinates

Experience has also shown that the materials considered here (Waspaloy and IN100) exhibit symmetrical da/dN vs ΔK relationships for simple cycling. For materials which do not display this symmetry, an asymmetric variation of the model is available. Here, the shape coefficient, C_2 , is separated into similar coefficients C_2 and C'_2 . The first of these coefficients determines model curvature above the point of inflection, while C'_2 controls curvature below inflection. The model remains a continuous function, and when the data is symmetric $C_2 = C'_2$, and the model reverts to its original form.

The hyperbolic sine equation was selected as the model for the following reasons:

- It exhibits the overall shape of typical da/dN vs ΔK plots, obtained over several decades of crack growth rates.
- All or part of the equation may be used to fit data, since the sinh has both a concave and a convex half and a nearly linear portion near inflection. Also, the slope at inflection can vary with the fitting constants. (By comparison, the slope of an x^3 model is always zero at inflection.)
- The sinh is not periodic (e.g., trigonometric tangent) nor asymptotic (e.g., tangent, or inverse hyperbolic tangent); therefore, when extrapolation becomes necessary, the sinh behaves well at distances removed from the data, quite unlike most polynomial, periodic, or asymptotic functions.
- This model requires no information other than (a vs N) data. By comparison, some other models in current use require both K_{th} and K_{Ic} , in addition to (a vs N) data, to model crack growth behavior. Both K_{th} and K_{Ic} are difficult to obtain experimentally, K_{th} because of the extremely small crack growth measurements necessary and K_{Ic} because of gross plasticity at the crack tip encountered in fracture-toughness testing at elevated temperatures.

c. SINH Descriptions of Basic Propagation

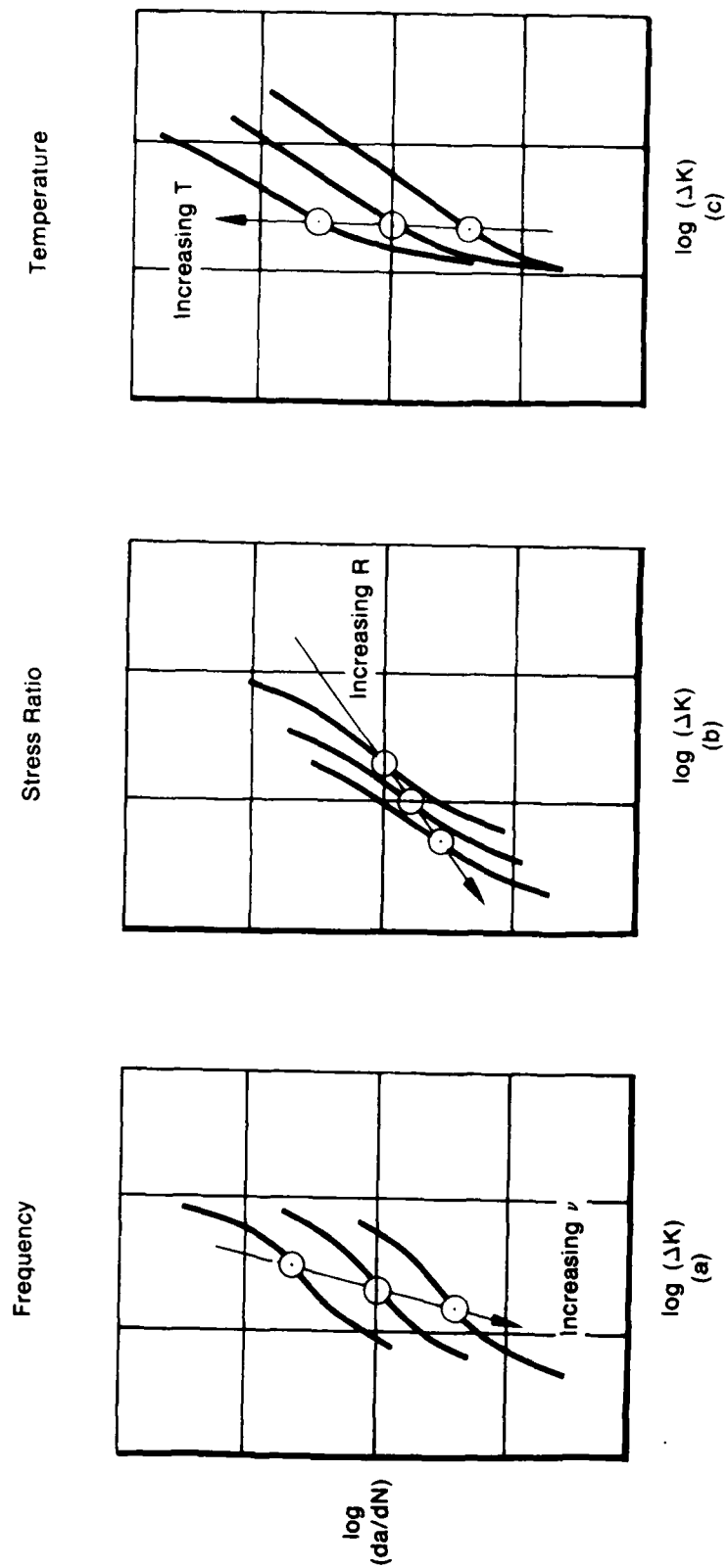
The hyperbolic sine model is easily adapted to describe fundamental parametric effects of operating conditions such as stress ratio, frequency, and temperature on crack growth rate.

Figure 17 schematically depicts the qualitative effects on crack propagation rate of frequency (Figure 17a), stress ratio (Figure 17b), and temperature (Figure 17c).

Because of the simple relationships observed between the coefficients of the SINH model and the fundamental propagation-controlling parameters, interpolations are straightforward. It is here that the model demonstrates its great usefulness: *the hyperbolic sine model provides descriptions of crack propagation characteristics where data are unavailable*. The interpolation algorithm is described under Algorithm Definition and Development.

2. Advanced Regression Considerations

Interpolative modeling of crack propagation as a function of operating parameters such as frequency, stress ratio, and temperature (Figure 17) requires a multiple regression capability which allows simultaneous consideration of several different collections of data, each differing from the others by only one FCP — controlling parameter. Separate regression of the individual data sets contributing to an interpolative model does not allow data at one condition to influence the model at another condition. However, the final model was to have broad interpolative capability with behavior at one condition used to describe FCP at another condition. Therefore, it is desirable to permit the data to exhibit their mutual influence during the modeling process.

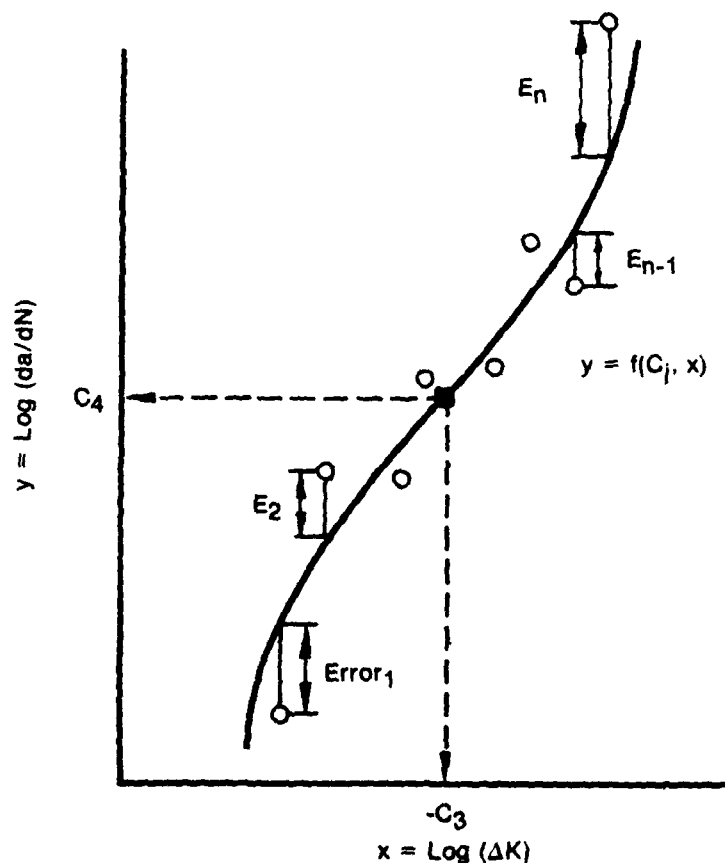


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Figure 17. Crack Propagation as Influenced by (a) Frequency, (b) Stress Ratio, and (c) Temperature

Pratt & Whitney Aircraft has developed a mathematical technique to accomplish this. Individual sets of data are treated independently relative to some of the SINH coefficients, while the entire collection is treated as an entity with respect to the interpolative coefficients (functions of v , R , T , etc.). This improved method was used to develop the propagation models presented in this report. The actual computational procedure employed in the modeling, referred to as the Method of Least Squares, is described in the following paragraphs.

The goal of this procedure is to determine model coefficients for which the resulting curve through the data will have the least (minimum) summed squared error between calculated and observed values for the dependent variable (see Figure 18). In this instance, the independent and dependent variables, x and y , are $\log(\Delta K)$ and $\log(da/dN)$, respectively.



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Figure 18. Method of Least Squares

Define the sum of the squared errors as

$$E^2 = \sum_{i=1}^n E_i^2 = \sum (y_{cal_i} - y_i)^2 \quad (7)$$

Since $y_{cal_i} = f(C_2, C_3, C_4, x_i)$, E is also a function of C_2, C_3, C_4 .

Now, E^2 will be a minimum when each of its partial derivatives is zero simultaneously. That is

$$\frac{\partial E^2}{\partial C_2} = \frac{2E \partial E}{\partial C_2} = 0 \quad (8)$$

$$\frac{\partial E^2}{\partial C_3} = \frac{2E \partial E}{\partial C_3} = 0 \quad (9)$$

$$\frac{\partial E^2}{\partial C_4} = \frac{2E \partial E}{\partial C_4} = 0 \quad (10)$$

when f is the SINH model,

$$E_i = C_1 \sinh(C_2(x_i + C_3)) + C_4 \cdot y_i \quad (11)$$

and

$$\frac{\partial E}{\partial C_2} = C_1 \cosh(C_2(x_i + C_3))(x_i + C_3) \quad (12)$$

$$\frac{\partial E}{\partial C_3} = C_1 \cosh(C_2(x_i + C_3))(C_2) \quad (13)$$

$$\frac{\partial E}{\partial C_4} = 1 \quad (14)$$

Now, substituting Equations 11, 12, 13, and 14 into Equations 8, 9, and 10, and solving* the resulting three simultaneous equations provides the values for C_2, C_3 , and C_4 for which Equation 7 will be a minimum.

The foregoing discussion explains the procedure for determining the coefficients for SINH curve. Suppose further that each SINH representation of FCP is related to the others, the relationship depending on differences in frequency, stress ratio, temperature, etc. Consider frequency as an example, and assume that the points of inflection are linearly related, viz:

$$C_{3,j} = C_{33} + C_{34}(C_{4,j}) \quad (15)$$

for j different SINH curves.

*In this instance, the resulting simultaneous equations are nonlinear in C_2, C_3 , and C_4 . The solution therefore requires some iterative procedure such as an N-dimensional Newton-Raphson method.

Assume also that C_2 and C_4 are related to test frequency by Equations 16 and 17:

$$C_4, j = C_{35} + C_{36} (\log (v)) \quad (16)$$

$$C_2, j = C_{37} + C_{38} (\log (v)) \quad (17)$$

Coefficients C_{33} through C_{38} can be then determined by substituting Equations 15, 16, and 17 into Equation 11 and differentiating with respect to C_{33} through C_{38} in a manner analogous to that used in determining C_2, C_3, C_4 in the foregoing discussion.

3. Algorithm Definition and Development

The computer code developed under Phase III has as its mathematical formulation three algorithms: the segregation, interpolation, and computation algorithms.

a. The Segregation Algorithm

The set of rules by which a mission profile is separated (segregated) into its elemental cumulative damage events constitutes the segregation algorithm. As formulated, the segregation algorithm translates an input isothermal stress-time profile, such as illustrated in Figure 5, into a parametric, cycle-by-cycle description of the loading sequence. This segregated mission definition, given in terms of the elemental mission segments addressed in the test program, provides input compatible with the interpolation algorithm.

Development of the segregation algorithm was based on the mission definition described under Phase I, Figures 2 through 6. A characteristic of these representative operational profiles is a high occurrence frequency for major load excursions (overloads). As discussed in Appendix A (Reference 6), the implication of this observation is to diminish the importance of long term overload effects and to place increased significance on the synergistic interaction which occurs immediately following the overload. As a result, a primary investigation conducted under the test program was to characterize the short term effects of overloading. Similarly, the interpolation algorithm, developed to address mission profiles representative of turbine disk operation, is not routinely applicable to missions which may contain infrequent overloads (e.g. airframe loading spectra).

The general procedure employed in the segregation algorithm is outlined as follows:

1. Define isothermal operating temperature
2. Locate load dwells
3. Locate major load excursions (overloads)
4. Calculate the number of cycles between successive overloads
5. Calculate overload ratio for each less severe cycle following an overload
6. Determine stress ratio and frequency of all fatigue cycles.

Upon completion of mission segregation, the data is passed to the interpolation algorithm, and the appropriate crack growth rate curves are obtained.

b. The Interpolation Algorithm

The fundamental strength of the hyperbolic sine model is its interpolative capacity. The procedure known as the interpolation algorithm for calculating the SINH coefficients, describing FCP under the influence of a segregated elemental event, is illustrated in the following paragraphs. For simplicity, the example considers only simple cycling with varying frequency, stress ratio, and temperature (v, R, T). The actual computer software includes other life-controlling parameters: period of load dwell, overload ratio, and cycles between overloads.

The coefficient (e.g., C_2 , C_3 , and C_4) at any intermediate value of an element life-controlling parameter, can be determined from Equation 18.

$$C_j = C_{j\text{base}} + \Delta C_j; \quad j = 2,3,4 \quad (18)$$

where:

$$C_j = \begin{bmatrix} C_2 \\ C_3 \\ C_4 \end{bmatrix} = \text{interpolated values of coefficients}$$

and:

$$\Delta C_j = \begin{bmatrix} \Delta C_2 \\ \Delta C_3 \\ \Delta C_4 \end{bmatrix} = \text{differences from baseline values.}$$

Since the SINH coefficients are linear functions of the controlling parameters,* it is evident that:

$$\begin{matrix} \begin{bmatrix} \Delta C_2 \\ \Delta C_3 \\ \Delta C_4 \end{bmatrix} \\ N \times 1 \end{matrix} = \begin{matrix} \begin{bmatrix} \partial C_2 / \partial v, \partial C_2 / \partial R, \partial C_2 / \partial T \\ \partial C_3 / \partial v, \partial C_3 / \partial R, \partial C_3 / \partial T \\ \partial C_4 / \partial v, \partial C_4 / \partial R, \partial C_4 / \partial T \end{bmatrix} \\ N \times N \end{matrix} \times \begin{matrix} \begin{bmatrix} \Delta v \\ \Delta R \\ \Delta T \end{bmatrix} \\ N \times 1 \end{matrix}$$

where:

$$\begin{bmatrix} \Delta v \\ \Delta R \\ \Delta T \end{bmatrix} = \text{differences from baseline values}$$

and the $N \times N$ partial derivative matrix is easily determined from the slopes of the lines relating each coefficient with each rate controlling parameter. The computation of the intermediate coefficients, using Equation 18, is then straightforward.

c. The Computational Algorithm

The product of the interpolation algorithm is a collection of SINH descriptions of crack propagation corresponding to the segregated mission cycles. The interpolated crack growth curves are representative of the cycle-by-cycle crack growth under the individual loading conditions, and the effects of load sequence synergism are implicit. The method of computation of crack growth under the complex mission.

A simple cycle-by-cycle integration is used to sum the incremental crack advances, Δa_i , which comprise the incremental cyclic life, ΔN_i , (or event life, ΔE_i)

$$da/dN = f(a, \Delta K, \dots) \quad (20)$$

$$\Delta a_i = f(a, \Delta K, \dots) \Delta N_i \quad (21)$$

*Strictly speaking, the coefficients are nonlinear functions of v , R , and T ; however, they are linear functions of other functions. This simplification was used here for presentation clarity.

The sum of all these incremental crack advances results in the crack propagation during one mission, $\Delta a_{\text{mission}}$

$$\Delta a_{\text{mission}} = \sum_{i=1}^n \Delta a_i$$

where n is the number of elemental events comprising the mission profile.

The total mission lifetime, N_{missions} , is similarly calculated as the number of mission crack advances, $\Delta a_{\text{mission}}$, required to reach critical cracklength.

$$a_{\text{critical}} = a_0 + \sum_{i=1}^{N_{\text{missions}}} \Delta a_{\text{mission}}$$

This summed numerical integration procedure is referred to as the computational algorithm.

4. SINH Descriptions of Crack Propagation

Interpolative crack propagation models developed from the data generated under the test programs outlined in Tables 3 and 4 are presented in the following pages. Each of the individual models describes the influence of a single test variable (e.g., temperature, frequency, stress ratio) upon crack propagation. The combination of these models forms a unified description of the crack growth behavior over the range of operating conditions addressed in the test matrices. This unified description is formalized in the interpolation algorithm.

a. Waspaloy (PWA 1007) Crack Propagation

The majority of the Waspaloy data presented in this report were generated under the current contract and represent crack propagation in a single heat of material. A limited amount of additional data (Reference 7), generated from a second heat of this same alloy, was also used. The inclusion of additional data aided in model refinement and extension.

Regression of the crack length vs cycle (a , N) data to produce crack growth rate vs applied stress intensity range (da/dN , ΔK) data, in general, was accomplished with the seven-point incremental polynomial technique (Reference 8). This reduction technique was found desirable for Waspaloy data but less beneficial when reducing IN100 data, since typical scatter in (da/dN , ΔK) data in Waspaloy is considerably more severe than in IN100.

The severity of data scatter in these two alloys is closely linked to grain size. Elevated temperature fatigue of Waspaloy and IN100 results in discontinuous advances of the observed surface crack, and the increments of discontinuous advance are on the order of the material grain size. As the magnitude of the discontinuous crack advance (Δa_{disc}) increases, the variability of the increment in crack growth (Δa) increases by a value within the range $\pm 2 (\Delta a_{\text{disc}})$, and the associated scatter in da/dN increases. The large grain size of Waspaloy (ASTM 2-7) makes this a significant effect, while the fine crystalline structure of IN100 (ASTM 12-14) results in much less inherent scatter in crack growth rate.

The mathematical procedure employed in the seven-point incremental polynomial technique for data reduction produces five fewer (da/dN , ΔK) data points than does the direct secant method. Generally, this presents no significant problem; however, (a, N) data sets containing a small number of points may be severely diminished during data reduction. Therefore, small data sets were reduced by the direct secant method and their specimen numbers bear the prefix "100." Data reduced with the seven-point incremental polynomial method have identification numbers beginning with "7AN" (See Appendix C).

(1) *Basic Propagation, Constant Load Amplitude Cycling*

(a) *Effect of Loading Rate (Frequency)*

Experience with turbine disk alloys indicates that changing test frequency, while holding stress ratio and temperature constant, produces crack growth curves similar in shape but shifted along a nearly vertical line passing through the points of inflection. The location of these inflection points is related to test frequency; reduced frequency (increased cycle duration) is observed to accelerate crack growth rate.

Figures 19 and 20 illustrate the effects of cyclic frequency on FCP in Waspaloy, at 649°C (1200 °F), $R = 0.1$. The four curves represent crack growth under frequencies of 0.00833, 0.167, 0.333, and 20 Hz (0.5 cpm, 10 cpm, 20 cpm, 20 Hz). Note that points of inflection describe a straight line, i.e.: $C_3 = C_{33} + C_{34} \times C_4$. Figure 21 demonstrates the interrelationships of the other SINH coefficients and test frequency. Note that the coefficients *exactly* describe a straight line, so that any aberrations in the model appear when the SINH curve is plotted with the data it represents. This model completely describes the effect of frequency on FCP in Waspaloy at this temperature by interpolation of the equations given in Figure 21.

(b) *Effect of Stress Ratio, 0.167 Hz (10 cpm)*

The influence of stress ratio (R) on crack propagation in Waspaloy (PWA 1007) fatigued at 0.167 Hz (10 cpm) 649°C (1200°F) is illustrated in Figures 22 through 24. Data from tests at four different stress ratios were used to develop a model (Figures 22 and 23) of this effect for $0.05 \leq R \leq 0.80$. A plot of the correlative parameters and the defining equations is given in Figure 24. Each of the SINH coefficients is defined as a linear function of $\log(1 - R)$ for the range of positive stress ratios.

This relationship should not be extrapolated into the range of negative stress ratios (i.e., tension-compression fatigue). Data gathered from tests at $R = -0.5$ and $R = -1.0$ demonstrate the invalid nature of this extrapolation. Crack propagation under negative stress ratio fatigue is discussed under "Auxiliary Investigations" later in this report.

(c) *Effect of Stress Ratio, 20 Hz*

The effect of stress ratio on fatigue crack propagation of Waspaloy is a function of the associated cyclic frequency of the loading. In order to address this functional dependence, testing was conducted at a frequency of 20 Hz and $0.05 \leq R \leq 0.80$. The resulting model is illustrated in Figures 25 and 26. A plot of the correlative parameters is shown in Figure 27. The combination of the 20 Hz stress ratio model and the similar 0.167 Hz model provides full interpolative capability for crack growth rate as a function of stress ratio and frequency simultaneously.

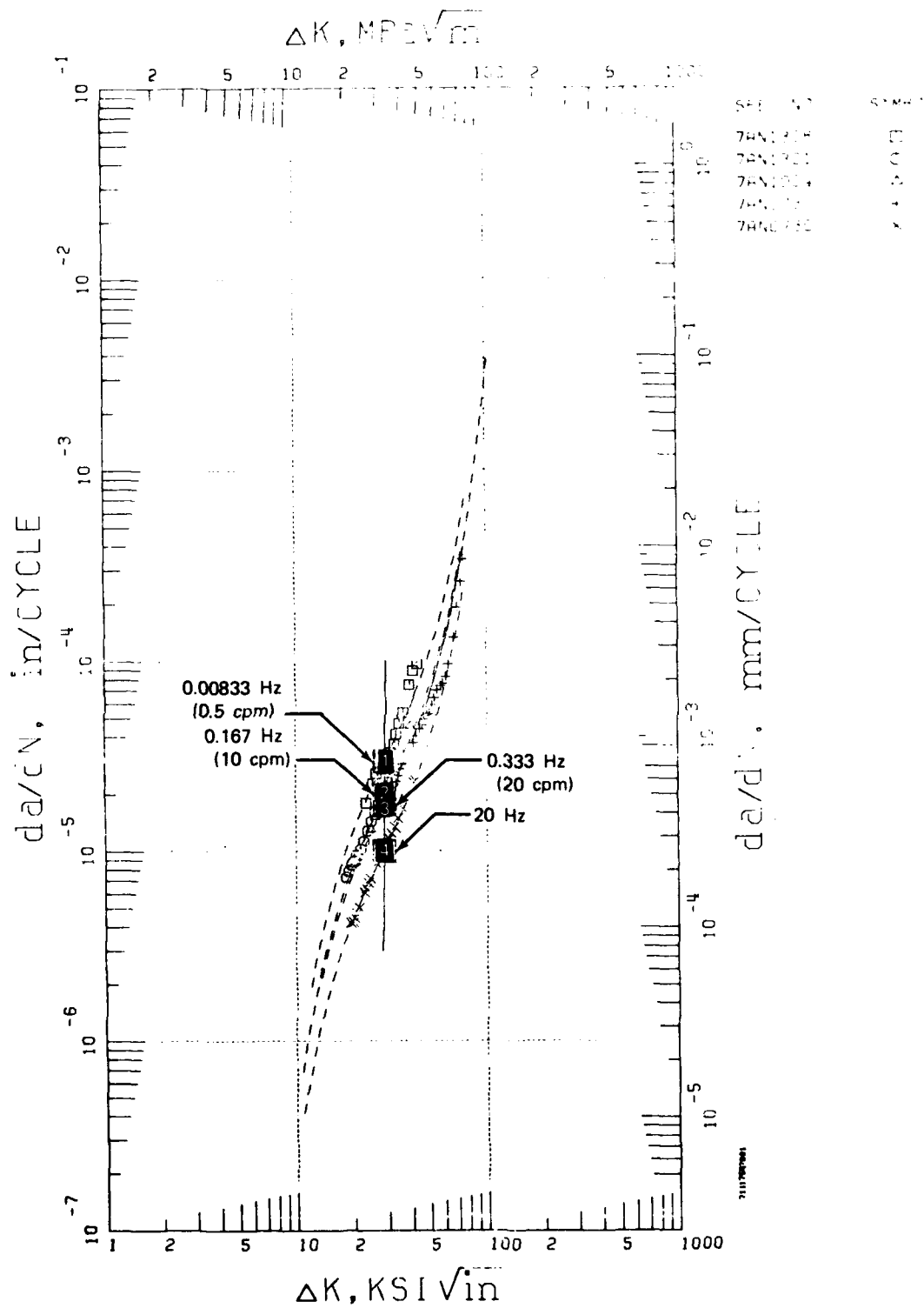


Figure 19. Waspaloy (PWA 1007) Crack Propagation, Frequency Model, 649°C (1200°F)

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R=0.1 T=1200F FREQ=0.5 CPM										
SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	T PE	THIK	REMARKS		
7AN1328	PWA 1007	1200F	AIR	.5 CPM	R=.1	RA	CN	.289	EN RSQD 0.9759 SEE 0.0709	
					Y=0.5000	SINH(4.102	(X	-1.468))	-4.527	
					(METRIC)	Y=0.5000	SINH(4.102	(X	-1.509))	-3.122
					*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=23.31 , AND X=43.79 ONLY. DO NOT EXTRAPOLATE.					
R=0.05 T=1200F FREQ=10CPM										
SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	T PE	THIK	REMARKS		
7AN1301	PWA 1007	1200F	AIR	10 CPM	R=.05	RA	MCT	.501	O	
7AN1004	PWA 1007	1200F	AIR	10 CPM	R=.05	CN		.301	Δ RSQD 0.9802 SEE 0.0313	
					Y=0.5000	SINH(4.102	(X	-1.465))	-4.709	
					(METRIC)	Y=0.5000	SINH(4.102	(X	-1.506))	-3.304
					*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=18.31 , AND X=39.98 ONLY. DO NOT EXTRAPOLATE.					
R=0.05 T=1200F FREQ=20CPM										
SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	T PE	THIK	REMARKS		
7AN0730	PWA 1007	1200F	AIR	20 CPM	R=.05	RA	MCT	.447	+ RSQD 0.9915 SEE 0.0978	
					Y=0.5000	SINH(4.102	(X	-1.464))	-4.751	
					(METRIC)	Y=0.5000	SINH(4.102	(X	-1.505))	-3.346
					*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=30.31 , AND X=75.74 ONLY. DO NOT EXTRAPOLATE.					
R=0.05 T=1200F FREQ=20HZ										
SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	T PE	THIK	REMARKS		
7AN0736	PWA 1007	1200F	AIR	20 HZ	R=.05	RA	MCT	.432 WS	X RSQD 0.9971 SEE 0.0145	
					Y=0.5000	SINH(4.102	(X	-1.461))	-5.000	
					(METRIC)	Y=0.5000	SINH(4.102	(X	-1.502))	-3.595
					*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=19.27 , AND X=42.41 ONLY. DO NOT EXTRAPOLATE.					
OVERALL STATISTICS FOR THIS COLLECTION OF GRC PS. TOTAL RSQD = 0.9820. AND STD.ERROR.EST. = 0.0024										

OVERALL STATISTICS FOR THIS COLLECTION OF GRC FS. TOTAL RSQD = 0.9820. AND STD.ERROR.EST. = 0.0624

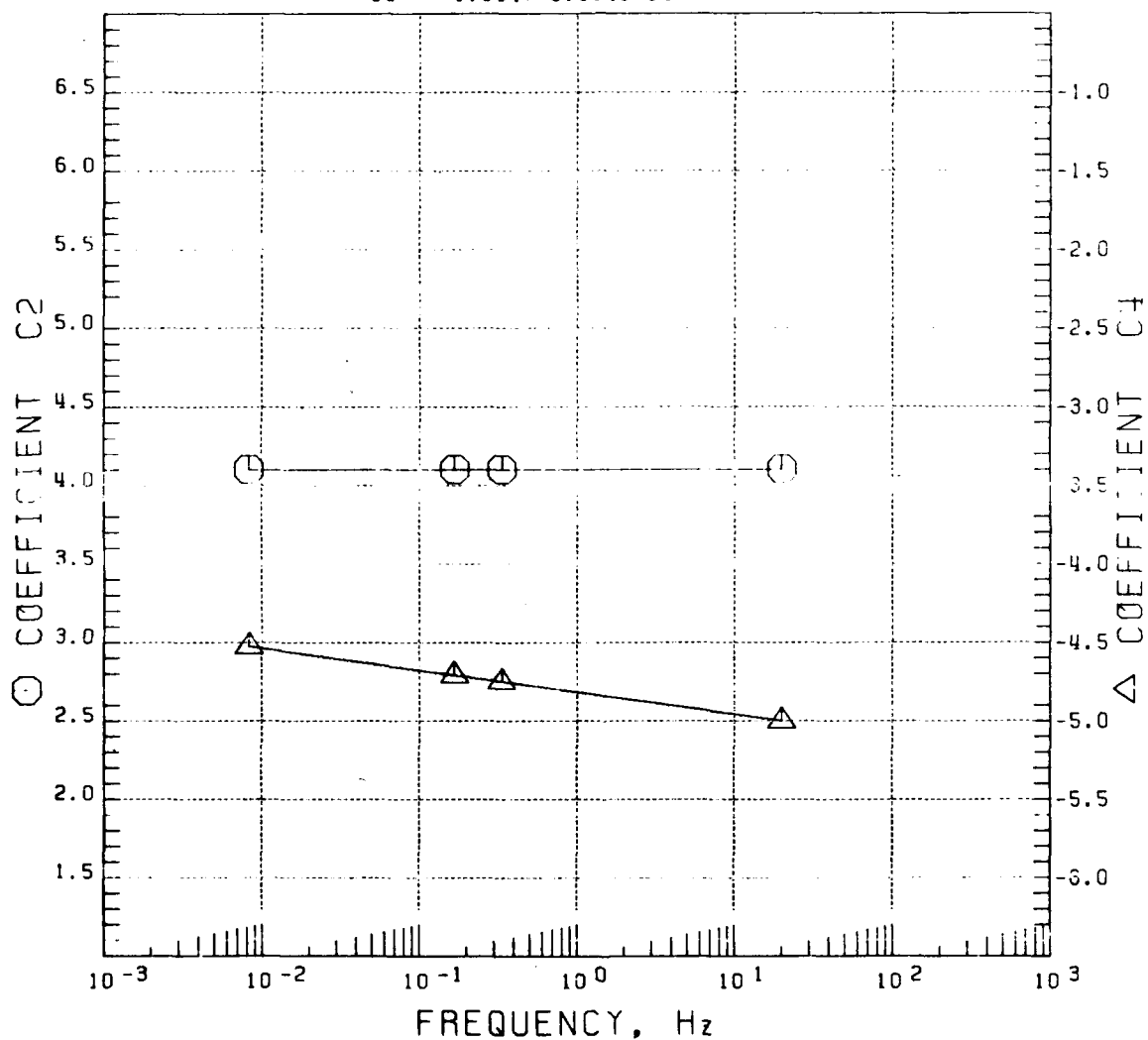
Figure 20. Statistics for Waspaloy (PW.A 1007) Crack Propagation, Frequency Model, 649°C (1200°F)

COEFFICIENTS C2 AND C4 VS. FREQUENCY

$$C2 = 4.1018 - 0.0002 \text{ LOG (FREQ)}$$

$$C4 = -4.8179 - 0.1400 \text{ LOG (FREQ)}$$

$$C3 = -1.5347 - 0.0148 C4$$



FD 168096

Figure 21. Waspaloy (PWA 1007) Frequency Model Correlative Parameters, 649°C (1200°F)

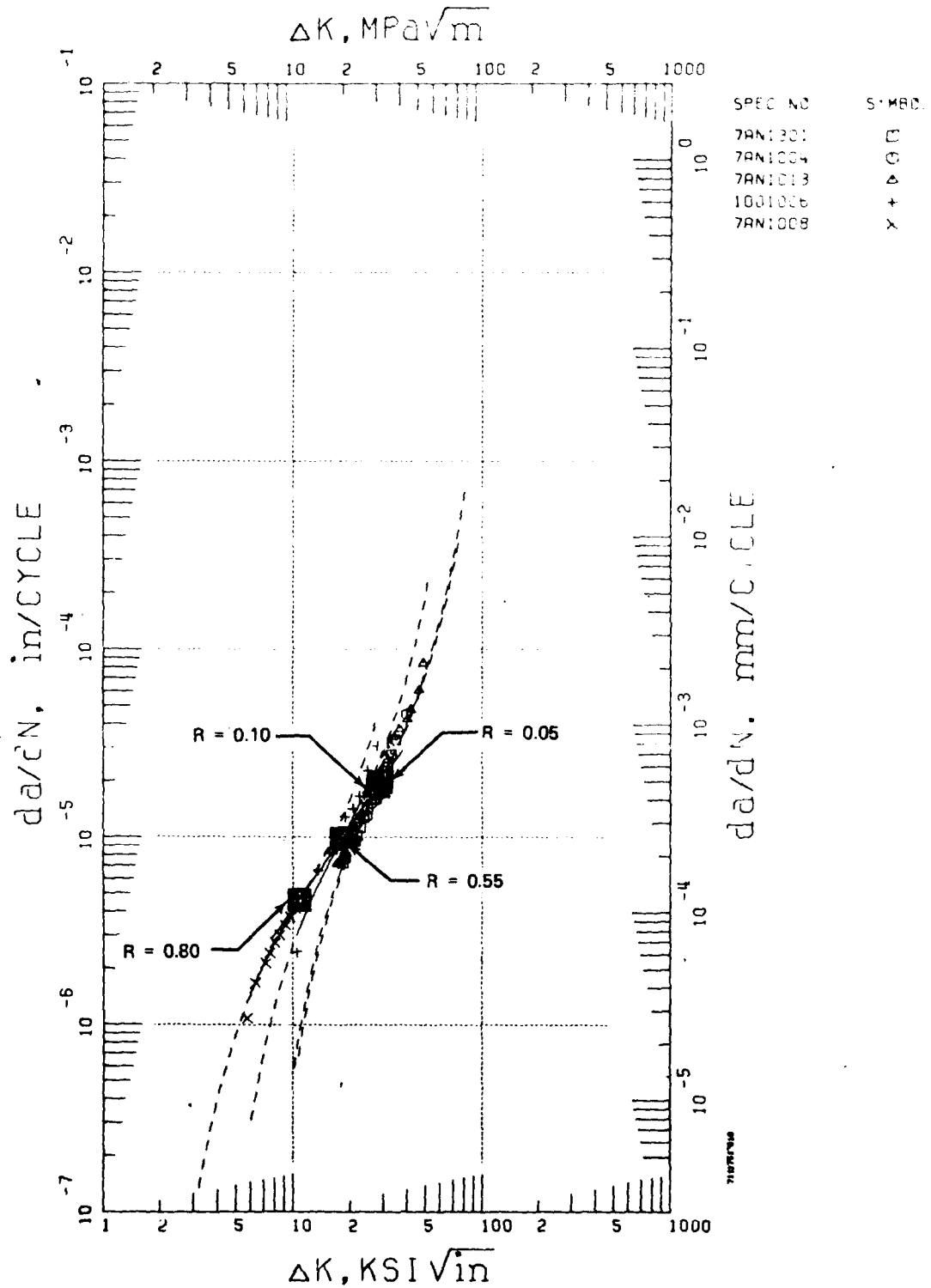


Figure 22. Waspaloy (PWA 1007) Crack Propagation, Stress Ratio Model, 0.167 Hz (10 cpm), 649°C (1200°F)

FD 168094

PRDE 71117517910

R=.05 T=1200F FREQ=10CPM

SPEC NO MATERIAL TEMP ATM FREQ R T PE THIK REMARKS
7AN1301 PWA 1007 1200F AIR 10 CPM R=.05 RA5 MCT .501
7AN1004 PWA 1007 1200F AIR 10 CPM R=.05 CN .301
-0.34 10.
Y=0.5000 SINH(4.102 (X -1.465)) -4.709
NRAFT 1 (METRIC) Y=0.5000 SINH(4.102 (X -1.506)) -3.304
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=18.31 , AND X=39.98 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 1

□
○ RSORD 0.9808 SEE 0.0713

R=.1 T=1200F FREQ=10CPM

SPEC NO MATERIAL TEMP ATM FREQ R T PE THIK REMARKS
7AN1013 PWA 1007 1200F AIR 10 CPM R=.1 RA5 MCT .318
-0.34 10.
Y=0.5000 SINH(4.080 (X -1.450)) -4.731
NRAFT 1 (METRIC) Y=0.5000 SINH(4.080 (X -1.491)) -3.326
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=17.09 , AND X=49.06 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 2

△ RSORD 0.9932 SEE 0.0801

R=.55 T=1200F FREQ=10CPM

SPEC NO MATERIAL TEMP ATM FREQ R T PE THIK REMARKS
1001006 PWA 1007 1200F AIR 10 CPM R=.55 CN .287
-0.34 10.
Y=0.5000 SINH(3.802 (X -1.259)) -5.009
NRAFT 1 (METRIC) Y=0.5000 SINH(3.802 (X -1.300)) -3.604
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=10.53 , AND X=27.87 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 3

+ RSORD 0.9951 SEE 0.0905

R=.8 T=1200F FREQ=10CPM

SPEC NO MATERIAL TEMP ATM FREQ R T PE THIK REMARKS
7AN1008 PWA 1007 1200F AIR 10 CPM R=.8 CN .300
-0.34 10.
Y=0.5000 SINH(3.470 (X -1.035)) -5.325
NRAFT 1 (METRIC) Y=0.5000 SINH(3.470 (X -1.076)) -3.930
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=5.27 , AND X=11.06 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 4

× RSORD 0.9992 SEE 0.1210

OVERALL STATISTICS FOR THIS COLLECTION OF GRAC-PS. TOTAL RSORD = 0.9854. AN

RSORD = 0.9998

10 168095

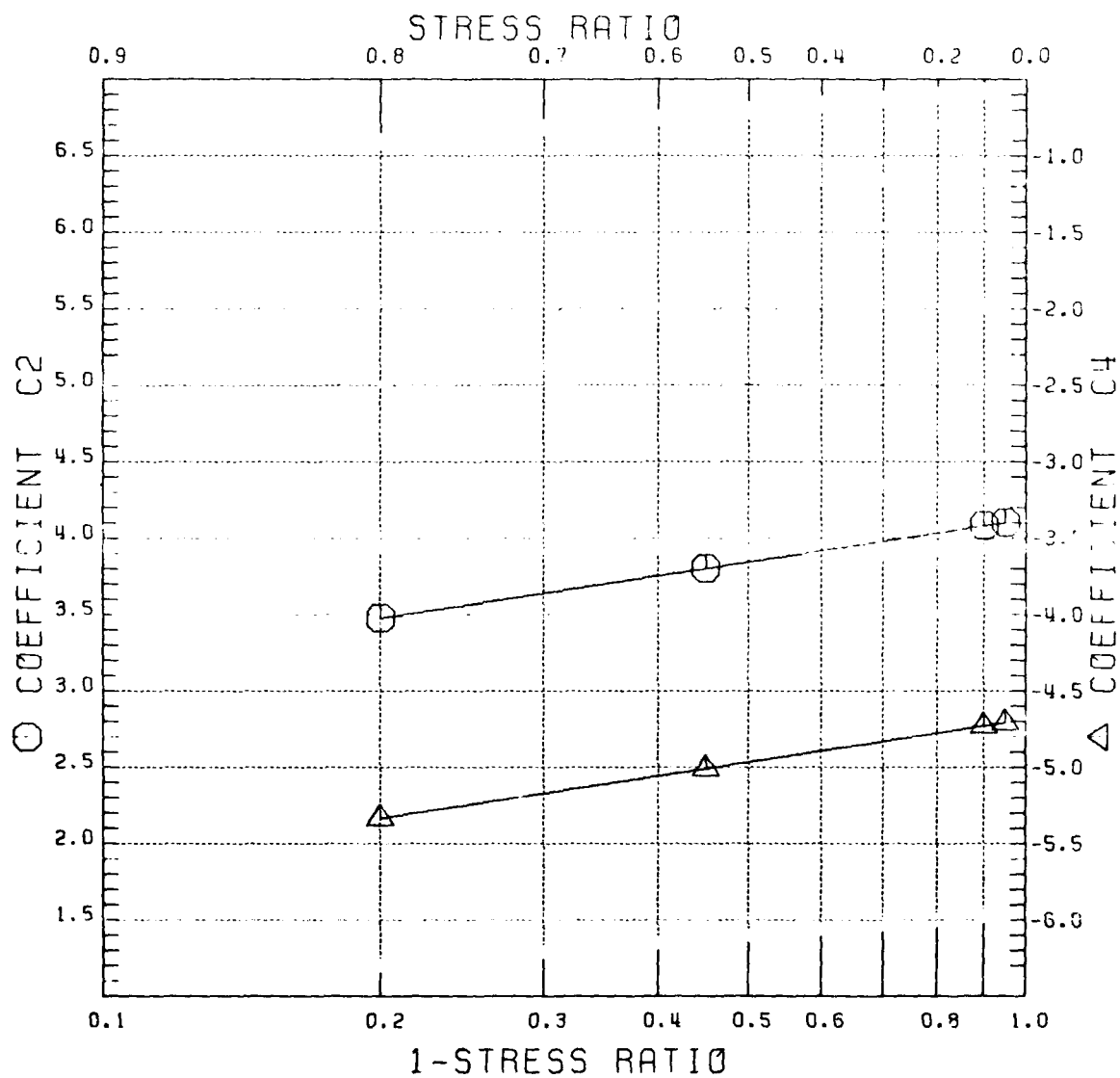
Figure 23. Statistics for Waspaloy (PW-A 1007) Crack Propagation, Stress Ratio Model, 0.167 Hz (10 cpm), 649°C (1200°F)

COEFFICIENTS C2 AND C4 VS. (1-STRESS RATIO)

$$C2 = 4.1226 + 0.9253 \text{ LOG}(1 - \text{STRESS RATIO})$$

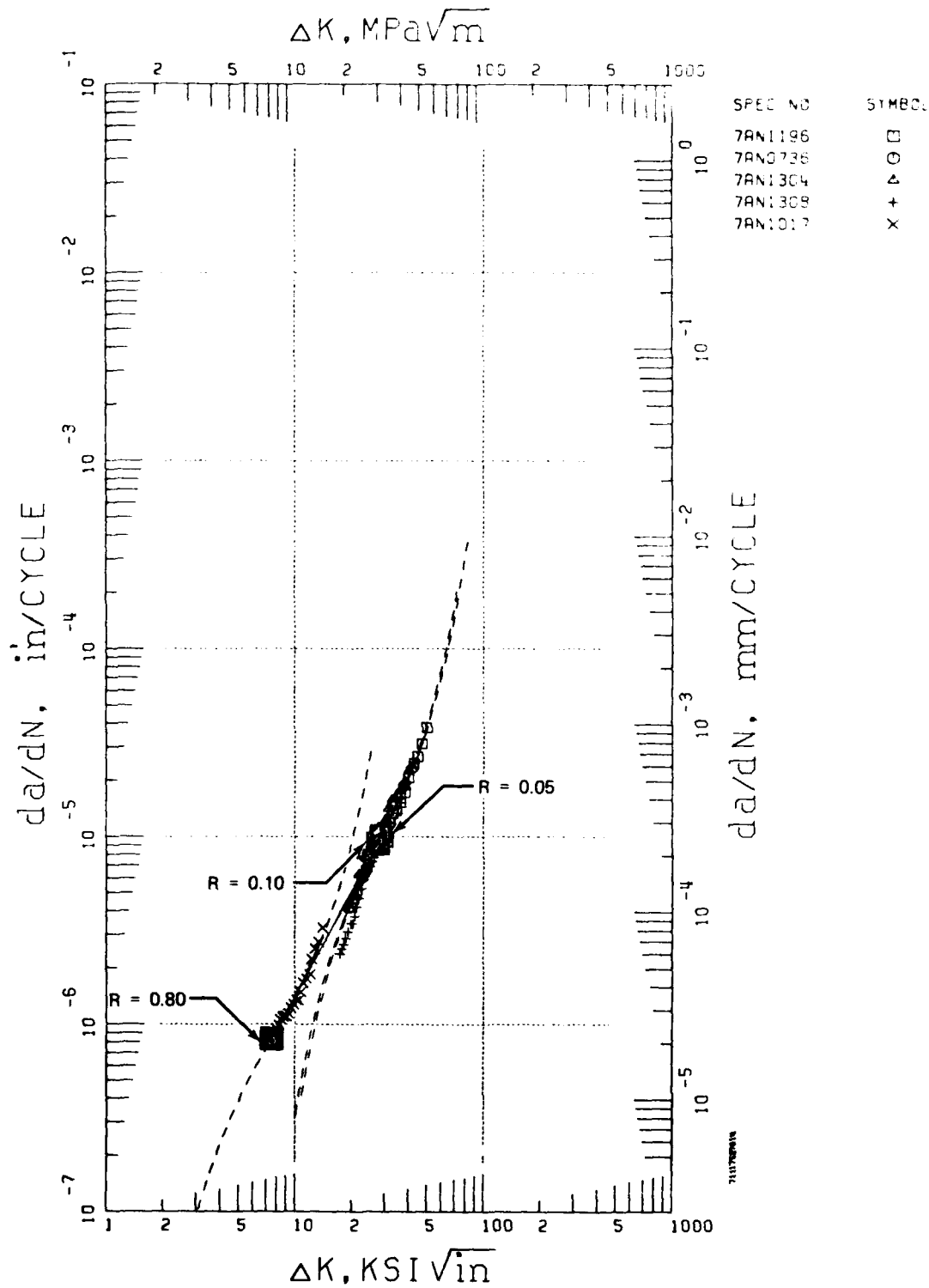
$$C4 = -4.6884 + 0.9248 \text{ LOG}(1 - \text{STRESS RATIO})$$

$$C3 = -4.7039 - 0.6878 C4$$



FD 168089

Figure 24. Waspaloy (PWA 1007) Stress Ratio Model Correlative Parameters, 0.167 Hz (10 cpm), 649°C (1200°F)



FD 168100

Figure 25. Waspaloy (PWA 1007) Crack Propagation, Stress Ratio Model, 20.0 Hz, 649°C (1200°F)

PAGE 71117527914

6 333435363738
 GROUP NO. 1
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN1196 PWA 1007 1200F AIR 20 HZ R=.05 RAD MCT .753 KEYHOLE
 7AN0736 PWA 1007 1200F AIR 20 HZ R=.05 RAD MCT .432 W6
 Y=0.5000 SINH(4.102 (X -1.461)) -5.000
 -0.53 0.
 NRAFT 1 (METRIC) Y=0.5000 SINH(4.102 (X -1.502)) -3.595
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 19.27 , AND X= 50.28 ONLY. DO NOT EXTRAPOLATE.

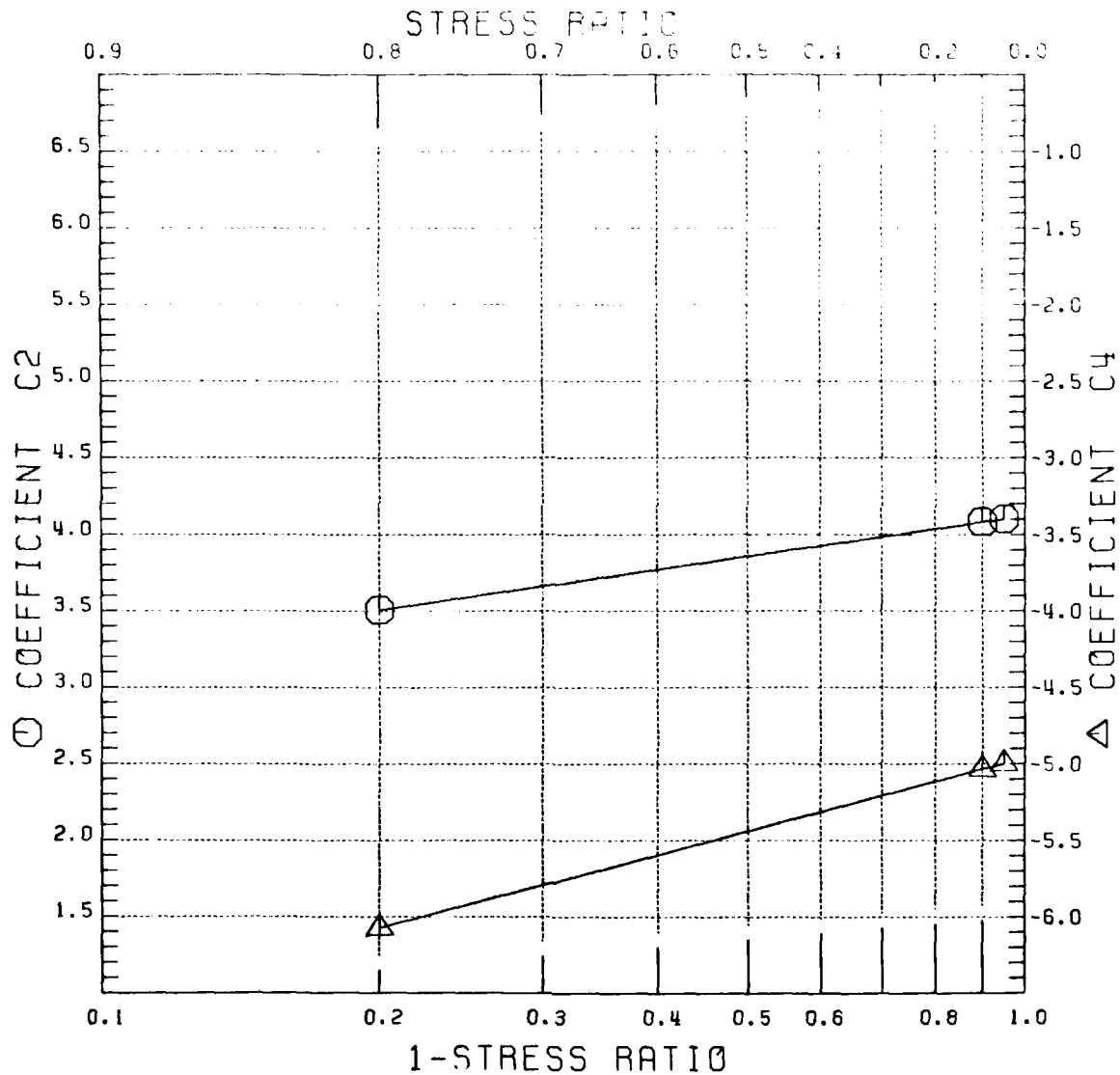
6 333435363738
 GROUP NO. 2
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN1304 PWA 1007 1200F AIR 20 HZ R=.1 RAD MCT .500
 7AN1308 PWA 1007 1200F AIR 20 HZ R=.1 RAD MCT .302
 Y=0.5000 SINH(4.081 (X -1.441)) -5.037
 -0.53 0.
 NRAFT 1 (METRIC) Y=0.5000 SINH(4.081 (X -1.482)) -3.632
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 17.36 , AND X= 40.18 ONLY. DO NOT EXTRAPOLATE.

6 333435363738
 GROUP NO. 3
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN1017 PWA 1007 1200F AIR 20 HZ R=.8 RAD MCT .300
 -0.53 0
 Y=0.5000 SINH(3.506 (X -0.879)) -6.077
 NRAFT 1 (METRIC) Y=0.5000 SINH(3.506 (X -0.920)) -4.672
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 6.92 , AND X= 14.07 ONLY. DO NOT EXTRAPOLATE.
 OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL ASDR = 0.9855. AND STD.ERROR.EST. = 0.0545
 F0 169877

Figure 26. Statistics for Waspaloy (PWA 1007) Crack Propagation, Stress Ratio Model, 20.0 Hz, 649°C (1200°F)

COEFFICIENTS C2 AND C4 VS. 1- STRESS RATIO

$$\begin{aligned} C2 &= -4.1215 + 0.3803 (1-1) \text{ MPa}^{-1/2} \\ C4 &= -4.9044 + 1.5318 (1-1) \text{ MPa}^{-1/2} \\ C3 &= -4.1629 - 0.5404 C4 \end{aligned}$$



FD 169878

Figure 27. Waspaloy (PWA 1007) Stress Ratio Model Correlative Parameters, 20 Hz, 649°C (1200°F)

(d) *Effect of Temperature*

The effect of operating temperature on crack propagation of Waspaloy (PWA 1007) is illustrated in the composite plot of Figure 28. (See also Figure 29.) This SINH model describes the detrimental influence of increasing temperature on crack growth in this alloy. The relationships defining the associated SINH coefficients are presented in Figure 30.

(2) *Crack Propagation Under Periodic Load Dwell*

(a) *Effect of Load Dwell, 649°C (1200°F)*

Crack propagation in Waspaloy (PWA 1007) under periodic load dwell, Figure 12, at 649°C (1200°F) is a function of the period of dwell. Tests conducted with dwells ranging from 120 to 900 sec, were used to develop the interpolative SINH model of the effect of dwell shown in Figure 31. (See also Figure 32.) While experience has demonstrated that the SINH coefficients are linear functions of the log of the period of dwell, this relationship does not completely describe the behavior of data of Figure 31. Coefficients C_2 and C_3 are linear functions, but two linear segments are required to define the behavior of C_4 with period of load dwell. This is shown in the plot of Figure 33.

(b) *Effect of Load Dwell, 732°C (1350°F)*

The crack propagation behavior of Waspaloy (PWA 1007) under periodic load dwell displays a significant dependence on operating temperature. A SINH model developed from data generated in Waspaloy at 732°C (1350°F) under dwells of 120 and 900 sec, is presented in Figure 34. (See also Figure 35.) The interpolative functions describing this behavior are given in Figure 36.

Comparison of the 649°C dwell data with data generated under similar loading at 732°C indicates that crack propagation rate under 900 sec dwell conditions is nearly independent of temperature. However, under 120 sec dwell loading, crack propagation at 732°C is significantly slower than at 649°C as shown in Figure 37. The reduced crack growth rate at the higher temperature is attributed to crack tip blunting which results from an appreciable creep component at 732°C. During the 732°C, 900 sec dwell test, crack tip blunting resulted in crack arrest at values of $\Delta K < 35 \text{ MPa } \sqrt{\text{m}}$ and in general, severely complicated data generation at this condition.

The interactive effect of periodic load dwell and operating temperature is included in the general interpolation algorithm developed under this contract.

(3) *Sustained Load Crack Growth*

Conventional experimental methods for determination of crack propagation behavior under sustained loading call for incremental crack length measurements over the duration of the test. This allows generation of crack growth rate vs applied stress intensity (da/dt vs K) data which characterize crack growth under the conditions of testing.

We have applied an alternative procedure to elevated temperature sustained load crack propagation testing (Reference 2). The underlying assumption of this method is that the sustained load crack growth curve exhibits a sigmoidal shape definable by an equation of the form:

$$da/dt = 10^{**} (C_1 \text{ SINH } (C_2 (\log K + C_3)) + C_4). \quad (24)$$

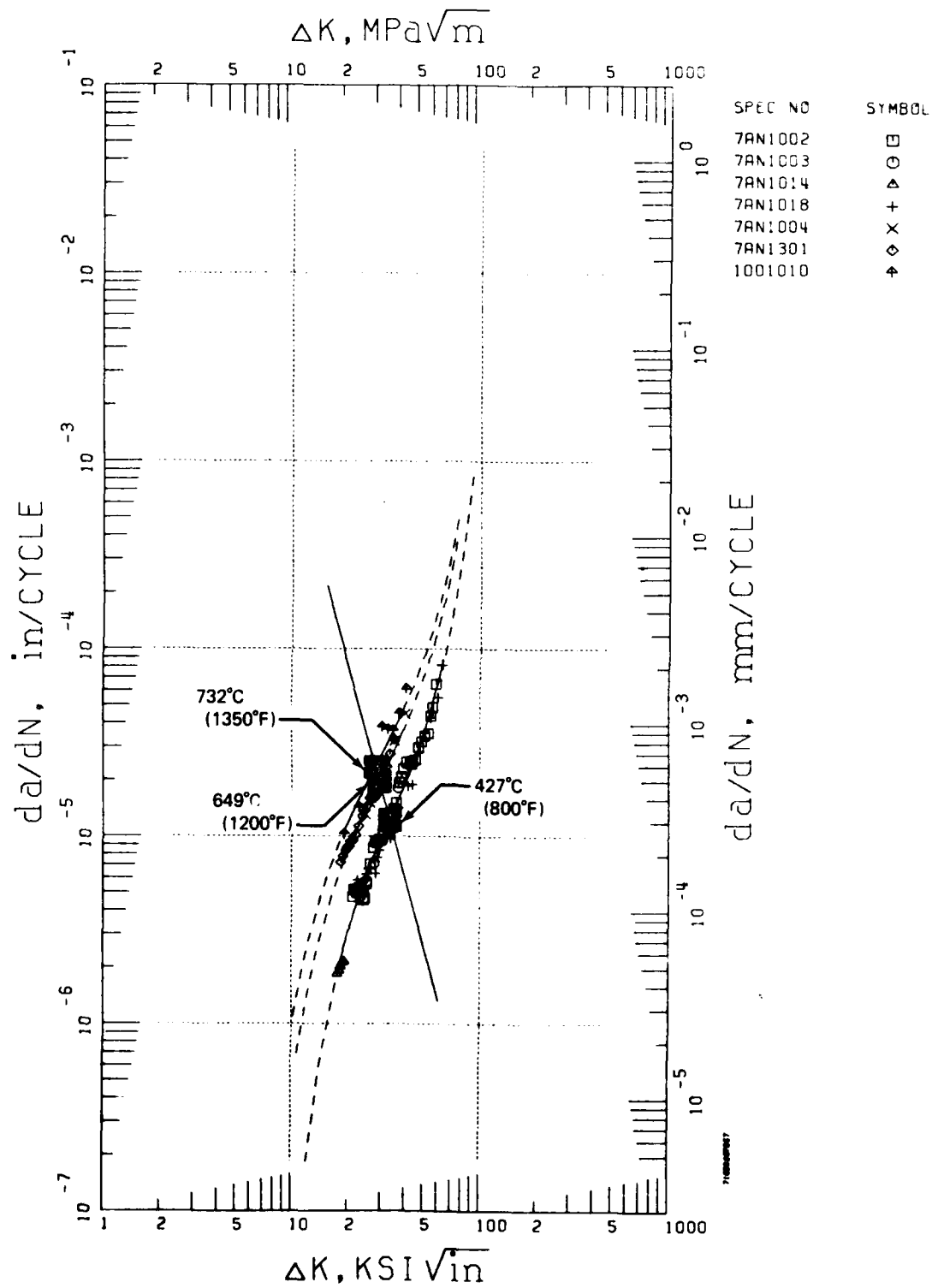


Figure 28. Waspaloy (PWA 1007) Crack Propagation, Temperature Model,
 $R = 0.05, 0.167 \text{ Hz (10 cpm)}$

PAGE 71630267957

R=.05 T=800F FREQ=10CPM
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN1002 PWA 1007 800F AIR 10 CPM R=.05 RAD MCT .499
 7AN1003 PWA 1007 800F AIR 10 CPM R=.05 CN .303
 7AN1014 PWA 1007 800F AIR 10 CPM R=.05 RAD MCT .300 PARTIAL
 7AN1018 PWA 1007 800F AIR 10 CPM R=.05 RAD MCT .298
 -0.35 0.
 NAFT 3
 (METRIC) Y=0.5000 SINH(4.604 (X -1.520)) -4.914;
 (METRIC) Y=0.5000 SINH(4.604 (X -1.561)) -3.509
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=17.55 , AND X=62.89 ONLY. DO NOT EXTRAPOLATE.

R=.05 T=1200F FREQ=10CPM
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN1004 PWA 1007 1200F AIR 10 CPM R=.05 CN .301
 7AN1301 PWA 1007 1200F AIR 10 CPM R=.05 RAD MCT .501
 -0.35 0.
 NAFT 3
 (METRIC) Y=0.5000 SINH(4.102 (X -1.465)) -4.709
 (METRIC) Y=0.5000 SINH(4.102 (X -1.506)) -3.304
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=18.31 , AND X=39.98 ONLY. DO NOT EXTRAPOLATE.

R=.05 T=1350F FREQ=10CPM
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 1001010 PWA 1007 1350F AIR 10 CPM R=.05 CN .301
 -0.35 0.
 NAFT 3
 (METRIC) Y=0.5000 SINH(3.913 (X -1.444)) -4.632
 (METRIC) Y=0.5000 SINH(3.913 (X -1.485)) -3.227
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=18.94 , AND X=40.47 ONLY. DO NOT EXTRAPOLATE.

OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL ASQRD = 0.9785, AND STD.ERROR, EST. = 0.0534

FD 169883

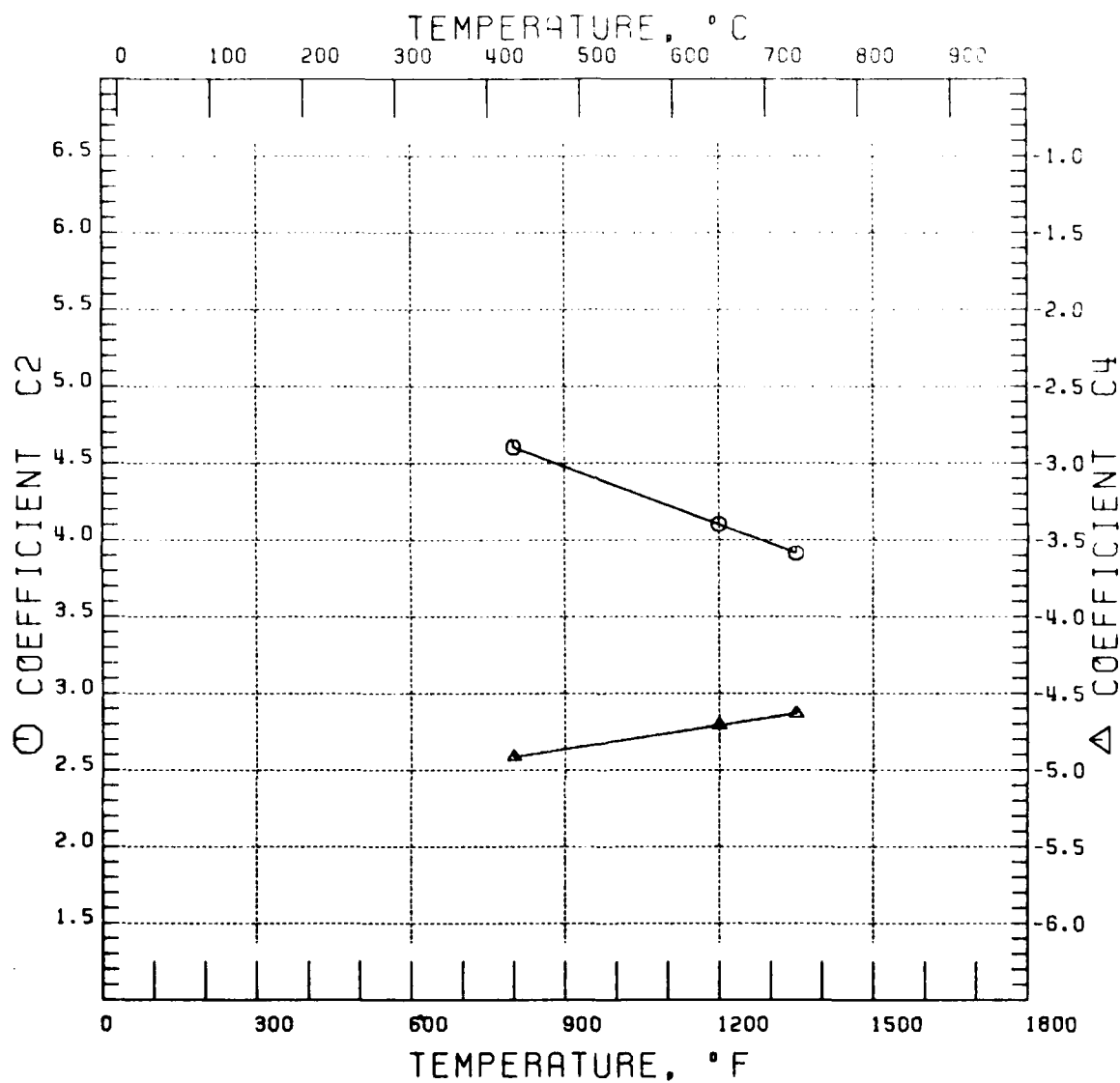
Figure 29. Statistics for Waspaloy (PWA 1007) Crack Propagation, Temperature Model, $R = 0.05$, 0.167 Hz (10 cpm)

COEFFICIENTS C2 AND C4 VS. TEMPERATURE

$$C2 = 5.6090 - 0.0013 \text{ TEMPERATURE}$$

$$C4 = -5.3242 + 0.0005 \text{ TEMPERATURE}$$

$$C3 = -0.1971 + 0.2692 C4$$



FD 169884

Figure 30. Waspaloy (PWA 1007) Temperature Model Correlative Parameters, $R = 0.05$, 0.167 Hz (10 cpm)

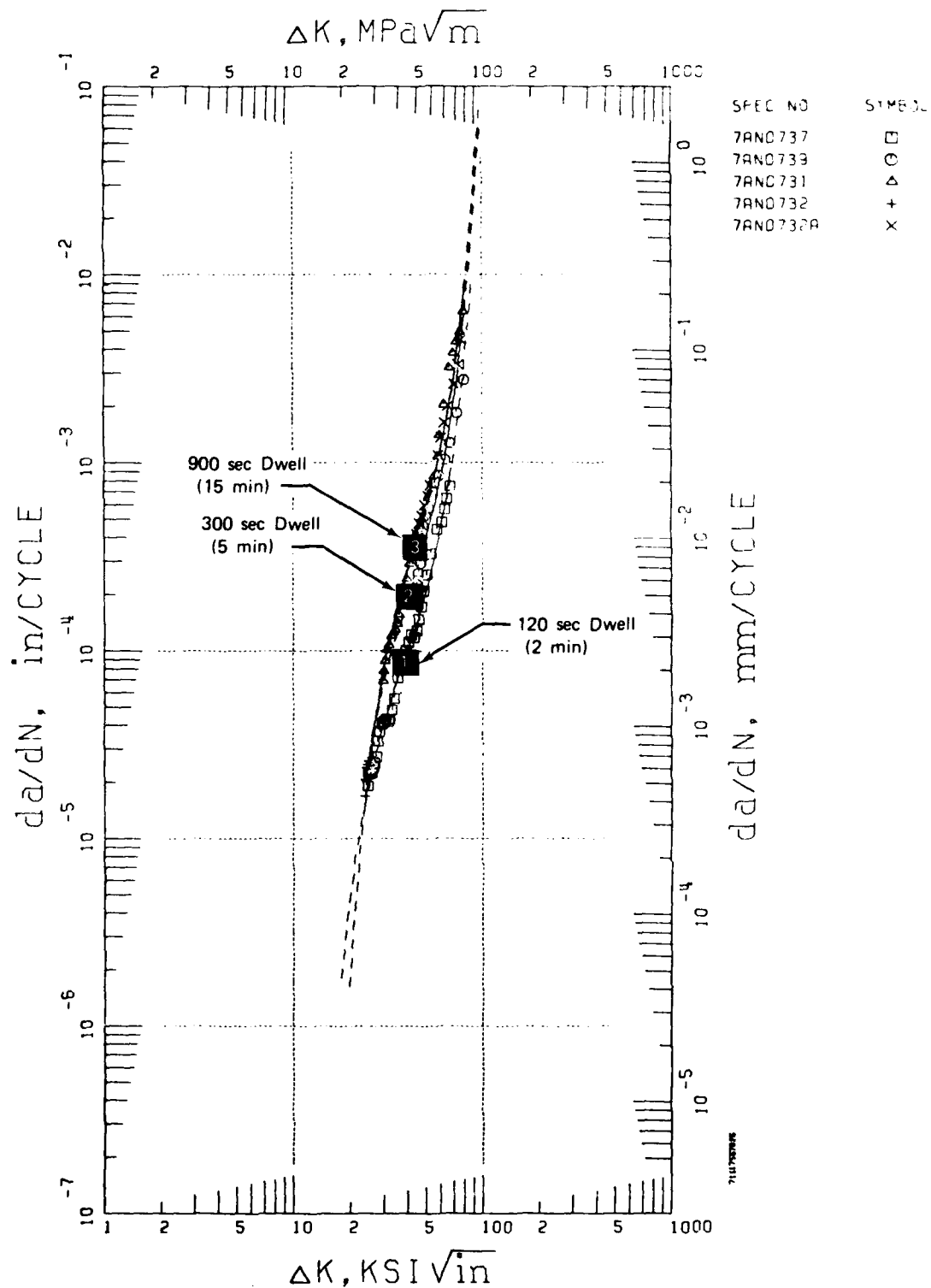


Figure 31. Waspaloy (PWA 1007) Crack Propagation, Dwell Model, $R = 0.05$, 649°C (1200°F)

PAGE 71117557925

TEST CONDITIONS

SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS GROUP NO. 1
 7AN0737 PWA 1007 1200F AIR 2 MDWL R=.05 RAD MCT .316
 -0.74 0.
 Y=0.5000 SINH(5.820 (X -1.584)) -4.054
 (METRIC) Y=0.5000 SINH(5.820 (X -1.625)) -2.649
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 24.68 , AND X= 67.84 ONLY. DO NOT EXTRAPOLATE.
 □ RSQRD 0.9924 SEE 0.0433

TEST CONDITIONS

SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS GROUP NO. 2
 7AN0739 PWA 1007 1200F AIR 5 MDWL R=.05 RAD MCT .377
 -0.74 0.
 Y=0.5000 SINH(6.140 (X -1.610)) -3.707
 (METRIC) Y=0.5000 SINH(6.140 (X -1.651)) -2.302
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 45.03 , AND X= 79.98 ONLY. DO NOT EXTRAPOLATE.
 ○ RSQRD 0.9161 SEE 0.1365

TEST CONDITIONS

SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS GROUP NO. 3
 7AN0731 PWA 1007 1200F AIR 15MDWL R=.05 RAD MCT .417
 7AN0732 PWA 1007 1200F AIR 15MDWL R=.05 RAD MCT .422 LOW K
 7AN0732A PWA 1007 1200F AIR 15MDWL R=.05 RAD MCT .422 HI K
 -0.74 0.
 Y=0.5000 SINH(6.523 (X -1.641)) -3.453
 (METRIC) Y=0.5000 SINH(6.523 (X -1.682)) -2.048
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 23.99 , AND X= 79.75 ONLY. DO NOT EXTRAPOLATE.
 △
 +
 X RSQRD 0.9921 SEE 0.0014
 OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL RSQRD = 0.9893, AND STD.ERROR.EXT. = 0.0721

FD 169889

Figure 32. Statistics for Waspaloy (PWA 1007) Crack Propagation, Duell Model, $R = 0.05$, 649°C (1200°F)

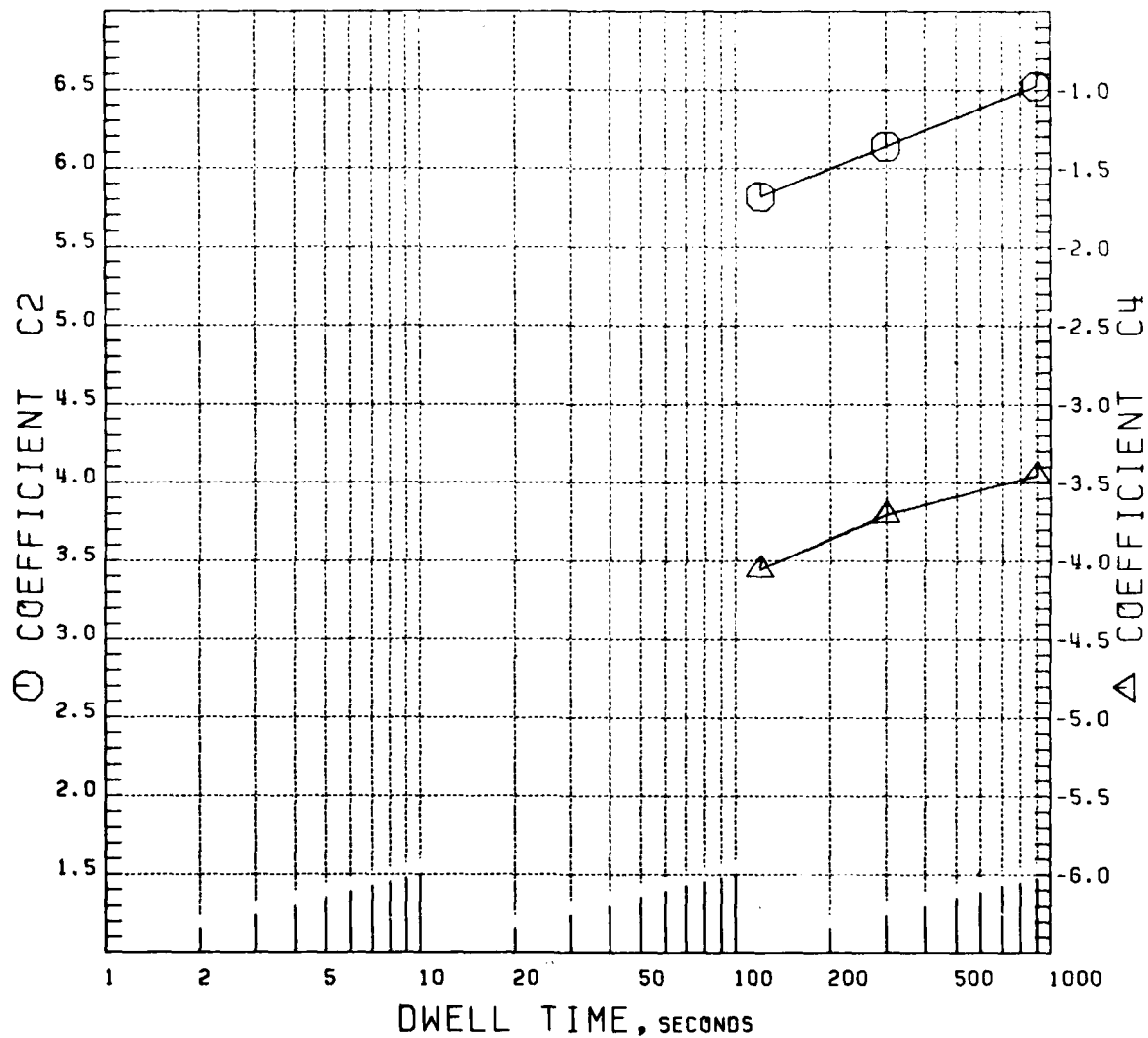
COEFFICIENTS C2 AND C4 VS. DWELL TIME

$$C2 = 4.1498 - 0.8034 (-\log (\text{Dwell Time}))$$

$$C3 = -1.4486 + 0.0651 (-\log (\text{Dwell Time}))$$

$$120 \text{ sec} \leq \text{Dwell} \leq 300 \text{ sec: } C4 = -5.8670 - 0.8720 (-\log (\text{Dwell Time}))$$

$$300 \text{ sec} \leq \text{Dwell} \leq 900 \text{ sec: } C4 = -5.0257 - 0.5324 (-\log (\text{Dwell Time}))$$



FD 169890

Figure 33. Waspaloy (PWA 1007) Dwell Model Correlative Parameters, $R = 0.05$, 649°C (1200°F)

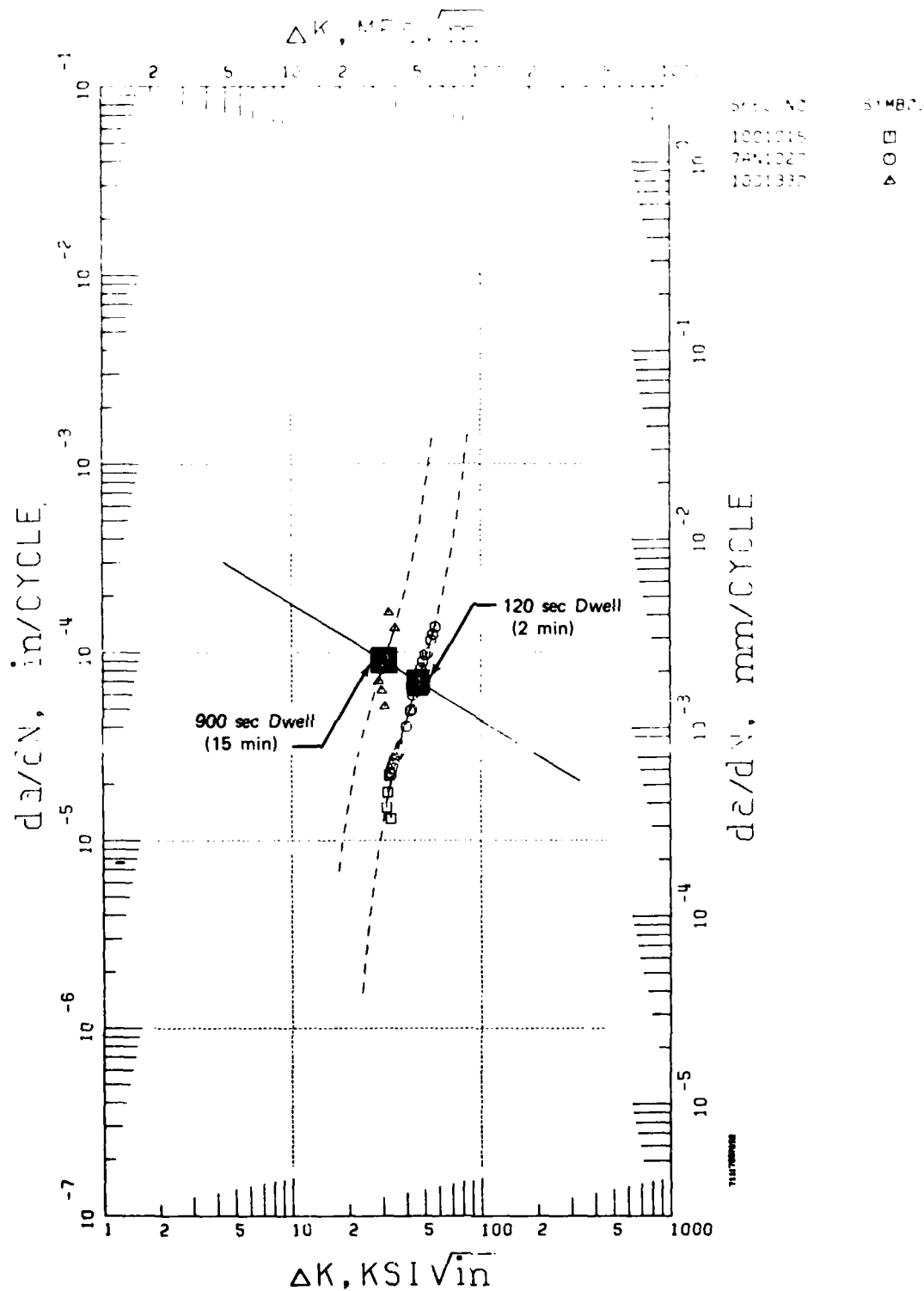


Figure 34. Waspaloy (PWA 1007) Crack Propagation, Dwell Model, $R = 0.10$, 732°C (1350°F)

FD 169893

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TEST CONDITIONS

SPEC NO	MATERIAL	TEMP	ATM	FREQ	A	TYPE	THICK	REMARKS
1001015	PWA 1007	1350F	AIR	2 MDWL	R=-.1	RAO MCT	.300	PARTIAL
7AN1027	PWA 1007	1350F	AIR	2 MDWL	R=-.1	RAO MCT	.299	
								$Y=0.5000 \sinh(6.402(X-1.668)) - 4.156$
								$(\text{METRIC}) Y=0.5000 \sinh(6.402(X-1.709)) - 2.751$
								*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN $X=31.69$, AND $X=57.41$ ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 1

TEST CONDITIONS

SPEC NO	MATERIAL	TEMP	ATM	FREQ	A	TYPE	THICK	REMARKS
1001330	PWA 1007	1350F	AIR	15 MDL	R=-.1	RAO CN	.299	
								$Y=0.5000 \sinh(6.315(X-1.490)) - 4.046$
								$(\text{METRIC}) Y=0.5000 \sinh(6.315(X-1.531)) - 2.641$
								*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN $X=28.38$, AND $X=35.16$ ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 2

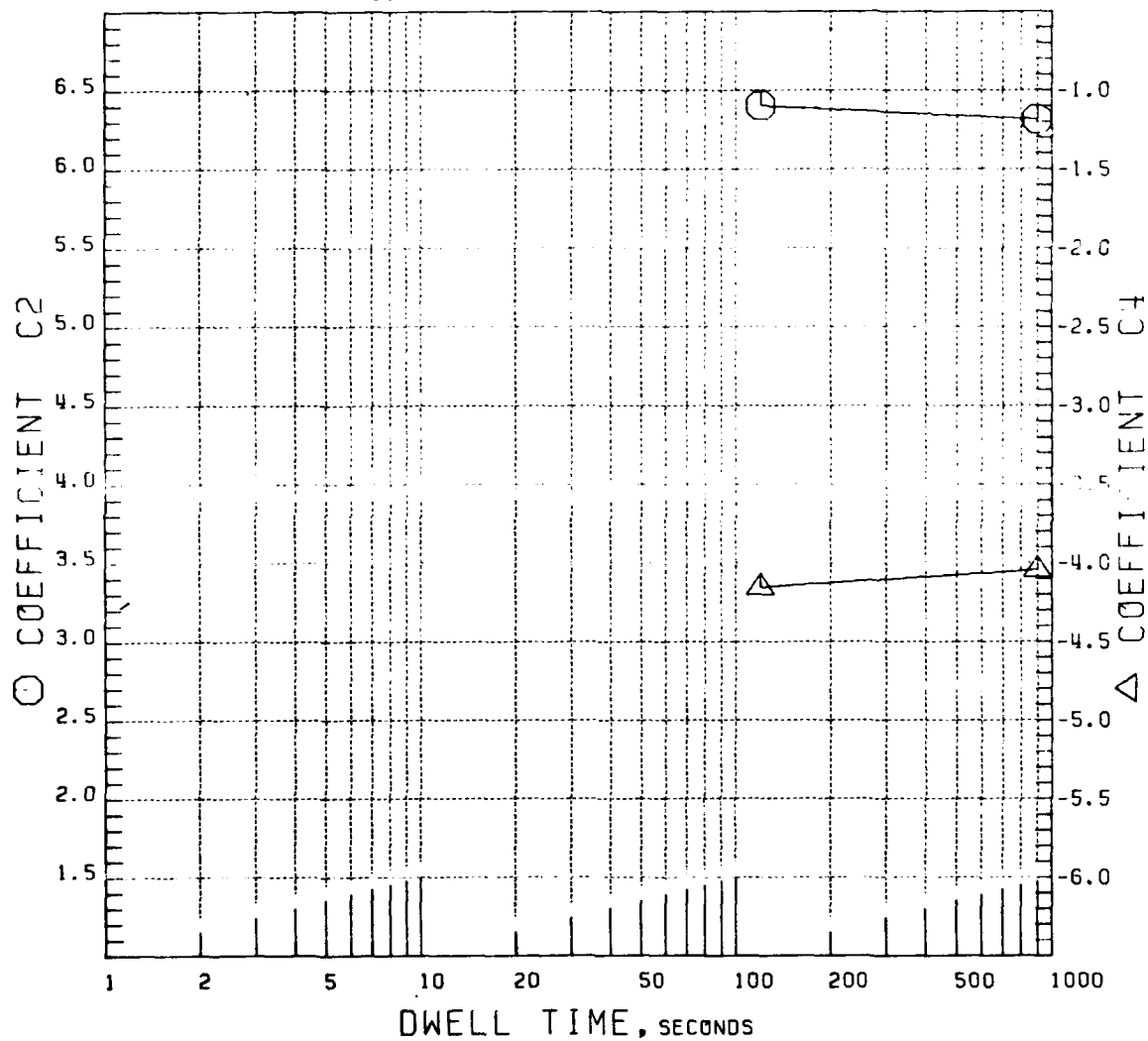
OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL RSOAD = 0.9401. AND STD. ERROR. EST. = 0.0784

FD 169894

Figure 35. Statistics for Waspaloy (PWA 1007) Crack Propagation, Dwell Model, $R = 0.10$, 732°C (1350°F)

COEFFICIENTS C2 AND C4 VS. DWELL TIME

$$\begin{aligned} C2 &= 6.6086 + 0.0994 (-\log(\text{DWELL TIME})) \\ C4 &= -4.4173 - 0.1257 (-\log(\text{DWELL TIME})) \\ C3 &= 5.0572 + 1.6182 C4 \end{aligned}$$



FD 169895

Figure 36. Waspaloy (PWA 1007) Dwell Model Correlative Parameters,
 $R = 0.10$, 732°C (1350°F)

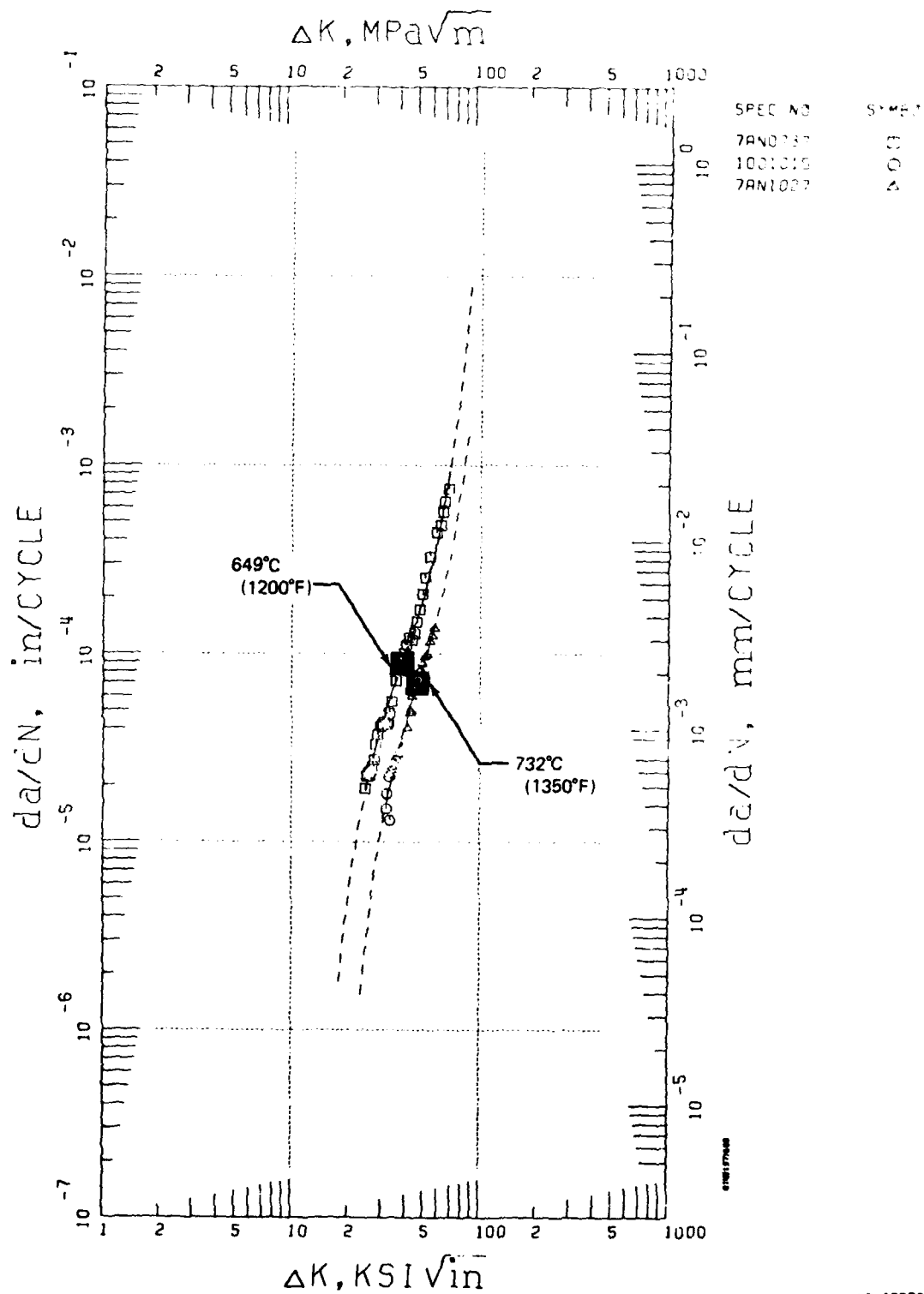


Figure 37. Waspaloy (PWA 1007), Effect of Temperature on Crack Propagation, 120 sec Dwell Loading

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The experimental procedure requires sustained load testing of a series of compact specimens which have been previously fatigue precracked. Test loads for the individual specimens are selected to produce a range of values of initial applied stress intensity for the collection of specimens. Assuming that cracking of all of the specimens follows a mutual propagation ($da/dt, K$) curve, data from the collection of tests may be used to define this propagation curve. The data required include: times of specimen failure, test load, initial (a_i) and final (a_f) crack length, and specimen geometry. The following mathematical procedure is employed to produce the crack growth curve:

- Initialize the coefficients of the crack growth curve at values which are characteristic of the material in question.
- Integrate the reciprocal of the crack growth curve from initial to final crack length to obtain calculated lives (time to failure) for each of the individual test specimens.
- Calculate the summed squared error for the actual vs observed lives for the test specimens.
- Generate a new set of SINH coefficients using the Newton-Raphson to minimize the calculated summed squared error.
- Repeat the last three steps above until convergence is achieved.

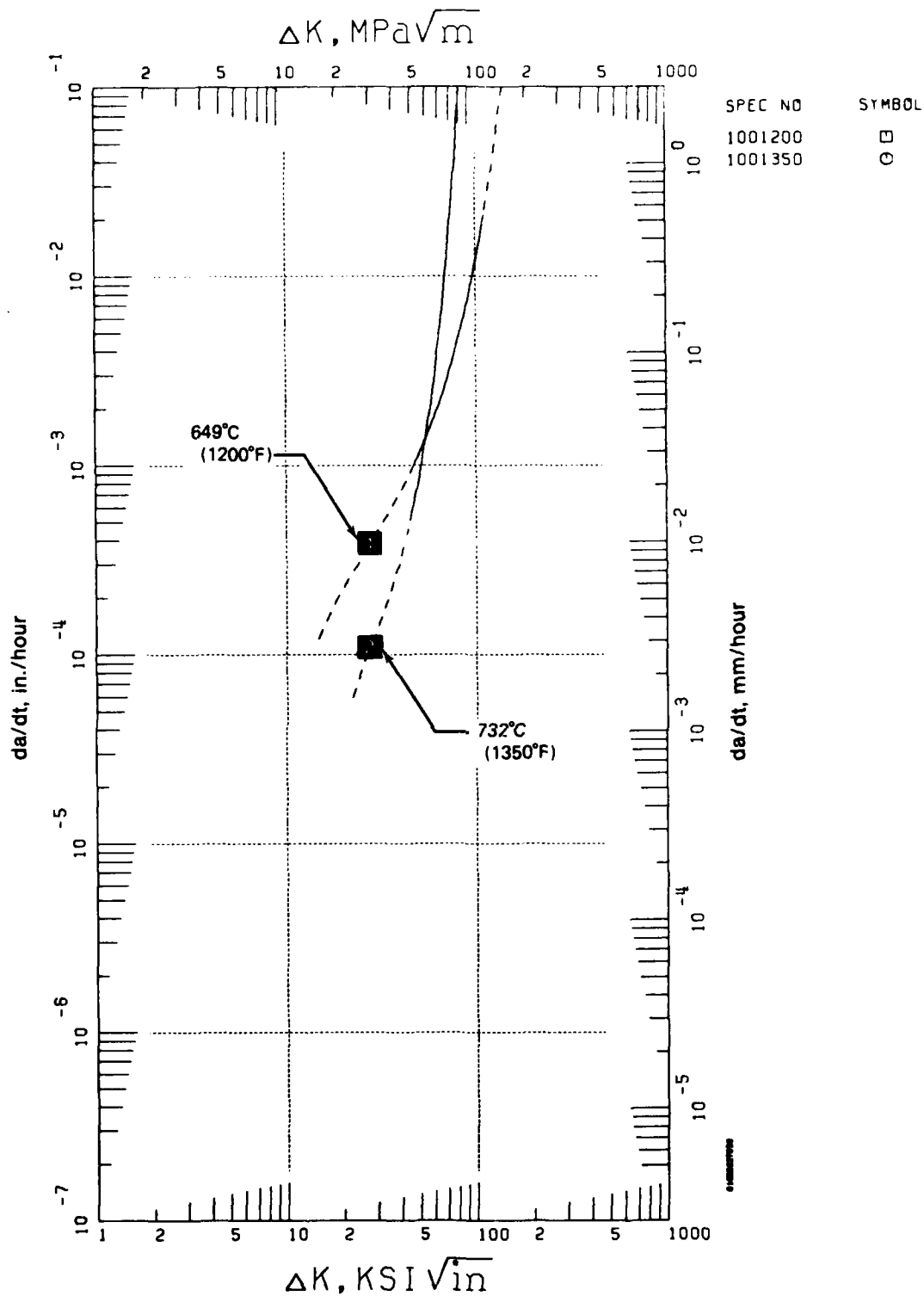
This procedure was applied to determine the sustained load crack growth behavior of Waspaloy (PWA 1007). Nine compact specimens were tested, five at 649°C (1200°F) and four at 732°C, to generate the crack growth model shown in Figure 38. (See also Figure 39.) The range of validity of these curves is approximately $45 \text{ MPa } \sqrt{\text{m}} \leq K \leq 110 \text{ MPa } \sqrt{\text{m}}$, and plotted crack growth rates are approximately equivalent. The crossing of the curves is an artifact of the range of testing, and extrapolation beyond the range of the data should not be attempted.

A plot of the actual vs calculated times to failure for all specimens used to generate the SINH curves is presented in Figure 40. Excellent correlation between actual and calculated lives is shown for the 649°C data. However, considerable difficulty was encountered in modeling sustained load crack propagation at 732°C. The data at this temperature display much less consistency than at 649°C. The basis for the inconsistency probably lies with a combination of factors which include ill-defined crack fronts and crack tunneling.

(4) Synergistic Crack Propagation

(a) LCF — Overload Interaction

Variable amplitude load sequences produce synergistic effects on crack propagation which complicate the life prediction procedure. The nature and significance of crack retardation experienced in turbine disks are discussed in Appendix A. Individual SINH models describing the effects on crack growth under representative load sequences are presented below. The analysis was performed on data generated using repetitive mission cycles as illustrated in Figure 14. As discussed previously (and in Appendix A), the overload-LCF sequence is defined as an "elemental damage event."



FD 169897

Figure 38. Waspaloy (PWA 1007) Crack Propagation Under Sustained Loading

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TEST CONDITIONS

SPEC NO	MATERIAL	TEMP	ATM	FREQ	A	TYPE	THICK	REMARKS	GROUP NO.
1200	-0.45 6. NAFT 0 *** IMPORTANT ***					6 1 2 304 5 6			1
								Y=0.5000 SINH(3.234 (X -1.440)) -3.413 (METRIC) Y=0.5000 SINH(3.234 (X -1.481)) -2.008 THIS EQUATION IS VALID BETWEEN X=45.00 , AND X= 110.00 ONLY. DO NOT EXTRAPOLATE.	0 RSQD 0.0000 SEE 0.0000

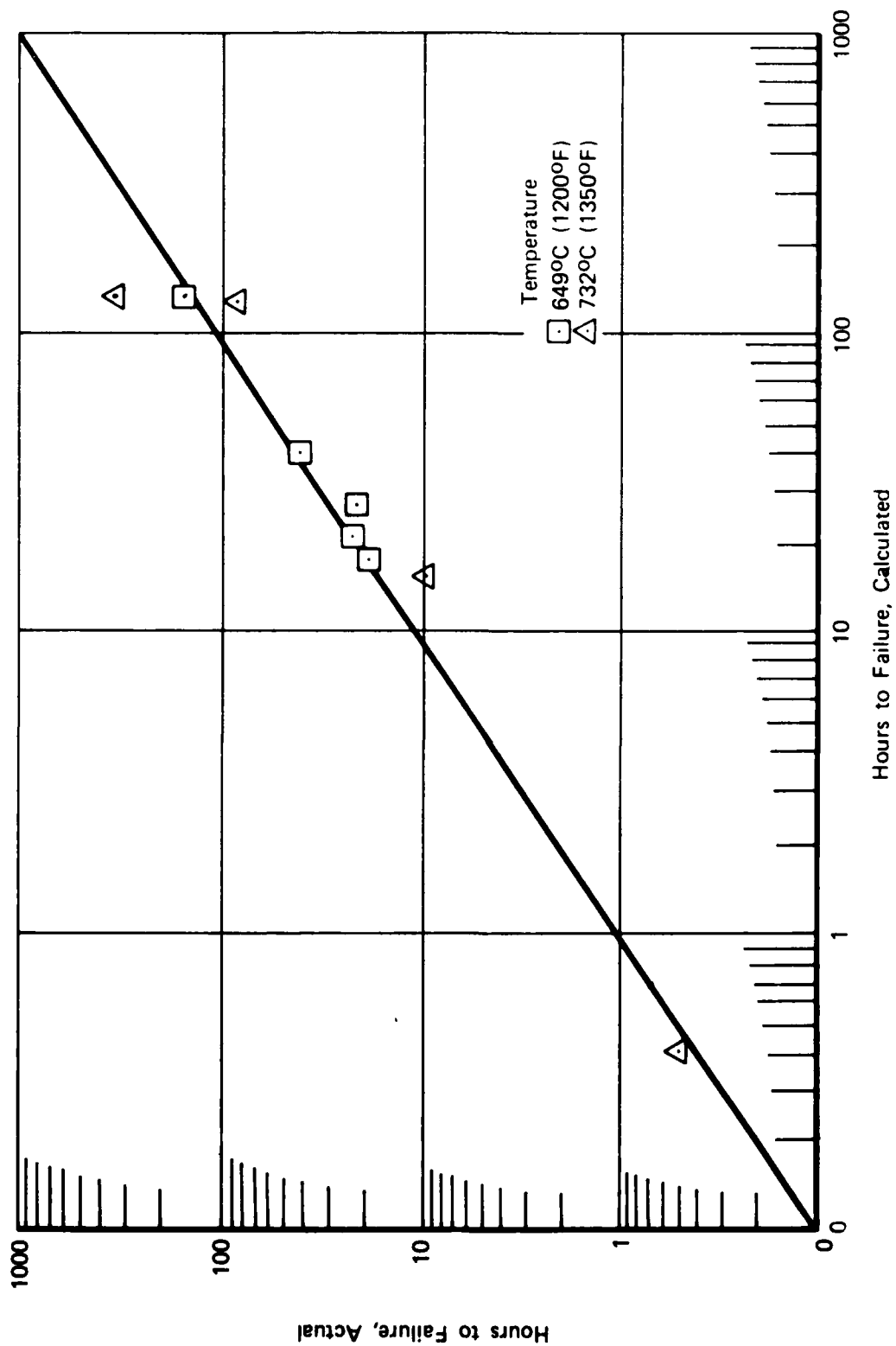
TEST CONDITIONS

SPEC NO	MATERIAL	TEMP	ATM	FREQ	A	TYPE	THICK	REMARKS	GROUP NO.
1350	-0.45 6. NAFT 0 *** IMPORTANT ***					6 1 2 304 5 6			2
								Y=0.5000 SINH(5.197 (X -1.440)) -3.962 (METRIC) Y=0.5000 SINH(5.197 (X -1.481)) -2.557 THIS EQUATION IS VALID BETWEEN X=45.00 , AND X= 110.00 ONLY. DO NOT EXTRAPOLATE.	0 RSQD 0.0000 SEE 0.0000

OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL RSQD = 0.0000. AND STD.ERROR.EST. = 0.0000

FD 169898

Figure 39. Statistics for Waspaloy (PWA 1007) Crack Propagation Under Sustained Loading



FD 169899

Figure 40. Waspaloy (PWA 1007), Actual vs Calculated Time to Failure of Sustained Load Crack Growth Specimens

(1) Effect of Number of Cycles Between Overloads

The number (ΔN_{OL}) of baseline fatigue cycles between successive overloads has a pronounced effect on the average crack growth rate produced by the repetitive loading of Figure 14. For tests under representative load sequence, da/dN vs ΔK data were generated with da/dN defined as the average crack growth per cycle ($\Delta a_{mission}/(\Delta N_{OL} + 1)$) and ΔK defined for the load range ($P_{max} - P_{min}$). Thus, the repetitive overload is treated as an isolated variable influencing crack growth, and the ΔK associated with the overhead is, by convention, equivalent to the baseline ΔK .

The results of testing of Waspaloy (PWA 1007) conducted under conditions of $R = 0.5$, 0.167 Hz, 649°C (1200°F), $OLR = P_{OL}/P_{max} = 1.50$, and $5 \leq \Delta N_{OL} \leq 40$ are presented in a composite, Figure 41. Figure 42 lists the statistics. Under the stated conditions, crack growth rate decreases as ΔN_{OL} increases. The SINH curves represent an interpolative model of the effect of the number of cycles between overloads. As shown in Figure 43, each of the defining SINH coefficients is a linear function of ($\Delta N_{OL} + 1$).

(2) Effect of Overload Ratio

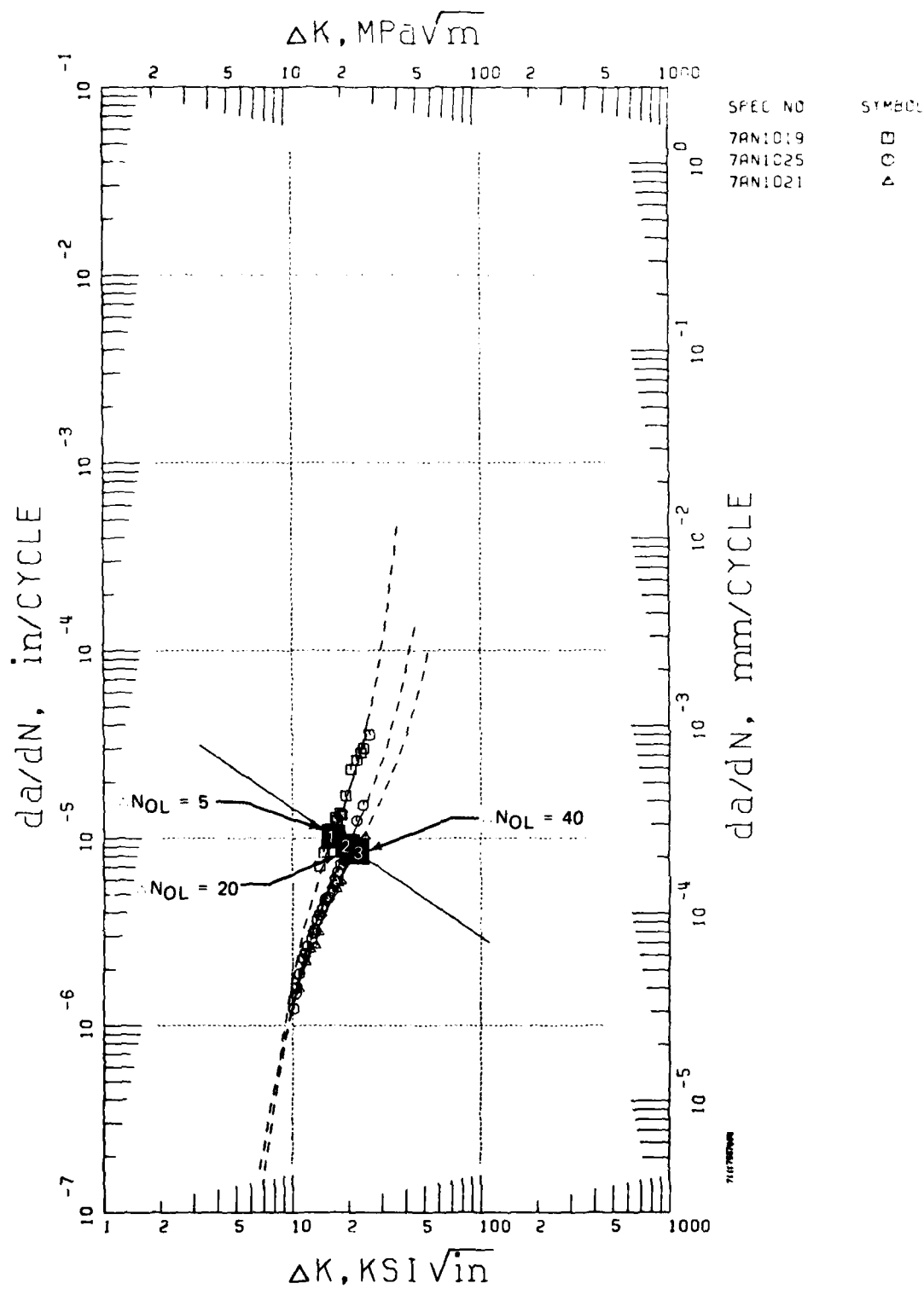
Waspaloy (PWA 1007) crack propagation data generated under periodic overload-fatigue, Figure 14, with overload ratios of 1.25 and 1.50 were investigated. The other conditions of testing were equivalent: $\Delta N_{OL} = 40$, $R = 0.50$, 0.167 Hz, and 649°C (1200°F). Under these conditions, average crack growth rate increases as OLR approaches one. When OLR is equal to one, K_{OL} equals K_{max} , and an observable ΔN_{OL} vanishes. Therefore, for $OLR = 1.0$ the effect of overload ratio reduces to baseline crack growth. This is shown in Figure 44, and the statistics are summarized in Figure 45. The SINH curve for $OLR = 1.0$ is that predicted by the constant load amplitude stress ratio model presented earlier. As shown in Figure 46, the SINH coefficients describing the effect of overload ratio are a linear function of OLR.

(b) LCF - Dwell Interaction

Investigation of possible synergistic interaction within an LCF-dwell sequence was performed using the repetitive mission shown in Figure 13. Crack propagation tests employing this mission were conducted for Waspaloy (PWA 1007) at 649°C (1200°F) and 732°C (1350°F). The crack growth data were reduced with da/dN calculated as the average crack advance per cycle, with the dwell cycle counted as one load cycle.

The results of three 649°C (1200°F) tests of 10, 20, and 40 sawtooth fatigue cycles between dwells of 120 sec produced similar crack growth rates, Figure 47. Furthermore, all of this data is adequately described by the previously developed model of baseline fatigue (0.167 Hz, $R = 0.10$, 649°C). Apparently, there is little interaction or effect on crack growth produced by the periodic application of the load dwell at maximum load under the conditions of testing.

The FCP rate under similar loading at 732°C (1350°F) was also found to be independent of the number of sawtooth cycles separating the periodic load dwells of 120 sec. The data presented in Figure 48 represent three different test conditions: 10, 20, and 40 cycles between dwells. All of this data is described by the single SINH curve shown. An interpolative model of the effect of temperature on crack growth under LCF-Dwell loading is illustrated in Figure 49 and the statistics shown on Figure 50. As shown, crack growth rate is independent of the number of cycles between dwells ($10 \leq \Delta N_{Dwell} \leq 40$) and is a linear function of temperature as shown in Figure 51.



FD 169769

Figure 41. Waspaloy (PWA 1007) Crack Propagation, Model of Effect of the Number of Cycles Between Overloads, $R = 0.50, 0.167 \text{ Hz}$ (10 cpm), 649°C (1200°F)

PAGE 81407407900

3 343638

GROUP NO. 1

SPEC NO MATERIAL TEMP ATM FREQ R TYPE THIK REMARKS

7AN1019 PWA 1007 1200F AIR 10 CPM R=.5 RAD MCT .299 0L1.5+5CY
 Y=0.5000 SIN(5.615 (X -1.218))-4.993
 -0.29 0.
 (METRIC) Y=0.5000 SIN(5.615 (X -1.259))-3.588
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 14.12 , AND X= 25.66 ONLY. DO NOT EXTRAPOLATE.
 GROUP NO. 2

3 343638

GROUP NO. 2

SPEC NO MATERIAL TEMP ATM FREQ R TYPE THIK REMARKS

7AN1025 PWA 1007 1200F AIR 10 CPM R=.5 RAD MCT .300 0L1.5+20CY
 Y=0.5000 SIN(4.461 (X -1.294))-5.043
 -0.29 0.
 (METRIC) Y=0.5000 SIN(4.461 (X -1.335))-3.636
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 10.16 , AND X= 23.77 ONLY. DO NOT EXTRAPOLATE.
 GROUP NO. 3

3 343638

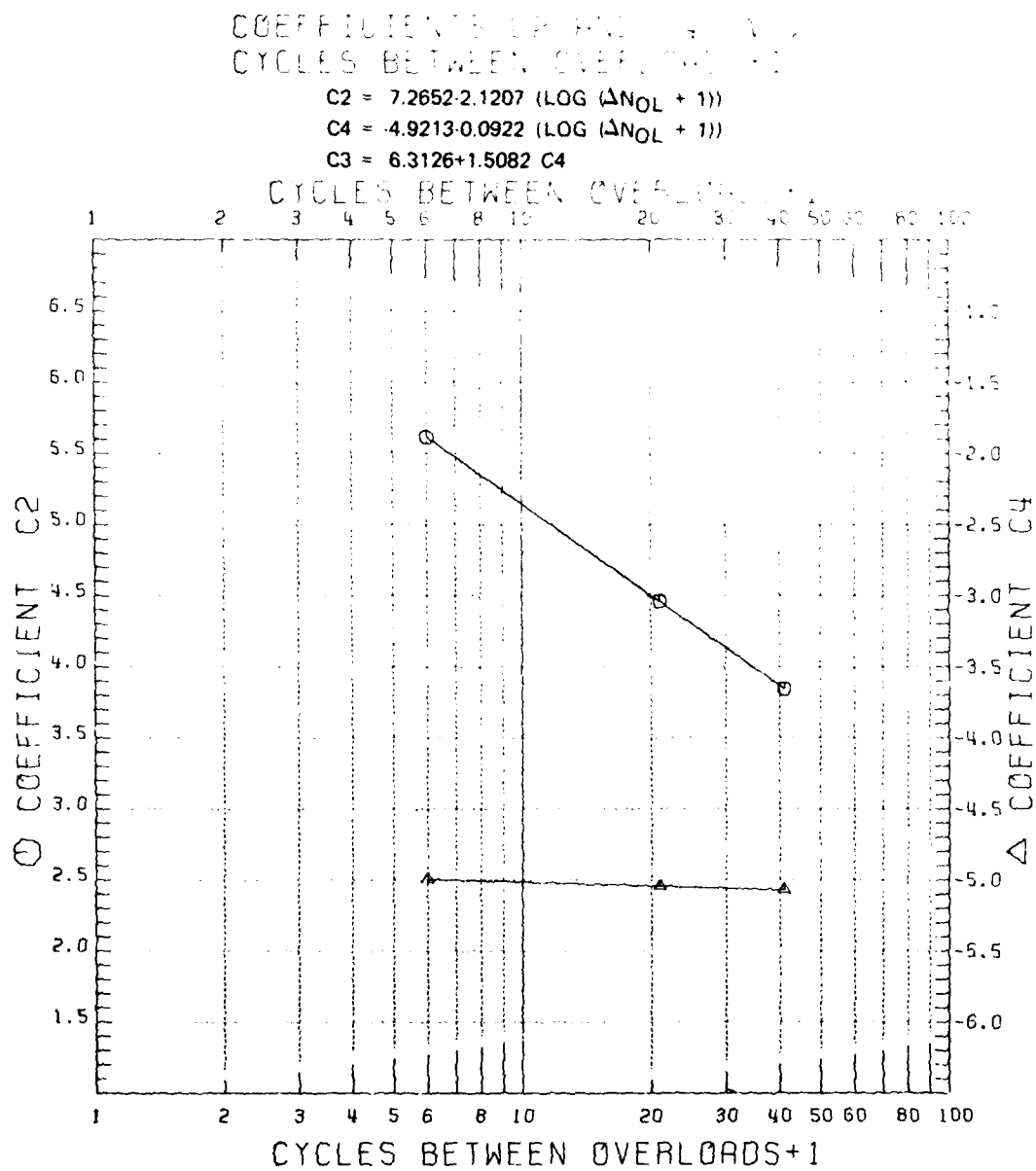
GROUP NO. 3

SPEC NO MATERIAL TEMP ATM FREQ R TYPE THIK REMARKS

7AN1021 PWA 1007 1200F AIR 10 CPM R=.5 RAD MCT .302 0L1.5+40
 Y=0.5000 SIN(3.845 (X -1.334))-5.070
 -0.29 0.
 (METRIC) Y=0.5000 SIN(3.845 (X -1.375))-3.605
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 10.91 , AND X= 24.29 ONLY. DO NOT EXTRAPOLATE.
 GROUP NO. 4

OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL RSQD = 0.9953. AND COEFFICIENT OF VARIATION = 0.0477
 FD 169770

Figure 42. Statistics for Waspalloy (PWA 1007) Crack Propagation, Model of Effect of the Number of Cycles Between Overloads, $R = 0.50$, 0.167 Hz (10 cpm), 649°C (1200°F)



FD 169771

Figure 43. Waspaloy (PWA 1007) Crack Propagation, Correlative Parameters, Model of Effect of ΔN_{OL} , $R = 0.50$, 0.167 Hz (10 cpm), 649°C (1200°F)

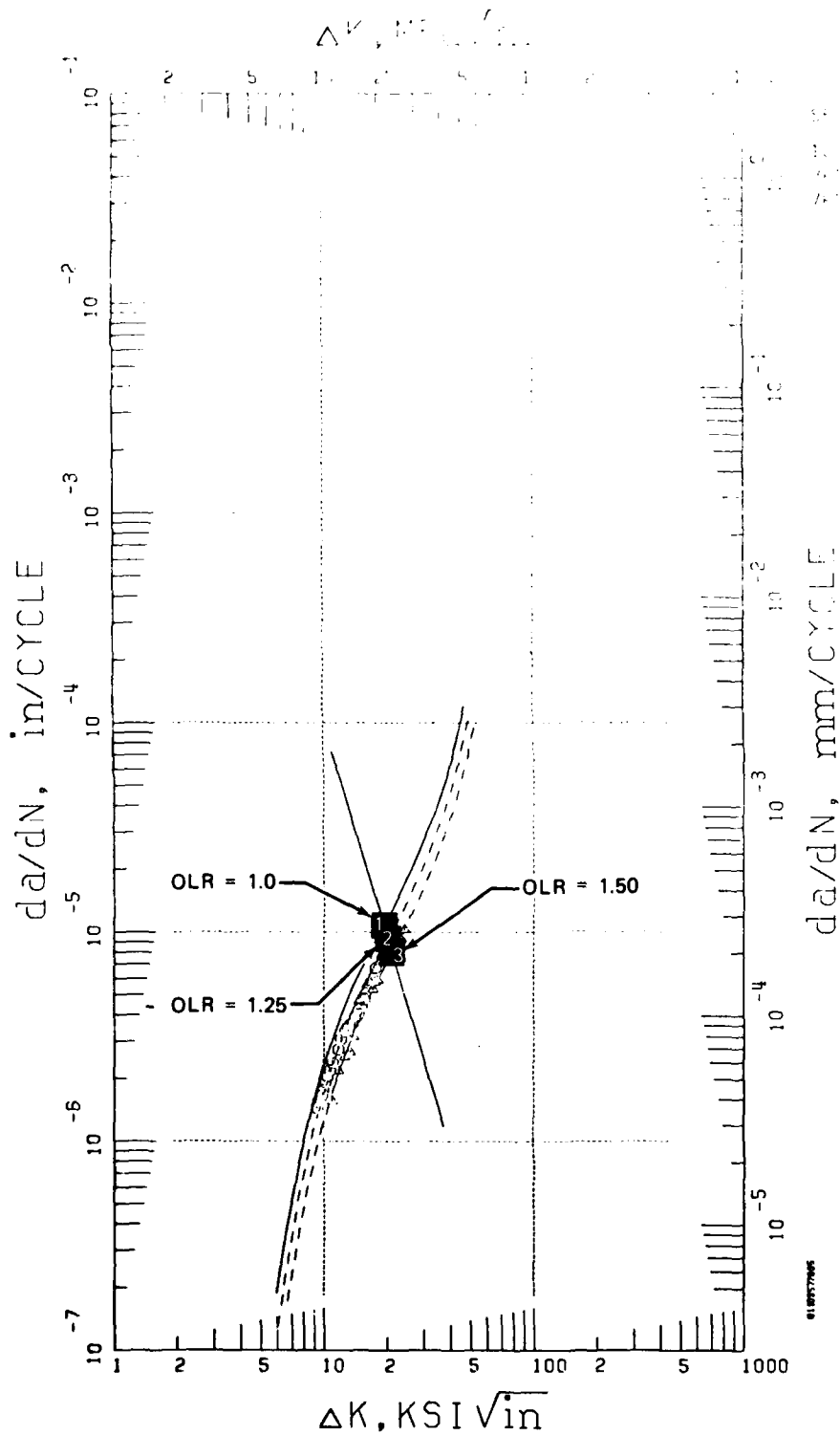


Figure 44. Waspaloy (PWA 1007) Crack Propagation, Overload Ratio Model, $R = 0.50$, 0.167 Hz (10 cpm), $649^{\circ}C$ ($1200^{\circ}F$)

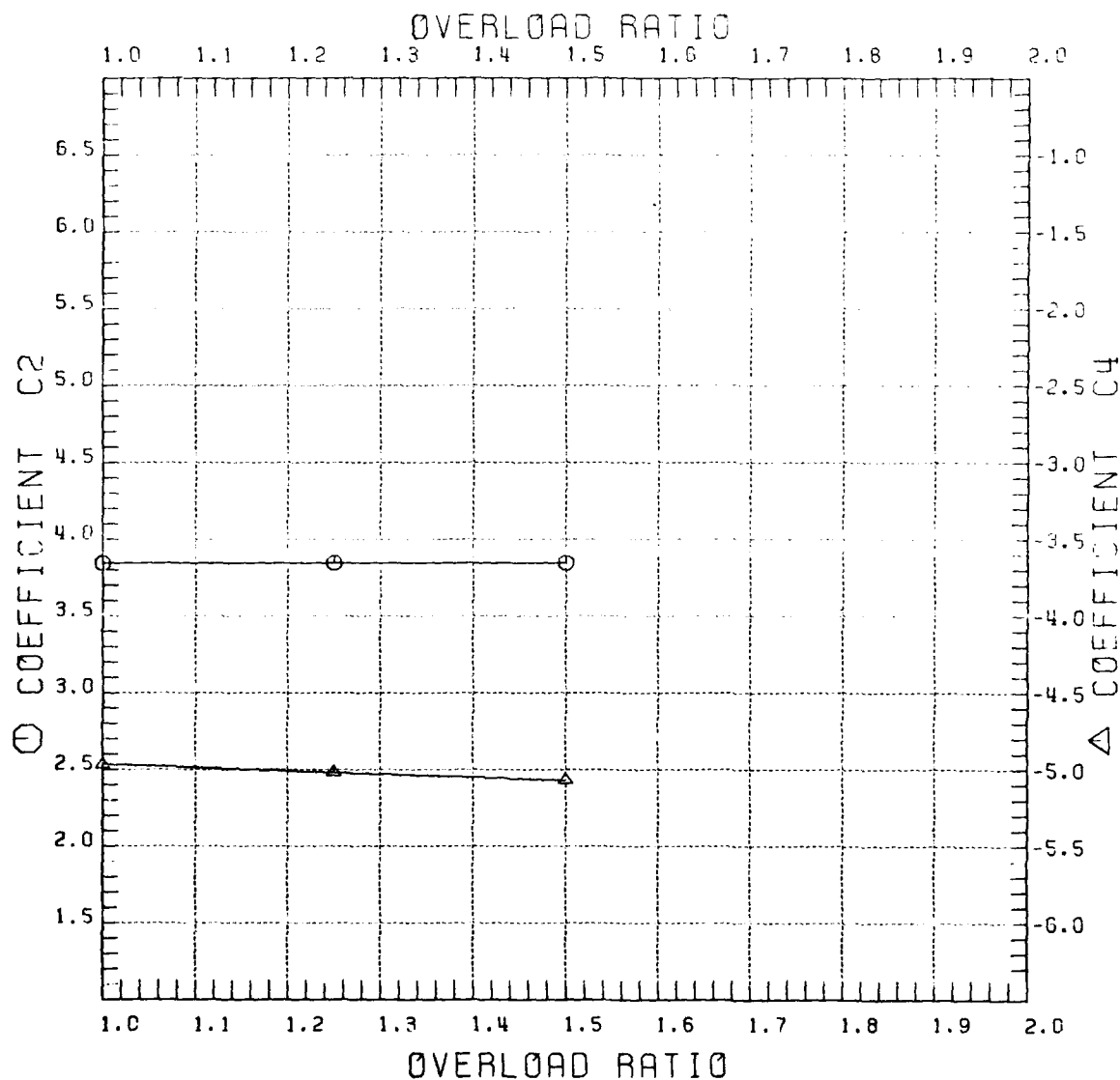
SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	THICK	REMARKS	GROUP NO.
100 BASE	PWA 1007	1200F	AIR	10 CPM	R = 0.5	3 34 36 38		1
-1.45 O.								
NRAFT 6								
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X = 1.00 , AND X = 1000.00 ONLY. DO NOT EXTRAPOLATE.								
OLR = 1.25 + 40 CYCLES								
SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	THICK	REMARKS	GROUP NO.
77AR1028	PWA 1007	1200F	AIR	10 CPM	R = 0.5	3 34 36 38		2
-1.45 O.								
NRAFT 6								
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X = 9.26 , AND X = 22.53 ONLY. DO NOT EXTRAPOLATE.								
OLR = 1.50 + 40 CYCLES								
SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	THICK	REMARKS	GROUP NO.
77AR1021	PWA 1007	1200F	AIR	10 CPM	R = 0.5	3 34 36 38		3
-1.45 O.								
NRAFT 6								
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X = 10.91 , AND X = 24.29 ONLY. DO NOT EXTRAPOLATE.								
OVERALL STATISTICS FOR THIS COLLECTION OF DATA. TOTAL FORD = 0.3121, AND STD. ERROR EST. = 1.0455								

Figure 45. Statistics for Waspaloy (PWA 1007) Crack Propagation, Overload Ratio Model, $R = 0.50$, 0.167 Hz (10 cpm), 649°C (1200°F)

FD 169775

COEFFICIENTS C2 AND C4 VS. OVERLOAD RATIO

$$\begin{aligned} C2 &= 3.8400 + 0.0040 \text{ OLR} \\ C4 &= -4.7630 - 0.2040 \text{ OLR} \\ C3 &= 0.9521 + 0.4510 C4 \end{aligned}$$



FD 169776

Figure 46. Waspaloy (PWA 1007) Crack Propagation, Overload Ratio
Model Correlative Parameters, $R = 0.50$, 0.167 Hz (10 cpm),
 649°C (1200°F)

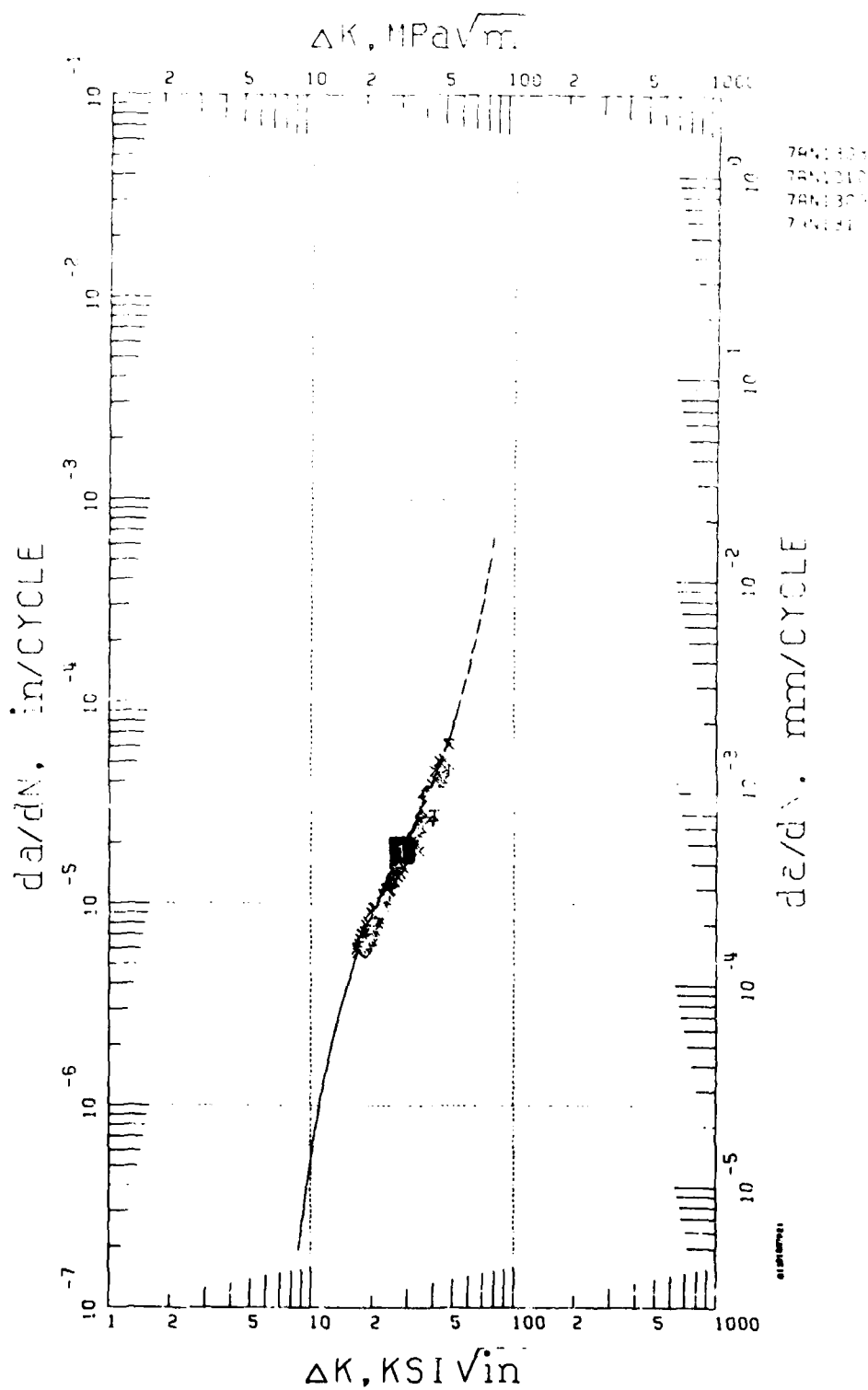


Figure 47. Waspaloy (PWA 1007) Crack Propagation, LCF-Dwell,
 $R = 0.10$, 649°C (1200°F), 0.167 (10 cpm) Sawtooth Fatigue
 Interrupted by Periodic 120 sec Load Dwell, $\Delta N_{\text{Dwell}} = 10, 20,$
 and 40

FD 169777

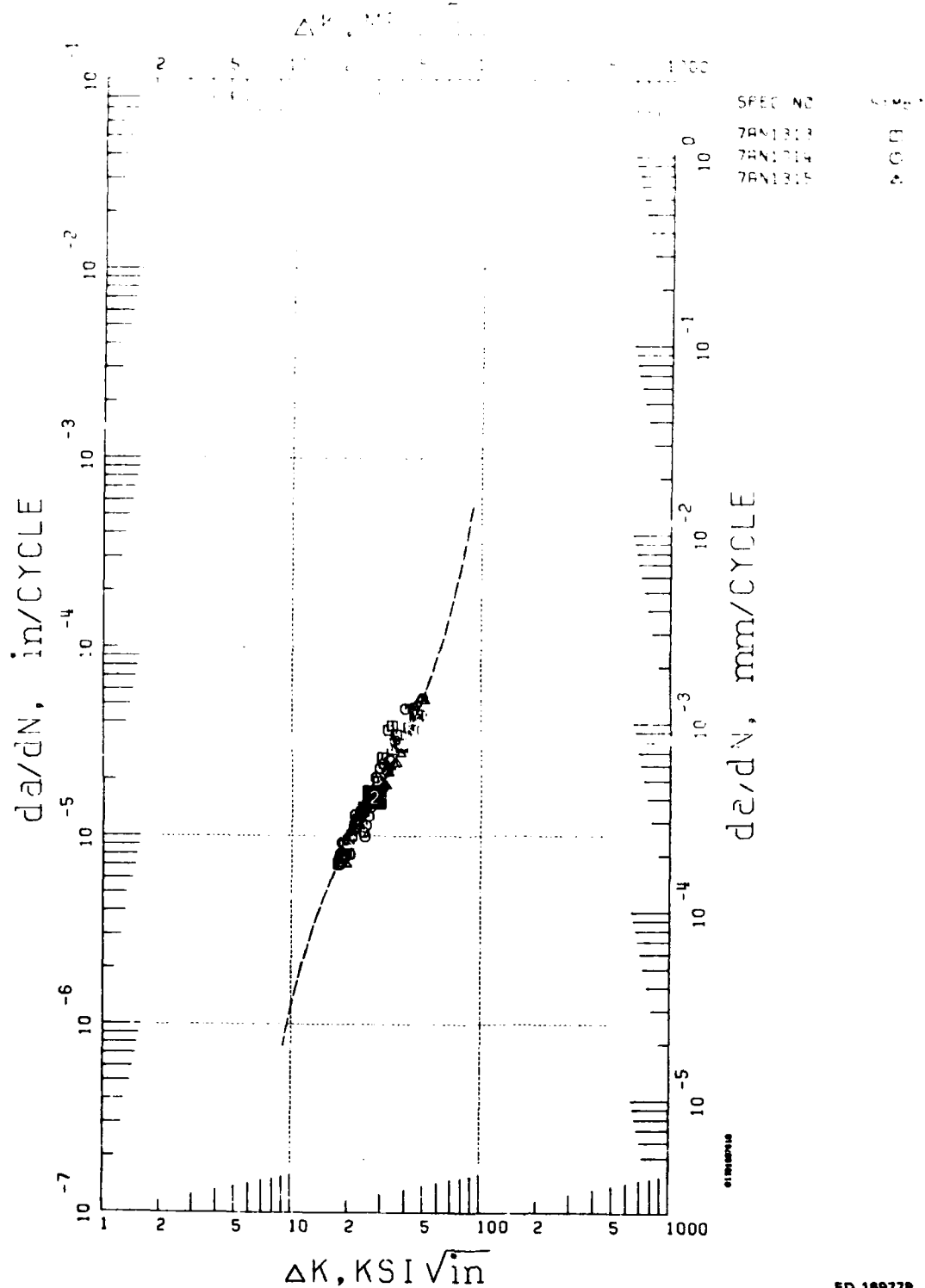


Figure 48. Waspaloy (PWA 1007) Crack Propagation, LCF - Dwell, $R = 0.10$, 732°C (1350°F), 0.167 (10 cpm) Sawtooth Fatigue Interrupted by Periodic 120 sec Load Dwell, $\Delta N_{\text{Dwell}} = 10, 20$, and 40

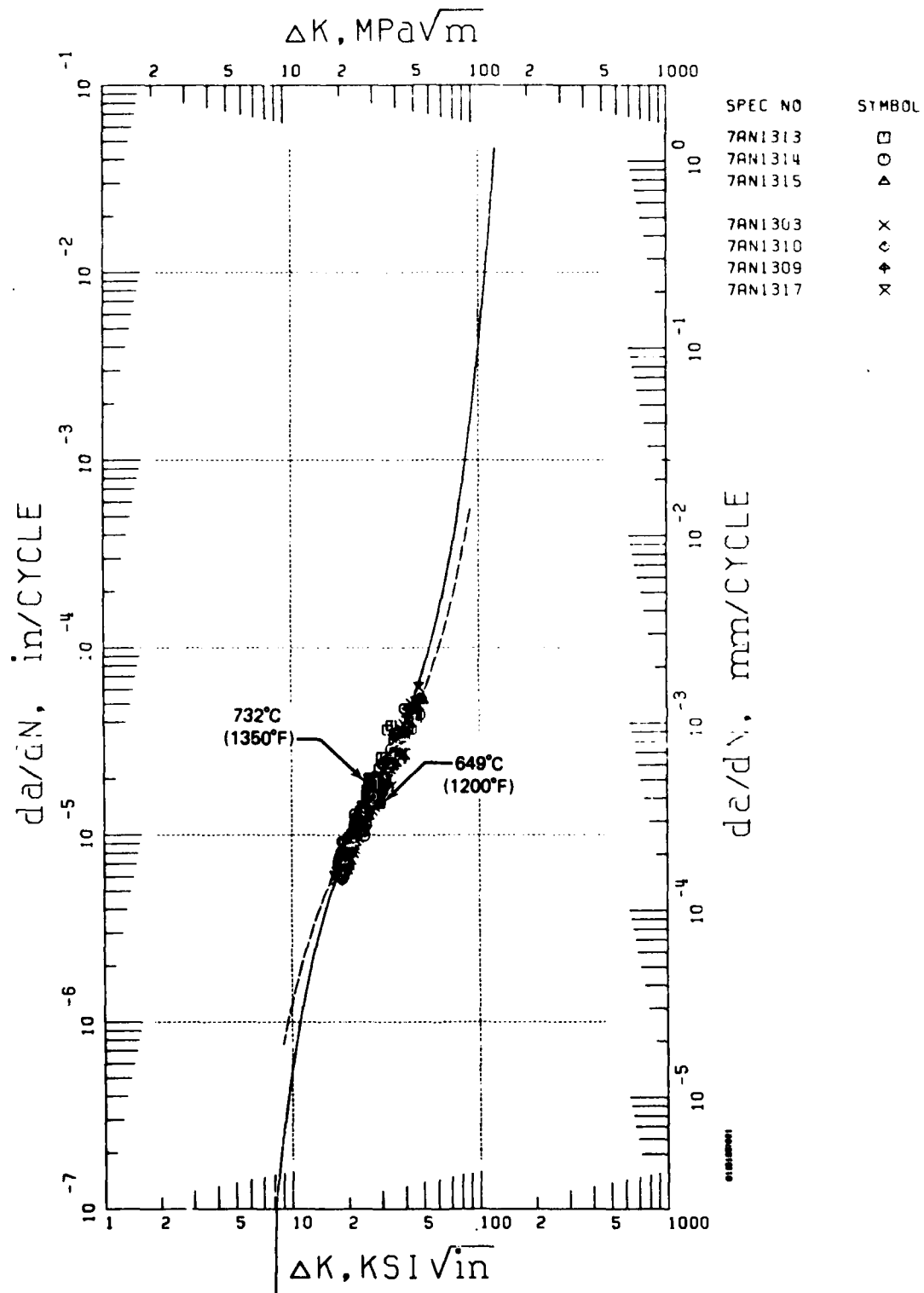


Figure 49. Waspaloy (PWA 1007) Temperature Model of LCF - Dwell Fatigue, $R = 0.10$

FD 169779

PAGE 01607167903

1350F, R=.1,
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN1313 PWA 1007 1350F AIR 10 CPM R=.1 RAD MCT .302 2MDWL+40CY
 7AN1314 PWA 1007 1350F AIR 10 CPM R=.1 RAD MCT .294 2MDWL+20CY
 7AN1315 PWA 1007 1350F AIR 10 CPM R=.1 RAD MCT .299 2MDWL+10CY
 -0.78 D.
 Y=0.5000 SINH(3.534 (X -1.434)) -4.796
 NRAFT 0 (METRIC) Y=0.5000 SINH(3.534 (X -1.475)) -3.391
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 17.75 , AND X= 50.53 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 1

1200F, R=.1,
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN1303 PWA 1007 1200F AIR 10 CPM R=.1 RAD MCT .500 2MDWL+20CY
 7AN1310 PWA 1007 1200F AIR 10 CPM R=.1 RAD MCT .292 2MDWL+20CY
 7AN1309 PWA 1007 1200F AIR 10 CPM R=.1 RAD MCT .304 2MDWL+40CY
 7AN1317 PWA 1007 1200F AIR 10 CPM R=.1 RAD MCT .302 2MDWL+10CY
 -0.78 D.
 Y=0.5000 SINH(4.080 (X -1.450)) -4.731
 NRAFT 0 (METRIC) Y=0.5000 SINH(4.080 (X -1.491)) -3.326
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 16.86 , AND X= 48.17 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 2

OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL RSQRD = 0.6130. AND STD.ERROR.EST. = 1.3272

FD 169780

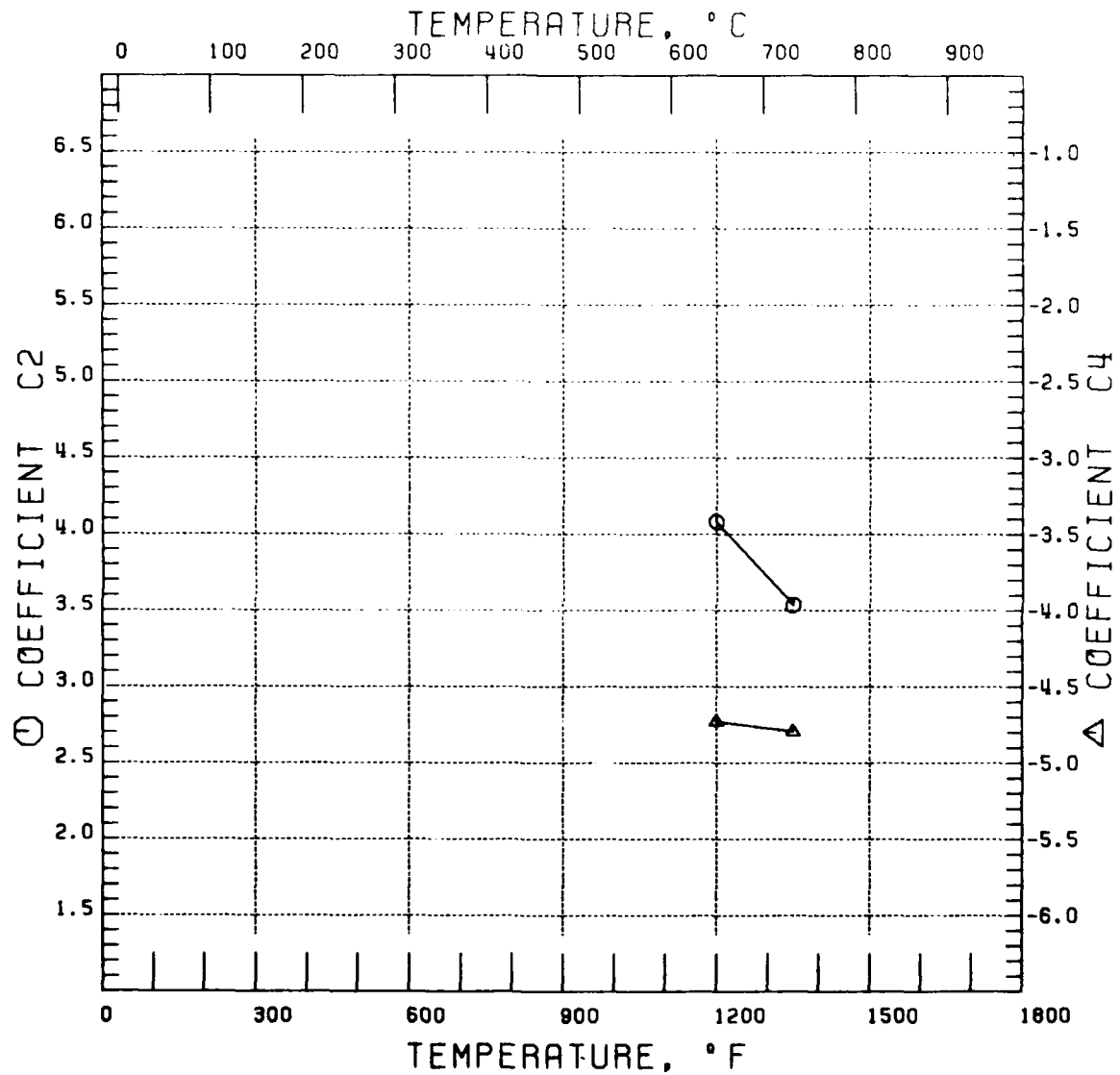
Figure 50. Statistics for Waspaloy (PWA 1007) Temperature Model of LCF-Dwell Fatigue, $R = 0.10$

COEFFICIENTS C2 AND C4 VS. TEMPERATURE

$$C2 = 8.4486 - 0.0036 \text{ TEMPERATURE}$$

$$C4 = -4.2112 - 0.0004 \text{ TEMPERATURE}$$

$$C3 = -2.6199 - 0.2473 \text{ C4}$$



FD 169781

Figure 51. Waspaloy (PWA 1007) Crack Propagation, Correlative Parameters, for Temperature Model of LCF - Dwell Fatigue, $R = 0.10$

b. GATORIZED® IN100 (PWA 1073) Crack Propagation

The majority of the IN100 crack growth data presented in this section were generated under a previous AFML contract (References 1, 2, and 3). Additional data have been produced in testing under the current contract, and data from both sources have been employed in model development. The models are presented in the following sections.

(1) Basic Propagation, Constant Load Amplitude Cycling

(a) Effect of Loading Rate (Frequency)

The influence of cyclic frequency on crack growth in IN100 was examined over the range $0.00833 \text{ Hz (0.5 cpm)} \leq \text{frequency} \leq 20 \text{ Hz}$, at 649°C and $R = 0.1$. An interpolative model of the effect of frequency developed from this data is shown in Figure 52 and Figure 53 shows the statistics. The SINH coefficients C2 and C4 are linear functions of $\log(\text{frequency})$ over the full range of the model. However, this is not the case for the coefficient C3 which locates the abscissa of the SINH inflection points. As illustrated in Figure 54, C3 is represented as a linear function for $0.00833 \text{ Hz (0.5 cpm)} \leq \text{frequency} \leq 0.167 \text{ Hz (10 cpm)}$, and a second function is defined over the range $0.167 \text{ Hz (10 cpm)} \leq \text{frequency} \leq 20 \text{ Hz}$. This relationship was required in order to produce an adequate description of the data over the range of testing. The $0.00833 \text{ Hz (0.5 cpm)}$ data exhibit anomalous test-to-test variability. All specimens were tested at identical conditions ($0.00833 \text{ Hz (10 cpm)}$, $R = 0.10$, 649°C); however, specimen 604 AF exhibited a much slower crack growth rate than the population of tests. In fact, the data of 604 AF agree well with the results of $0.167 \text{ Hz (10 cpm)}$. This variability cannot be attributed to heat-to-heat effects, since specimen 605 AF (which is in agreement with the remaining data) was taken from the same heat of material as 604 AF. While no error in the 604 AF data analysis or the recorded test conditions can be found, an unknown error in testing is believed to be responsible for the anomalous behavior.

(b) Effect of Stress Ratio, 0.167 Hz

An interpolative model of the effect of stress ratio on crack propagation in IN100 (PWA 1073) was developed from data over the range $0.1 \leq R \leq 0.8$. The cyclic frequency was 0.167 Hz and the test temperature was 649°C . The base condition of $R = 0.10$ is defined by a collection of data from six tests and three heats of material. The composite SINH model for the effect of stress ratio is illustrated in Figure 55 and Figure 56 gives the statistics. The associated correlative parameters are linear functions of $\log(1-R)$ for positive stress ratios as shown in Figure 57.

The effect of negative stress ratio fatigue on crack propagation of IN100 is discussed under auxiliary investigations.

(c) Effect of Stress Ratio, 20 Hz

The effect of stress ratio on crack growth in IN100 (PWA 1073) fatigued at a frequency of 20 Hz , is described by the model shown in Figure 58, and Figure 59 reviews the statistics. The defining SINH coefficients are illustrated in Figure 60.

(d) Effect of Temperature

Results of crack propagation testing of IN100 (PWA 1073) conducted at 0.167 Hz , $R = 0.1$, and $538^\circ\text{C (1000}^\circ\text{F)} \leq T \leq 732^\circ\text{C (1350}^\circ\text{F)}$, were used to develop an interpolative SINH model of the effect of temperature. This model is presented in Figure 61, the statistics presented in Figure 62, and the defining SINH coefficients are given in Figure 63.

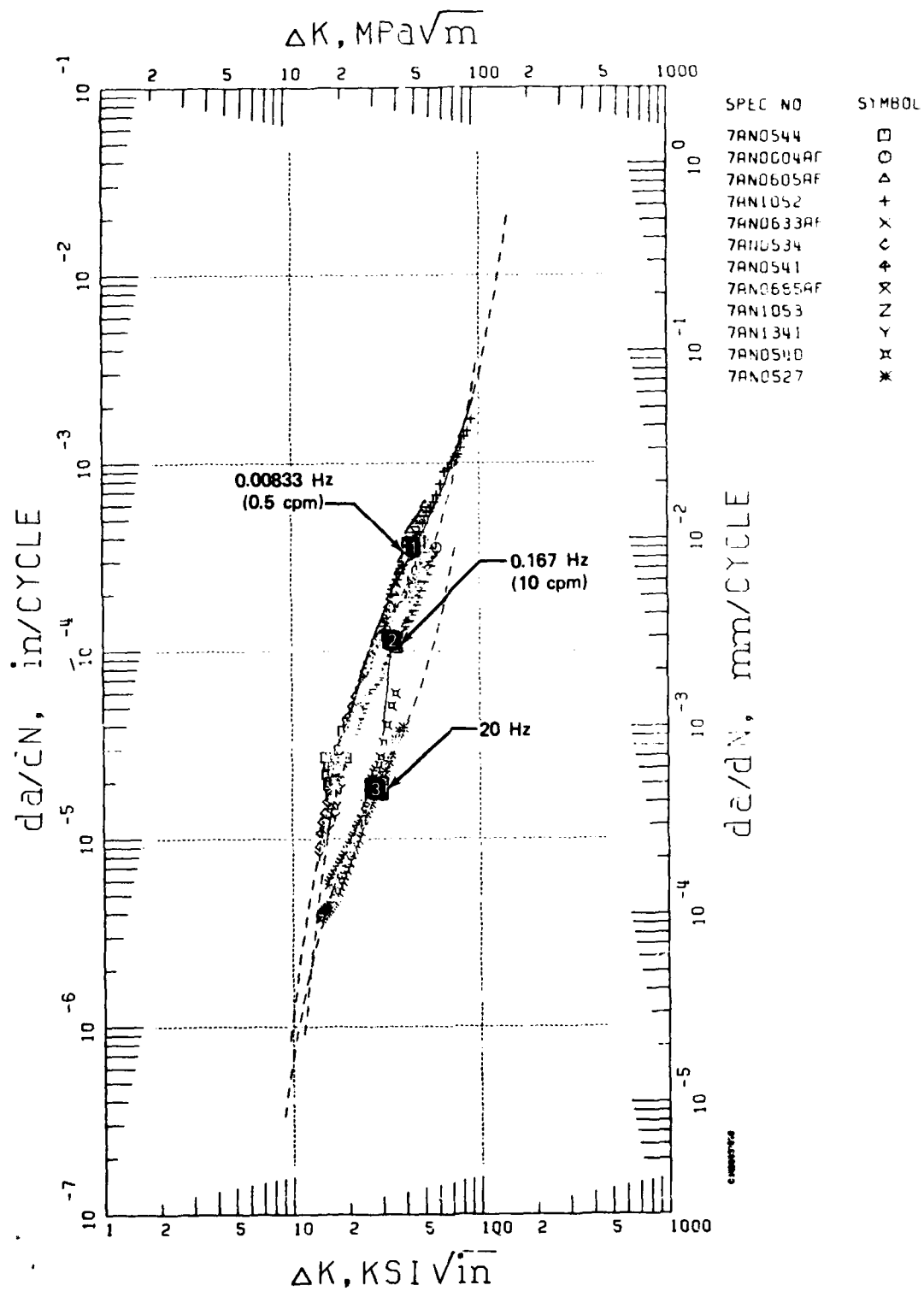


Figure 52. IN100 (PWA 1073) Crack Propagation, Frequency Model,
 $R = 0.10, 649^{\circ}\text{C} (1200^{\circ}\text{F})$

FD 169785

PRGE 81409437948

R=.1 T=1200F FREQ=.5CPM

SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	TYPE	THICK	REMARKS
7A10544	PWA 1073	1200F	AIR	.5 CPM	R=.1	RAJ MCT	.409	BAER
7A10544F	PWA 1073	1200F	AIR	.5 CPM	R=.1	RAJ MCT		
7A10545F	PWA 1073	1200F	AIR	.5 CPM	R=.1	RAJ MCT		
7A10545	PWA 1073	1200F	AIR	.5 CPM	R=.1	RAJ MCT	.285	
Y=0.5000 SIN(3.960 (X -1.651)) -3.454								
NRAFT 2 (METRIC) Y=0.5000 SIN(3.960 (X -1.652)) -3.050								
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=15.11 , AND X= 90.97 ONLY. DO NOT EXTRAPOLATE.								

R=.1 T=1200 FREQ=10CPM

SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	TYPE	THICK	REMARKS
7A10533F	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ MCT	.250	
7A10534	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ MCT	.5	
7A10541	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ MCT	.4995	HAEP
7A10545F	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ MCT	.870	
7A10545	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ MCT	.299	
7A10541	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ MCT	.296	
Y=0.5000 SIN(3.961 (X -1.525)) -3.947								
NRAFT 2 (METRIC) Y=0.5000 SIN(3.961 (X -1.570)) -3.542								
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=13.76 , AND X= 55.79 ONLY. DO NOT EXTRAPOLATE.								

R=.1 T=1200F FREQ=20HZ

SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	TYPE	THICK	REMARKS
7A10540	PWA 1073	1200F	AIR	20 HZ	R=.1	RAJ MCT	.412	
7A10527	PWA 1073	1200F	AIR	20 HZ	R=.1	RAJ MCT	.25	BA1083H28 R
Y=0.5000 SIN(3.962 (X -1.448)) -4.734								
NRAFT 2 (METRIC) Y=0.5000 SIN(3.962 (X -1.488)) -3.829								
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=14.07 , AND X= 39.07 ONLY. DO NOT EXTRAPOLATE.								

OVERALL STATISTICS FOR THIS COLLECTION OF CAPS. TOTAL RESORD = 0.9783, AND SID. ERROR. EST. = 0.0861

FD 140786

Figure 53. Statistics for IN100 (PWA 1073) Crack Propagation, Frequency Model, R = 0.10, 649°C (1200°F)

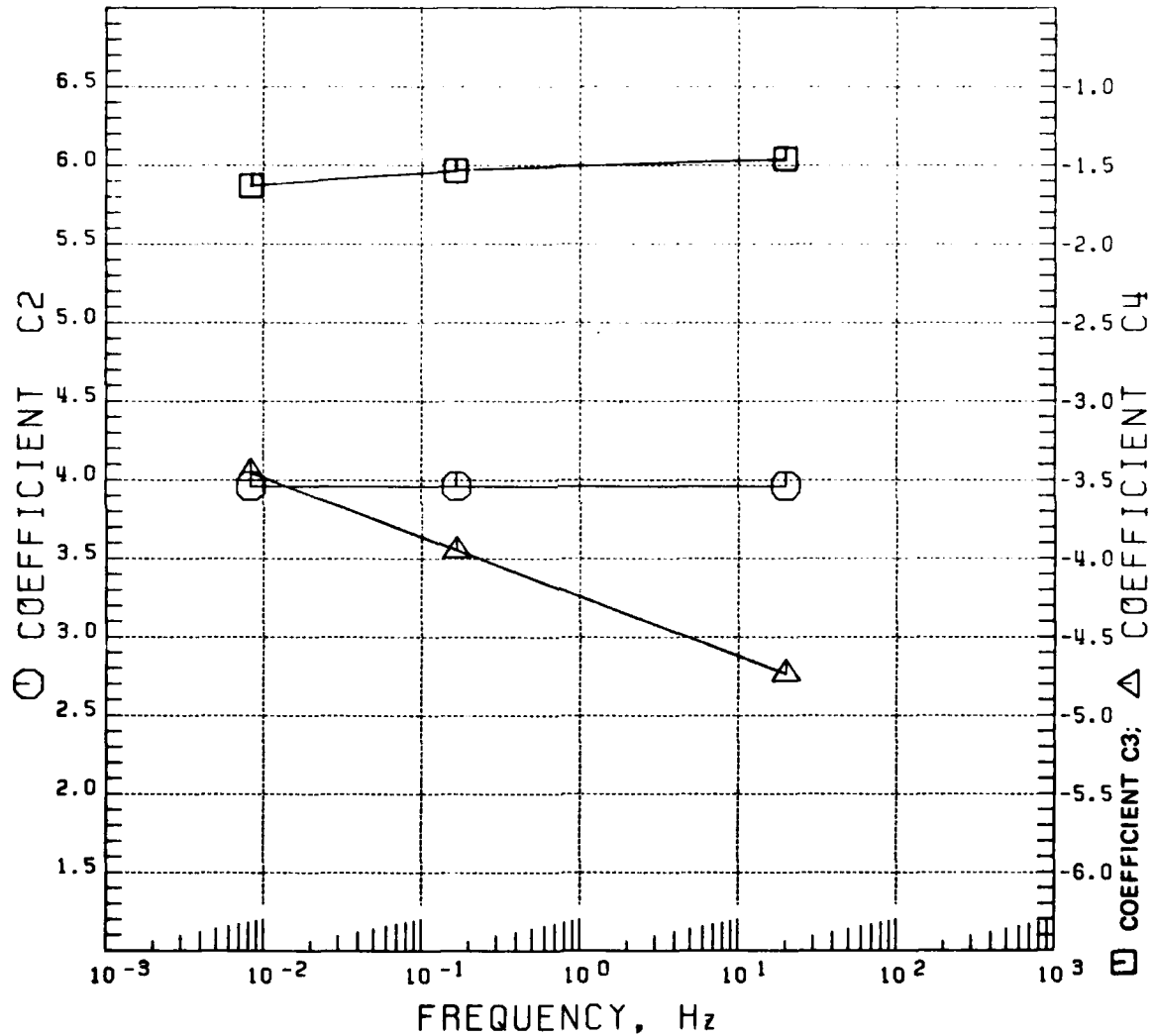
COEFFICIENTS C2, AND C4 VS. FREQUENCY

$$C2 = 3.9614 + 0.0005 \text{ LOG (FREQ)}$$

$$C4 = -4.2146 - 0.3786 \text{ LOG (FREQ)}$$

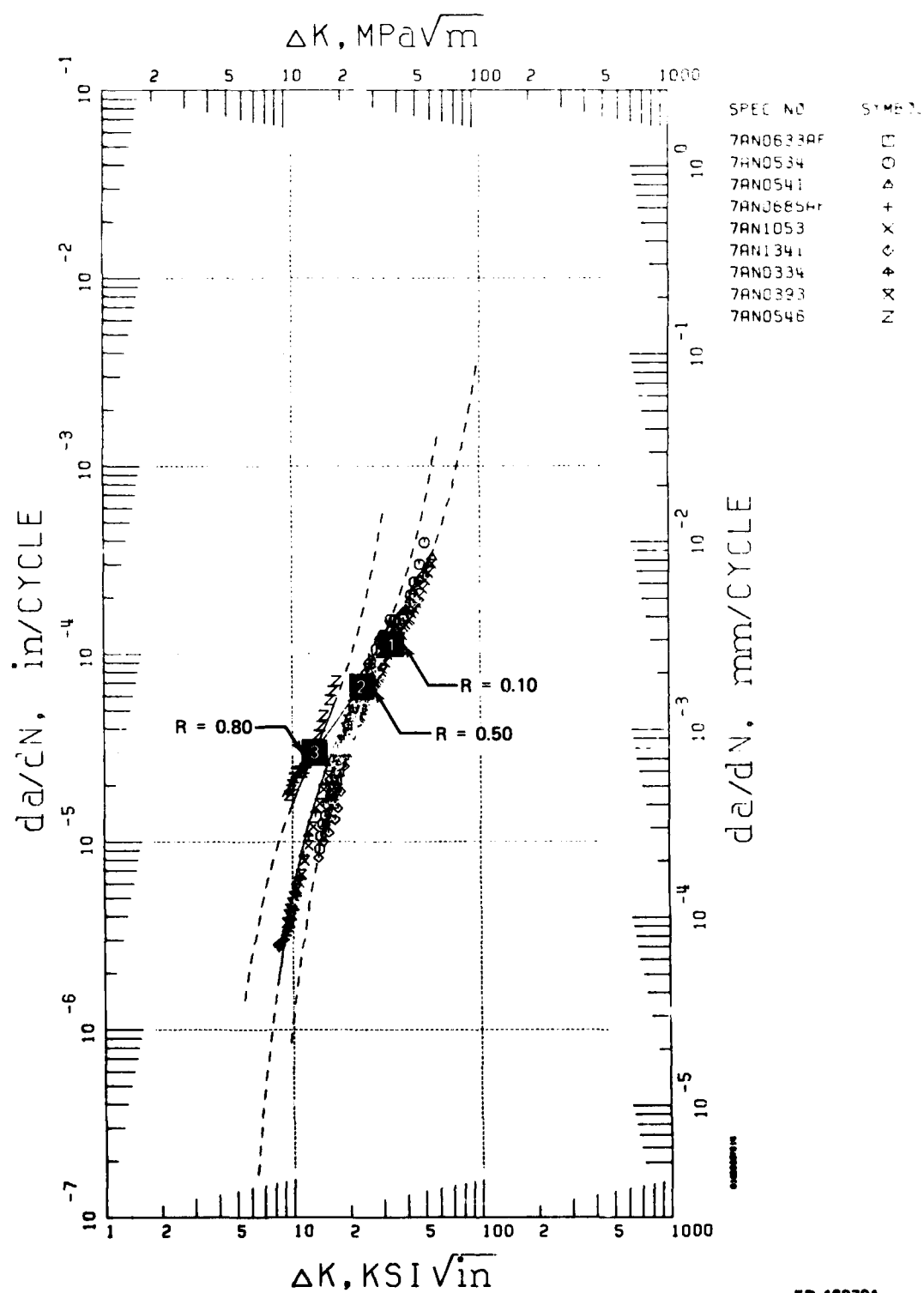
$$0.00833 \text{ Hz} < \text{FREQ} < 0.1667 \text{ Hz: } C3 = -1.4560 + 0.0938 \text{ LOG (FREQ)}$$

$$0.1667 \text{ Hz} < \text{FREQ} < 20 \text{ Hz: } C3 = -1.4987 + 0.0390 \text{ LOG (FREQ)}$$



FD 169787

Figure 54. IN100 (PWA 1073) Crack Propagation, Frequency Model Correlative Parameters, $R = 0.10$, 649°C (1200°F)



FD 169791

Figure 55. IN100 (PWA 1073) Crack Propagation, Stress Ratio Model, 0.167 Hz (10 cpm), 649° (1200°F)

PAGE 81608267914

A=.1 T=1200F FREQ=10CPM									
SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	TYPE	THICK	REMARKS	GROUP NO.
7AN0633AF	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ MCT	.250		1
7AN0534	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ MCT	.5		
7AN0541	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ MCT	.4995	HREP	
7AN0685AF	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ MCT	.870		
7AN1053	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ MCT	.299		
7AN1341	PWA 1073	1200F	AIR	10 CPM	R=.1	RAJ CN	.286		
-1.16 0.									
Y=0.5000 SINH(3.961 (X -1.529)) -3.947									
Y=0.5000 SINH(3.961 (X -1.570)) -2.542									
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 13.76 , AND X= 55.79 ONLY. DO NOT EXTRAPOLATE.									
NRAFT 1									
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 13.76 , AND X= 55.79 ONLY. DO NOT EXTRAPOLATE.									
X ASORD 0.9803 SEE 0.0531									
A=.5 T=1200F FREQ=10CPM									
SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	TYPE	THICK	REMARKS	GROUP NO.
7AN0334	PWA 1073	1200F	AIR	10 CPM	R=.5	RAJ MCT	.5	BREP8349	2
7AN0393	PWA 1073	1200F	AIR	10 CPM	R=.5	RAJ MCT	.5		
-1.15 0.									
Y=0.5000 SINH(4.192 (X -1.368)) -4.172									
Y=0.5000 SINH(4.192 (X -1.409)) -2.767									
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 8.33 , AND X= 33.17 ONLY. DO NOT EXTRAPOLATE.									
NRAFT 1									
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 8.33 , AND X= 33.17 ONLY. DO NOT EXTRAPOLATE.									
X ASORD 0.9845 SEE 0.0793									
A=.8 T=1200F FREQ=10CPM									
SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	TYPE	THICK	REMARKS	GROUP NO.
7AN0546	PWA 1073	1200F	AIR	10 CPM	R=.8	RAJ MCT	.503	HREP	3
-1.16 0.									
Y=0.5000 SINH(4.551 (X -1.117)) -4.522									
Y=0.5000 SINH(4.551 (X -1.158)) -3.117									
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 9.55 , AND X= 17.15 ONLY. DO NOT EXTRAPOLATE.									
NRAFT 1									
*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 9.55 , AND X= 17.15 ONLY. DO NOT EXTRAPOLATE.									
Z ASORD 0.9689 SEE 0.0841									
OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL ASORD = 0.9842, AND STD.ERROR.EST. = 0.0604									

FD 169792

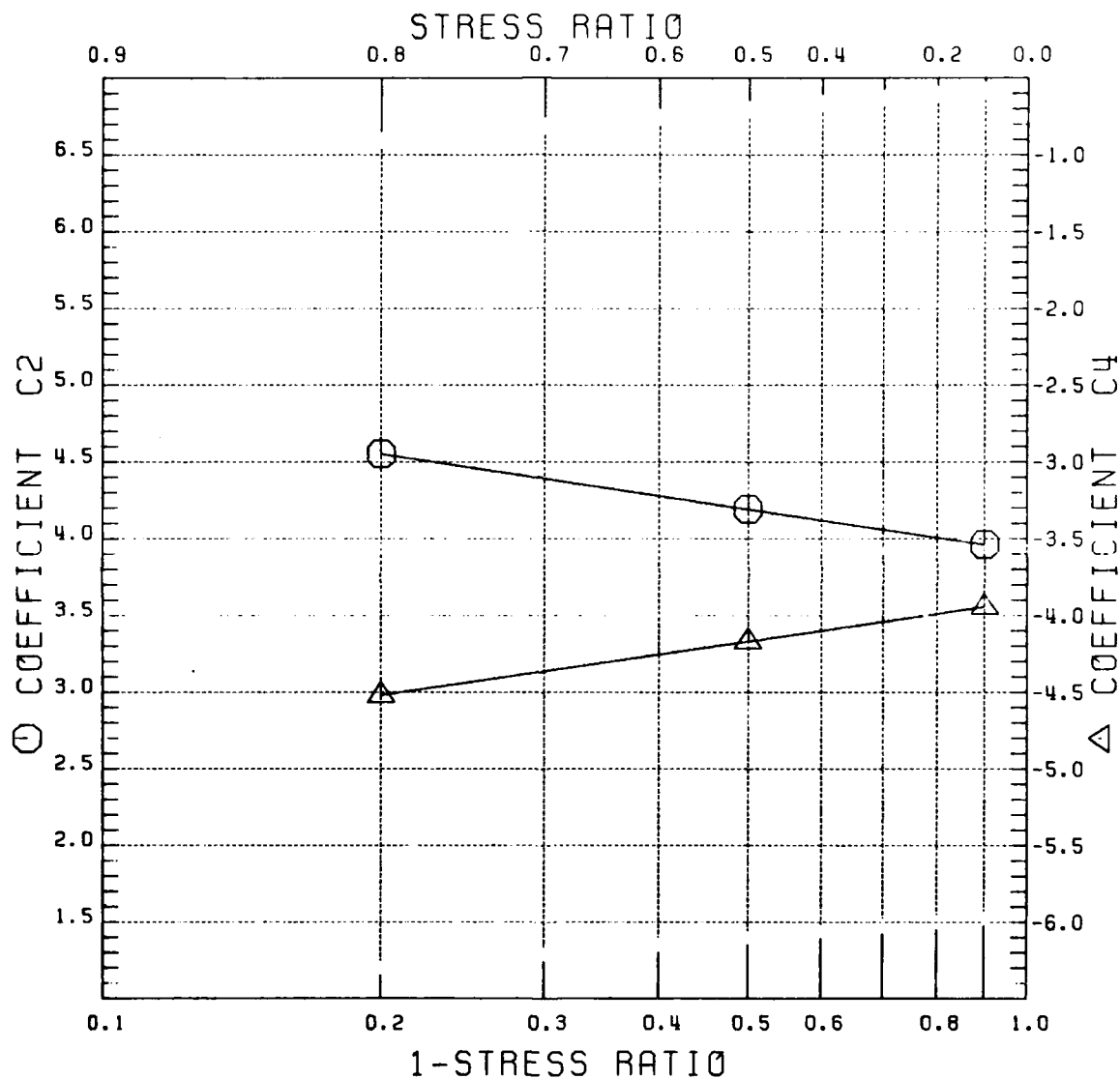
Figure 56. Statistics for IN100 (PWA 1073) Crack Propagation, Stress Ratio Moduli, 0.167 Hz (10 cpm), 649°C (1200°F)

COEFFICIENTS C2 AND C4 VS. (1-STRESS RATIO)

$$C2 = 3.9197 - 0.9031 \text{ LOG}(1 - \text{RATIO})$$

$$C4 = -3.9067 + 0.8796 \text{ LOG}(1 - \text{RATIO})$$

$$C3 = -4.3602 - 0.7173 C4$$



FD 169793

Figure 57. IN100 (PWA 1073) Crack Propagation, Stress Ratio Model
Correlative Parameters, 0.167 Hz (10 cpm), 649°C (1200°F)

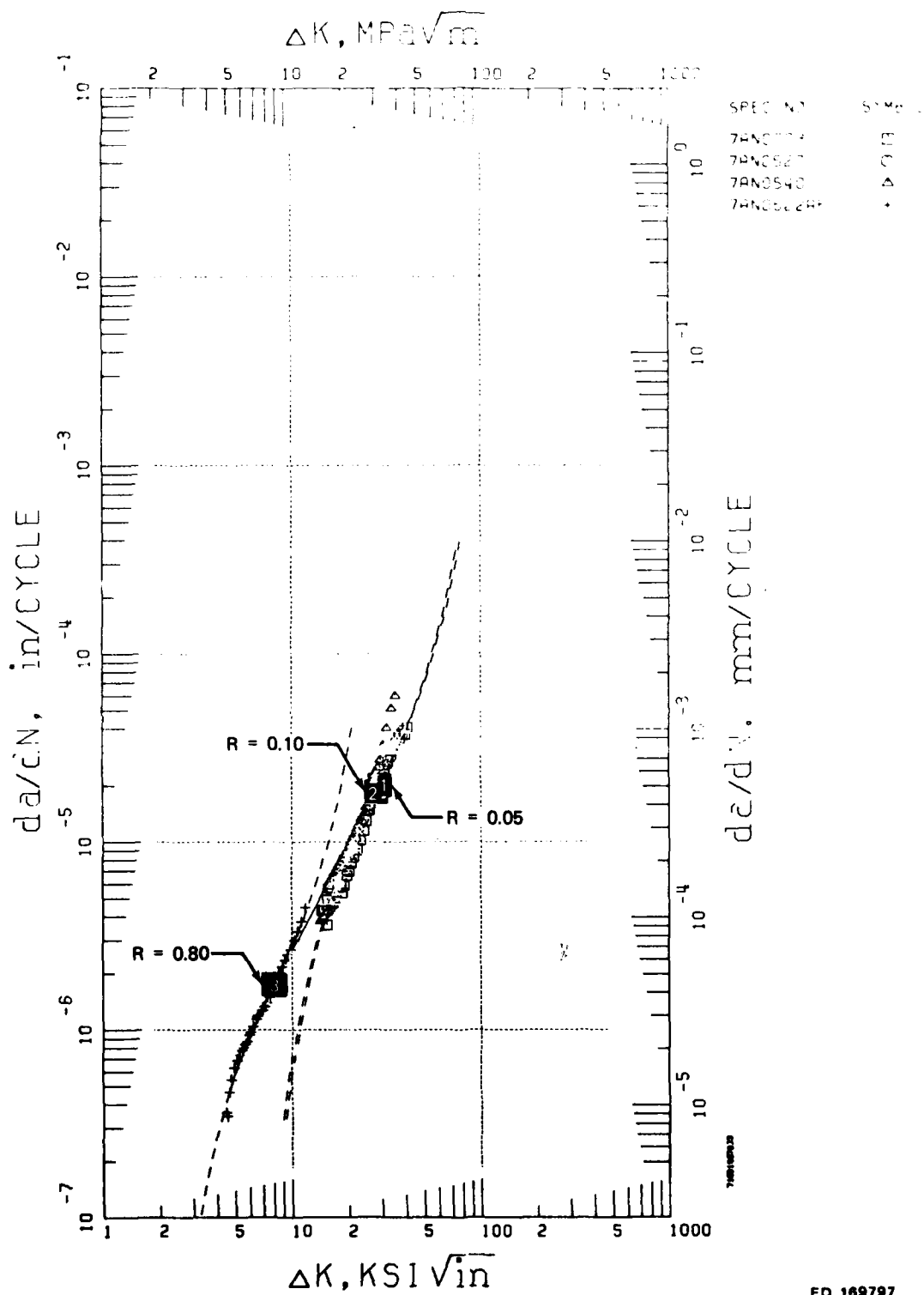


Figure 58. IN100 (PWA 1073) Crack Propagation, Stress Ratio Model, 20 Hz, 649°C (1200°F)

PAGE 71031487933

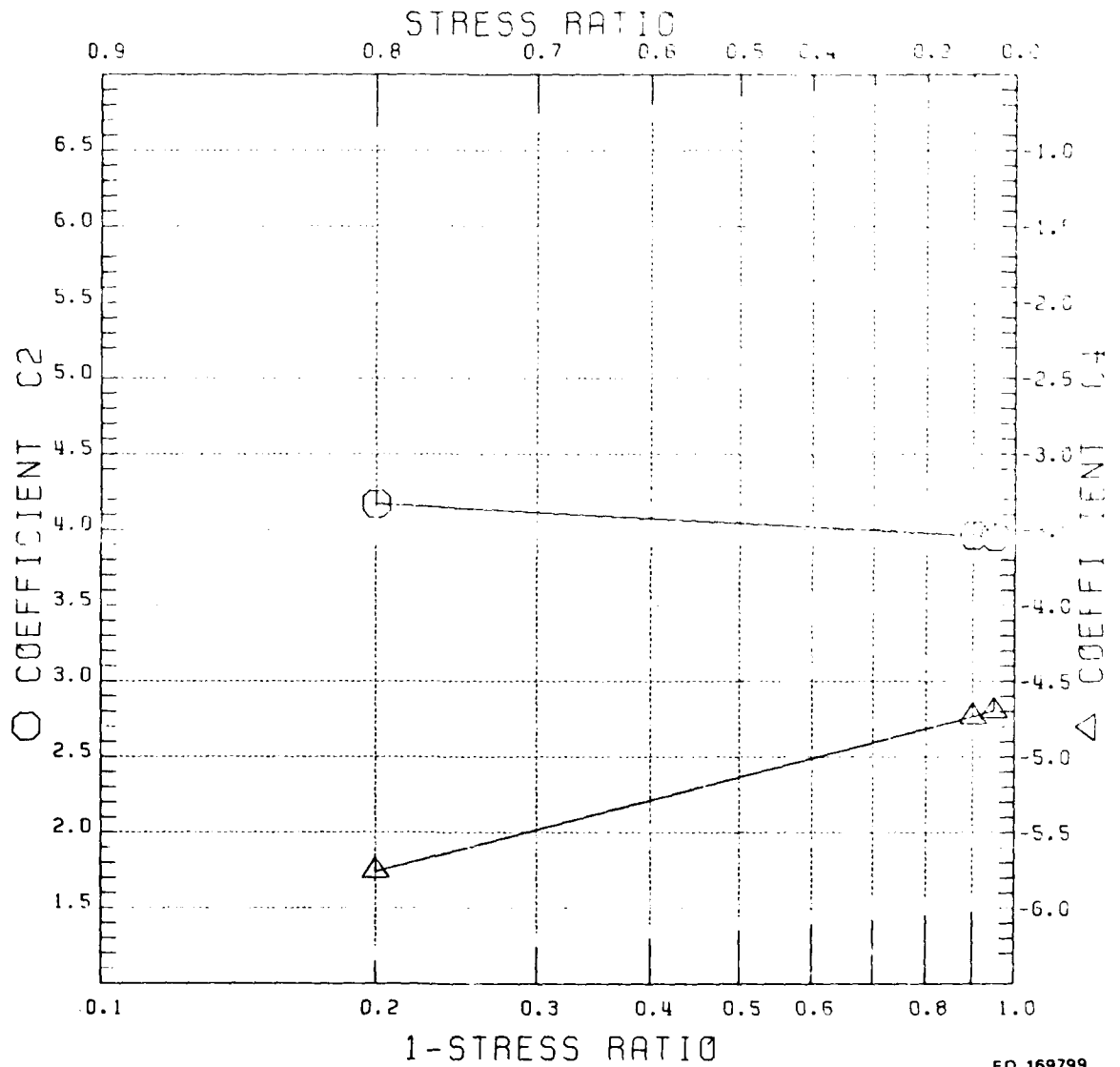
1200F. R=.05. IN100 F MODEL
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN0703 PWA 1073 1200F AIR 20 HZ R=.05 RAD MCT .249
 -0.41 0. Y=0.5000 SINH(3.955 (X -1.468)) -4.697
 NRAFT 1 (METPIC) Y=0.5000 SINH(3.955 (X -1.508)) -3.292
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 14.38 , AND X= 41.30 ONLY. DO NOT EXTRAPOLATE.
 GROUP NO. 1
 □ RSQRD 0.9570 SEE 0.0748
 1200F. R=.1. 20 HZ. IN100
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN0527 PWA 1073 1200F AIR 20 HZ R=.1 RAD MCT .25 BA1083H28 R
 7AN0540 PWA 1073 1200F AIR 20 HZ R=.1 RAD MCT .442
 -0.41 0. Y=0.5000 SINH(3.962 (X -1.448)) -4.734
 NRAFT 1 (METPIC) Y=0.5000 SINH(3.962 (X -1.489)) -3.326
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 14.07 , AND X= 39.07 ONLY. DO NOT EXTRAPOLATE.
 GROUP NO. 2
 ○ RSQRD 0.9487 SEE 0.0817
 1200F. R=.8. 20 HZ. IN100
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN0622P PWA 1073 1200F AIR 20 HZ R=.8 RAD MCT .205
 -0.41 0. Y=0.5000 SINH(4.170 (X -0.904)) -5.758
 NRAFT 1 (METPIC) Y=0.5000 SINH(4.170 (X -0.945)) -4.353
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 4.49 , AND X= 11.78 ONLY. DO NOT EXTRAPOLATE.
 GROUP NO. 3
 + RSQRD 0.9910 SEE 0.0270
 OVERALL STATISTICS FOR THIS COLLECTION OF GRC FS, TOTAL RSQRD = 0.9827, AND STD.ERROR.EST. = 0.0095

FD 169799

Figure 59. Statistics for IN100 (PWA 1073) Crack Propagation, Stress Ratio Model, 20 Hz, 649°C (1200°F)

COEFFICIENTS C2 AND C4 VS. (1-STRESS RATIO)

$$\begin{aligned} C2 &= 3.9474 - 0.3184 \log(1-RRATIO) \\ C4 &= -4.6523 + 1.5576 \log(1-RRATIO) \\ C3 &= -3.9627 - 0.5312 C4 \end{aligned}$$



FD 169799

Figure 60. IN100 (PWA 1073) Crack Propagation, Stress Ratio Model
Correlative Parameters, 20 Hz, 649°C (1200°F)

AD-4004 934

PRATT AND WHITNEY AIRCRAFT GROUP WEST PALM BEACH FL 0-ETC P/O 21/5
CUMULATIVE DAMAGE FRACTURE MECHANICS UNDER ENGINE SPECTRA.(U)

JAN 88 J H LARSEN, B J SCHWARTZ, C O ANNIS F33619-77-C-8153

UNCLASSIFIED

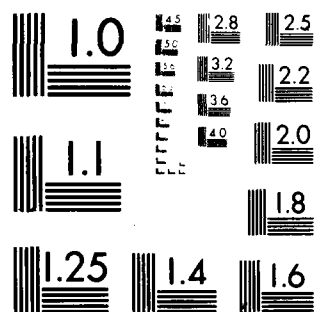
PWA-PR-11044

APPL -TR-79-4109

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2 OF 3

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AD9944.55



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

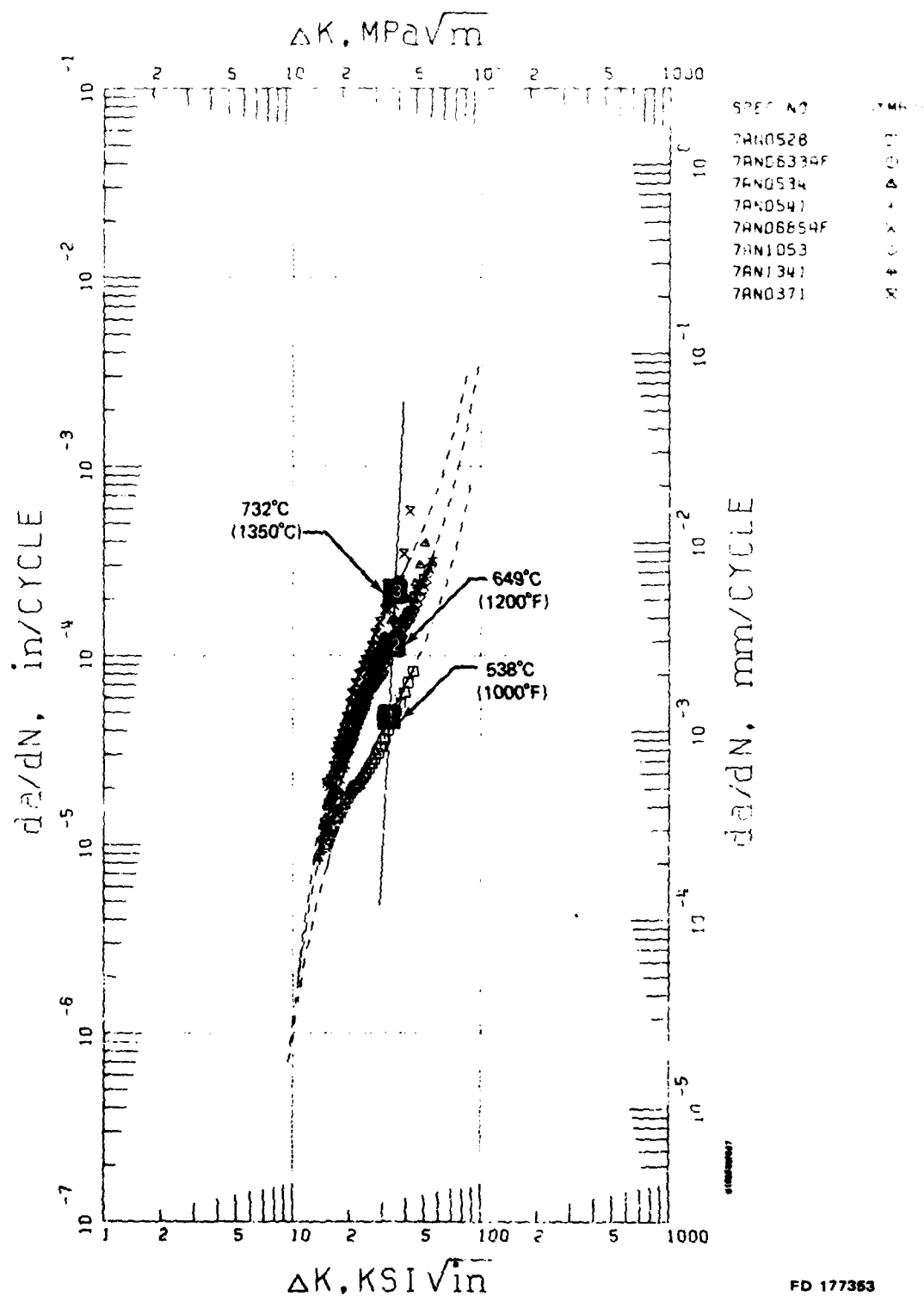


Figure 61. IN100 (PWA 1073) Crack Propagation, Temperature Model, $R = 0.10, 0.167 \text{ Hz (10 cpm)}$

PAGE 81608237937

R=.1 T=1000F FREQ=10CPM
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN0528 PWA 1073 1000F AIR 10 CPM R=.1 RAD MCT .250 BAI0B3H28
 -0.09 0.
 Y=0.5000 SINH(3.761 (X -1.511)) -4.327
 (METRIC) Y=0.5000 SINH(3.761 (X -1.552)) -2.922
 NRAFT 3
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=14.77 , AND X=43.91 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 1

ASQD 0.9778 SEE 0.0735

R=.1 T=1200F FREQ=10CPM
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN0534 PWA 1073 1200F AIR 10 CPM R=.1 RAD MCT .250
 7AN0541 PWA 1073 1200F AIR 10 CPM R=.1 RAD MCT .4995 HARP
 7AN0685AF PWA 1073 1200F AIR 10 CPM R=.1 RAD MCT .870
 7AN1053 PWA 1073 1200F AIR 10 CPM R=.1 RAD MCT .299
 7AN1341 PWA 1073 1200F AIR 10 CPM R=.1 RAD CN .296
 -0.09 0.
 Y=0.5000 SINH(3.961 (X -1.529)) -3.947
 (METRIC) Y=0.5000 SINH(3.961 (X -1.570)) -2.542
 NRAFT 3
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=13.76 , AND X=55.79 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 2

ASQD 0.9803 SEE 0.0531

R=.1 T=1350F FREQ=10CPM
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN0371 PWA 1073 1350F AIR 10 CPM R=.1 RAD MCT
 -0.09 0.
 Y=0.5000 SINH(4.111 (X -1.543)) -3.662
 (METRIC) Y=0.5000 SINH(4.111 (X -1.584)) -2.257
 NRAFT 3
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X=15.18 , AND X=42.06 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 3

ASQD 0.9816 SEE 0.0628

OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL ASQD = 0.9801. AND STD.ERROR.EST. = 0.0563

FD 177354

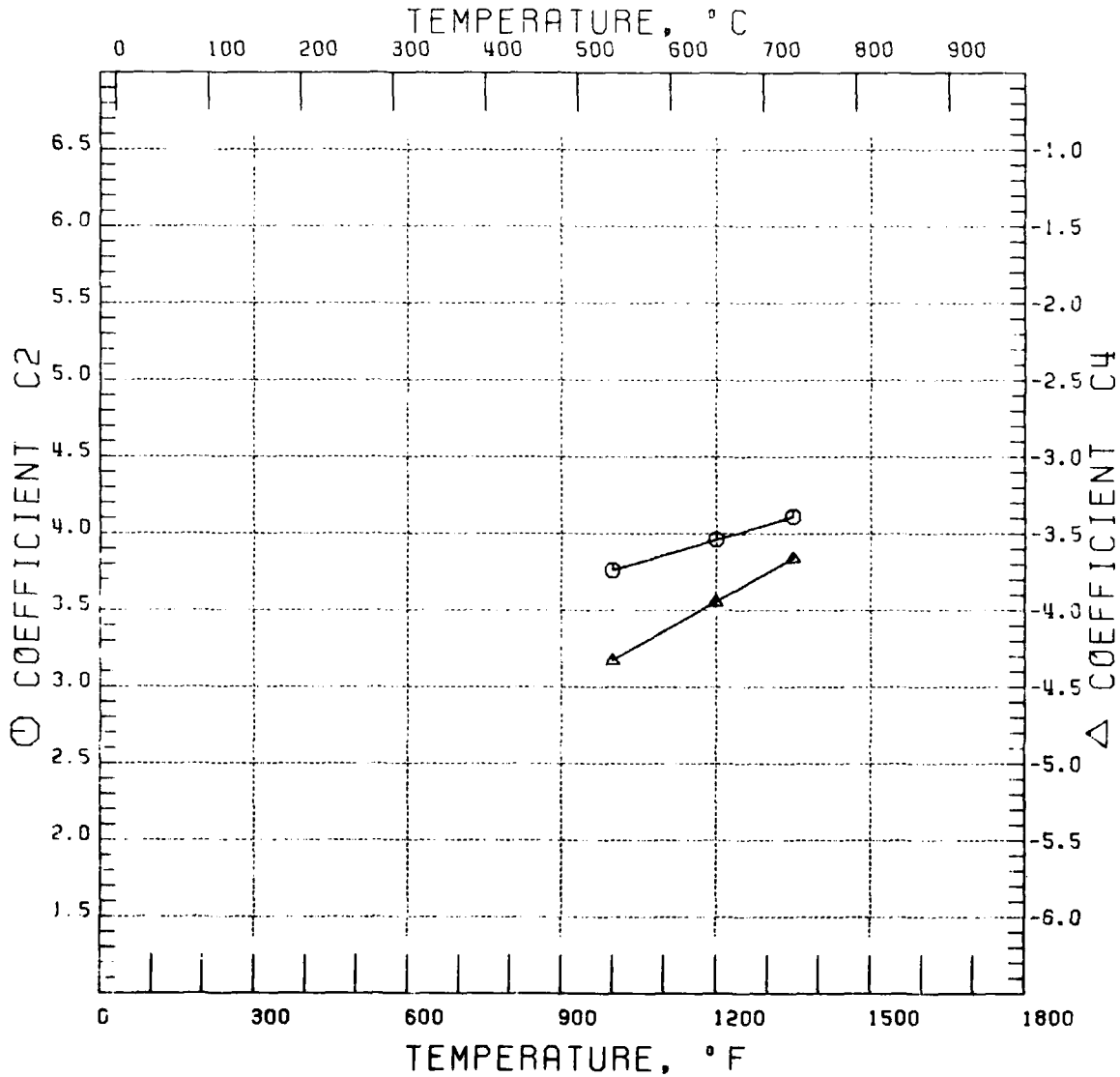
Figure 62. Statistics for IN100 (PWA 1073) Crack Propagation, Temperature Model, $R = 0.10$, 0.167 Hz (10 cpm)

COEFFICIENTS C2 AND C4 VS. TEMPERATURE

$$C2 = 2.7610 + 0.0010 \text{ TEMPERATURE}$$

$$C4 = -6.2270 + 0.0019 \text{ TEMPERATURE}$$

$$C3 = -1.7188 - 0.0481 C4$$



FD 177355

Figure 63. IN100 (PWA 1073) Crack Propagation, Temperature Model
Correlative Parameters, $R = 0.10, 0.167 \text{ Hz (10 cpm)}$

(2) Crack Propagation Under Periodic Load Dwell

(a) Effect of Load Dwell, 649°C (1200°F)

Crack propagation under periodic load dwell in GATORIZED® IN100 (PWA 1073) was investigated using the repetitive loading shown in Figure 12. The period of load dwell was 60, 120, and 600 sec, in three tests where $R = 0.10$ and $T = 649^\circ\text{C}$. The composite model of the effect of the period of load dwell is illustrated in Figure 65. Figure 64 lists the statistics. The interpolative SINH coefficients are shown in Figure 66.

(b) Effect of Load Dwell, 732°C (1350°F)

The effect of period of load dwell on crack growth in IN100 tested at 732°C is described by the interpolative SINH model presented in Figure 67. Figure 68 gives the statistics. The increased crack growth rate associated with increased dwell period is correlated with the SINH coefficients as shown in Figure 69.

(3) Sustained Load Crack Growth

Under a previous Air Force program the sustained load crack growth behavior of IN100 (PWA 1073) was determined (Reference 2). The experimental and analytical procedures used were the same as described earlier in this report for Waspaloy sustained load crack growth. The results of the IN100 investigation, presented in Figures 70 and 71, demonstrate the deleterious influence of increasing temperature on sustained load crack growth. The correlation between these curves and 10 tests of 12.7 mm (0.50 in.) thick compact specimens is illustrated in Figure 72.

(4) Synergistic Crack Propagation

(a) LCF -- Overload Interaction

The nature of crack retardation resulting from load sequencing representative of military gas turbine operation is discussed in Appendix A. Testing based on the repetitive load cycle shown in Figure 14 was used to characterize synergistic interaction for LCF-overload fatigue of GATORIZED® IN100. Interpolative models of crack propagation as a function of overload occurrence frequency and relative magnitude are presented below.

(1) Effect of Cycles Between Overloads

Under constant load amplitude fatigue ($R = 0.50$) at 649°C (1200°F) periodically interrupted by a single overload ($OLR = 1.5$), crack propagation in IN100 displays a strong dependence on the number of baseline fatigue cycles between overloads (ΔN_{OL}). Results of crack propagation tests conducted with $\Delta N_{OL} = 5, 20$, and 40 cycles are plotted in composite fashion in Figure 73. Figure 74 presents the statistics. The associated SINH curves represent an interpolative model of the effect of number of cycles between successive periodic overloads. As shown in Figure 75, the defining SINH coefficients are linear functions of the logarithm of the number of cycles per repetitive mission ($\log(\Delta N_{OL} + 1)$).

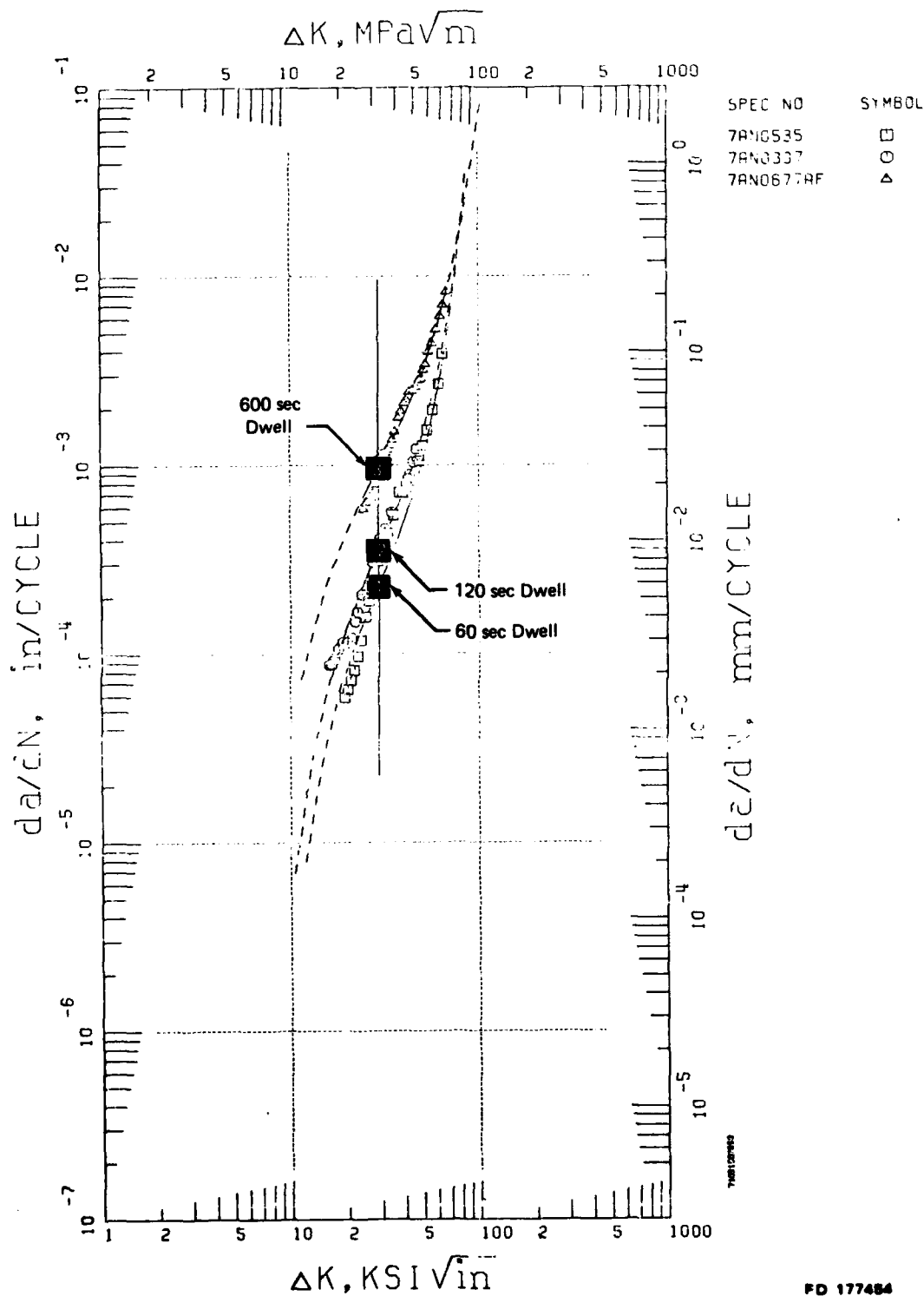


Figure 64. IN100 (PWA 1073) Crack Propagation, Dwell Model, $R = 0.10$, 649°C (1200°F)

PAGE 71031507953

TEST CONDITIONS

SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS GROUP NO. 1
 7AN0535 PWA 1073 1200F AIR 1 MDWL R=.1 RAD MCT .405 BRER
 -1.16 0.
 Y=0.5000 SINH(4.663 (X -1.466)) -3.644
 (METRIC) Y=0.5000 SINH(4.663 (X -1.507)) -2.239
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 19.48 , AND X= 64.16 ONLY. DO NOT EXTRAPOLATE.

TEST CONDITIONS

SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS GROUP NO. 2
 7AN0337 PWA 1073 1200F AIR 2 MDWL R=.1 RAD MCT .44 BAEPB049
 -1.16 0.
 Y=0.5000 SINH(4.402 (X -1.466)) -3.456
 (METRIC) Y=0.5000 SINH(4.402 (X -1.507)) -2.051
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 16.06 , AND X= 46.80 ONLY. DO NOT EXTRAPOLATE.

TEST CONDITIONS

SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS GROUP NO. 3
 7AN0677AF PWA 1073 1200F AIR 10 MDWL R=.1 MCT
 -1.16 0.
 Y=0.5000 SINH(3.795 (X -1.466)) -3.619
 (METRIC) Y=0.5000 SINH(3.795 (X -1.507)) -1.614
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 24.36 , AND X= 67.70 ONLY. DO NOT EXTRAPOLATE.

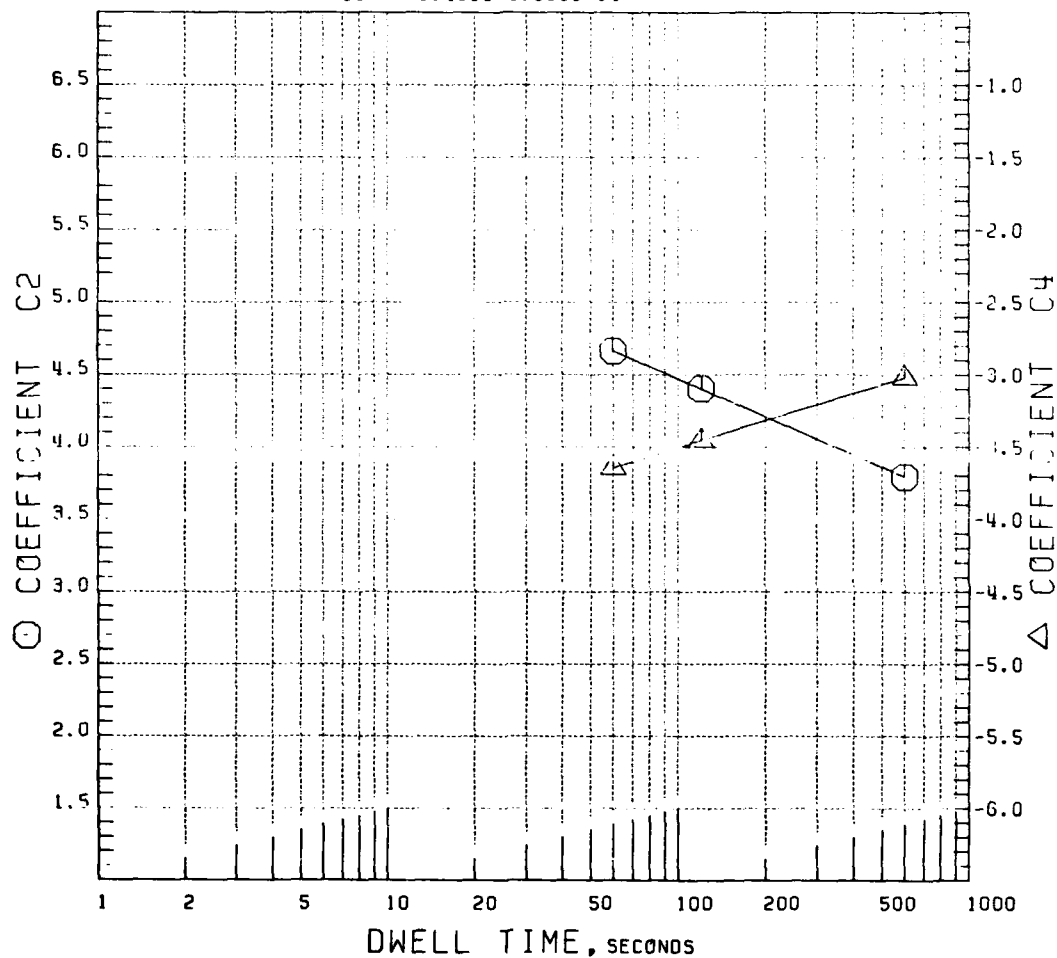
OVERALL STATISTICS FOR THIS COLLECTION OF CRACKS. TOTAL R50FD = 0.9830. AND STD.ERROR.EST. = 0.0789

FD 177455

Figure 65. Statistics for IN100 (PWA 1073) Crack Propagation, Dwell Model, $R = 0.10$, 649°C (1200°F)

COEFFICIENTS C2 AND C4 VS. DWELL TIME

$$\begin{aligned} C2 &= 6.2065 + 0.8679 (-\log(\text{DWELL TIME})) \\ C4 &= -4.7567 - 0.6256 (-\log(\text{DWELL TIME})) \\ C3 &= -1.4660 + 0.0000 C4 \end{aligned}$$



FD 177456

Figure 66. IN100 (PWA 1073) Crack Propagation, Dwell Model Correlative Parameters, $R = 0.10$, 649°C (1200°F)

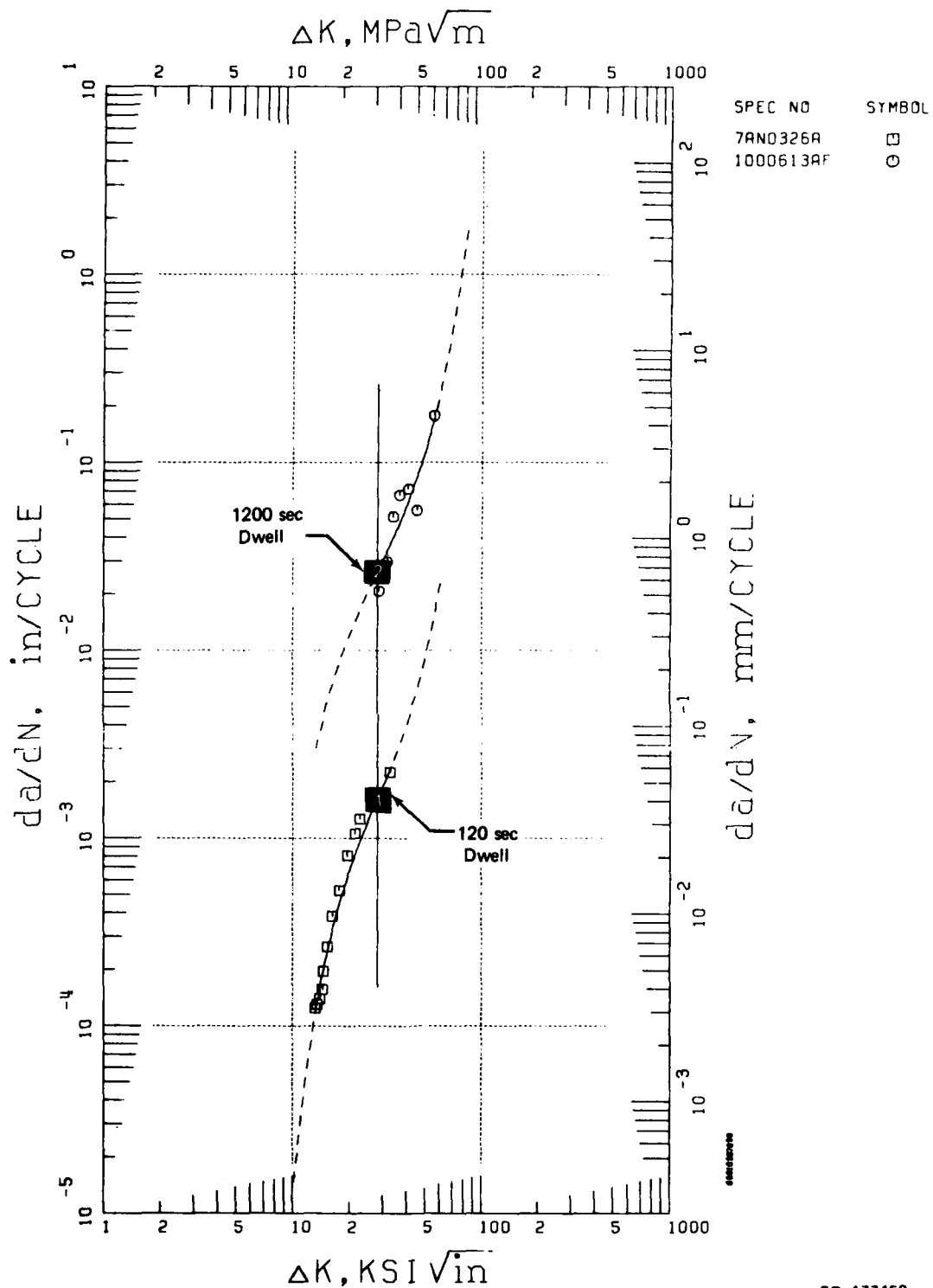


Figure 67. IN100 (PWA 1073) Crack Propagation, Dwell Model, $R = 0.10$, 732°C (1350°F)

FD 177459

PAGE 80910367936

TEST CONDITIONS

SPEC NO MATERIAL PWA 1073
7AN0326A
-0.77 0.
NAFT 4
*** IMPORTANT ***

6 333435363738

TEMP ATM FREQ R TYPE THICK REMARKS
1350F AIR 2 MDWL R=.1 RAD MCT .436 BAEPH86
Y=0.5000 SINH(4.762 (X -1.450)) -2.792
(METRIC) Y=0.5000 SINH(4.762 (X -1.491)) -1.387
*** THIS EQUATION IS VALID BETWEEN X= 13.27 , AND X= 32.85 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 1

□ RSQRD 0.9817 SEE 0.0826

TEST CONDITIONS

SPEC NO MATERIAL PWA 1073
1000613AF
-0.77 0.
NAFT 4
*** IMPORTANT ***

6 333435363738

TEMP ATM FREQ R TYPE THICK REMARKS
1350F AIR 20MDWL R=.1 RAD MCT .25 20MIN.DWELL
Y=0.5000 SINH(4.263 (X -1.450)) -1.582
(METRIC) Y=0.5000 SINH(4.263 (X -1.491)) -0.177
*** THIS EQUATION IS VALID BETWEEN X= 28.65 , AND X= 55.75 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 2

□ RSQRD 0.8358 SEE 0.1479

□ RSQRD 0.9939. AND STD.ERROR. EST. = 0.1070

OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL RSQRD = 0.9939. AND

FD 177460

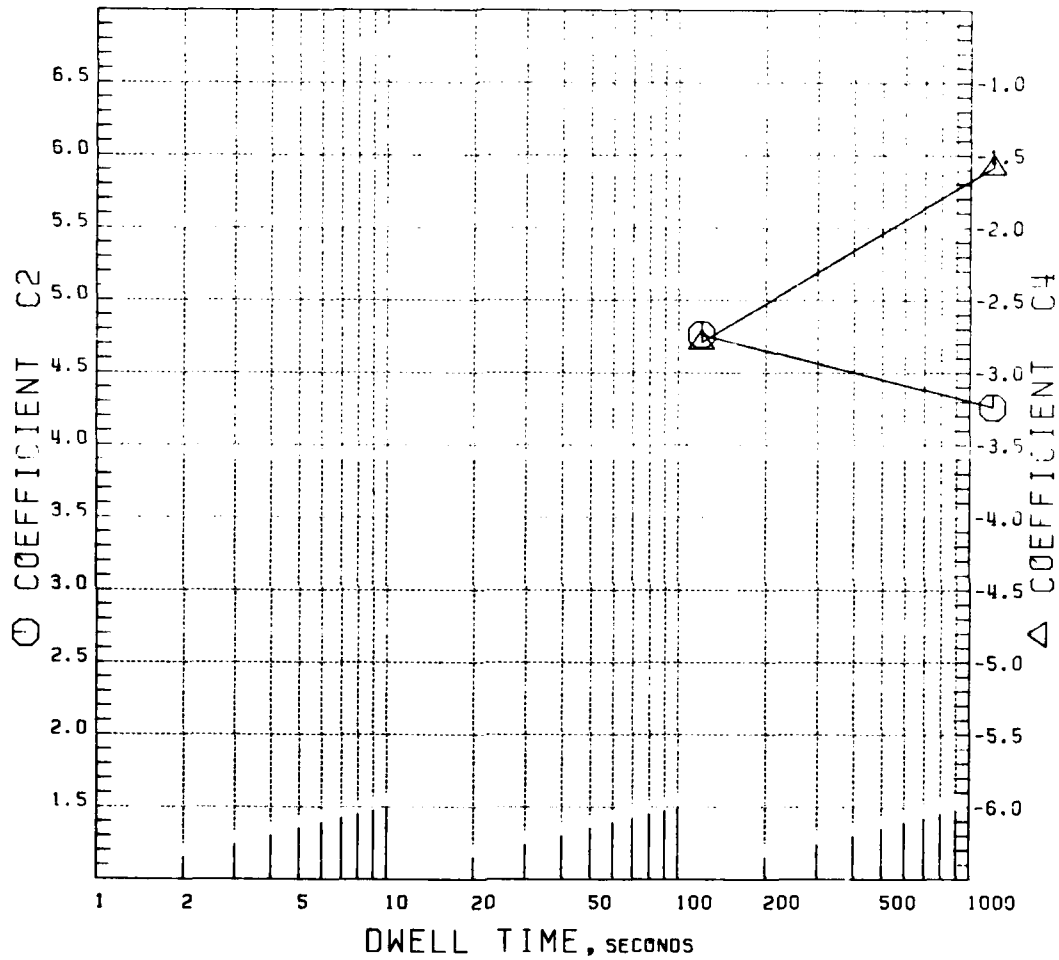
Figure 68. Statistics for IN100 (PWA 1073) Crack Propagation, Dwell Model, $R = 0.10$, 732°C (1350°F)

COEFFICIENTS C2 AND C4 VS. DWELL TIME

$$C2 = 5.7995 + 0.4990 (-\log(\text{DWELL TIME}))$$

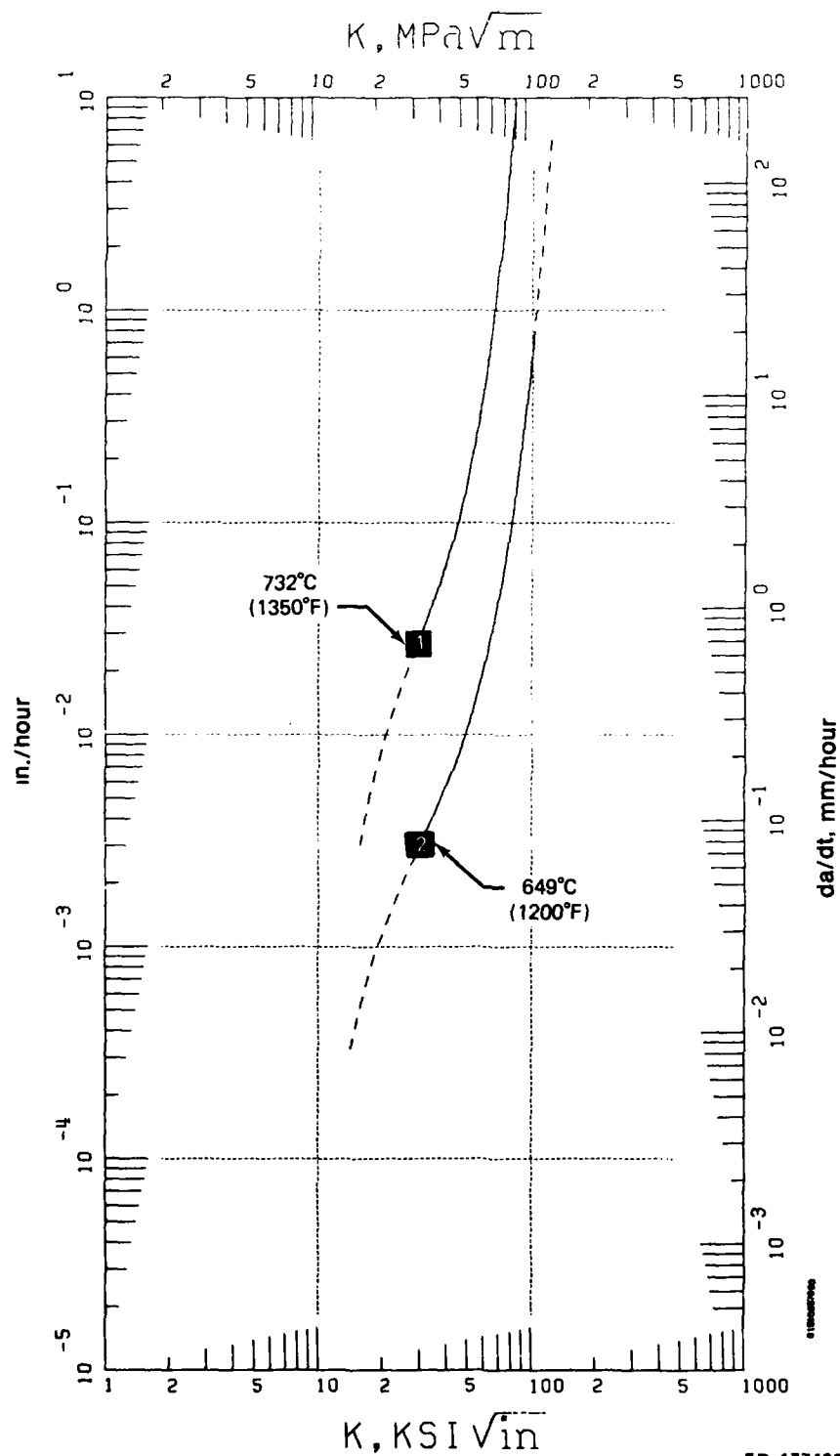
$$C4 = -5.3078 - 1.2100 (-\log(\text{DWELL TIME}))$$

$$C3 = -1.4500 - 0.0000 C4$$



FD 177461

Figure 69. IN100 (PWA 1073) Crack Propagation, Dwell Model Correlative Parameters, $R = 0.10$, 732°C (1350°F)



FD 177462

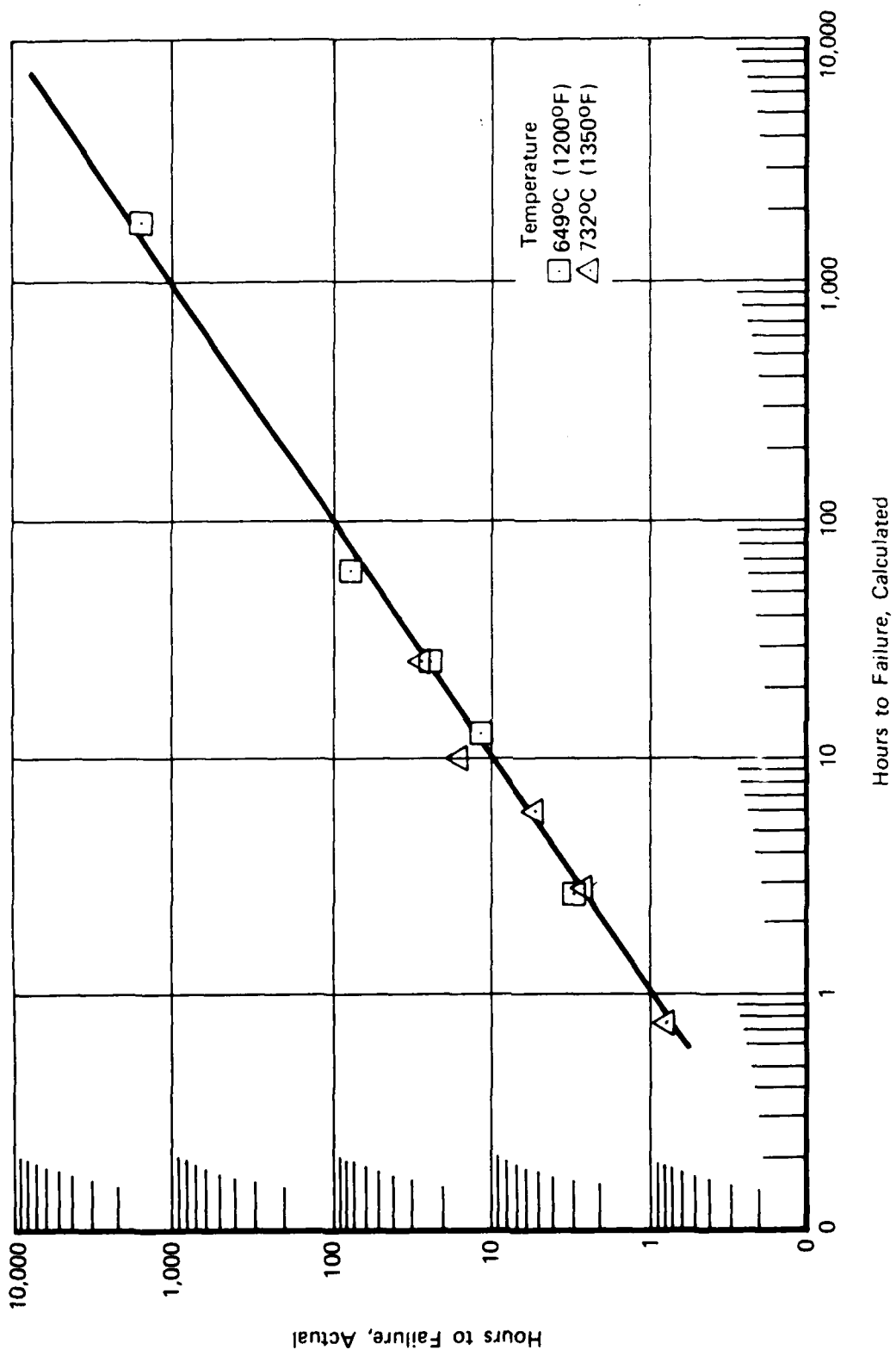
Figure 70. IN100 (PWA 1073) Crack Propagation Under Sustained Loading, 649°C (1200°F) and 732°C (1350°F)

PAGE 81510247959

				3 2 3 4				GROUP NO. 1	
MATERIAL	TEMP	ATM	FREQ	R	TYPE	THICK	REMARKS		
PWA 1007	1200	AIR	DA/DT		MCT	0.50			
-8.52 0.							Y=0.5000 SINH(4.297 (X -1.479)) -2.519		
NAFT 0							(METRIC) Y=0.5000 SINH(4.297 (X -1.520)) -1.114		
*** IMPORTANT ***							THIS EQUATION IS VALID BETWEEN X= 30.00 , AND X= 100.00 ONLY. DO NOT EXTRAPOLATE.		
				3 2 3 4				GROUP NO. 2	
MATERIAL	TEMP	ATM	FREQ	R	TYPE	THICK	REMARKS		
PWA 1007	1350	AIR	DA/DT		MCT	0.50			
-8.52 0.							Y=0.5000 SINH(5.200 (X -1.467)) -1.570		
NAFT 0							(METRIC) Y=0.5000 SINH(5.200 (X -1.508)) -0.165		
*** IMPORTANT ***							THIS EQUATION IS VALID BETWEEN X= 30.00 , AND X= 100.00 ONLY. DO NOT EXTRAPOLATE.		

FD 177463

Figure 71. Statistics for IN100 (PWA 1073) Crack Propagation Under Sustained Loading, 649°C (1200°F) and 732°C (1350°F)



FD 177464

Figure 72. Actual vs Calculated Times to Failure for 10 Compact Specimens Tested Under Sustained Load at 649°C (1200°F) and 732°C (1350°F)

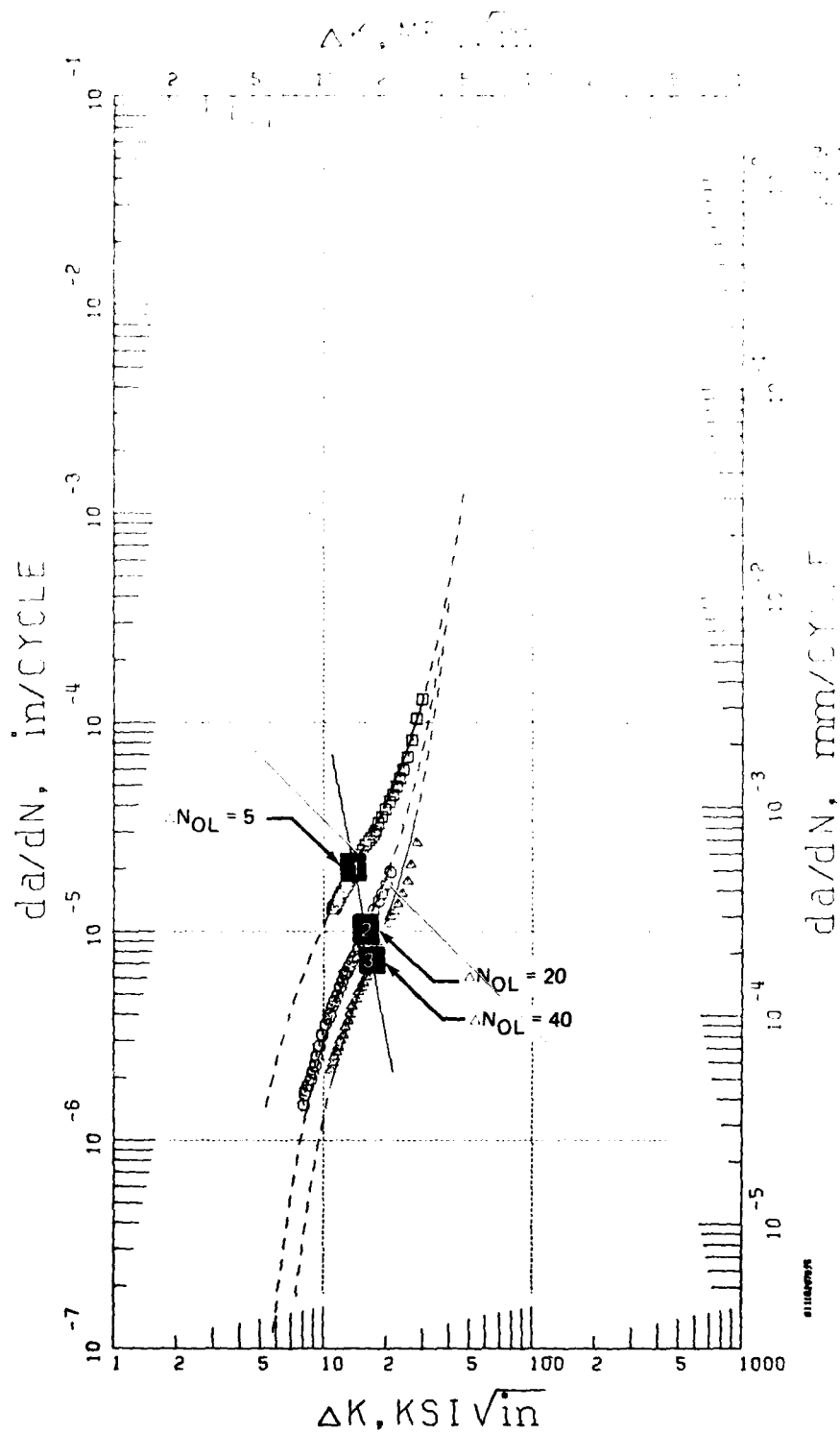


Figure 73. IN100 (PWA 1073) Crack Propagation, Model of the Effect of the Number of Cycles Between Overloads, $R = 0.50$, 0.167 Hz (10 cpm), 649°C (1200°F) $OLR = 1.50$

FD 177468

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SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN0680AF PWA 1073 1200F AIR MIX R=.5 RAD MCT .251 0L1.5+SCY
 -0.51 0.
 NRFT 5 Y=0.5000 SINH(3.766 (X -1.143))-4.69C
 (METRIC) Y=0.5000 SINH(3.766 (X -1.184))-3.285
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 11.13 , AND X= 29.63 ONLY. DO NOT EXTRAPOLATE.
 GROUP NO. 1

SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN0671AF PWA 1073 1200F AIR MIX R=.5 RAD MCT .253 0L1.5+2CCY
 -0.51 0.
 NRFT 5 Y=0.5000 SINH(4.741 (X -1.198))-4.981
 (METRIC) Y=0.5000 SINH(4.741 (X -1.239))-3.576
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 8.05 , AND X= 20.88 ONLY. DO NOT EXTRAPOLATE.
 GROUP NO. 2

SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7AN0675AF PWA 1073 1200F AIR MIX MCT .251 0L1.5+4CCY
 -0.51 0.
 NRFT 5 Y=0.5000 SINH(5.262 (X -1.228))-5.136
 (METRIC) Y=0.5000 SINH(5.262 (X -1.269))-3.731
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 10.78 , AND X= 27.85 ONLY. DO NOT EXTRAPOLATE.
 OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL RSDPO = 0.9953. AND STD. DEVIATION = 0.0460
 GROUP NO. 3

Figure 74. Statistics for IN100 (PWA 1073) Crack Propagation, Model of the Effect of the Number of Cycles Between Overloads
 $R = 0.50, 0.167 \text{ Hz (10 cpm), } 649^{\circ}\text{C (1200}^{\circ}\text{F) OLR} = 1.50$

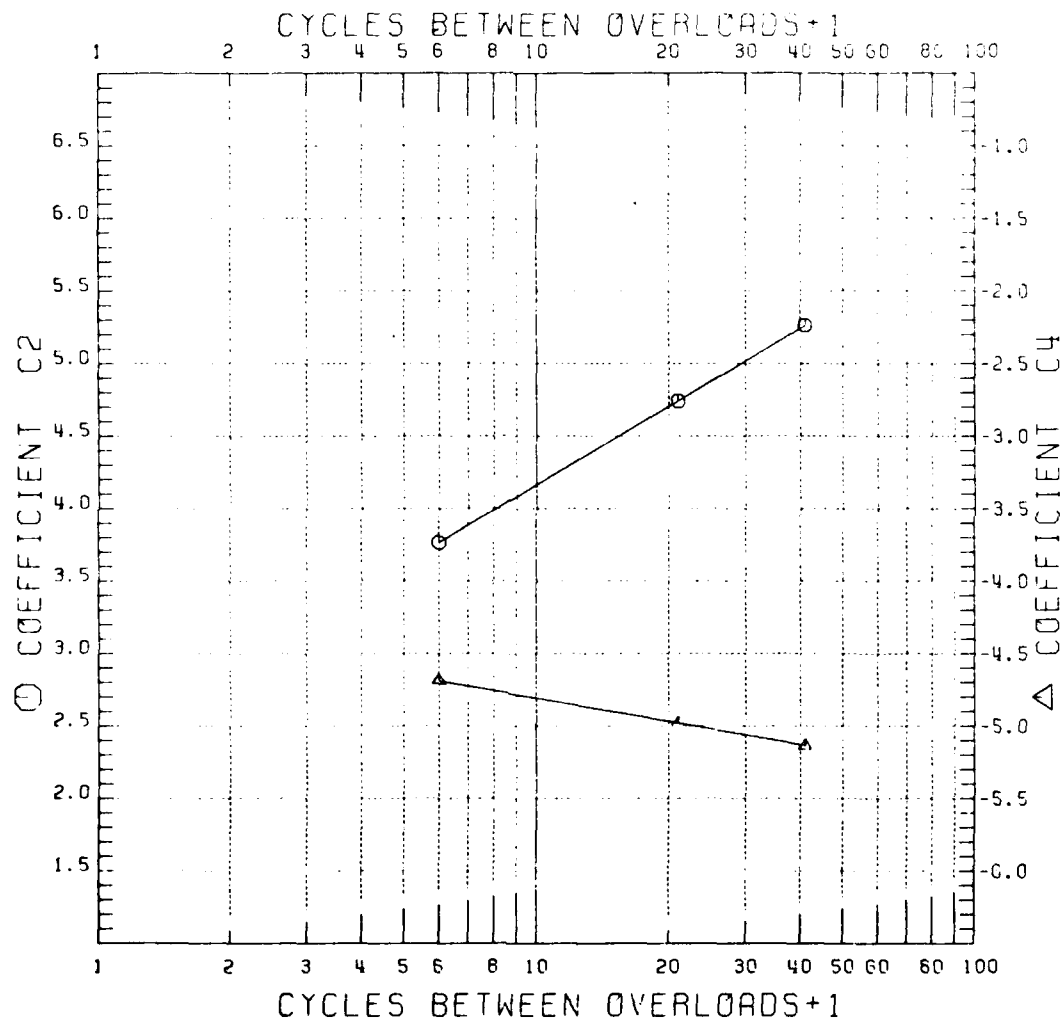
FD 177469

COEFFICIENTS C2 AND C4 VS.
CYCLES BETWEEN OVERLOADS+1

$$C2 = 2.3703 + 1.7930 (\log (\Delta N_{OL} + 1))$$

$$C4 = -4.2735 - 0.5348 (\log (\Delta N_{OL} + 1))$$

$$C3 = -0.2501 + 0.1904 C4$$



FD 177470

Figure 75. IN100 (PWA 1073) Crack Propagation, Correlative Parameters
Model of Effect of ΔN_{OL} , $R = 0.50$, 0.167 Hz (10 cpm), 649°C
(1200°F), $OLR = 1.50$

(2) Effect of Overload Ratio

Under periodic overload-fatigue the effect of increasing overload ratio (P_{OL}/P_{max}) while holding ΔN_{OL} constant is to decrease the average rate of crack propagation produced by the load sequencing. Tests of IN100 were conducted using the repetitive load sequence shown in Figure 14. Similar to the tests discussed above, the temperature was 649°C (1200°F), $R = 0.50$, and the cyclic frequency was 0.167 Hz (10 cpm). The number of cycles between overloads, ΔN_{OL} , was held constant at 40, and overload ratio was varied over the range $1.0 \leq OLR \leq 1.50$.

Under an overload ratio of 1.0, the load range is constant and crack growth reduces to the case of the constant ΔP baseline. For overload ratios of 1.25 and 1.50 average growth rate is reduced. A composite of these data, and the associated SINH model, is presented in Figure 76. Figure 77 gives the statistics. The defining SINH coefficients are linear functions of OLR as illustrated in Figure 78.

(b) LCF — Dwell Interaction

Crack propagation testing of IN100 fatigued at 649°C (1200°F) under the repetitive LCF-dwell sequence shown in Figure 13 revealed little or no effect of the periodic dwell. As illustrated in Figure 79, data generated with 10, 20, and 40 cycles of 0.167 Hz (10 cpm) sawtooth fatigue ($R = 0.1$) between dwells correlated well with the crack growth curve representing sawtooth fatigue only. Figure 80 presents the statistics.

Similar tests conducted at 732°C (1350 °F) demonstrated a mild effect of the periodic load dwell. The results of tests conducted with 10, 20, and 40 cycles between dwells are shown in a composite presented in Figure 81. Figure 82 presents the statistics. For purposes of comparison, the SINH curves describing crack growth under baseline fatigue (732°C, 0.167, $R = 0.10$) and repetitive dwell (732°C, 120 sec dwell, $R = 0.10$) are also shown. The SINH curves representing the individual LCF-dwell data sets are given by an interpolative model of this effect, and the defining coefficients are illustrated in Figure 83.

5. Auxilliary Investigation

a. Negative Stress Ratio Effects

Tension-compression fatigue ($R \leq 0$) may occur in isolated disk locations during mission operation as shown in Figure 4. Fatigue crack propagation under such negative stress ratio cycling is not accurately predicted by a simple extrapolation of a stress ratio model developed for tension-tension ($R \geq 0$) fatigue. Due to a difference in the mechanism of crack growth associated with the positive vs negative load excursion, a separate evaluation of crack growth is required for $R \leq 0$.

Considering the work of Elber (Reference 7), the effective stress intensity range operating at the crack tip is $\Delta K_{eff} = (K_{max} - K_{closure})$, where $K_{closure}$ is the stress intensity at which physical closing of the crack tip occurs on unloading. Under a compressive stress field, a crack tip singularity does not exist, and $K = 0$ for all $\sigma_{applied} \leq 0$. While for a given K_{max} , the applied stress intensity range ($\Delta K = K_{max} - K_{min}$) remains constant for negative stress ratio fatigue, $\Delta K_{effective}$ is increased slightly as $K_{closure}$ decreases due to compressive yielding.

In order to examine the effect of representative tension-compression fatigue on crack growth in Waspaloy and IN100, the matrix of tests outlined in Table 5 was conducted. The investigation was performed at 427°C (800°F) and 649°C (1200°F) and spanned the range of $-1.0 \leq R \leq 0.0$; the cyclic frequency was 0.167 Hz (10 cpm). The crack growth specimen employed in these tests was of through-thickness center crack geometry, Figure 11a.

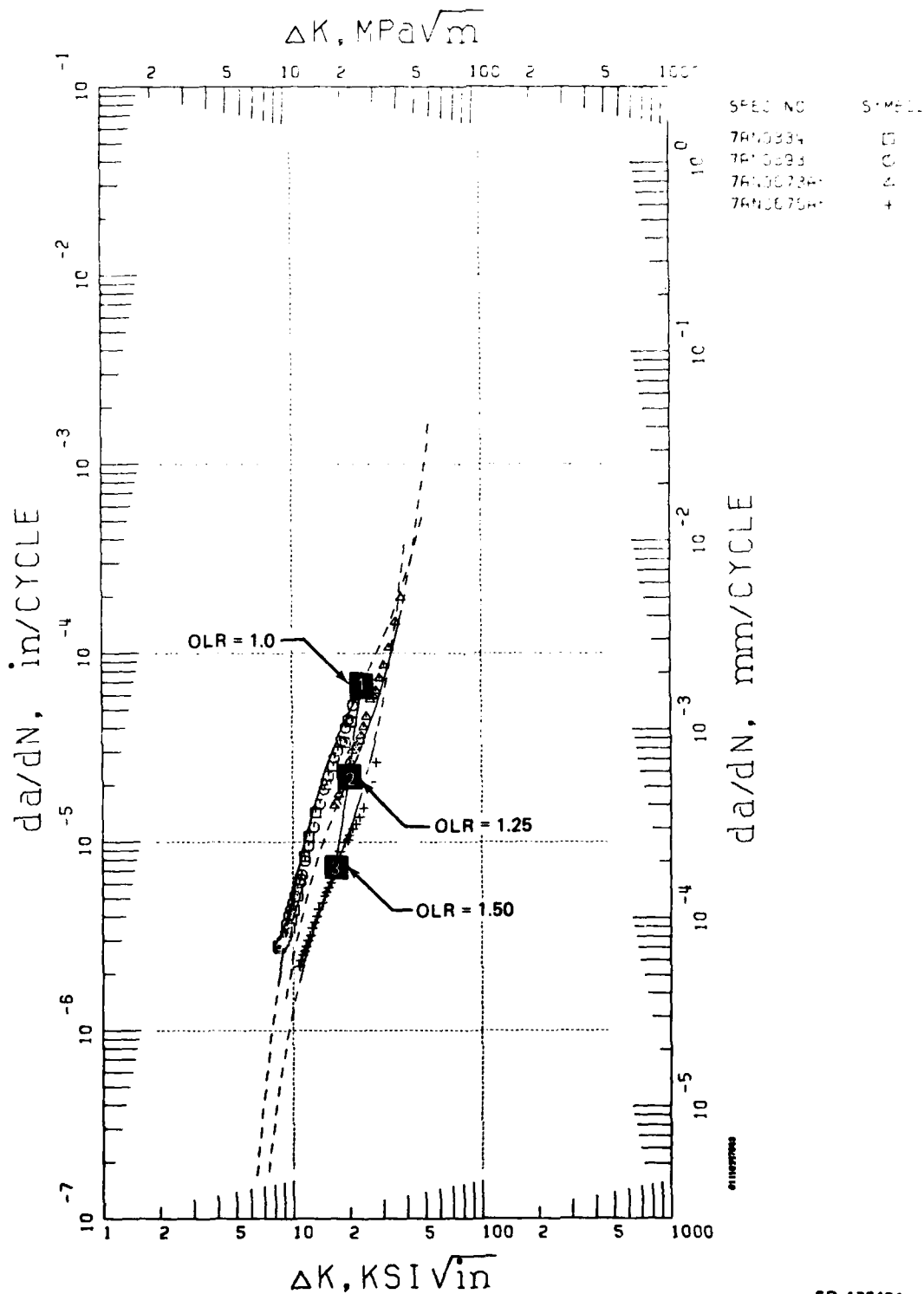


Figure 76. IN100 (PWA 1073) Crack Propagation, Overload Ratio Model,
 $R = 0.50, 0.167 \text{ Hz (10 cpm), } 649^\circ\text{C (1200}^\circ\text{F), } \Delta N_{OL} = 40$

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DLR = 1.00

SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	TYPE	THIK	REMARKS
7AN0334	PWA 1073	1200F	AIR	10 CPM	R=.5	RAD	MCT .5	BAEPB3H9
7AN0393	PWA 1073	1200F	AIR	10 CPM	R=.5	RAD	MCT .5	
								Y=0.5000 SINH(4.192 (X -1.368)) -4.172
								(METRIC) Y=0.5000 SINH(4.192 (X -1.409)) -2.767
								*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 8.33 , AND X= 21.89 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 1

DLR = 1.25 + 40 CYCLES

SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	TYPE	THIK	REMARKS
7AN0673AF	PWA 1073	1200F	AIR	MIX	R=.5	RAD	MCT 0.1125+40	
								Y=0.5000 SINH(4.727 (X -1.298)) -4.654
								(METRIC) Y=0.5000 SINH(4.727 (X -1.339)) -3.249
								*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 16.61 , AND X= 37.69 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 2

DLR = 1.50 + 40 CYCLES

SPEC NO	MATERIAL	TEMP	ATM	FREQ	R	TYPE	THIK	REMARKS
7AN0675AF	PWA 1073	1200F	AIR	MIX			MCT .251 0.115+40CY	
								Y=0.5000 SINH(5.262 (X -1.228)) -5.136
								(METRIC) Y=0.5000 SINH(5.262 (X -1.269)) -3.731
								*** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 10.78 , AND X= 27.85 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 3

OVERALL STATISTICS FOR THIS COLLECTION OF GROUPS. TOTAL RECORD = 0.9768. AND STD.ERROR.FST. = 0.0748

FD 177475

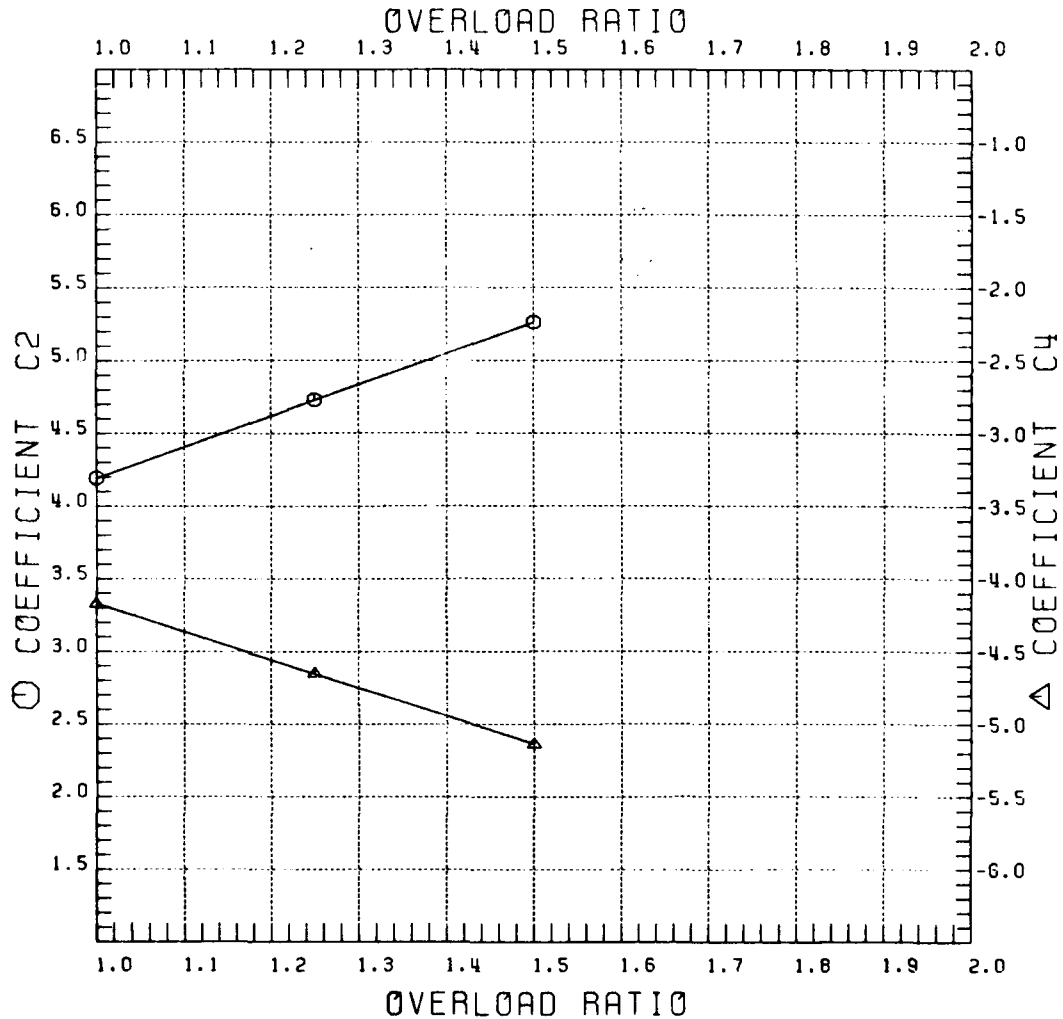
Figure 77. Statistics for IN100 (PWA 1073) Crack Propagation, Overload Ratio Model, $R = 0.50$, 0.167 Hz (10 cpm) 649°C (1200°F)
 $\Delta N_{OL} = 40$

COEFFICIENTS C2 AND C4 VS.
OVERLOAD RATIO

$$C2 = 2.0513 + 2.1407 \text{ OLR}$$

$$C4 = -2.2434 - 1.9286 \text{ OLR}$$

$$C3 = -1.9748 - 0.1455 \text{ C4}$$



FD 177476

Figure 78. IN100 (PWA 1073) Crack Propagation, Overload Ratio Model
Correlative Parameters, $R = 0.50$, 0.167 Hz (10 cpm), 649°C
(1200°F), $\Delta N_{OL} = 40$

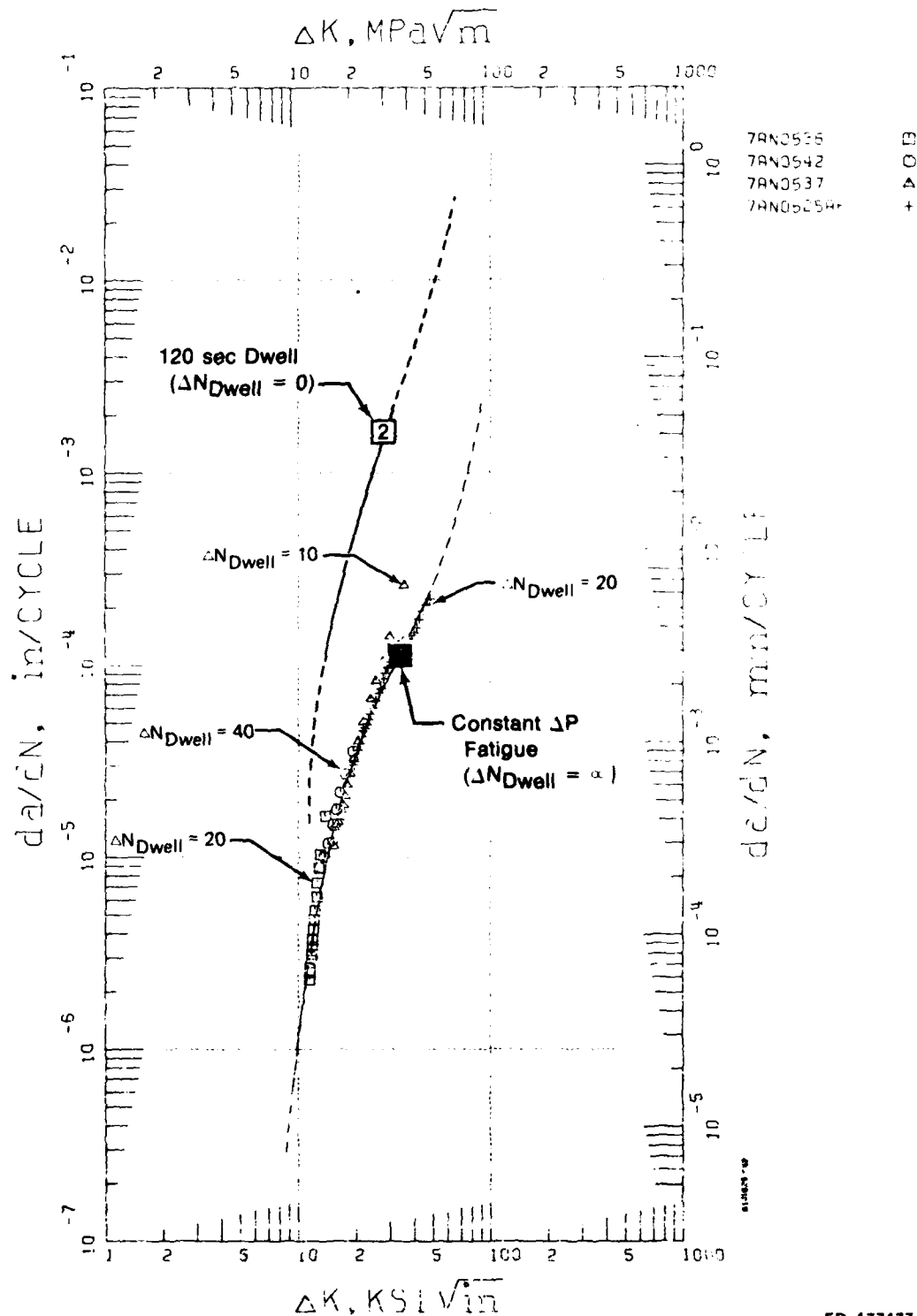


Figure 79. IN100 (PWA 1073) Crack Propagation, $R = 0.10$, 649°C (1200°F), 0.167 Hz (10 cpm) Sawtooth Fatigue Interrupted by Periodic 120 Dwell at Peak Load, $\Delta N_{\text{Dwell}} = 10, 20, \text{ and } 40$

PAGE 61316297942

1200F. R=.1. 20380
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE TH K REMARKS
 7ANJ536 PWA 1073 1200F AIR MIX R=.1 RAD MCT .470 20CY + 2MDWL
 -0.24 0. Y=0.5000 SINH(3.961 (X -1.529)) -3.947
 WAFT 0 (METRIC) Y=0.5000 SINH(3.961 (X -1.570)) -2.542
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 11.39 , AND X= 13.83 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 1

ASOPD 0.9992 SEE 0.1326

1200F. R=.1. 40380

SPEC NO MATERIAL TEMP ATM FREQ R TYPE TH K REMARKS
 7ANJ542 PWA 1073 1200F AIR MIX R=.1 RAD MCT .500 40CY + 2MDWL
 -0.24 0. Y=0.5000 SINH(3.961 (X -1.529)) -3.947
 WAFT 0 (METRIC) Y=0.5000 SINH(3.961 (X -1.570)) -2.542
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 12.98 , AND X= 19.14 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 2

ASOPD 0.9973 SEE 0.1058

1200F. R=.1. 10380

SPEC NO MATERIAL TEMP ATM FREQ R TYPE TH K REMARKS
 7ANJ537 PWA 1073 1200F AIR MIX R=.1 RAD MCT .470 10CY + 2MDWL
 -0.24 0. Y=0.5000 SINH(3.961 (X -1.529)) -3.947
 WAFT 0 (METRIC) Y=0.5000 SINH(3.961 (X -1.570)) -2.542
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 15.11 , AND X= 35.41 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 3

ASOPD 0.9921 SEE 0.1157

1200F. R=.1. 20380

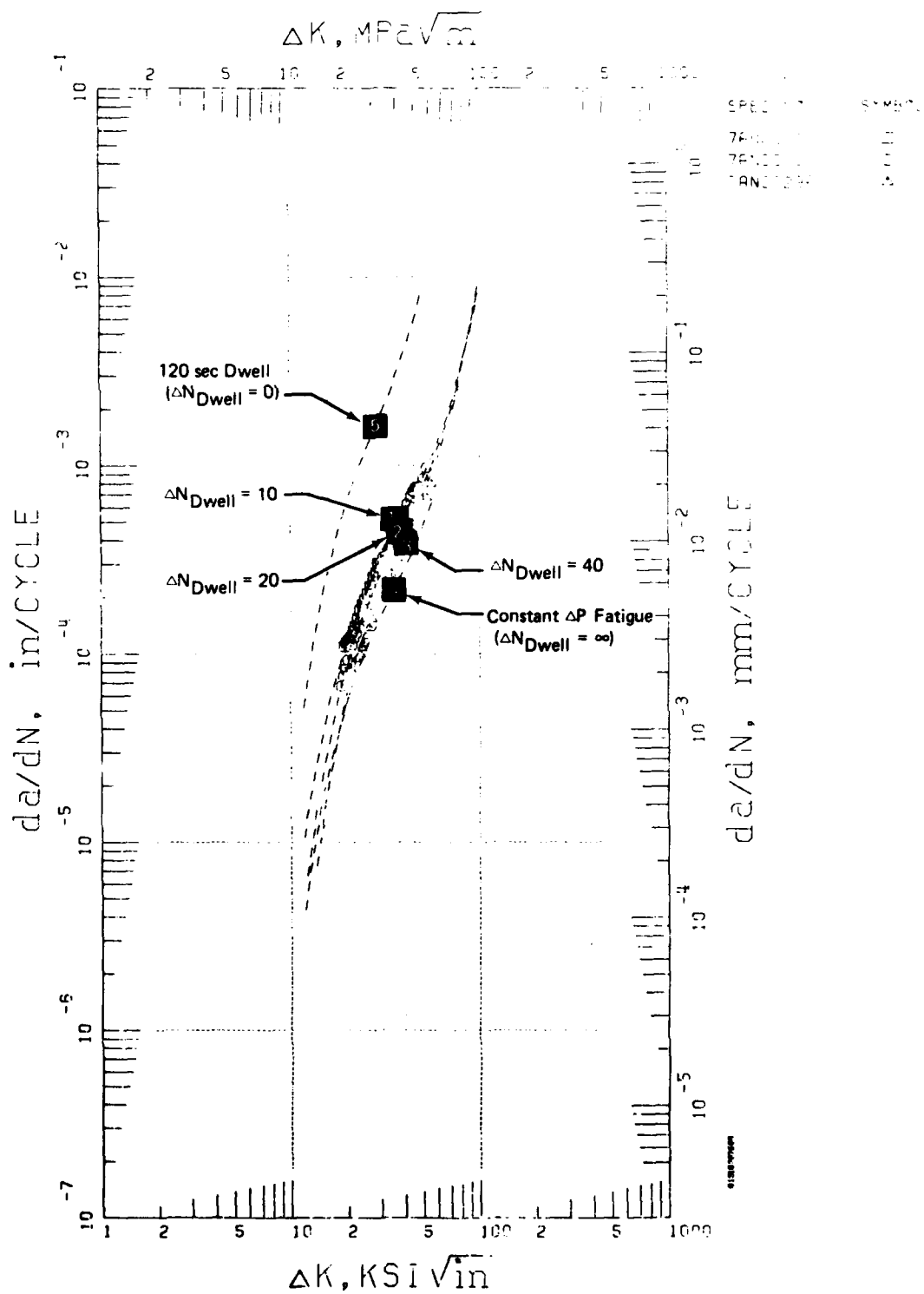
SPEC NO MATERIAL TEMP ATM FREQ R TYPE TH K REMARKS
 7ANJ525 PWA 1073 1200F AIR MIX R=.1 RAD MCT .254 20CY + 2MDWL
 -0.24 0. Y=0.5000 SINH(3.961 (X -1.529)) -3.947
 WAFT 0 (METRIC) Y=0.5000 SINH(3.961 (X -1.570)) -2.542
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 19.47 , AND X= 48.34 ONLY. DO NOT EXTRAPOLATE.

GROUP NO. 4

ASOPD 0.9947 SEE 0.0342

FD 177478

Figure 80. Statistics for IN100 (PWA 1073) Crack Propagation, $R = 0.10$, 649°C (1200°F) 0.167 Hz (10 cpm), Sawtooth Fatigue Interrupted by Periodic 120 Dwell at Peak Load, $\Delta N_{\text{Dwell}} = 10, 20, \text{ and } 40$



FD 177482

Figure 81. IN100 (PWA 1073) Crack Propagation, Model of LCF-Dwell Interaction, $R = 0.10$, 732°C (1350°F)

PHCE 81316287905

1350F, R=1.1, 10020
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7513521AF PWA 1073 1350F AIR MIX R=1.1 RAD MCT .237 1002 + 2MDWL
 -1.35 0. Y=0.5000 SIN(4.828 (X -1.568)) -3.323
 WFT 0 (METRIC) Y=0.5000 SIN(4.828 (X -1.609)) -1.918
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 19.19 , AND X= 47.26 ONLY. DO NOT EXTRAPOLATE.

1350F, R=1.1, 20020
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7513525AF PWA 1073 1350F AIR MIX R=1.1 RAD MCT .240 2002 + 2MDWL
 -1.35 0. Y=0.5000 SIN(4.065 (X -1.580)) -5.360
 WFT 0 (METRIC) Y=0.5000 SIN(4.065 (X -1.621)) -1.955
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 18.50 , AND X= 52.18 ONLY. DO NOT EXTRAPOLATE.

1350F, R=1.1, 40020
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 7513529AF PWA 1073 1350F AIR MIX R=1.1 RAD MCT .251 4002 + 2MDWL
 -1.35 0. Y=0.5000 SIN(4.301 (X -1.592)) -5.398
 WFT 0 (METRIC) Y=0.5000 SIN(4.301 (X -1.633)) -1.992
 *** IMPORTANT *** THIS EQUATION IS VALID BETWEEN X= 20.80 , AND X= 55.82 ONLY. DO NOT EXTRAPOLATE.

1350F, R=1.1, 60020
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 PWA 1073 1350 AIR 10 cpm R=0.1
 -1.35 0. Y=0.5000 SIN(4.111 (X -1.543)) -3.662
 WFT 0 (METRIC) Y=0.5000 SIN(4.111 (X -1.584)) -2.257

1350F, R=1.1, 80020
 SPEC NO MATERIAL TEMP ATM FREQ R TYPE THICK REMARKS
 PWA 1073 1350 AIR 2 MDWL R=0.1
 -1.35 0. Y=0.5000 SIN(4.752 (X -1.450)) -2.792
 WFT 0 (METRIC) Y=0.5000 SIN(4.752 (X -1.491)) -1.335

FD 177483

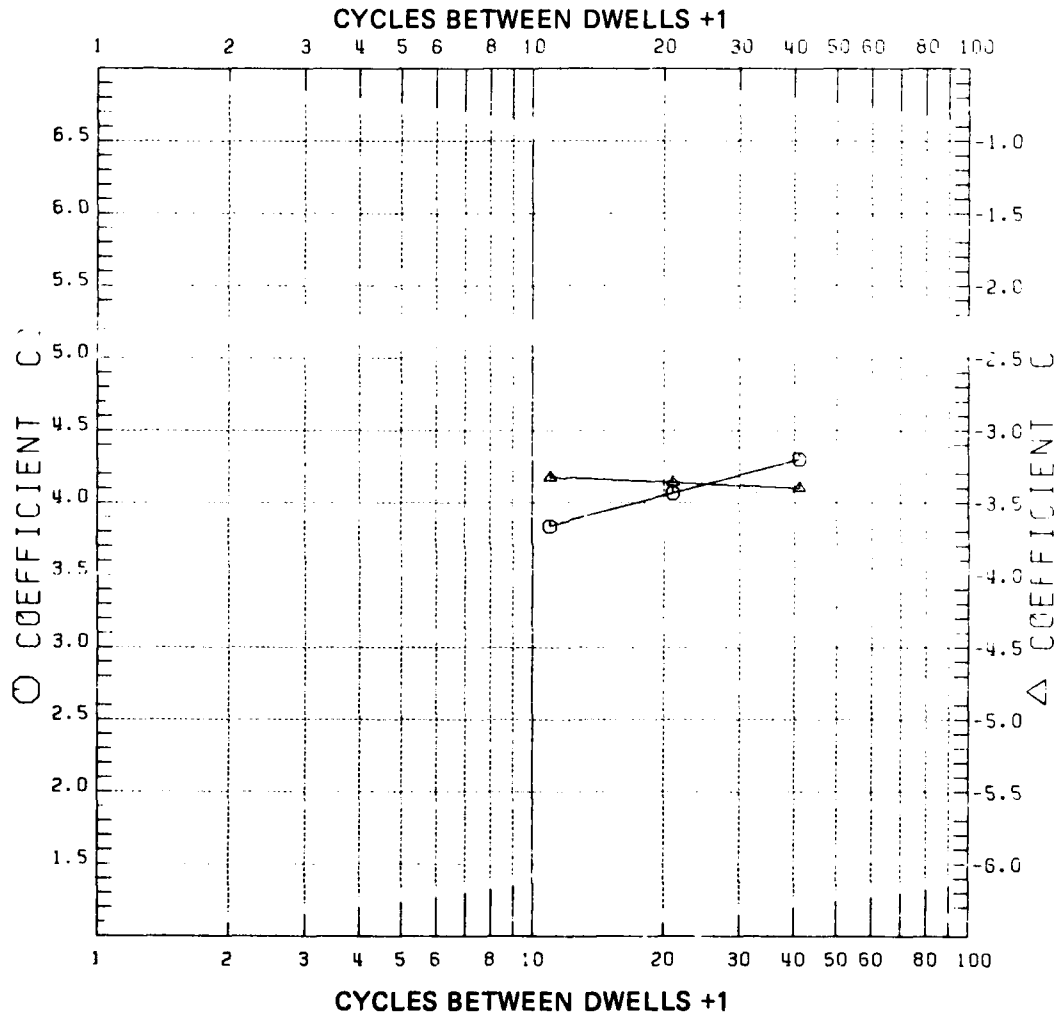
Figure 82. Statistics for IN100 (PWA 1073) Crack Propagation, Model of LCF-Dwell Interaction, $R = 0.10$, 732°C (1350°F)

COEFFICIENTS C2 AND C4 VS
CYCLES BETWEEN DWELLS +1

$$C2 = 2.9940 + 0.8103 (\text{LOG } (\Delta N_{\text{Dwell}} + 1))$$

$$C4 = -3.1864 - 0.1313 (\text{LOG } (\Delta N_{\text{Dwell}} + 1))$$

$$C3 = -0.5045 + 0.3201 C4$$



FD 177484

Figure 83. IN100 (PWA 1073) Crack Propagation, Correlative Parameters
for Model of LCF-Dwell Interaction, $R = 0.10$, 732°C (1350°F)

All tests were conducted with the specimen carefully aligned and ends rigidly fixed. In spite of such efforts to achieve a uniform nominal stress field in the specimen, crack growth irregularities observed in several specimens suggested the presence of a bending stress. The irregular crack growth was characterized by unequal rates of propagation at the opposing specimen surfaces, producing crack front asymmetry. This condition required the rejection of data from several completed tests and subsequent retesting.

(1) *Waspaloy*

The results of the 427°C (800°F) negative stress ratio tests for Waspaloy are presented in Figure 84. The rate of crack propagation is observed to be similar for $R = -0.5$ and $R = -1.0$ fatigue, and crack growth under both of these stress ratios is more rapid than the illustrated curve for $R = 0$ cycling. Since all data are regressed with $K_{min} = 0$ for compressive stress excursions, the comparison of the negative R data with the $R = 0$ curve isolates the influence of the compressive excursion.

The effect of negative stress ratio cycling on crack propagation of Waspaloy at 649°C (1200°F) is illustrated in Figure 85. Again the compressive loading is observed to increase crack growth above the rate produced by $R = 0$ fatigue.

(2) *IN100*

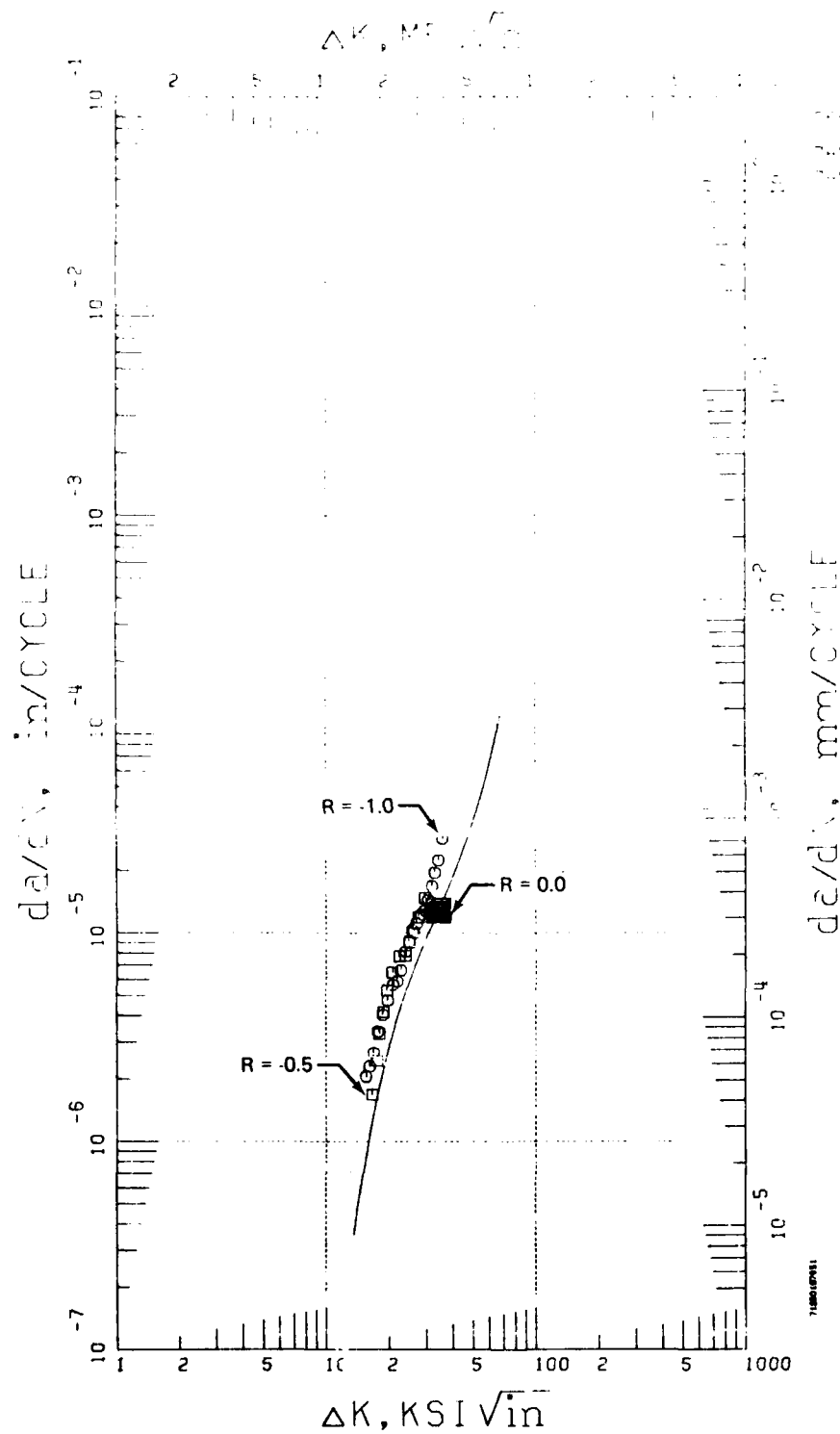
Crack propagation in IN100 subject to negative stress ratio exhibited anomalous behavior. At 427°C (800°F), Figure 86, the effect of $R = -0.5$ fatigue is nearly equivalent to behavior under $R = 0$ cycling, however, decreasing stress ratio to $R = -1.0$ (specimen 793) is observed to reduce crack growth rate significantly below that of baseline ($R = 0$) fatigue. Close examination of the data from specimen 793 revealed no satisfactory explanation for the slower crack growth. While this specimen was taken from a separate heat of IN100, experience with this alloy indicates that the anomalous behavior cannot be explained as a heat-to-heat effect.

Anomalous crack growth was also observed in 649°C (1200°F) negative stress ratio testing of IN100. As illustrated in Figure 87, crack propagation under $R = -0.5$ fatigue was observed to be more rapid than under $R = -1.0$ cycling. Propagation under both conditions was more severe than for $R = 0$ fatigue.

(3) *Interpolative Modeling of Crack Growth*

The basis for the anomalies in crack propagation exhibited by the negative stress ratio data is believed to be the tendency for asymmetric crack growth, as previously discussed. While the data presented were taken from specimens displaying very limited crack asymmetry, such behavior appears to be the source of appreciable test-to-test variability for tension-compression fatigue. Similar crack asymmetry and data variability were not observed under tension-tension fatigue. The use of a large capacity testing machine, having a very rigid load train, should significantly reduce the variability for tension-compression fatigue. Such equipment was not available for the current program.

In the light of the observed variability in the generated crack propagation data for negative stress ratio fatigue, interpolative models of crack growth behavior could not be reliably developed. Multiple tests at each condition are suggested in order to appropriately characterize the effect of tension-compression cycling.



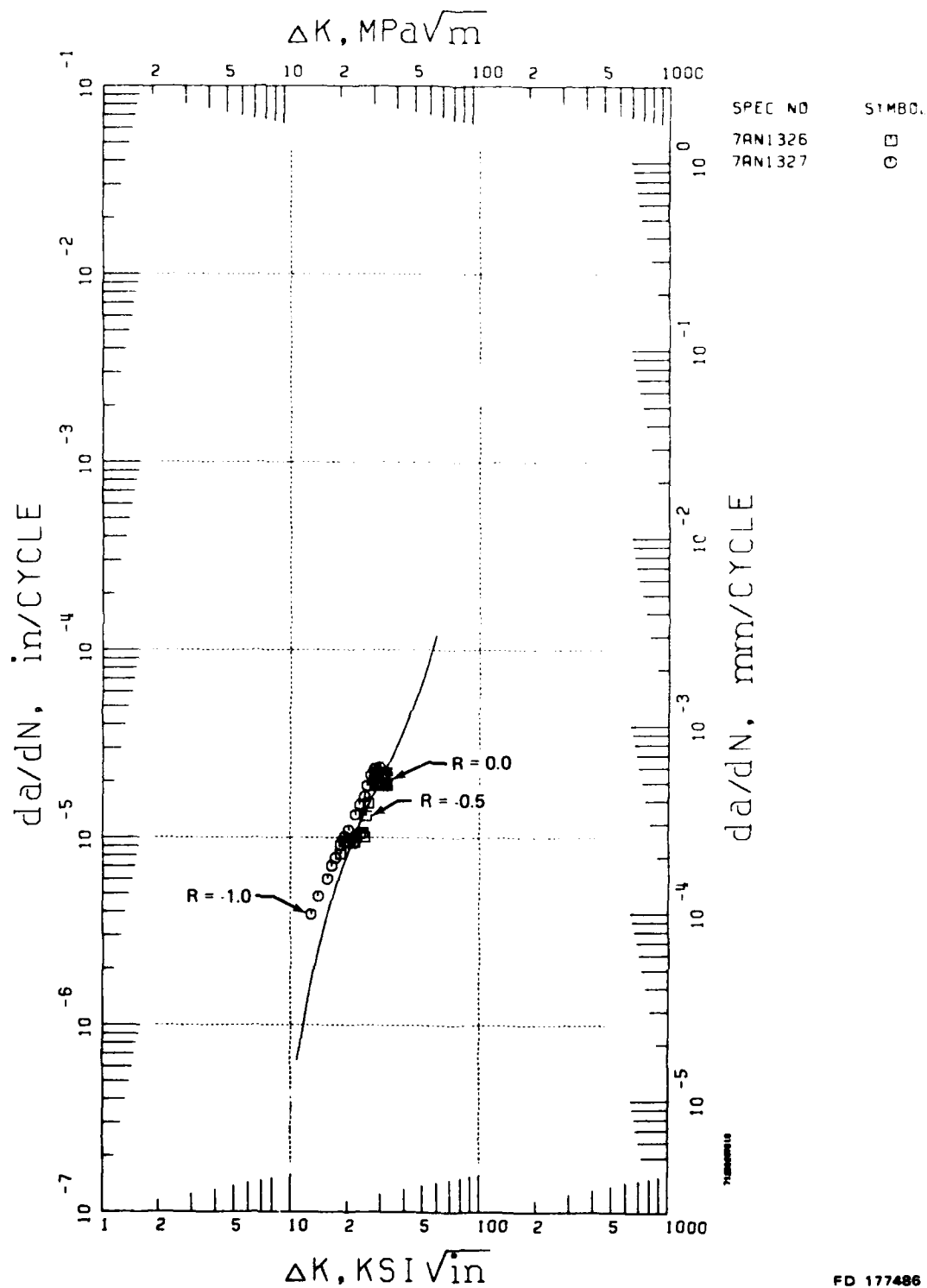


Figure 85. Waspaloy (PWA 1007) Crack Propagation, Negative Stress Ratio Effect, 0.167 Hz (10 cpm), 649°C (1200°F)

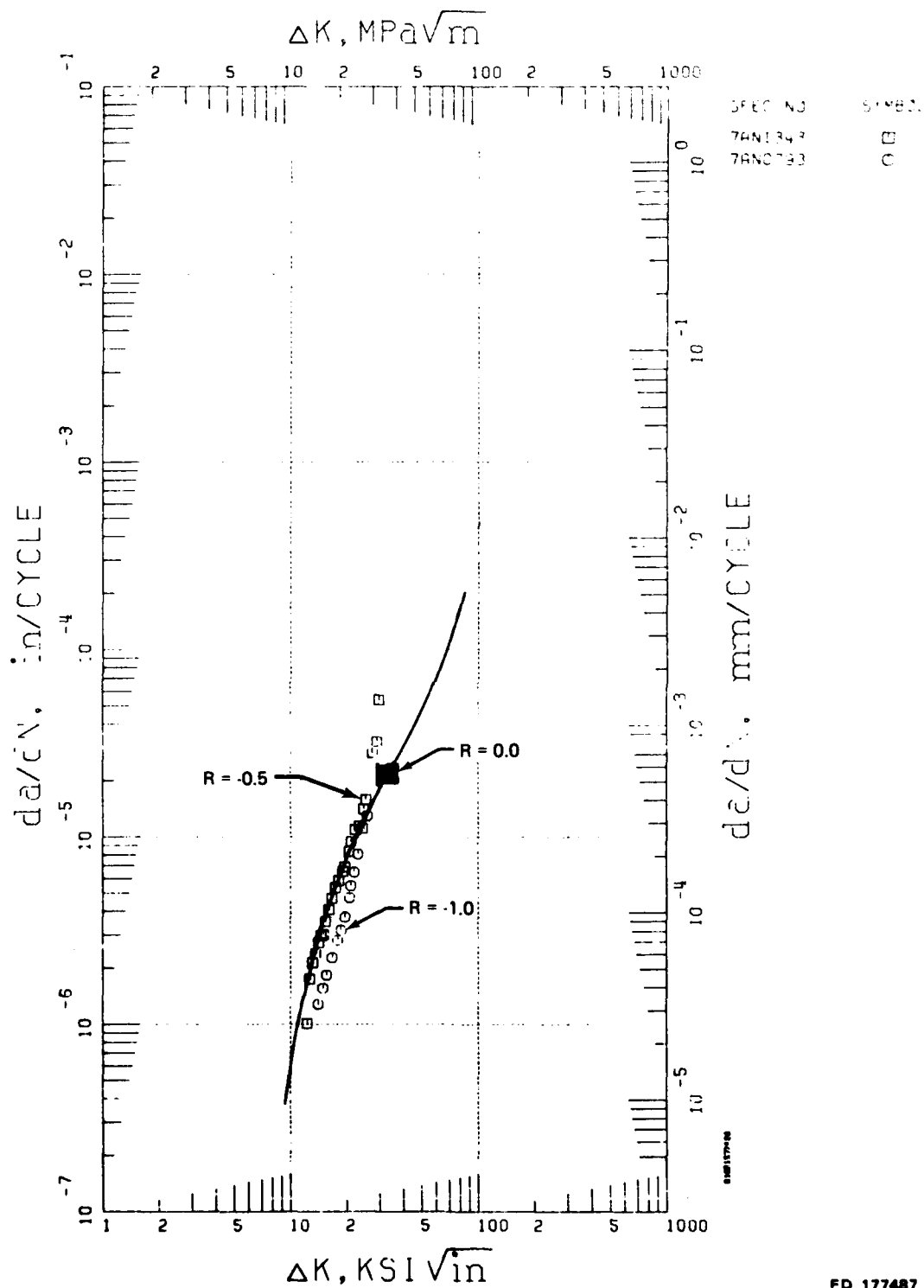
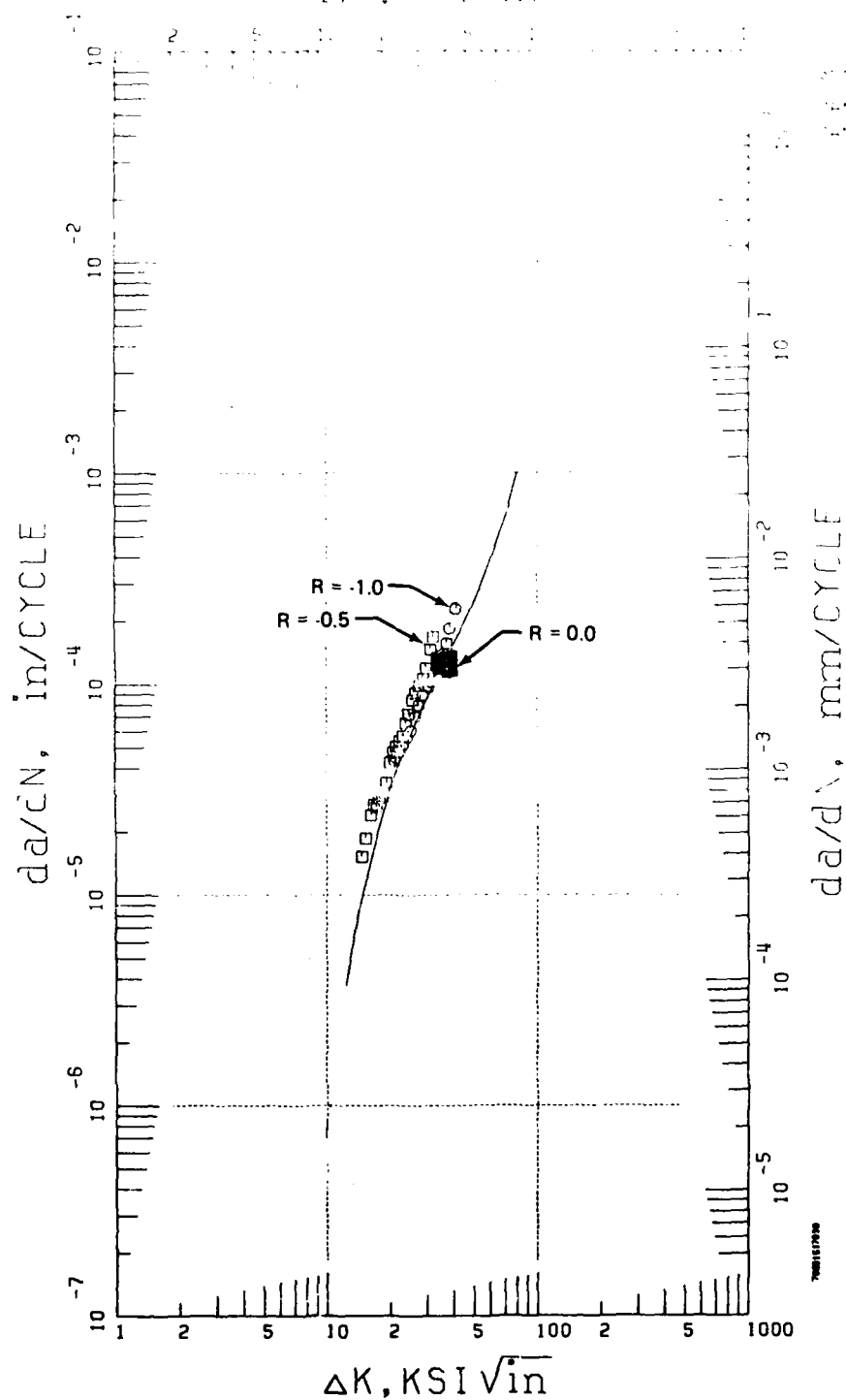


Figure 86. IN100 (PWA 1073) Crack Propagation, Negative Stress Ratio Effect, 0.167 Hz (10 cpm), 427°C (800°F)



FD 177488

Figure 87. IN100 (PWA 1073) Crack Propagation, Negative Stress Ratio Effect, 0.167 Hz (10 cpm) 649°C (1200°F)

b. Effect of Net Section Stress

The effect of high net section stress on crack propagation in Waspaloy (PWA 1007) was investigated using the through-thickness center crack specimen in Figure 11a. This specimen was selected for its small obtainable crack size and the ability to achieve high net section stresses at stress intensities comparable with those of the baseline testing. Tests of two specimens were conducted with $\sigma_{net} > 0.8 \sigma_{yield}$, $T = 649^{\circ}\text{C}$ (1200°F), $R = 0.05$, and a frequency of 0.167 Hz (10 cpm). The resulting data are presented in Figure 88, and their relationship to the baseline crack growth curve is illustrated. Crack propagation under the high stress loading is observed to be slightly less rapid than under equivalent test conditions with significantly reduced stress. Thus, the interpolative models of crack propagation in Waspaloy (PWA 1007) should be applicable, but slightly conservative when used to predict crack growth in a stress field of magnitude approaching the material yield strength.

Similar findings have been reported (Reference 2) for the effect of high net section stress on elevated temperature crack propagation in GATORIZED[®] IN100 (PWA 1073).

c. Prior Plastic Deformation

Component crack propagation life predictions are made using da/dN data obtained from virgin (unstrained) material. However, cracks occurring in real hardware often initiate in regions of high stress concentration such as boltholes or blade attachment areas. Material in these regions may be subjected to many strain cycles in excess of 1.0%. It is assumed that FCP behavior (da/dN vs ΔK) in this material is essentially the same as that for virgin material and that data generated on virgin specimens can be used to describe FCP in pre-strained material. The purpose of this auxiliary investigation was to test this hypothesis, using Waspaloy (PWA 1007) and IN100 (PWA 1073).

(1) Waspaloy

In order to simulate the cyclic loading experienced in the vicinity of a bolthole in a Waspaloy turbine disk, 1.0% tensile strain range cycling ($\epsilon_{mean} = \frac{1}{2} \epsilon_{max}$) was applied to unnotched center-crack specimens (Figure 11a). The specimens (1321 and 1323) were cycled at 649°C (1200°F) and 0.167 Hz (10 cpm) for 10% (200 cycles) of the expected crack initiation life. Determination of the cyclic stress-strain behavior of Waspaloy was performed using the strain control specimen of Figure 89, and typical hysteresis loops are presented in Figure 90. During the elevated temperature pre-strain cycling, specimen 1321 was monitored with acoustic emission equipment, and a plot of the resulting emission count is presented in Figure 91. The initially high acoustic activity attenuated to a stable level within the first 50 cycles. Acoustic emission reflects damage accumulation during testing. No detectable flaws resulted from the pre-straining.

The unnotched specimens were removed from the test machine, and a through-thickness center flaw was machined in each using electric discharge methods. From this point the specimens were treated the same as virgin specimens. The notched specimens were returned to the testing machine, precracked at room temperature, and the crack was propagated to failure under constant load amplitude fatigue $T = 649^{\circ}\text{C}$ (1200°F), 0.167 Hz (10 cpm), and a stress ratio of 0.1. The crack propagation data (da/dN vs ΔK) and a SINH curve representing crack propagation in virgin (unstrained) Waspaloy are presented in Figure 92. Crack growth in the pre-strained material is approximately 30% faster than in virgin material. The crack growth rate in the pre-strained specimens is approximately 30% faster than observed from the virgin material tests. However, this deviation is explainable by intrinsic data scatter for crack propagation testing.

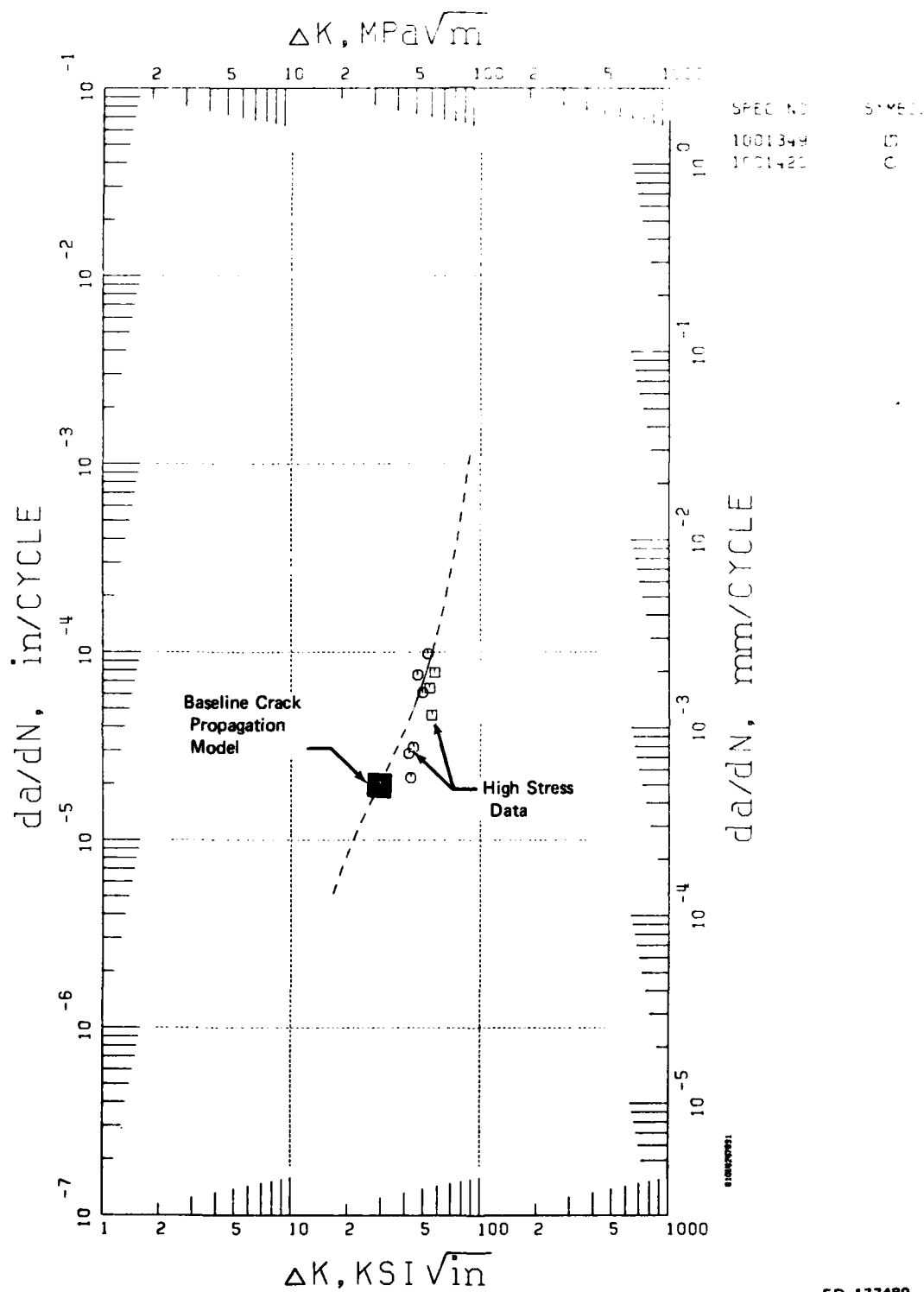
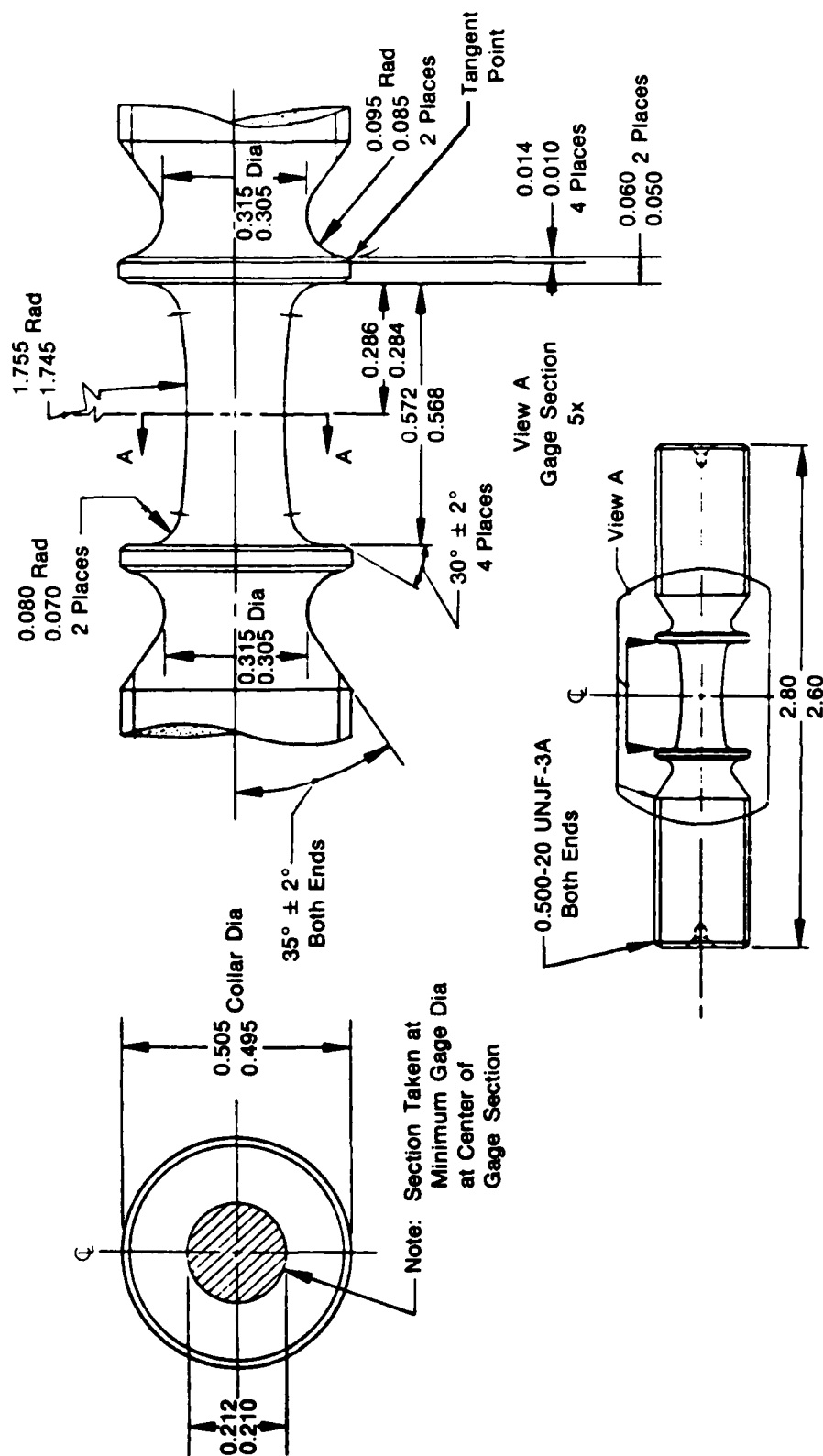
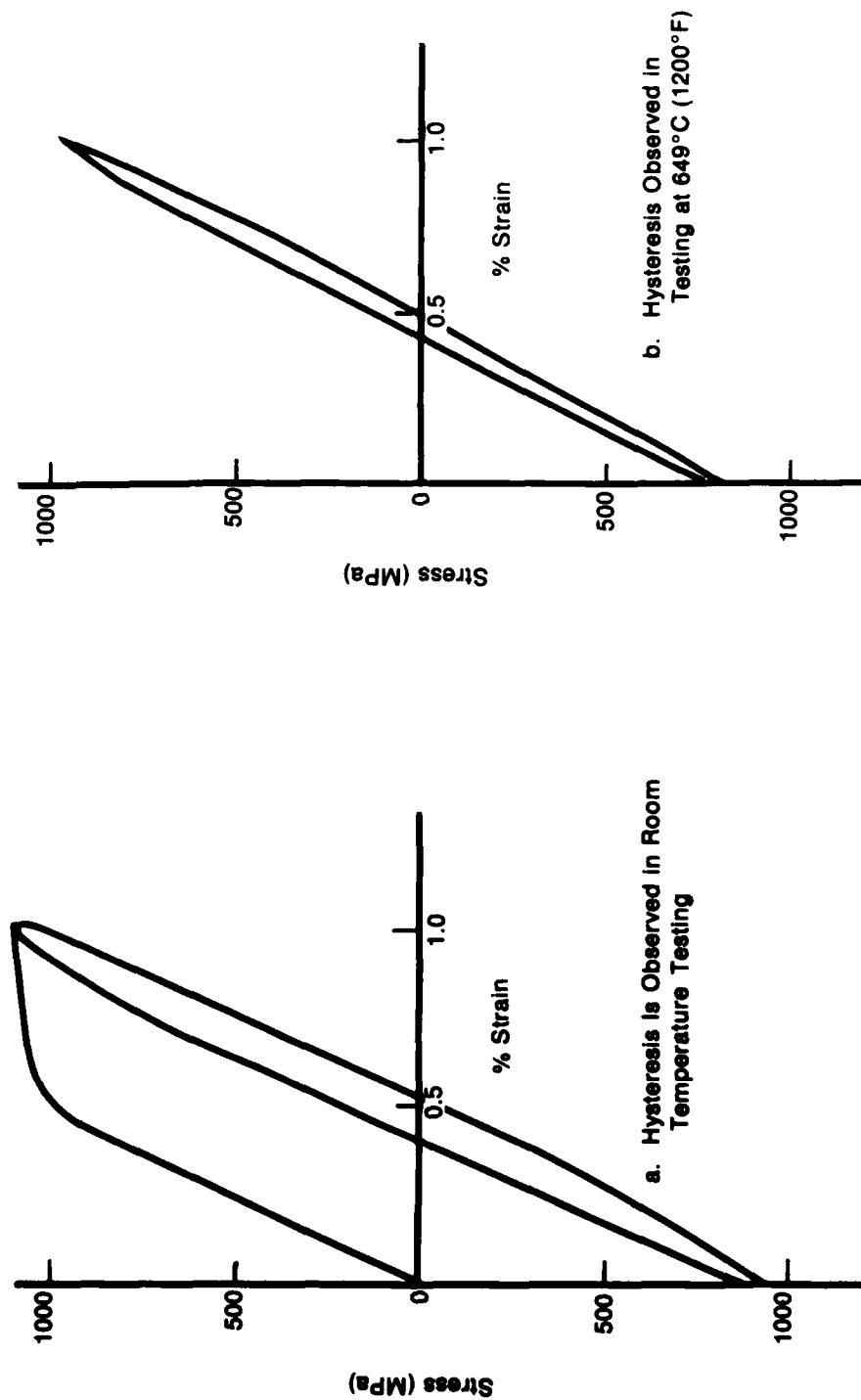


Figure 88. Waspaloy (PWA 1007) Crack Propagation, High Stress Effect, $R = 0.05$, 0.167 Hz (10 cpm), 649°C (1200°F)



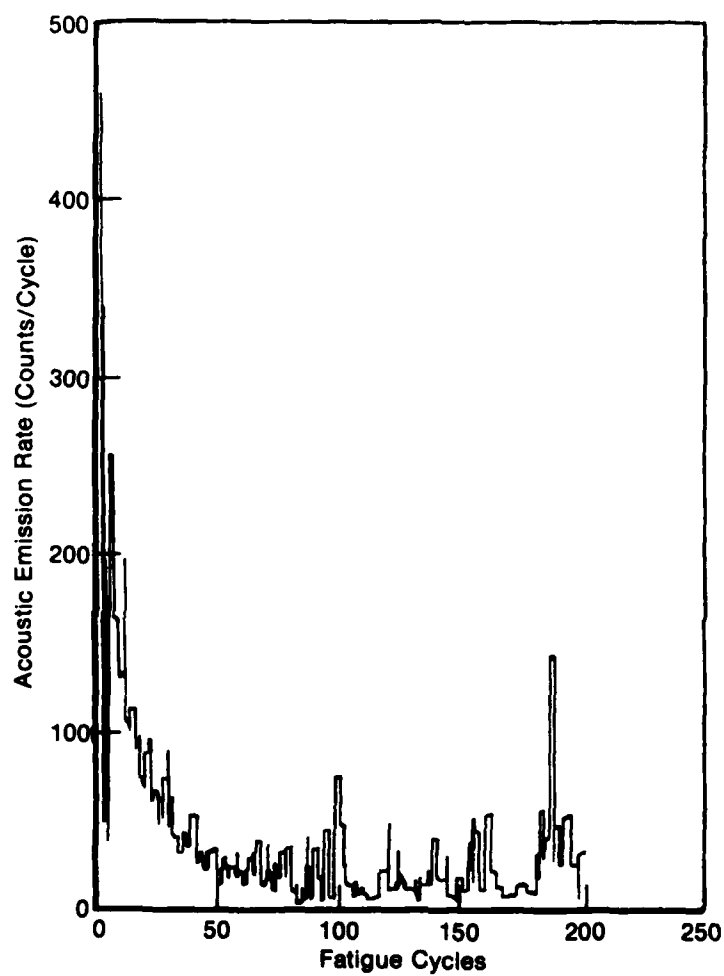
PTD 110005

Figure 89. Strain Controlled Low Cycle Fatigue Specimen



FD-1000

Figure 90. Hysteresis Observed in 1.0% Strain Controlled Testing



FD 139887

Figure 91. Acoustic Emission Record of Prestrain Cycling of Waspaloy (PWA 1007) Specimen

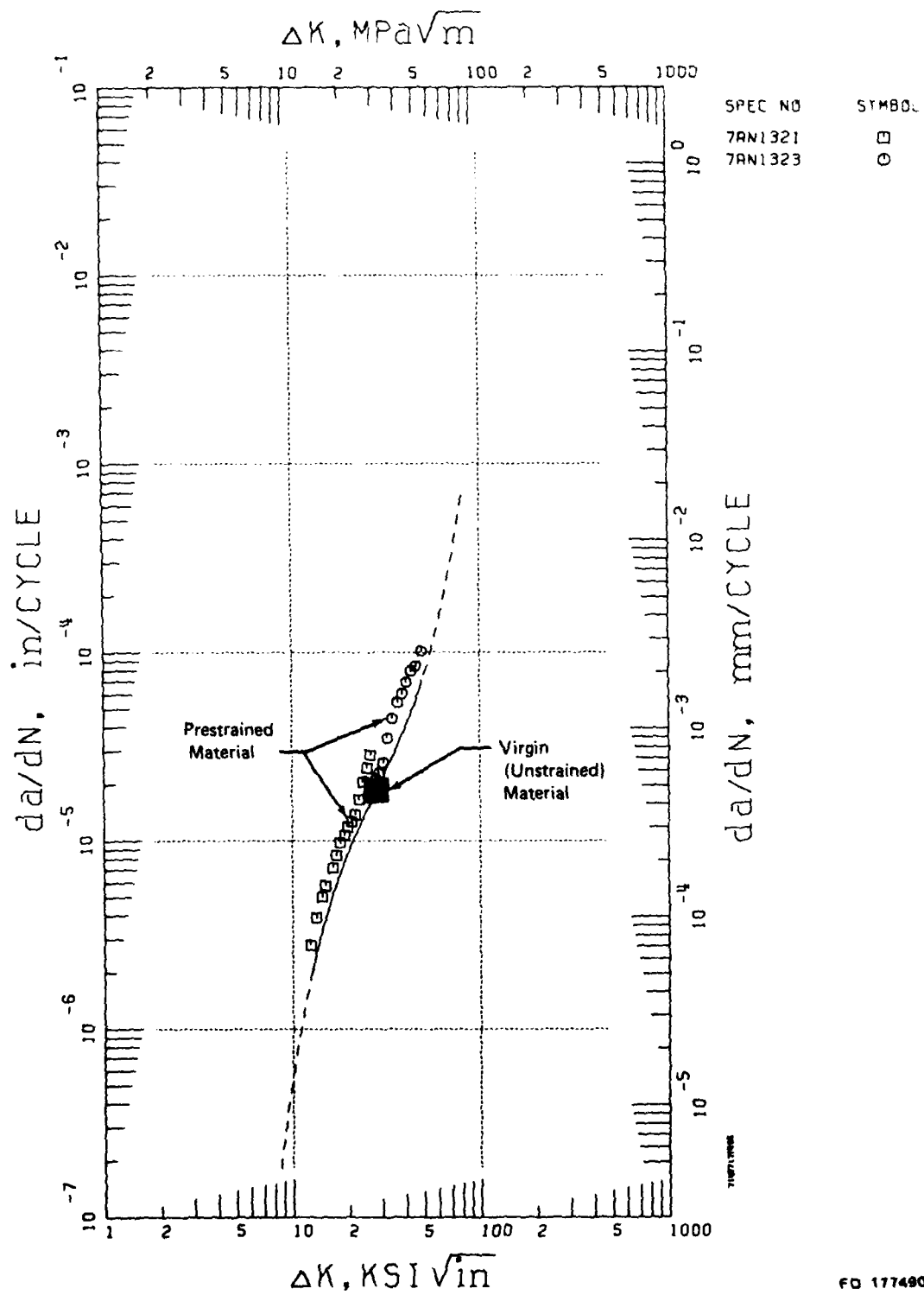


Figure 92. Waspaloy (PWA 1007) Crack Propagation, Effect of Prior Plastic Deformation, $R = 0.10$, 0.167 Hz (10 cpm), 649°C (1200°F)

FD 177490

(2) IN100

The effect of 1.0% strain cycling prior to crack propagation was also examined in IN100. The procedure was as described for Waspaloy, and the results are illustrated in Figure 93. Crack propagation in pre-strained IN100 was observed to be generally equivalent to characteristic crack growth in virgin IN100.

(3) Component Life Prediction

The results of the Waspaloy and IN100 tests discussed above indicate different effects of 1.0% pre-strain cycling. Using a crack growth model developed for virgin material data, prediction of fatigue crack life in pre-strained Waspaloy (PWA 1007) are expected to be slightly anticonservative, while for IN100, little model bias is indicated. However, the tests results for both materials fall within the range of intrinsic data scatter. Therefore, fatigue crack growth models representing virgin material data from both alloys are applicable to life prediction in pre-strained material.

d. Overload-Underload-LCF Interaction

Flight mission stress analysis which was conducted under Phase I of this contract revealed the existence of compressive stresses within the loading spectrum of a cooled turbine disk (Figure 4). The compressive stresses occurred immediately following a major tensile load excursion (overload) and were expected to have a detrimental influence upon crack propagation rate by reducing the beneficial effect of the overload.

A test was conducted to examine the effect on crack propagation of compressive loading in the repetitive mission sequence of overload-underload-low cycle fatigue, Figure 94. The resulting data was reduced with the hyperbolic sine model and is presented in the comparative plot of Figure 95. The three data sets are from tests of IN100 at 649°C (1200°F) and (1) constant load amplitude fatigue, $R = 0.5$; (2) constant load amplitude fatigue, $R = 0.5$, interrupted by a periodic overload (Overload Ratio = $P_{OL}/P_{max} = 1.5$) every 21 cycles; and (3) identical to (2) with the addition of a single compressive load excursion with an underload of (P_{UL}/P_{max}) = -0.45.

Crack propagation resulting from the overload-LCF loading (curve 2) is significantly less rapid than under similar constant load amplitude fatigue (curve 1). However, the overload-underload-LCF mission produces crack propagation which is slightly more severe than under constant ΔP fatigue. That is, in IN100 (PWA 1073) cycled at 649°C (1200°F) the effect of the minor compressive load excursion ($U_{OL} = -0.45$) following an overload (OLR = 1.5, $\Delta N_{OL} = 20$) is to erase the beneficial effect of the overload, and the combined effect of the overload-underload sequence is detrimental to the crack propagation life.

Further examination of the influence of overload-underload-LCF sequencing on crack growth is beyond the scope of the present contract. Such research is suggested for a future program.

e. Thermal-Mechanical Fatigue

Because the study of thermal-mechanical synergism is particularly complex, it has been assumed that the effects of frequency, stress ratio, dwells, and overloads occurring with changing temperature can be approximated by considering the isothermal increments of each parameter. The results of a survey test, discussed below, tend to substantiate this approach.

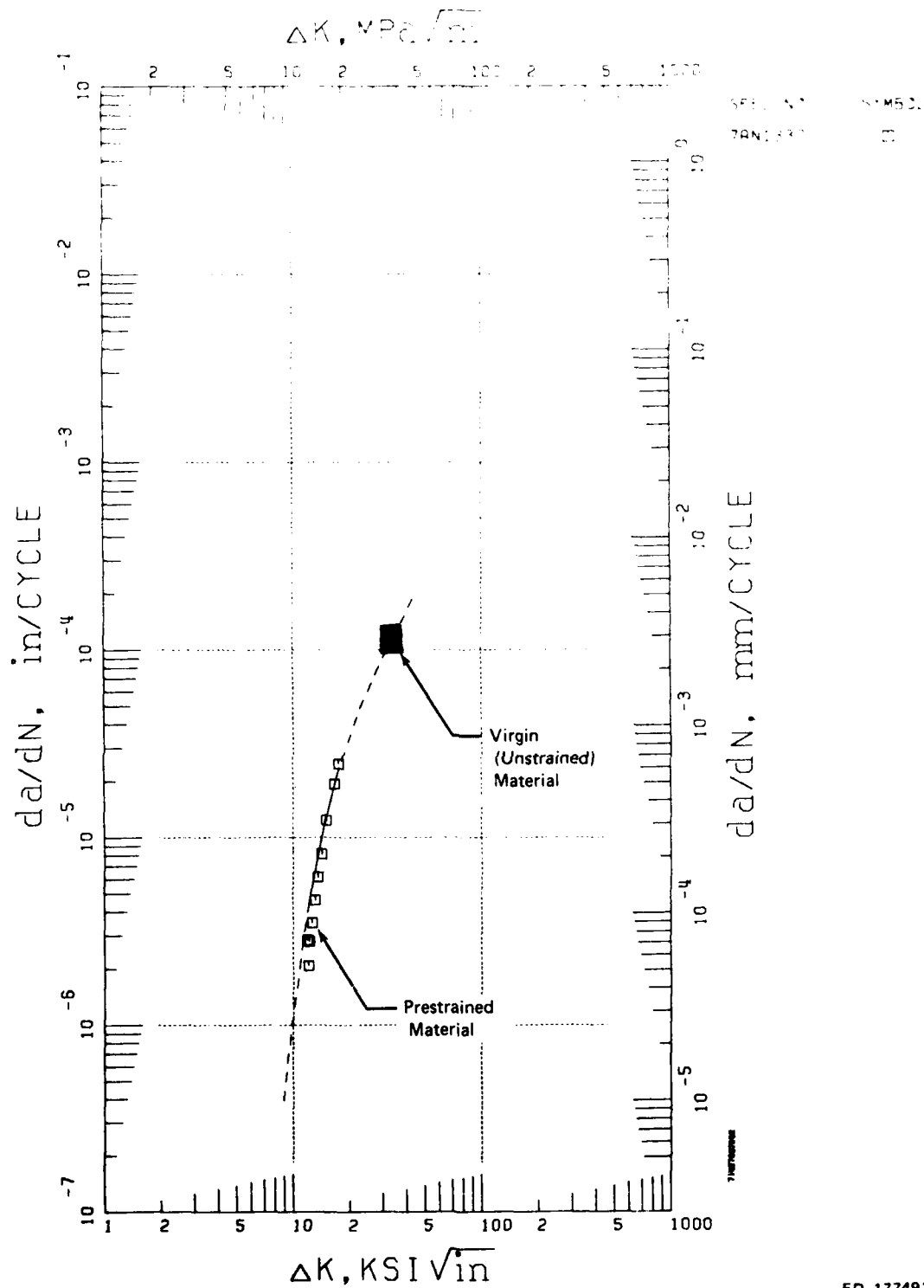
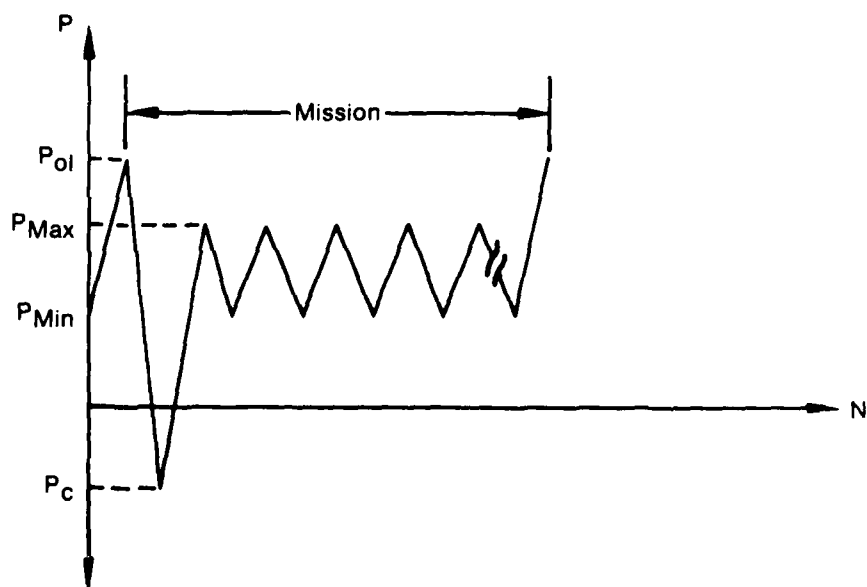


Figure 93. IN100 (PWA 1073) Crack Propagation, Effect of Prior Plastic Deformation, $R = 0.10, 0.167 \text{ Hz (10 cpm), } 649^\circ\text{C (1200}^\circ\text{F)}$



FD 118891

Figure 94. Overload-Underload-LCF Mission

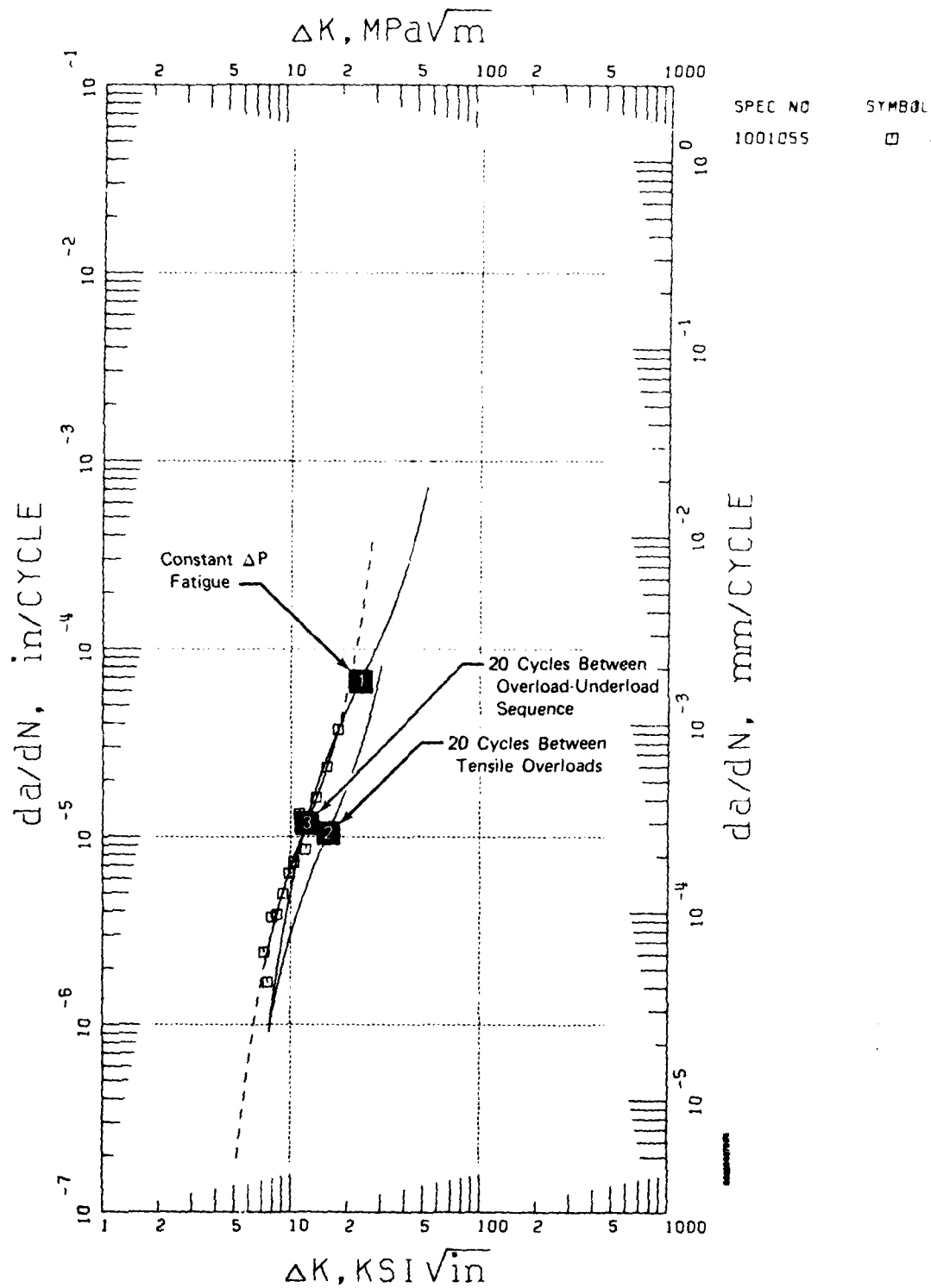


Figure 95. IN100 (PWA 1073) Crack Propagation, Effect of Overload-Underload Sequence, $R = 0.50$, 0.167 Hz (10 cpm), 649°C (1200°F), $\text{OLR} = 1.5$, $\Delta N_{\text{OL}} = 20$

FD 177396

The thermal-mechanical fatigue (TMF) test conducted under this task employed saw-tooth waveforms for both thermal and mechanical cycling. Temperature and load cycling were applied 180° out-of-phase as shown in Figure 96, and the test specimen was of through-thickness center crack geometry as shown in Figure 11a. The applied cyclic frequency was 0.0167 Hz (1 cpm) which required heating and cooling rates of 556°C (1000°F) per minute for temperature cycling between 427°C (800°F) and 704°C (1300°F).

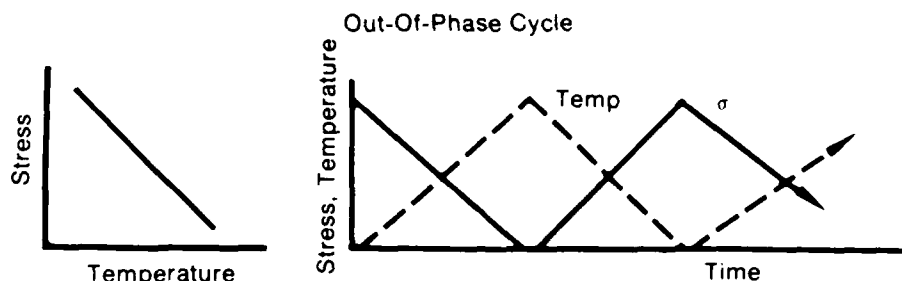


Figure 96. Thermal-Mechanical Fatigue Cycle

Specimen heating was accomplished with electrical induction, and forced air was used to achieve the proper cooling rate. An investigation of the through-thickness thermal gradient in the specimen was conducted by mounting thermocouples on the specimen surface and in a drill hole located at the specimen center. The internal temperature lagged the surface temperature by a maximum of 56°C (100°F) for a 556°C (1000°F) per minute cooling rate.

Figure 97 compares the thermal-mechanical FCP observed under out-of-phase cycling (maximum temperature occurring at minimum load) with crack growth under isothermal conditions at the same frequency and stress ratio (0.0167 Hz (10 cpm), $R = 0.10$). The four SINH curves represent isothermal crack growth at a series of temperatures which spans the range of thermal cycling (427°C (800°F) to 704°C (1300°F)). The TMF data are observed to correlate well with results of isothermal tests conducted at 427°C. This temperature coincides with the temperature at which peak loading occurs during the TMF cycle, signifying the importance of the peak load vs temperature condition. This result indicates that TMF behavior is more closely related to isothermal FCP than originally thought.

1. Effect of Specimen Thickness

An investigation of the effect of specimen thickness on elevated temperature crack propagation of Waspaloy (PWA 1007) was conducted at 427°C (800°F) and 649°C (1200°F). At each temperature, specimens of three thicknesses (2.54, 7.62, and 12.70 mm) (0.1, 0.3, and 0.5 in.) were tested at similar conditions (0.0167 Hz (10 cpm), $R = 0.05$). The results of these tests are illustrated in Figure 98 and 99. At each temperature, equivalent rates of crack growth are observed for the 7.62 and 12.70 mm thick specimens, while a much slower rate of crack propagation occurred in the 2.54 mm thick specimen. From these findings it is concluded that the rate of FCP of Waspaloy (PWA 1007) becomes thickness independent at some thickness less than 7.62 mm (0.30 in.).

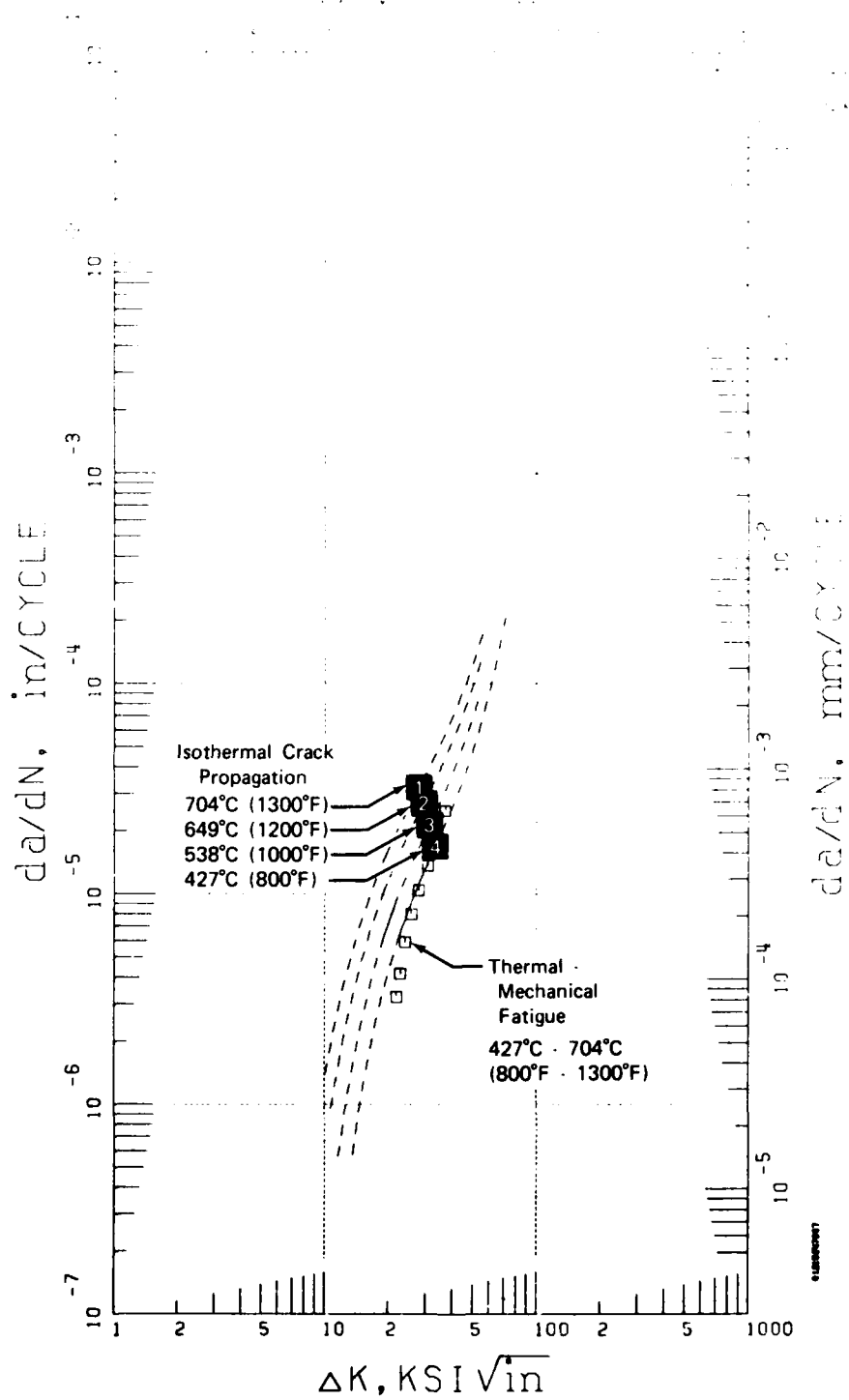
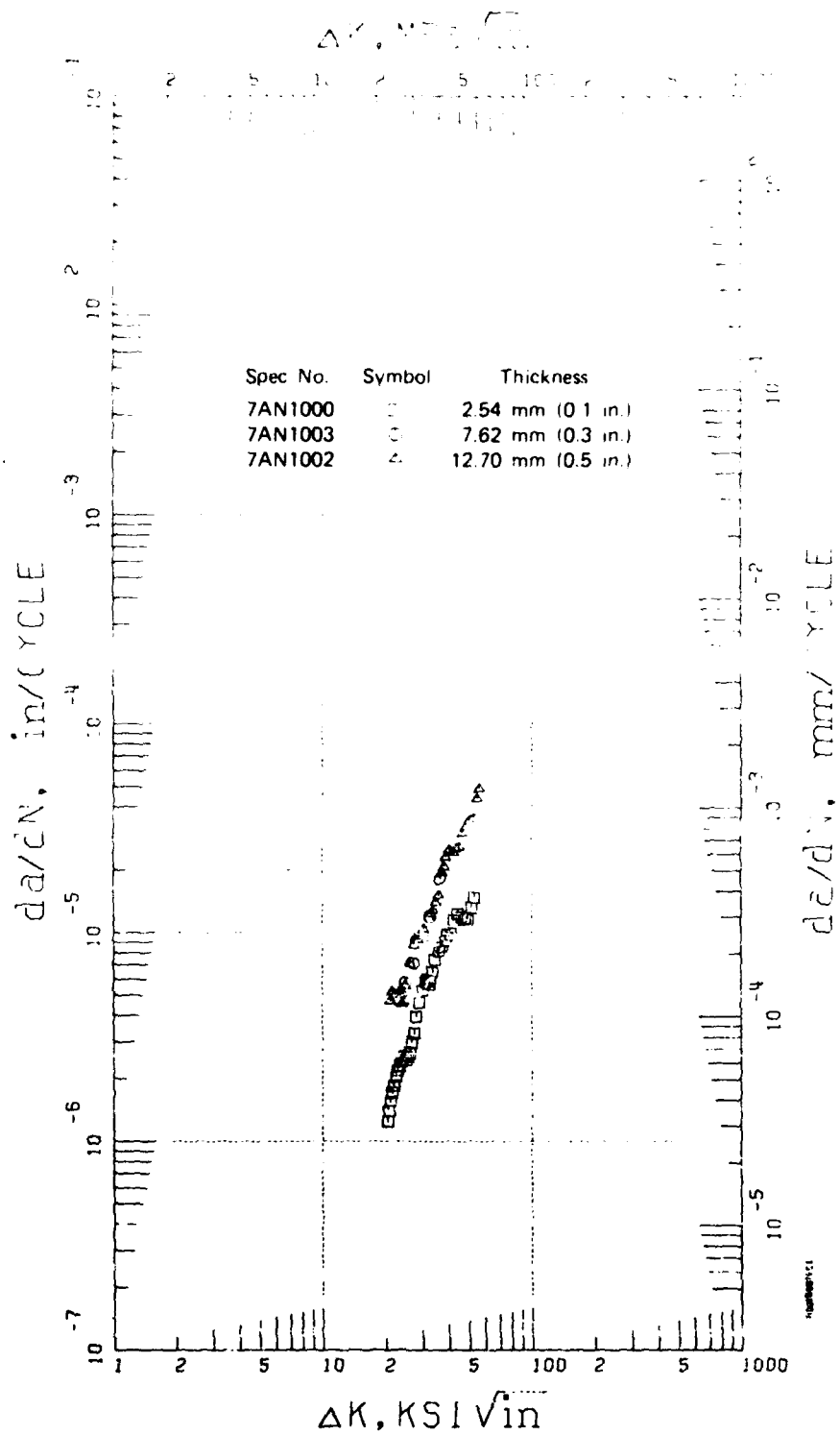


Figure 97. IN100 (PWA 1073) Crack Propagation, Thermal-Mechanical Fatigue, $R = 0.10$, 0.167 Hz (10 cpm)



FD 177358

Figure 98. Waspaloy (PWA 1007) Crack Propagation, Effect of Specimen Thickness, $R = 0.05$, 0.167 Hz (10 cpm), 427°C (800°F)

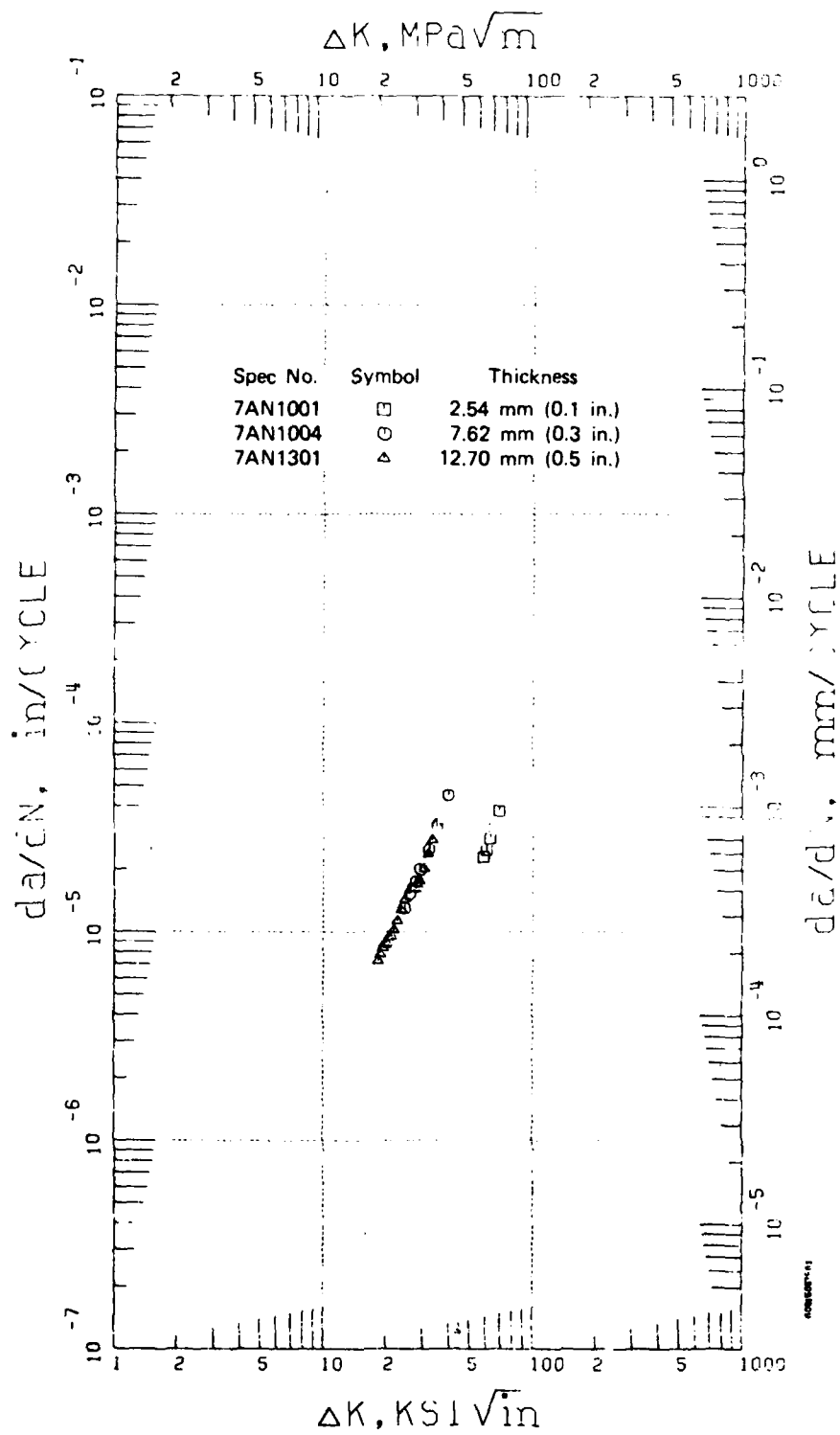


Figure 99. Waspaloy (PWA 1007) Crack Propagation, Effect of Specimen Thickness, $R = 0.05$, 0.167 Hz (10 cpm), 649°C (1200°F)

D. PHASE IV — MODEL DEMONSTRATION

The goal of this phase of the program was to demonstrate the accuracy of the developed crack propagation model. During the initial step of this effort, the Air Force project engineer provided two mission profiles upon which life history (a vs N) predictions were made. Subsequently, crack propagation tests of Waspaloy (PWA 1007) and IN100 (PWA 1073) were conducted under repetitive application of the provided missions in two specimen geometries — compact and surface flaw.

1. Demonstration Missions

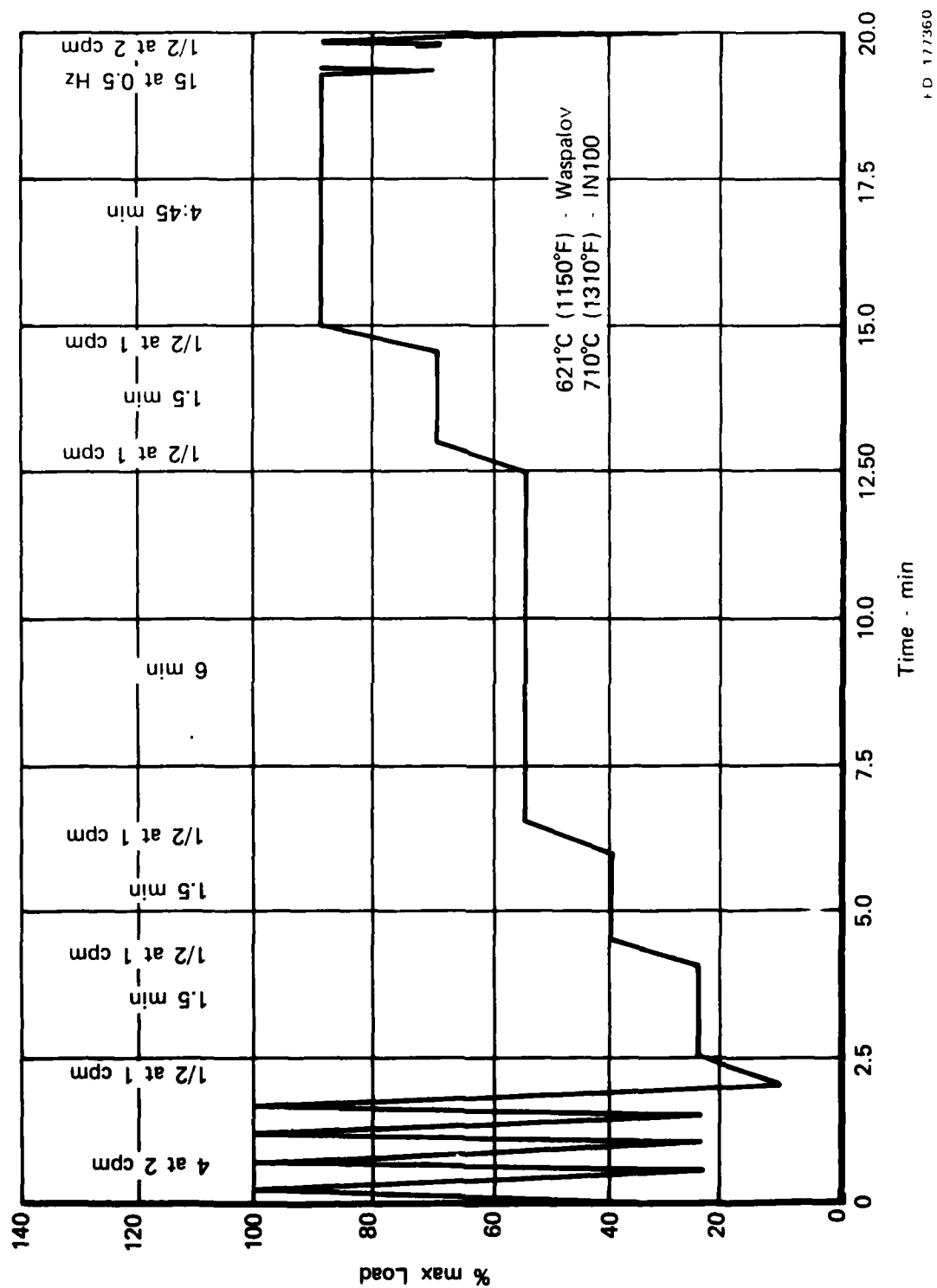
The two demonstration missions supplied by the Air Force are illustrated in Figures 100 and 101. In order to fully exercise the predictive capability of the crack growth model, these missions were chosen to be extreme cases. They were not defined to simulate engine operation. The first mission, Figure 100, was composed of a series of major load excursions, followed by series of load dwells of increasing magnitude, and ending with a flurry of fatigue cycles at a high load ratio. This was contrasted with the second demonstration mission, shown in Figure 101, which contained much more prominent load sequence effects.

2. Mission Segregation and Life Prediction

Cumulative damage segmentation of the model demonstration missions presented in Figure 100 and 101 was accomplished by use of the segregation algorithm discussed earlier. This computerized procedure characterized the individual loading cycles in terms of basic fatigue parameters such as maximum load (P_{max}), load ratio (r), and frequency. Furthermore, the segregation algorithm accounted for load sequence effects which result in crack growth synergism. Major load excursions were identified and load sequence parameters describing overload ratio and occurrence frequency were defined by the algorithm.

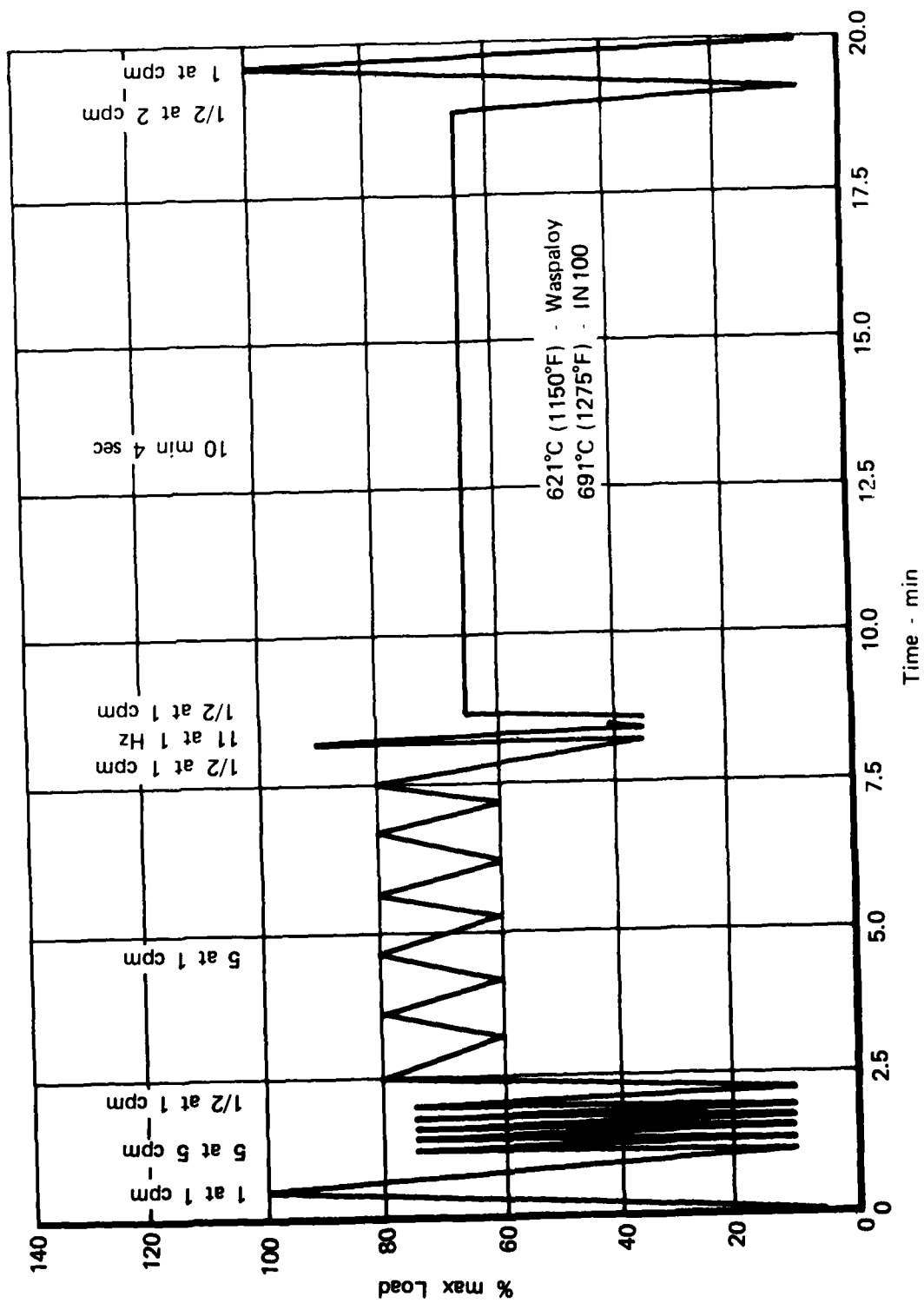
For example, model demonstration mission number 1 begins with four major load excursions. These were defined in terms of P_{max} , R , and frequency, and the fourth of these cycles were identified as an overload affecting subsequent cycles. All of the remaining cycles in this mission were of reduced maximum load and are therefore influenced by the overload. The number of overload affected cycles (ΔN_{OL}) was defined, and the overload ratios P_{OL}/P_{max} were calculated for the individual post-overload cycles. Note that the subsequent repetitive mission marks the end of the cycles influenced by the overload, since the overload ratio returns to 1.0

The occurrence of the series of staircase load dwells within mission 1 posed an unusual situation. As discussed earlier, testing under LCF-Dwell load sequencing revealed that the crack growth resulting from the intermittent load dwells was significantly slower than observed for equivalent repetitive load dwells. This behavior occurred in both Waspaloy and IN100 and agrees with the findings of Macha, Grandt, and Wicks. (Reference 10.) These researchers, performing elevated temperature crack propagation testing of IN100, observed minimal effect of load dwells in a representative mission load sequence. This finding is incorporated in the segregation algorithm by defining as zero the crack growth associated with sustained load mission segments. Crack propagation produced by a load dwell cycle was assumed to result entirely from the initial load excursion in the dwell cycle. In the event that successive, increasing load dwells occurred, the staircase loading sequence was reduced to a single monotonic load excursion. Therefore, the staircase sequence of mission 1 was characterized as a single loading cycle which occurred during the indicated time interval.



10 177360

Figure 100. Model Demonstration Mission, No. 1



FD 177 1

Figure 101. Model Demonstration Mission, No. 2

Segregation of model demonstration mission number 2 (Figure 101) was also performed by the computer algorithm. All cycles were defined in terms of load, load ratio, and frequency, and the first cycle was identified as an overload. The last cycle in the mission, being equivalent to the overload cycle, terminated the calculated effect of the initial overload. The number of overload affected crack growth cycles was determined and the individual ratios were calculated.

The mission segregations discussed above were the basis of a synergistic model life prediction accounting for load sequence interactions. A cycle-by-cycle partitioning of the test missions assuming that load sequence does not affect crack growth (i.e. that linear damage summation method) was performed by truncating the load sequence parameters from the output of the synergistic segregation algorithm. This abbreviated mission segregation formed the basis of the SINH Linear Damage Model life prediction.

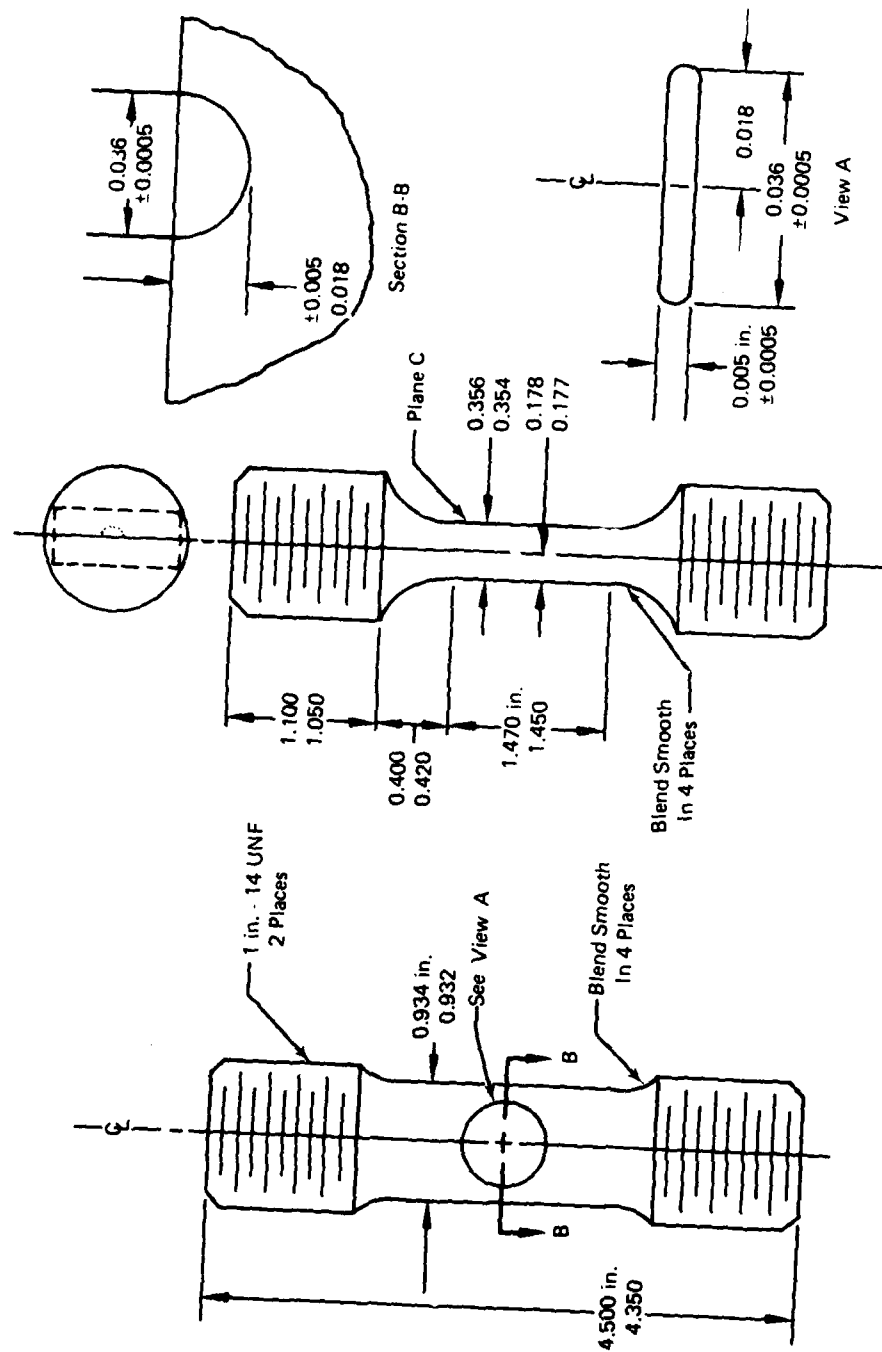
The segregated missions were subsequently input into the interpolation algorithm which defined a characteristic crack growth curve for each unique loading condition. The output of this routine was that used in a cycle-by-cycle integration of crack growth, known as the Computational Algorithm, to obtain life calculations for a total of eight demonstration specimens. There were four specimens in each material, Waspaloy (PWA 1007) and IN100 (PWA 1073). Two specimen geometries (compact and surface flaw) were tested under each of the two missions (Figures 100 and 101). Since a linear damage and a synergistic model life prediction was calculated for each of the eight specimens, a total of sixteen life calculations were performed. These were recorded with the Air Force project engineer prior to mechanical testing.

3. Demonstration Testing

The two specimen geometries used in demonstration testing were the compact (Figure 11b) and the surface flaw specimen (Figure 102). The compact specimen has a well characterized stress intensity solution (Reference 5) and was used extensively during the test program, while the surface flaw specimen is less familiar and was unused in data generation. The stress intensity solution for this specimen was taken from calculations performed by P&WA/Commercial Products Division (Reference 11). Figure 103 compares this analytically determined surface flaw K-solution and a solution calculated using handbook values (Reference 12).

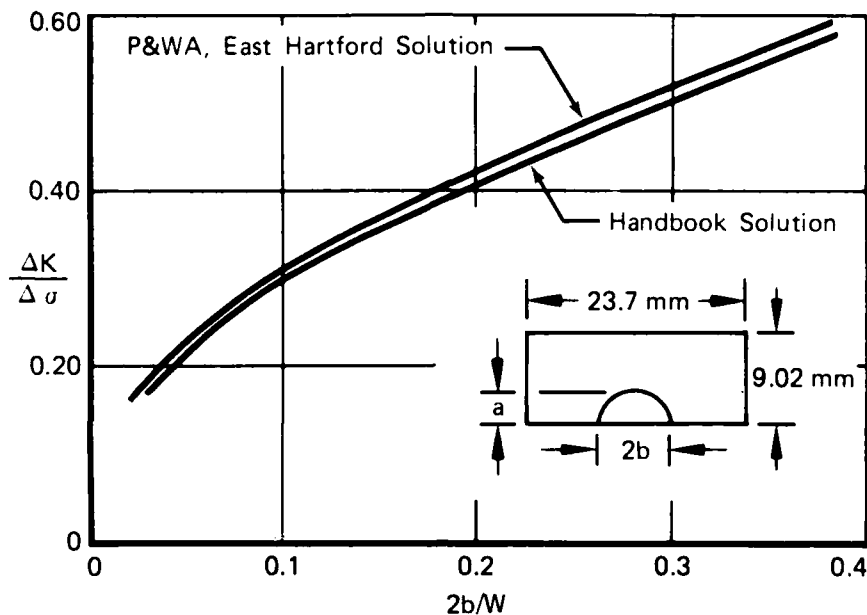
Experimental verification of the accuracy of the stress intensity solution was performed by testing a Waspaloy (PWA 1007) surface flaw specimen at fatigue conditions equivalent to baseline data generated, under the test program of this contract. This data is illustrated in Figure 104 with $2b/w \leq 0.45$, and good correlation with the SINH curve generated from baseline data is observed.

All testing was performed on servocontrolled hydraulic machines operated under load control with mission profile described by either an MTS minicomputer or a DATATRAK® controller. The atmosphere was laboratory air, and specimen heating was accomplished using clamshell resistance furnaces.



FD 17-1362

Figure 102. Surface Flow Specimen



FD 177363

Figure 103. Comparison of K-Calibration Curves for Surface Flaw Specimen

4. Model Verification

Model demonstration tests were conducted to determine the accuracy of the crack propagation models developed under this program. The procedure of modeling crack growth under complex loading conditions was equivalent for both Waspaloy and IN100. The test data from all specimens were treated in a uniform fashion. In order to eliminate transient effects on crack propagation commonly associated with change from room temperature precracking conditions to elevated temperature test conditions, the initial 0.635 mm (0.025 in.) of crack growth was deleted from all data sets.

a. Waspaloy (PWA 1007)

All mission testing to evaluate the effectiveness of the Waspaloy (PWA 1007) crack propagation model was conducted at a single temperature: 621°C (1150°F). The results of tests performed under Mission 1 (Figure 100) using compact and surface flaw specimens are presented in Figures 105 and 106, respectively. For both specimens, the life predictions agree well with the data.

A parameter which may be used to sample the accuracy of the live prediction is the ratio of calculated cycles to failure vs actual cycles to failure (N_c/N_A). For the compact specimen (Figure 105) this parameter demonstrates the superior accuracy of the synergistic model as compared to the life prediction using linear damage summation.

The results of the test of the surface flaw specimen, Figure 106, indicate that the total life prediction is more accurate using SINH linear damage summation. However, the accuracy of the surface flaw stress intensity factor solution diminishes for $2b/w > 0.45$ due to the proximity of the edges and back surface of the specimen. For the surface flaw specimens tested in this program, this corresponds to a half crack length of approximately 5.3 mm (0.210 in.). Therefore, the data of crack length greater than this value are not entirely valid and should not be used for model evaluation. These data are shown as solid triangles.

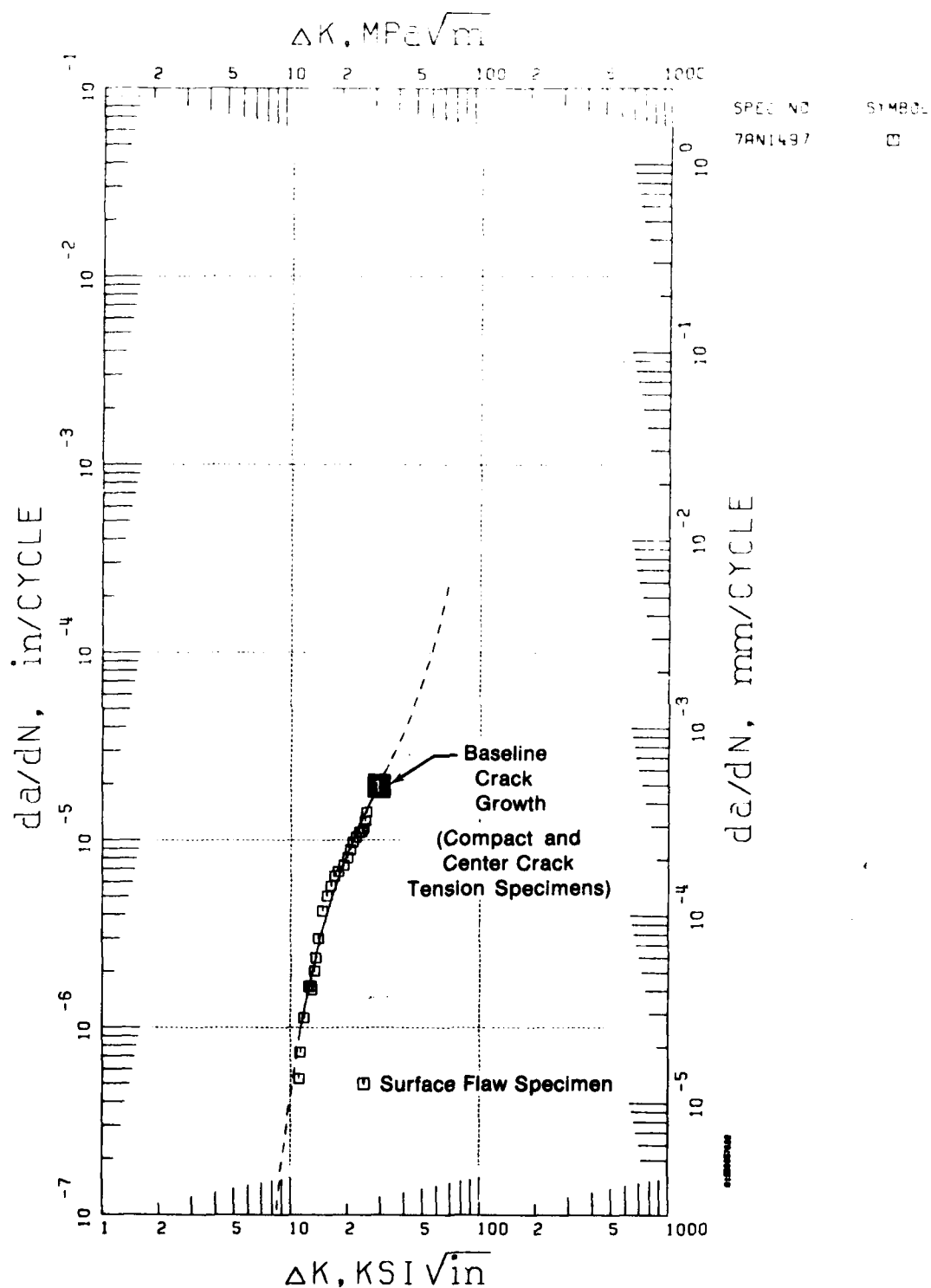
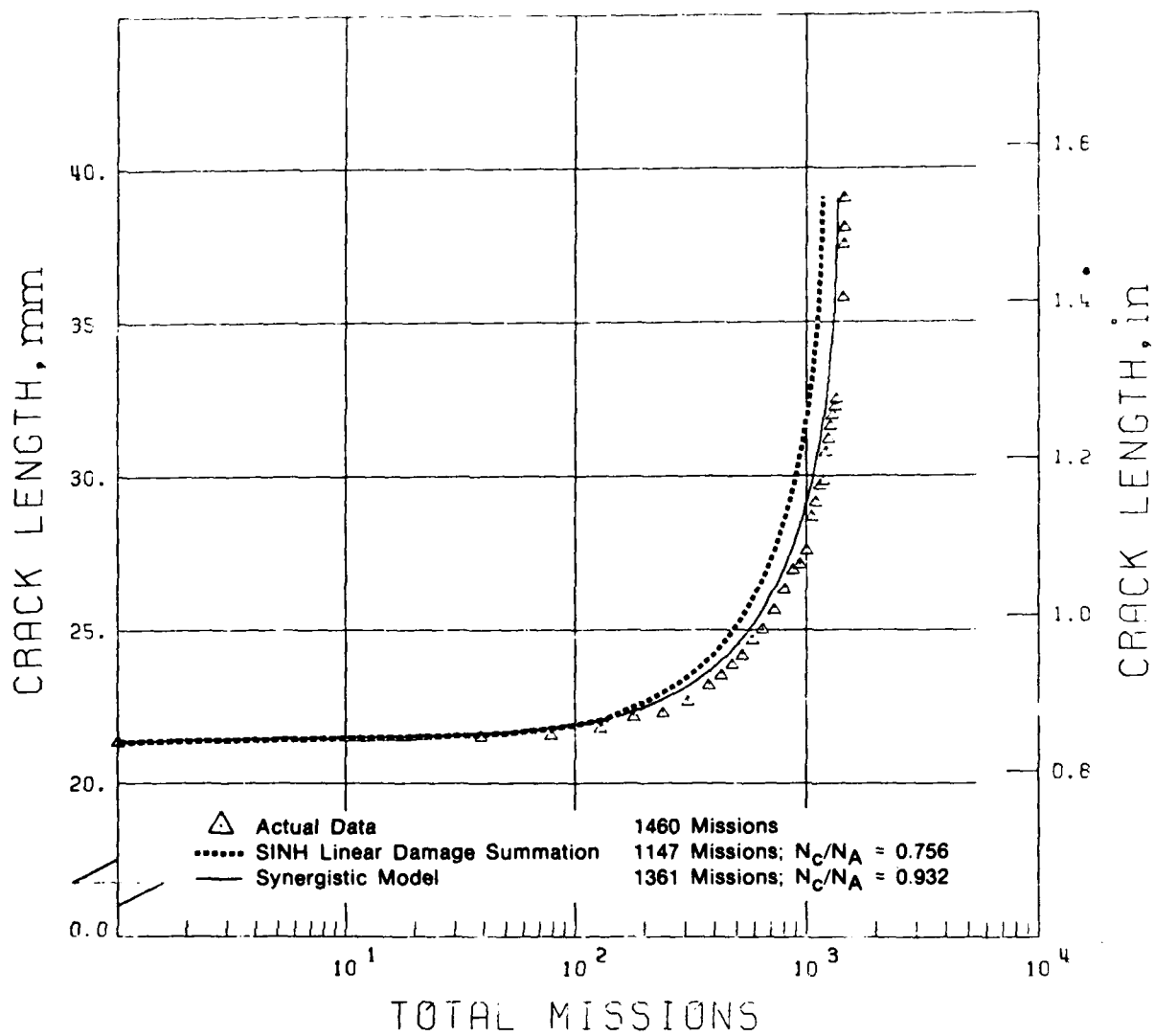


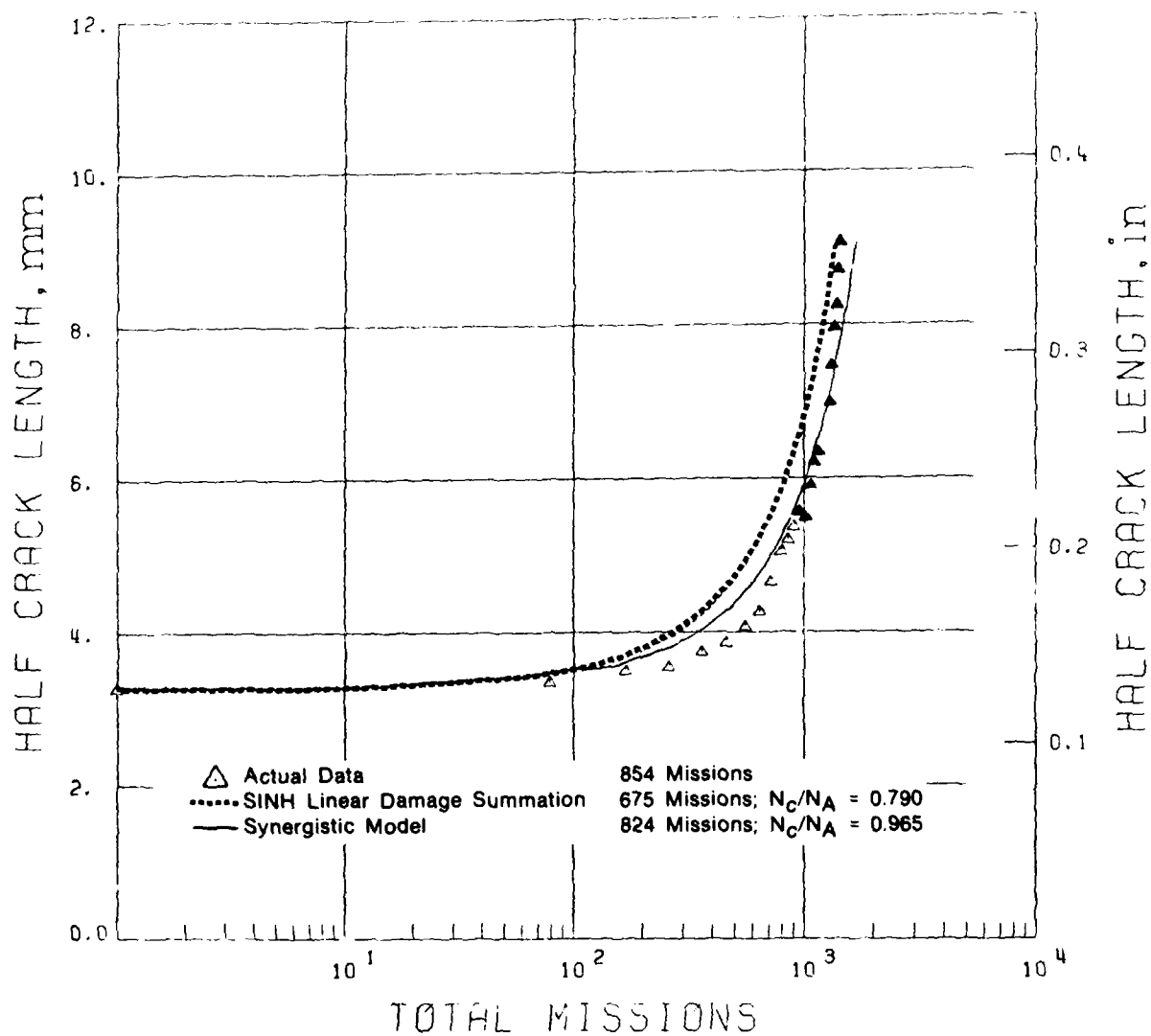
Figure 104. Waspaloy (PWA 1007) Crack Propagation, Comparison of Data Generated in a Surface Flaw Specimen With Baseline Data, $R = 0.05, 0.167 \text{ Hz (10 cpm)}, 649^\circ\text{C (1200}^\circ\text{F)}$

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FD 177365

Figure 105. Waspaloy (PWA 1007) Model Description Test, Mission 1, Compact Specimen No. 1565, 621°C (1150°F)



FD 177366

Figure 106. Waspaloy (PWA 1007) Model Demonstration Test, Mission 1, Surface Flaw Specimen No. 1500, 621°C (1150°F)

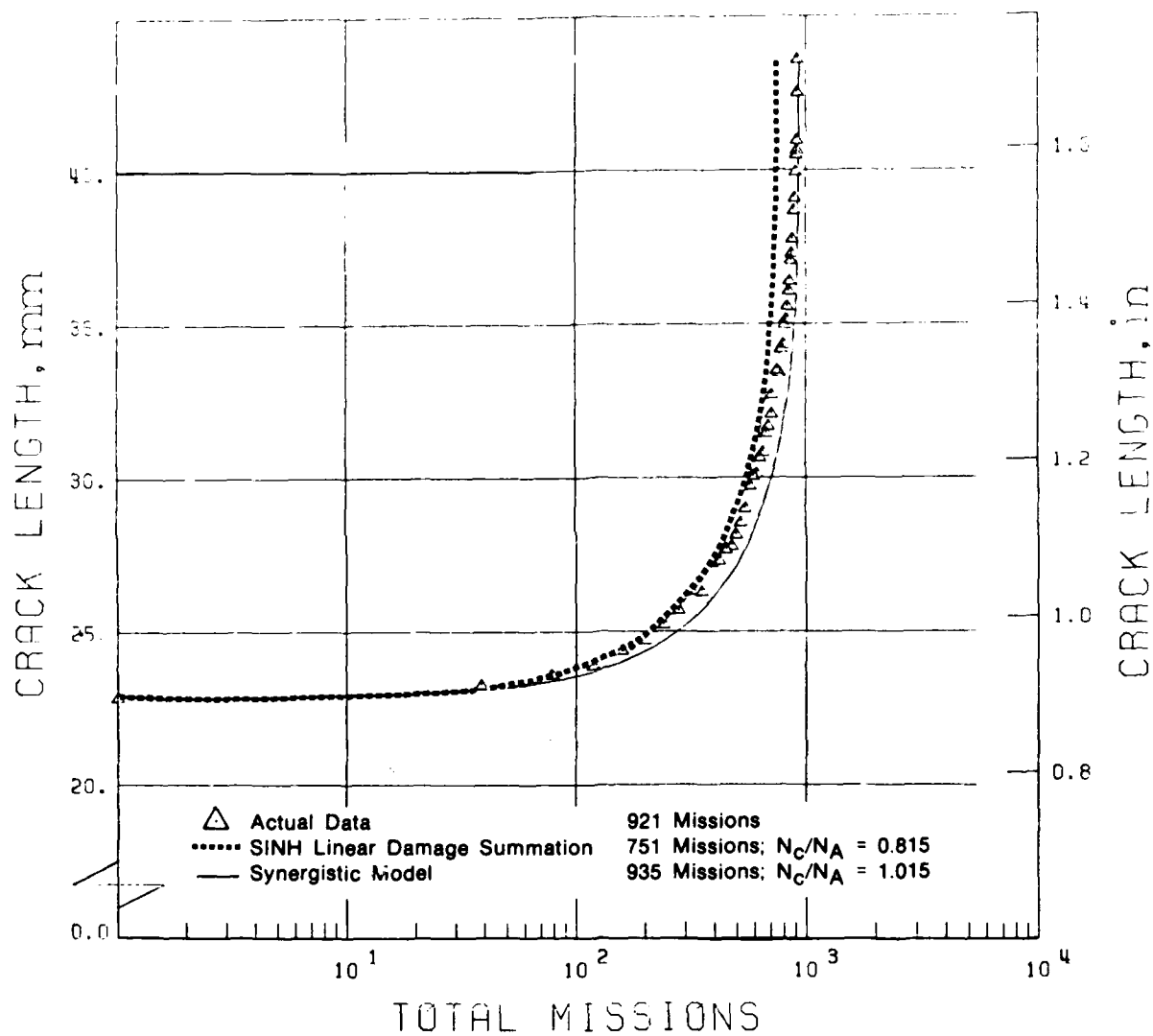
Model demonstration tests of Waspaloy fatigued according to Mission 2 (Figure 101) were also predicted well by the SINH model. Test results from the compact specimen, Figure 107, revealed good accuracy for both the SINH linear damage and the synergistic SINH models. Early in the life of the specimen the prediction using SINH linear damage methods corresponds closely to the actual fatigue data, while the synergistic prediction is superior when considering the total life of the specimen.

Both synergistic and SINH linear damage calculations of crack growth resulting from Mission 2 loading were less adequate in predicting the life of the surface flaw specimen. These predictions and the actual data, are presented in Figure 108. The three, inconsistently long, crack length measurements which are highlighted, are the work of an inexperienced technician. Discounting these isolated data points and recalling that the stress intensity factor solution for this specimen loses accuracy for half crack length greater than approximately 5.3 mm (0.210 in.), both life calculations are demonstrated as conservative. The approximate values N_{calc}/N_{actual} for the linear damage and synergistic models are 0.58 and 0.73 respectively for the 5.3 mm crack.

b. IN100 (PWA 1073)

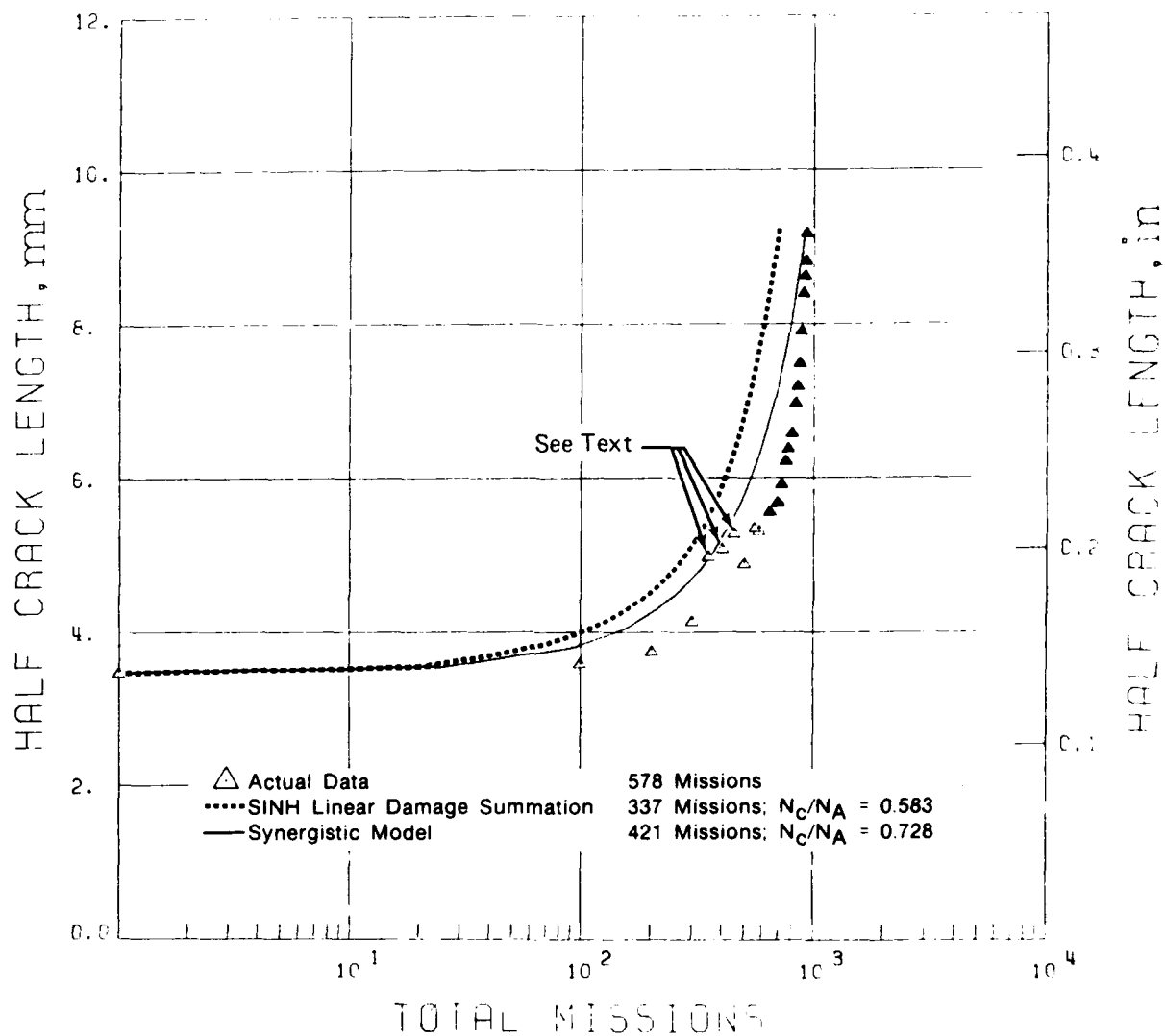
The IN100 demonstration specimen life predictions of Mission 1 (Figure 101) calculated using the interpolative SINH models were less accurate than the Waspaloy predictions. Both synergistic and SINH linear damage calculations gave anticonservative life predictions of both specimen geometries, tested at 710°C (1310°F), as shown in Figures 109 and 110. Test results of the compact specimen (Figure 109) show the synergistic and linear damage calculations to overpredict the actual specimen life as demonstrated by the respective values of N_c/N_A of 3.76 and 2.94. The prediction errors for the surface flaw specimens were similar (synergistic model: $N_c/N_A = 1.57$; linear damage summation: $N_c/N_A = 1.25$).

The capability of the IN100 interpolative SINH model demonstrated much more effective in predicting crack growth in the Mission 2 (Figure 101) loading sequence. In test at 691°C (1275°F) of a compact specimen (Figure 111) the synergistic model prediction was extremely accurate ($N_c/N_A = 0.96$), while the life calculation using methods of linear damage summation indicate a much shorter life ($N_c/N_A = 0.64$). In a similar Mission 2 model demonstration test using a surface flaw specimen (Figure 112) the synergistic model prediction exhibited reasonable accuracy ($N_c/N_A = 0.67$), while the linear damage summation calculation was significantly conservative ($N_c/N_A = 0.36$).



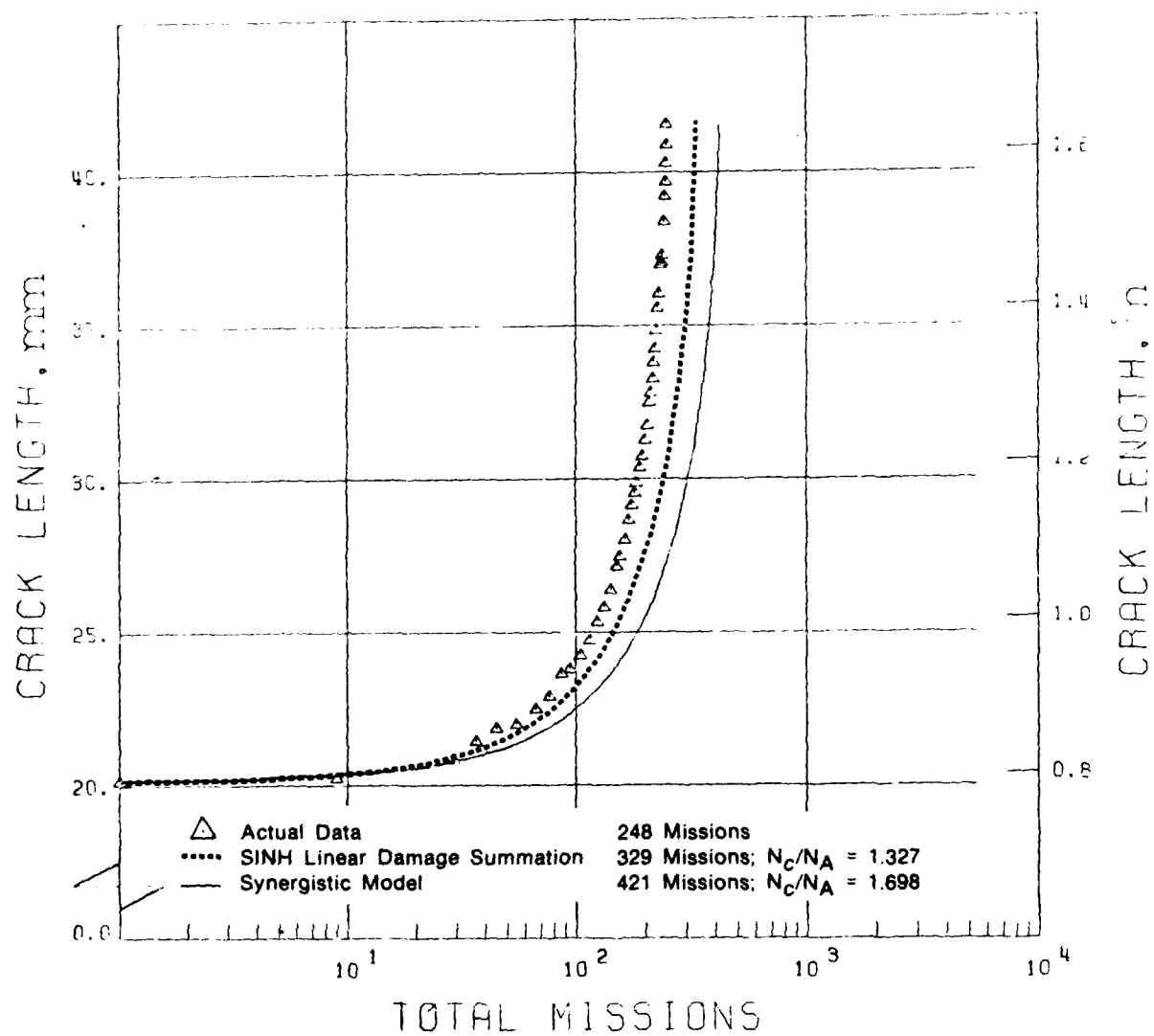
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Figure 107. Waspaloy (PWA 1007) Model Demonstration Test, Mission 2, Compact Specimen No. 1563, 621°C (1150°F)



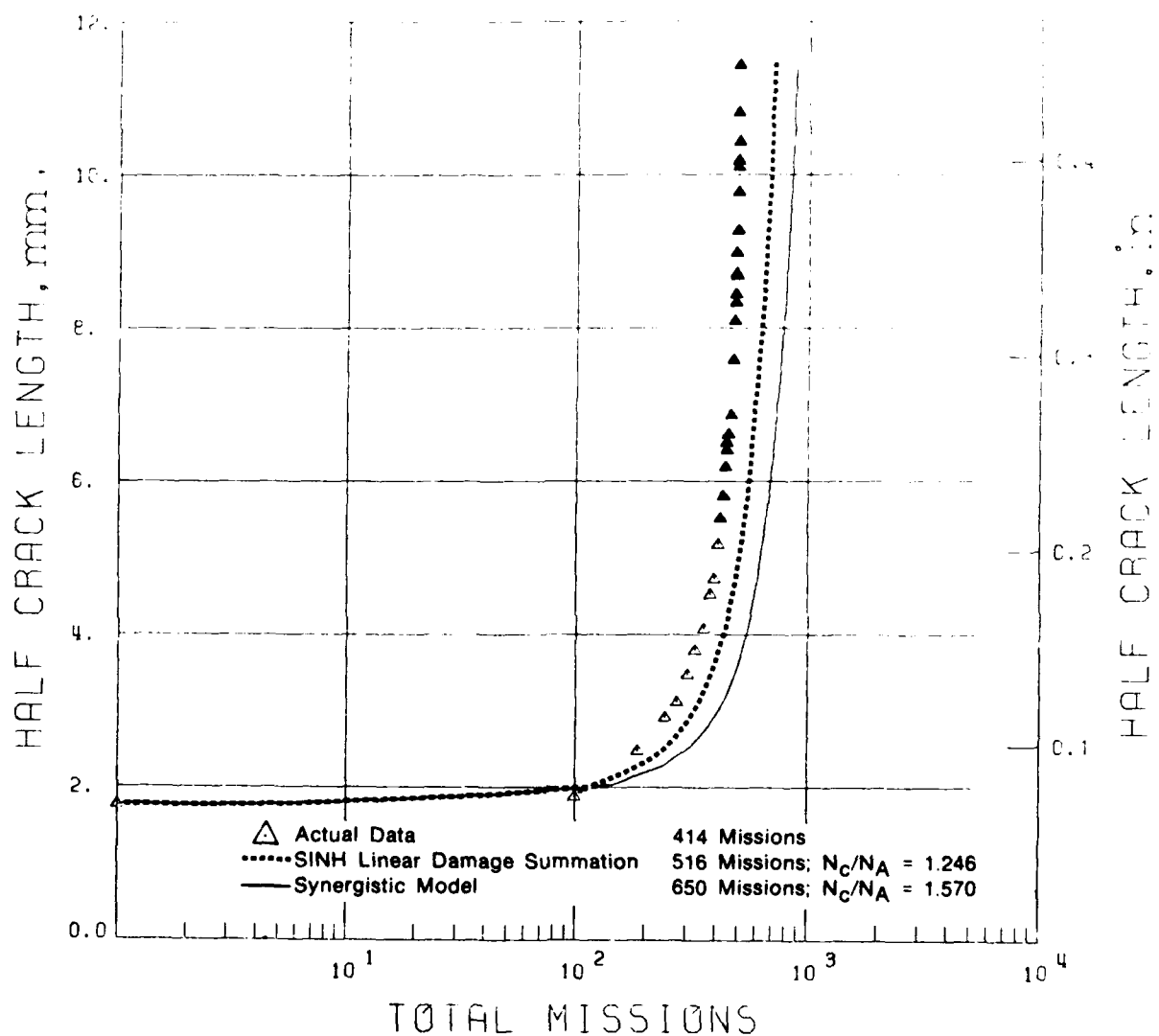
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Figure 108. Waspaloy (PWA 1007) Model Demonstration Test, Mission 2, Surface Flaw Specimen No. 1498, 621°C (1150°F)



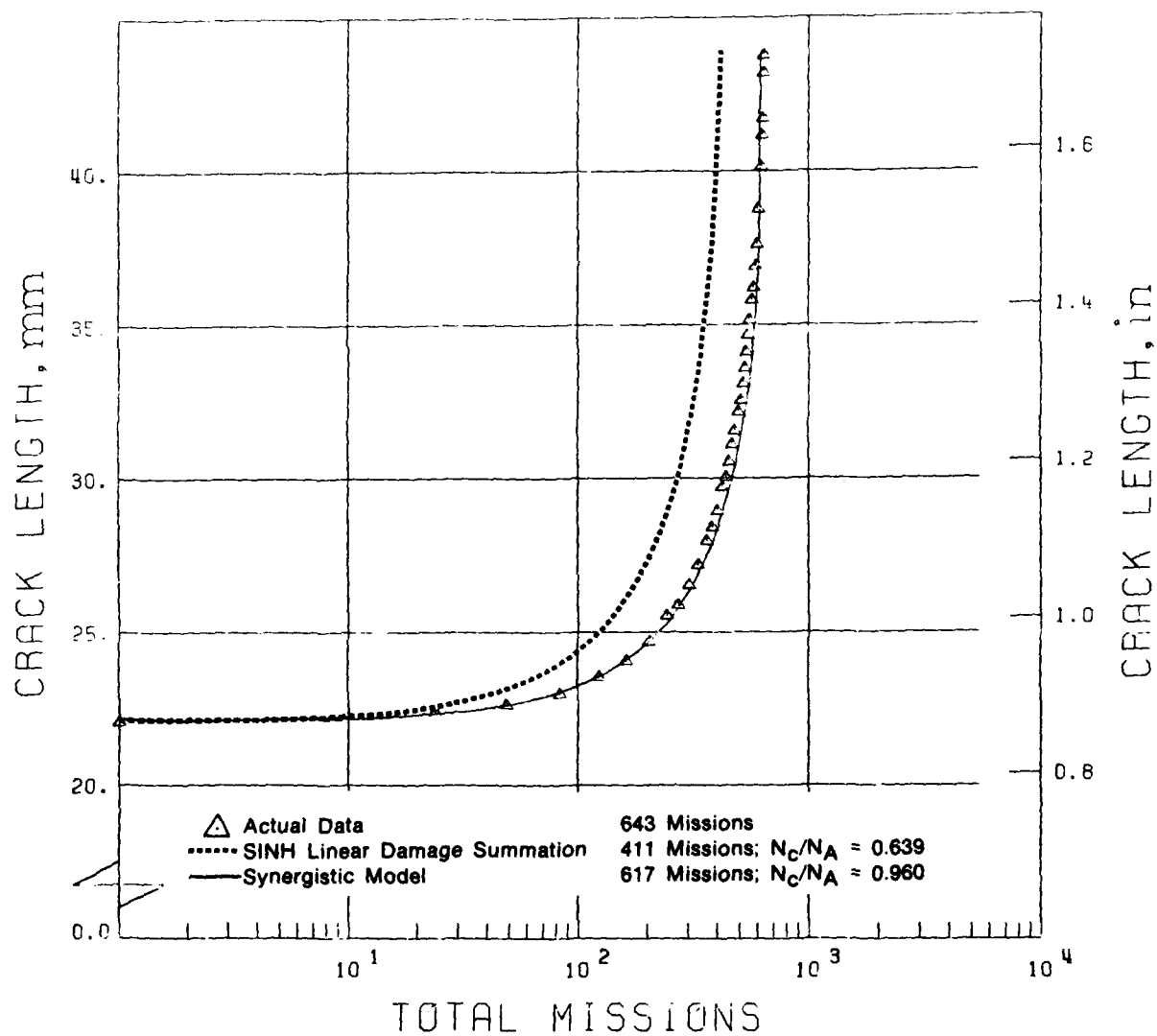
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Figure 109. IN100 (PWA 1073) Model Demonstration Test, Mission 1, Compact Specimen No. 1334, 710°C (1310°F)



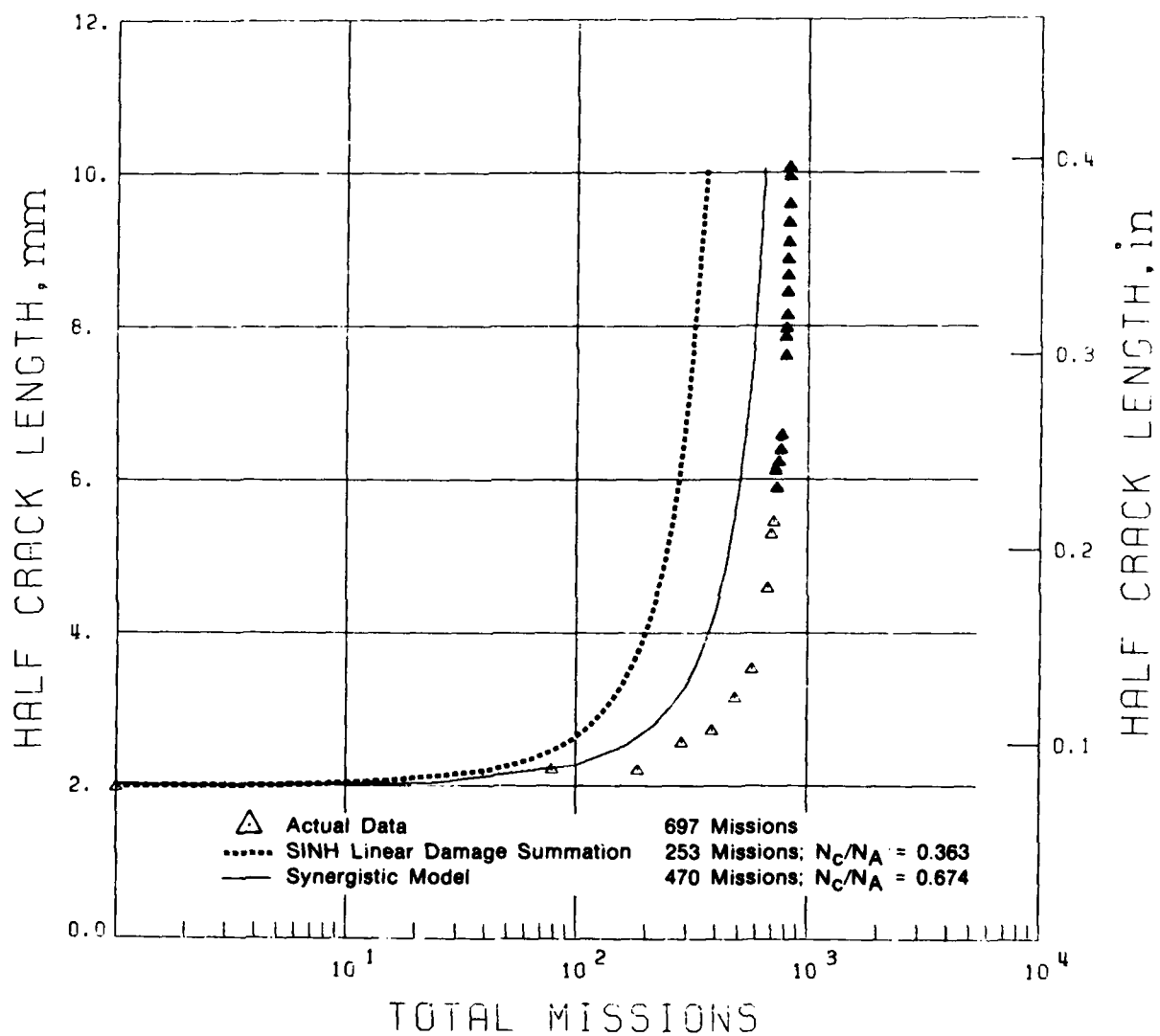
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Figure 110. IN100 (PWA 1073) Model Demonstration Test, Mission 1,
 Surface Flaw Specimen No. 1473, 710°C (1310°F)



FD 177371

Figure 111. IN100 (PWA 1073) Model Demonstration Test, Mission 2, Compact Specimen No. 1333, 691°C (1275°F)



FD 177372

Figure 112. IN100 (PWA 1073) Model Demonstration Test, Mission 2, Surface Specimen No. 1575, 691°C (1275°F)

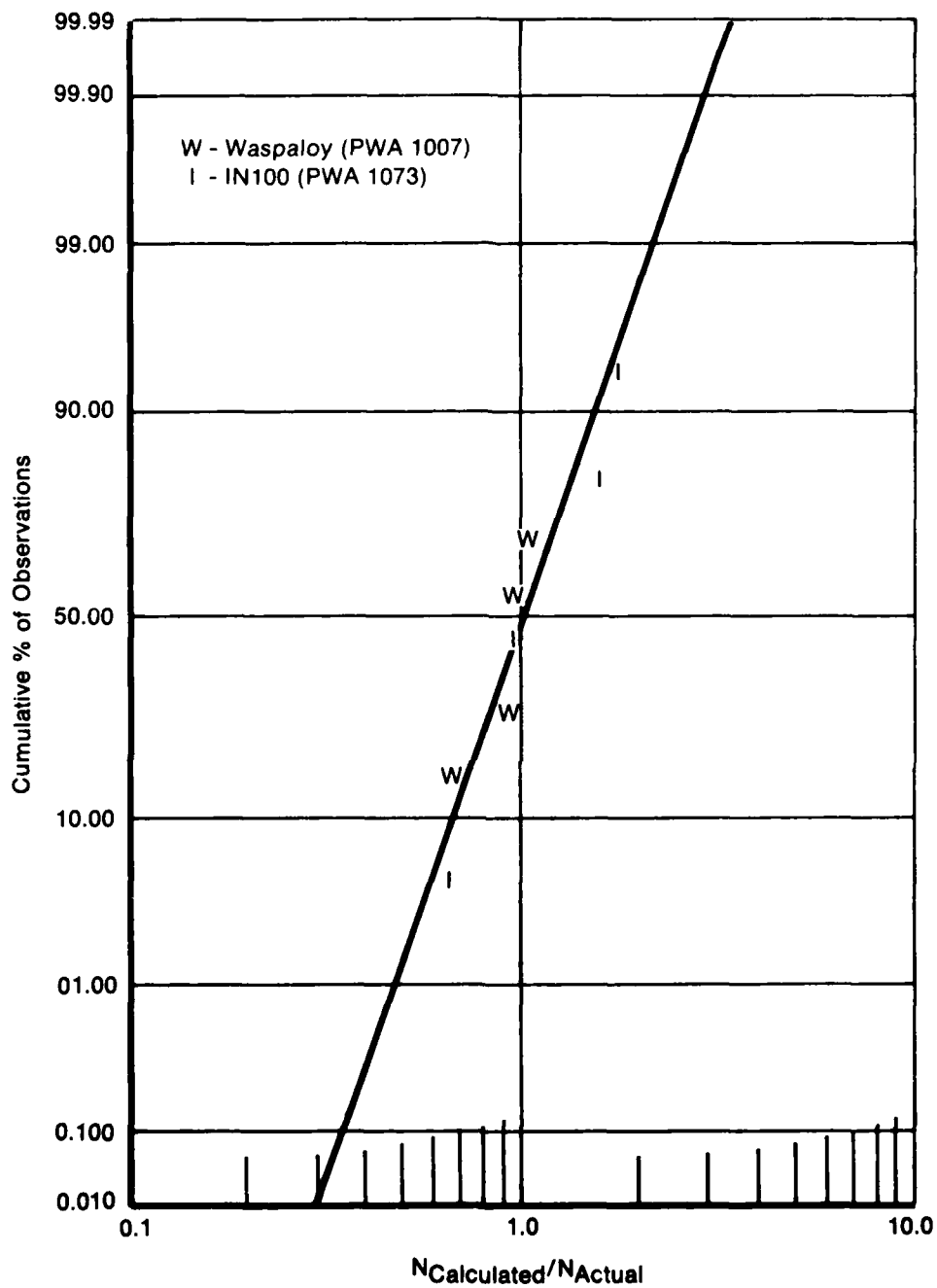
5. Critique

The basic goal of the model demonstration program was to determine the effectiveness of the crack propagation models to predict elevated temperature fatigue crack growth in Waspaloy (PWA 1007) and IN100 (PWA 1073) under load sequencing representative of turbine disk operation. This evaluation tests the capability of the three-part specimen life prediction procedure composed of the segregation, interpolation, and computation algorithms.

An assessment of the results of the model demonstration program may be accomplished by constructing a log-normal probability plot of values of $N_{\text{calculated}}/N_{\text{Actual}}$ for the collection of demonstration specimens. Such a plot is presented in Figure 113. Values of N_c/N_A which are less than 1.0 indicate conservative life predictions while values greater than 1.0 are anticonservative, the statistical analysis of the test results provided by this plot shows the mean of all values of N_c/N_A to be 1.07. That is, the average life prediction given by the synergistic model is 7% greater than the actual specimen life. This highly accurate result demonstrates the excellent capability of this model to describe cumulative damage effects on crack growth in Waspaloy and IN100. This may be contrasted with a similar analysis of results of the SINH Linear Damage Model. The mean value of these predictive errors is 20% less than the actual specimen life. While the error associated with the nonsynergistic model was not excessive for these demonstration tests, a considerably more significant load sequence effect may be expected under more representative missions. In order to permit usage of available testing machines, the model demonstration missions were of limited cycle count. More representative mission load sequences have less frequently occurring overloads, resulting in increased crack growth synergism (greater error in the nonsynergistic life calculation).

While the average model behavior is represented by the statistical mean, the distribution of the sample of values of N_c/N_A about the mean provides an assessment of the variability in predictive assuarcy. For example, the plot of the synergistic model results (Figure 113) indicates that for one hundred future life calculations, the maximum prediction error should be anticonservative by a factor of approximately 2.2. One in 1000 future predictions may be anticonservative by a factor of 3.0. Similar results occur for an analysis of the SINH Linear Damage Model predictions.

The above worst case analysis considers the Waspaloy and IN100 data together. However, the prediction errors for Waspaloy were generally less than for IN100. The maximum and minimum errors were observed in IN100. The primary source of this defference is not believed to be the difference in material. Rather, a difference in testing temperature for the two materials appears to be responsible. All Waspaloy demonstration testing was conducted at 621°C (1150°F), while the Mission 1 and Mission 2 IN100 tests were run at 710°C (1310°F) and 691°C (1275°F) respectively. At the lower temperture, Waspaloy displays relatively limited creep crack growth; however crack propagation in IN100 under sustained load becomes more appreciable in the indicated temperture ranges for these tests. Both demonstration missions have significant load dwell components, and at the IN100 operating temperatures cracking tends to violate Linear Elastic Fracture Mechanics. Since variability in creep crack growth data is generally much more severe than observed by cyclic fatigue crack growth, it is not suprising that the IN100 results are more extreme than the Waspaloy findings.



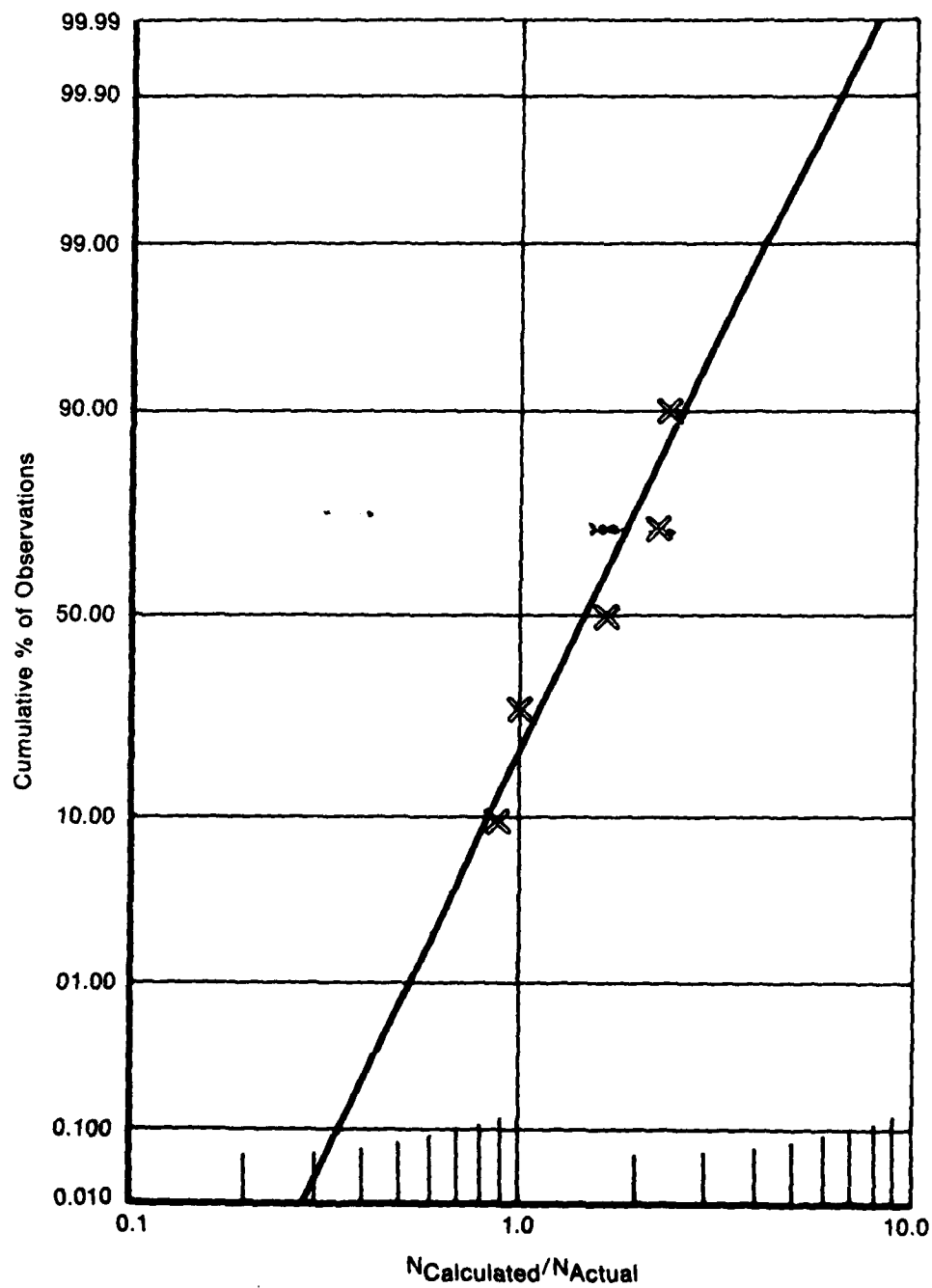
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Figure 113. Log-Normal Probability Plot of Synergistic Model Demonstration of Test Results

In order to examine the hypothesis that test-to-test variability in crack growth was responsible for much of the scatter in the IN100 model demonstration results, a number of replicate tests were performed. The most severe creep conditions were selected: Mission 1 and 710°C (1301°F). The results of five such tests are presented in Figure 114. The variability of these data is significantly more severe than observed for the collection of the separate demonstration tests of Figure 113. The extreme data scatter for the replicate tests indicates that much of the variability in values of N^*/N^A for the original eight specimens was the result of test-to-test material scatter rather than an arbitrary error in the cumulative damage model prediction.

Another source of model prediction error was extrapolation of ΔK to values beyond the limits of the data base used in model development. The range in ΔK over which data was generated in the initial test program was necessarily limited by the scope of the contract.

While it is difficult to assess the relative contribution of errors in Cumulative Damage Model and intrinsic material data scatter, the combination of these errors is represented by model demonstration results of Figure 113. The capability of the synergistic model to predict crack propagation under loading similar to demonstration missions 1 and 2 is described by this plot. As stated earlier, these missions were chosen to be extreme cases which would exercise the model. Typical operating missions for turbine disks are expected to be less severe, therefore, more accurate life predictions are expected for field usage than was observed for the demonstration test program.



FD 188311

Figure 114. Log-Normal Probability Plot of Results of Replicate Demonstration Tests. IN100, 710°C (1310°F), Mission 1.

SECTION III CONCLUSIONS

The primary accomplishment of this contract was the development of a computer based mathematical model for prediction of elevated temperature crack propagation of Waspaloy (PWA 1007) and GATORIZED® IN100 (PWA 1073) subject to load sequencing representative of turbine disk operation. The following conclusions are drawn from the results of testing and analysis which supported construction of the model.

1. Loading spectra representative of turbine disk operation contain major and minor load excursions, as well as load dwells, which lead to synergistic effects on crack propagation. In the missions evaluated, the occurrence frequency of major load excursions (overloads) was high (generally every 50 cycles, or less), and the observed overload ratio (P_{OL}/P_{max}) was generally less than 1.5. Compressive stress excursions may occur in some disks at some location (eg. cooling holes).
2. Crack propagation data (da/dN vs ΔK), generated under constant load amplitude cycling (and repetitive load sequencing) of Waspaloy (PWA 1007) and IN100 (PWA 1073), are effectively described by an equation of the form

$$\log \frac{da}{dN} = 0.5 \text{ SINH } (C_2 (\log \Delta K + C_3)) + C_4$$

where C_2 , C_3 , and C_4 are empirical functions of the parameters of component operation.

3. For the given material, Waspaloy (PWA 1007) or IN100 (PWA 1073), equations of the form given above provide the capability for multiparameter (eg. frequency, stress ratio, temperature, overload ratio) interpolations to define representative crack growth relationships.
4. Of the two superalloys Waspaloy (PWA 1007) and IN100 (PWA 1073), the former is considerably more prone to test-to-test variability of crack propagation properties. The basis of this variability is the large range of acceptable crystalline grain size for Waspaloy (PWA 1007) as compared to IN100 (PWA 1073).
5. Under constant load amplitude cycling with dwell at peak load, the rate of crack propagation of Waspaloy (PWA 1007) increases with increasing period of load dwell. However, for a period of load dwell of 120 sec, crack propagation in this alloy is significantly more rapid at 649°C (1200°F) than at 732°C (1350°F). The higher temperature apparently promotes creep-induced crack tip blunting which reduces the rate of crack growth in this alloy.
6. Negative stress ratio fatigue of Waspaloy (PWA 1007) and IN100 (PWA 1073) in the range of $-1.0 \leq R < 0.0$ appears to produce slightly more rapid crack growth than observed under $R = 0$ cycling. This effect on crack propagation of the tensile-compressive cycling is not adequately predicted by an extrapolation of the effect of positive stress ratios.

7. Elevated temperature crack propagation data (da/dN vs ΔK) of Waspaloy (PWA 1007) fatigued at representative stresses are conservative as compared to similar crack growth in stress fields approaching the material yield strength.
8. The effect of prior plastic deformation 1.0% strain cycling; $\epsilon_{mean} = 1/2 \epsilon_{max}$ on subsequent elevated temperature (649°C) crack propagation of Waspaloy (PWA 1007) is to increase crack propagation slightly above characteristic cracking behavior of virgin (unstrained) material. In IN100 (PWA 1073) the effect of similar prestrain is negligible. Test results of both materials are within the material scatterband.
9. Under repetitive overload-underload-LCF cycling of IN100 (PWA 1073) at 649°C (1200°F), the effect of the compressive load cycle following the overload is to reduce the beneficial effect of the tensile overload.
10. A periodic dwell ($10 \leq \Delta N_{Dwell} \leq 40$) at peak load, interrupting otherwise constant load amplitude cycling ($R = 0.1$), has a negligible effect on crack propagation of Waspaloy (PWA 1007) and IN100 (PWA 1073) at 649°C (1200°F). The effect of similar periodic load dwells on the 732°C (1350°F) crack propagation of Waspaloy is also insignificant; however, the periodic dwell increases crack growth rate of IN100 at this temperature. At low values of ΔK , this increase is generally predictable using linear damage summation methods.
11. Under constant load amplitude fatigue ($R = 0.5$) interrupted by periodic overloads, the elevated temperature average crack propagation rate of Waspaloy (PWA 1007) and IN100 (PWA 1073) decreases with increasing overload ratio ($1.0 \leq OLR \leq 1.5$) and with increasing cycles between overloads ($5 \leq \Delta N_{OL} \leq 40$). Over this range of representative loading sequences, the effect of the overloading on crack growth is much more pronounced in IN100 than in Waspaloy.
12. The interpolative model of elevated temperature crack propagation in Waspaloy (PWA 1007) and IN100 (PWA 1073) are effective for prediction of cumulative damage effects under mission loading.

APPENDIX A
OBSERVATION OF CRACK RETARDATION RESULTING FROM LOAD
SEQUENCING CHARACTERISTIC OF MILITARY GAS TURBINE OPERATION

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ABSTRACT

The nature of crack propagation resulting from flight loading representative of military gas turbine operation is investigated. Mission stress profiles for turbine disks fabricated from the superalloys GATORIZED® IN100 and Waspaloy contain load sequences which produce synergistic effects on crack propagation. Major load throttle excursions, overloads, occur routinely during flight, and a retardation in subsequent crack propagation generally results. Such mission load interaction effects have been addressed in crack propagation testing employing repetitive overload-fatigue sequences. The influences of overload ratio ($P_{\text{overload}}/P_{\text{max}}$) and the number of fatigue cycles between overloads have been investigated for crack propagation at 649°C (1200°F), and an interpolative model of these effects is presented. A determination of the instantaneous crack retardation following a mission major load excursion is accomplished with an unconventional method. The existence of a deceleration in crack growth rate, delayed retardation, following a mission overload is verified. Typically, this period is greater than the total number of baseline fatigue cycles applied between engine mission overloads, and delayed retardation is largely, if not entirely, responsible for the beneficial effects of the overloading.

Key words: crack propagation, fatigue, retarding, superalloys

Presented at ASTM Symposium on "Effect of Load Spectrum Variables on Fatigue Crack Initiation and Propagation" San Francisco, CA, May 1979. Submitted to ASTM for publication 1979.

INTRODUCTION

Operational loading spectra imposed on rotating disks in a military gas turbine engine contain load sequences which differ significantly from the high cycle loading encountered in flight of an airframe. Fatigue of a superalloy engine disk is a low cycle phenomenon resulting from throttle excursions and associated thermal stresses. Major and minor throttle excursions compose a load sequence from which synergistic crack propagation results, and this load interaction is complicated by elevated temperature operation and concomitant time dependent behavior.

Typical loading spectra are derived from service missions which include ferry, training, and terrain following radar (TFR) activity. A mission composite is presented in Figure A-1 (Reference 1). The loading spectra may contain frequent single or multiple major load excursions (overloads) with a small number (usually no more than 50) of less severe throttle excursions between overloads. As a result of this frequent overloading, crack growth immediately following an overload is of increased significance, while the crack retardation commonly observed many cycles after an overload application is of reduced importance since this retarded growth is soon interrupted by another overload excursion.

This paper reports the finding of an investigation into the effects of frequent overloading on elevated temperature fatigue crack propagation (FCP) of the superalloys GATORIZED[®] IN100 and Waspaloy. An empirical model of these overload effects is described, and the characteristic retardation of crack growth which follows the frequent overloads is determined.

CRACK RETARDATION

The crack propagation resulting under the complex of loading and environment encountered in a military gas turbine engine is not predicted satisfactorily by residual stress (References 2 and 3) or closure (Reference 4) models, and a need for further study of this isolated problem exists. The current work has employed an empirical model (References 5, 6 and 7) of elevated temperature FCP under spectrum loading. The basic philosophy of this approach is that any complex mission spectrum can be segregated into elemental damage events which can be quantitatively described. The crack propagation life expected under such a spectrum can then be computed as a linear addition of the damage associated with properly segregated events. Mission segregation is based on the definition of an "elemental damage event" as the smallest repeating load-time sequence which results in FCP not predictable by linear damage accumulation alone. A simplified mission consisting of a single overload followed by a block of constant load amplitude fatigue cycles is such an elemental damage event.

Figure A-2a presents a schematic of a crack growth curve, crack length (a) vs number of applied fatigue cycles (N), illustrating the common effects of a single overload on previously unretarded crack growth. When the crack growth produced by constant load amplitude fatigue is interrupted by an overload, crack growth accelerates corresponding to the overload (Reference 8). Thereafter, the rate of crack propagation quickly decelerates, and after a small number of subsequent fatigue cycles the rate of crack growth achieves a minimum. This deceleration to a minimum rate of crack propagation is known as delayed retardation, and the period of delayed retardation is defined as the number (N_{DR}) of post-overload fatigue cycles required to achieve the minimum crack growth rate. Following delayed retardation, crack growth continues at a near minimum rate for an extended period, and the exhaustion of the retardation process is marked by an acceleration of crack growth to regain the unretarded rate. The total period of crack retardation, N^* , is defined as the number of cycles during which crack growth rate is retarded following an overload application. The nature of the transient crack propagation behavior which results following an overload is further revealed by differentiating the crack growth curve, Figure A-2a, to give crack propagation rate, da/dN , as a function of N , Figure A-2b.

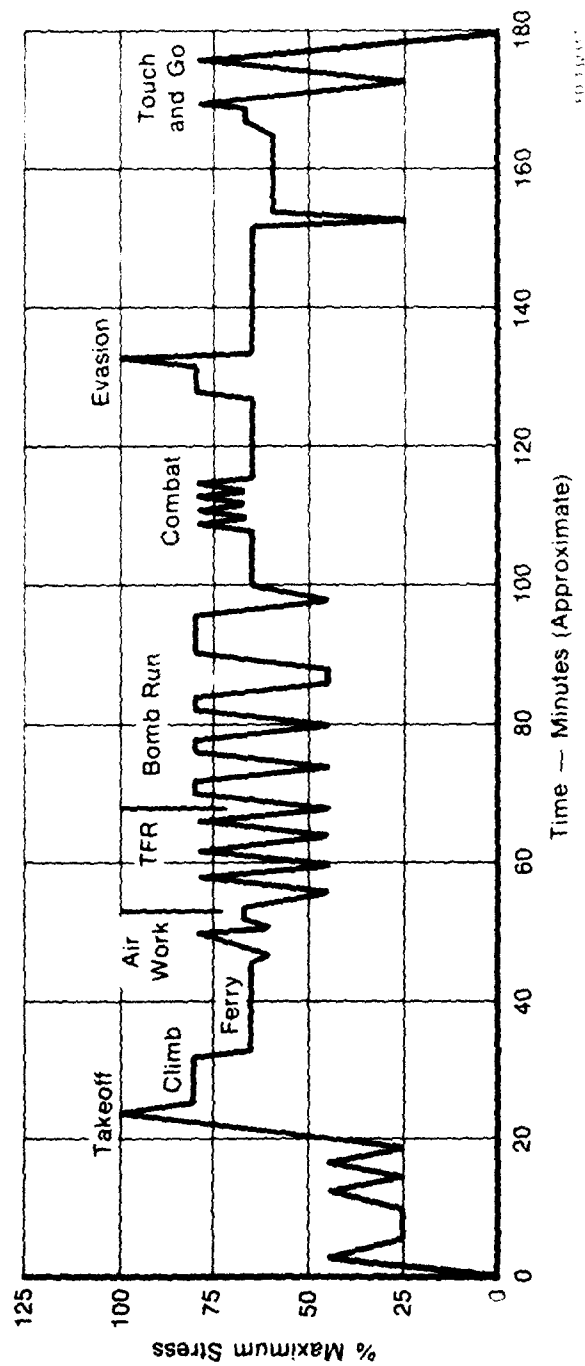


Figure A-1. Composite Mission Stress Profile

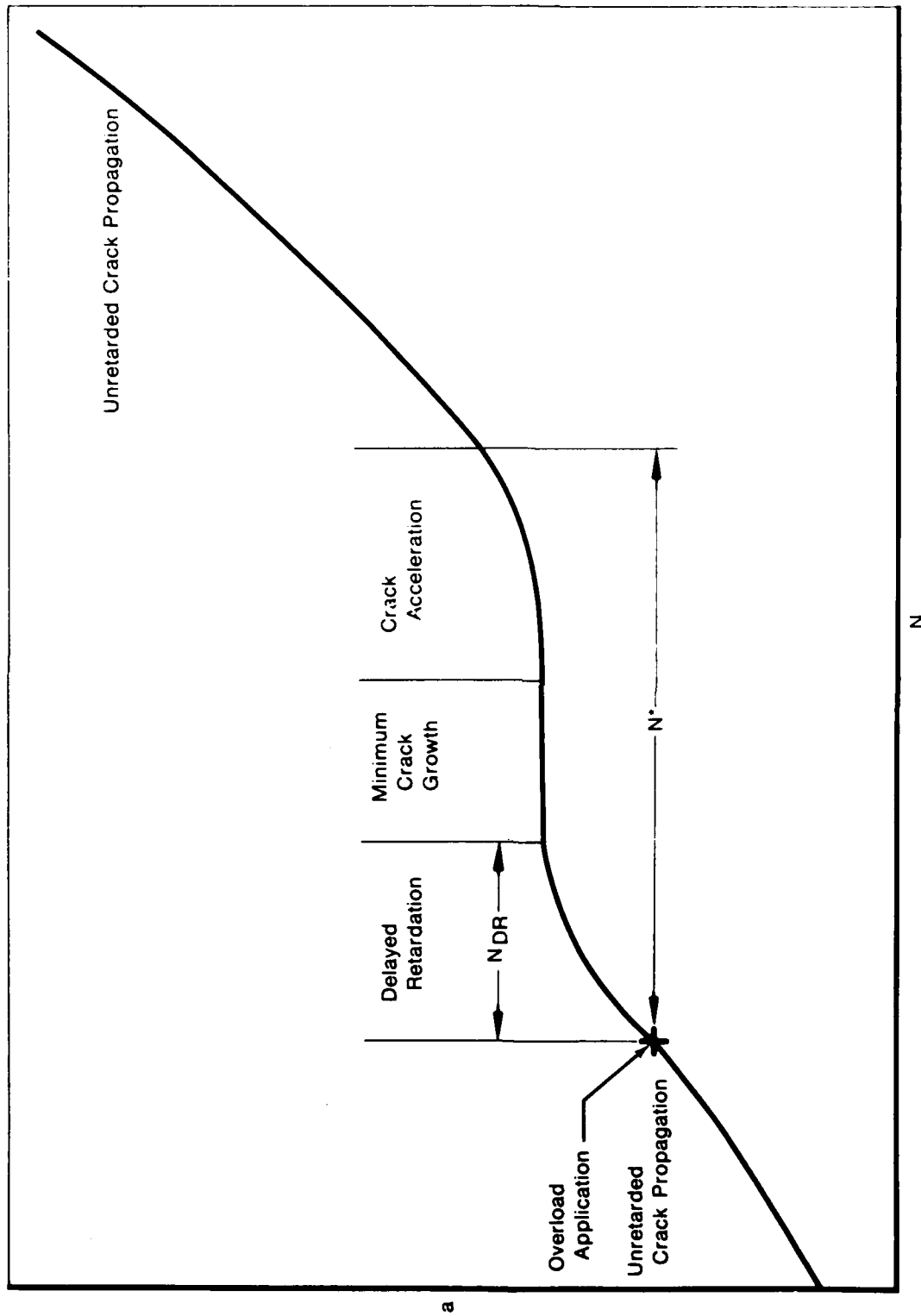


Figure A-2a. Fatigue Crack Retardation Resulting from the Application of a Single Overload

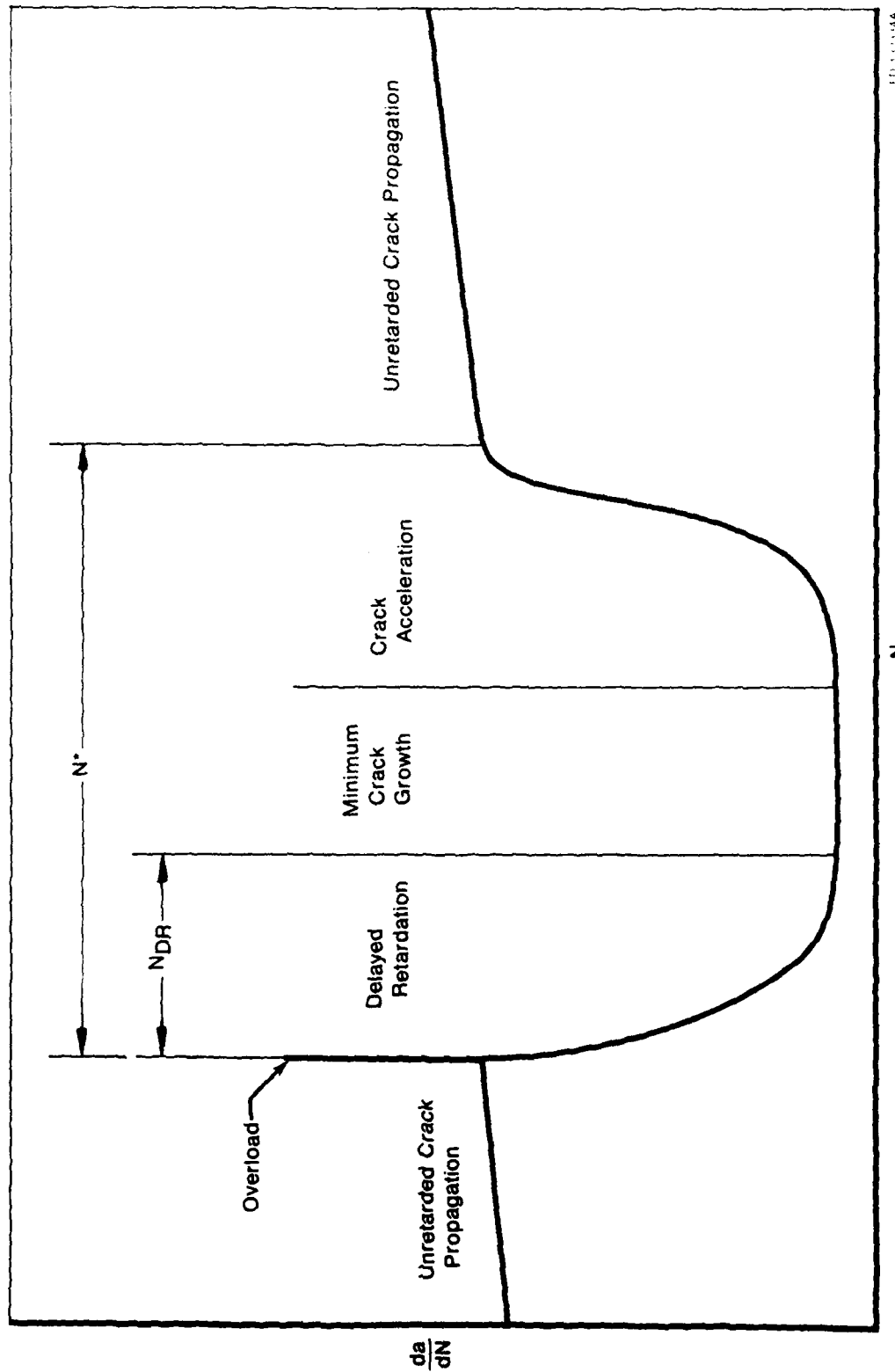


Figure A-2b. Fatigue Crack Retardation Resulting from the Application of a Single Overload

Overloads which occur at cyclic intervals less than N^* interrupt and restart the crack retardation process. The beneficial effect offered by intermittent overloads has been observed to be reduced as the number of cycles between overloads, DN_{OL} , is reduced to fewer than N^* cycles (Reference 9 and 10). As DN_{OL} becomes small, the relative importance of delayed retardation is increased, and the average crack growth rate associated with the overload-fatigue sequence increases.

PROCEDURE

Fatigue crack propagation tests of the nickel base superalloys GATORIZED IN100 and Waspaloy were conducted on electrohydraulic testing machines operated under load control. All tests were performed in air at 649°C (1200°F) and the loading waveform was that of an isosceles triangle applied at a frequency of 0.167 Hz (10 cpm). Compact specimens (Figure A-3) of C-R (circumferential-radial) orientation (Reference 11) were machined from disk forgings representative of engine disk material. The test specimens were pre-cracked at room temperature using standard procedures (Reference 11).

Testing was designed to evaluate the influence of frequently applied periodic overloads on otherwise constant load amplitude (ΔP) fatigue crack growth. A schematic of the basic loading sequence is presented in Figure A-4. The baseline load ratio (R = minimum load/maximum load = P_{min}/P_{max}) was 0.5 for all tests. The variables of test were the overload ratio ($OLR = (P_{OL}/P_{max})$, 1.25, 1.50) and the number of baseline fatigue cycles between overloads ($\Delta N_{OL} = 5, 20, \text{ and } 40$).

During propagation testing, crack lengths were measured on both surfaces of the specimen with a traveling microscope. To facilitate this procedure, the test was interrupted, and the mean load was applied while holding the specimen at the temperature of testing. The increment in crack length measurement was 0.50 mm (0.020 in.) and the measurement error was ± 0.025 mm (0.001 in.). The resulting "a" vs "N" data were reduced with a seven-point incremental polynomial technique (Reference 12) to produce da/dN vs ΔK data.

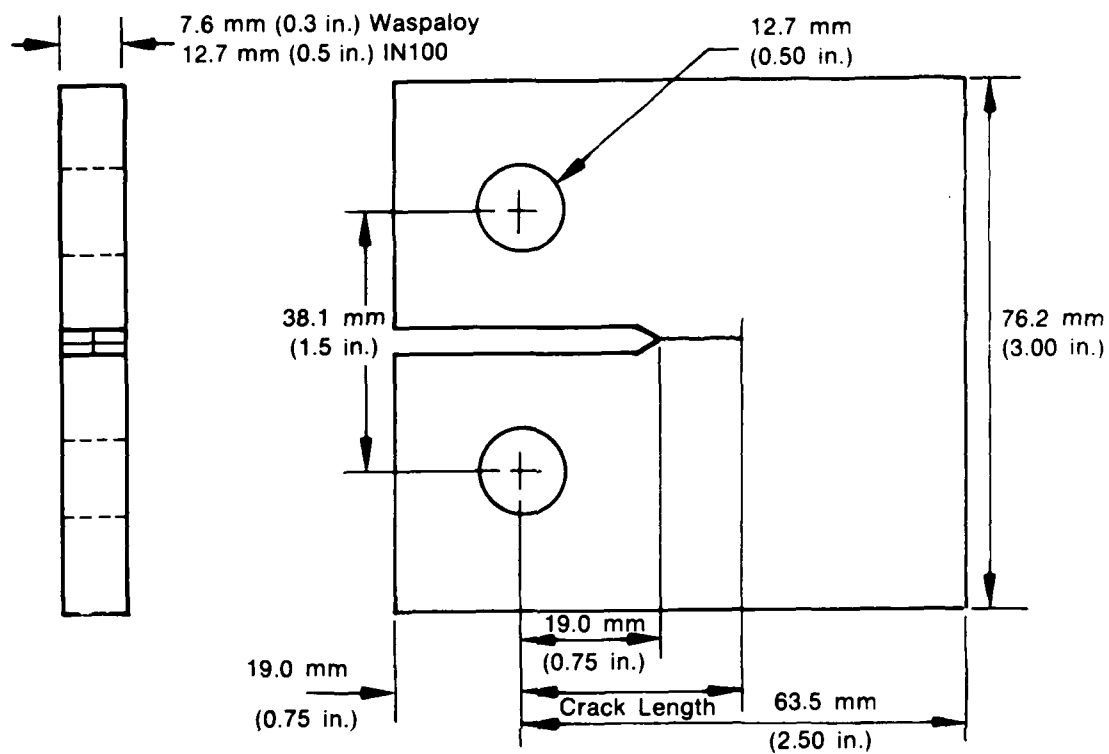
RESULTS AND DISCUSSION

The crack retardation associated with a single periodic overload is generally reflected in a local perturbation in the "a" versus "N" crack growth curve. However, as ΔN_{OL} becomes small, the resolution in crack length measurement must be increased in order to perceive the transient variations in crack growth which occur between successive overloads. In the present experiment, ΔN_{OL} is exceedingly small relative to the increment in measurement of surface crack length, and no transient variations in crack growth are observed. Rather, the collection of all "a" versus "N" data represents a trend in crack propagation resulting from very frequent periodic overloads.

Reducing the "a" versus "N" data to the form of da/dN versus ΔK data and performing a least square regression produces analytical functions which represent the average crack growth rate for the specific combination of OLR and DN_{OL} . The regression equation was based on the hyperbolic sine function and is given as: (References 5, 6 and 7)

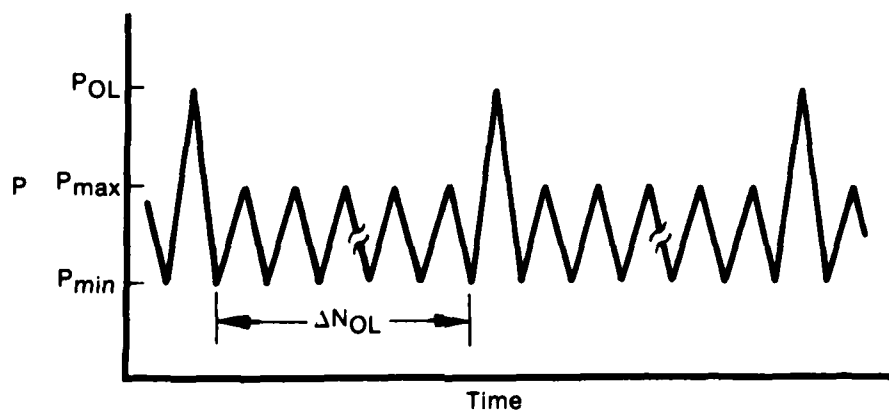
$$\log (da/dN) = C_1 \sinh (C_2 (\log \Delta K + C_3)) + C_4 \quad (A1)$$

where C_1 = 0.5, a material constant,
 C_2 = horizontal shape coefficient,
 C_3 = $\log (\Delta K)$ at the point of inflection,
 C_4 = $\log (da/dN)$ at the point of inflection, and
 ΔK = baseline stress intensity factor range.



FD 119166A

Figure A-3. Compact Specimen



FD 162145

Figure A-4. Periodic Overload Fatigue

The increased magnitude of the overload stress intensity range (ΔK_{OL}) is not reflected in the plotted value of DK . Rather, the overload is treated as an isolated variable influencing crack growth, and its impact is revealed in the dependent variable, da/dN . Thus, under the load sequencing of Figure 4, DK is defined as $K_{max} - K_{min}$ for all cycles (including the overload) and da/dN is the calculated average crack growth per cycle (including the overload).

Defining fatigue with periodic overloading as a succession of repetitive overload-fatigue missions (elemental damage events) as in Figure A-4, one may plot a series of crack growth rate curves for the collection of test missions. Figure A-5 presents such data, illustrating the effect of ΔN_{OL} on elevated temperature fatigue crack propagation in GATORIZED IN100. For purposes of comparison, a single regression curve (without data) representing crack growth under constant amplitude loading has also been plotted. This baseline crack growth is observed to be essentially equivalent to propagation under periodic overloading with $\Delta N_{OL} = 5$ (6 cycles per overload-fatigue mission). The equivalence of crack growth rates results from a balance of overload accelerated crack growth and the subsequent crack retardation. As ΔN_{OL} increases to 20 and 40, the average effect of the overloading becomes more beneficial than damaging, and the resultant propagation rate is reduced significantly below that produced under constant ΔP fatigue.

The dependence of da/dN on ΔN_{OL} may be described by an interpolative model of the associated SINH curves. The coefficients of Equation (A1) are defined as a function of ΔN_{OL} :

$$C_i = a_i + b_i (\Delta N_{OL} + 1) \quad i = 2, 3, 4 \quad (A2)$$

Thus, over the range $5 \leq \Delta N_{OL} \leq 40$, da/dN is given by a continuous function (Equation A1) for which the three coefficients are uniquely defined (Equation A2). Interpolations on ΔN_{OL} define representative SINH curves giving average crack growth associated with periodic overload fatigue of ΔN_{OL} cycles between overloads. This permits prediction of crack growth where no actual data exist. The relationship of Equation (A2) also provides the capability for limited extrapolation beyond the data base.

The effect of overload ratio on fatigue crack propagation may also be described by an interpolative model of the SINH coefficients. Figure A-6 illustrates this effect for periodic overloading ($\Delta N_{OL} = 40$) with overload ratios of 1.0, 1.25, and 1.5. Data of overload ratio 1.0 is generated under constant ΔP fatigue, and any interpolative model of OLR must converge to this condition regardless of the value of ΔN_{OL} . The expression which defines the SINH coefficients as a function of overload ratio is

$$c_i = d_i + e_i (OLR) \quad i = 2, 3, 4 \quad (A3)$$

Thus, for periodic overload-fatigue with $\Delta N_{OL} = 40$, the combination of Equations (A1) and (A3) uniquely define crack propagation for $1.0 \leq OLR \leq 1.5$.

Having established that the SINH coefficients are linear functions of overload ratio for the case of $\Delta N_{OL} = 40$, it is assumed that a similar linear relationship describes the dependence of crack propagation for $\Delta N_{OL} \leq 40$. This allows combination of the functions (2) and (3), permitting full interpolation over the region defined by $1.0 \leq OLR \leq 1.5$ and $5 \leq \Delta N_{OL} \leq 40$. The coefficients of Equation (A1) are given by:

$$C_i = \alpha_i + \beta_i (OLR) + \gamma_i (\log (\Delta N_{OL} + 1)) + \delta_i (OLR) (\log (\Delta N_{OL} + 1)) \quad (A4)$$

$$i = 2, 3, 4$$

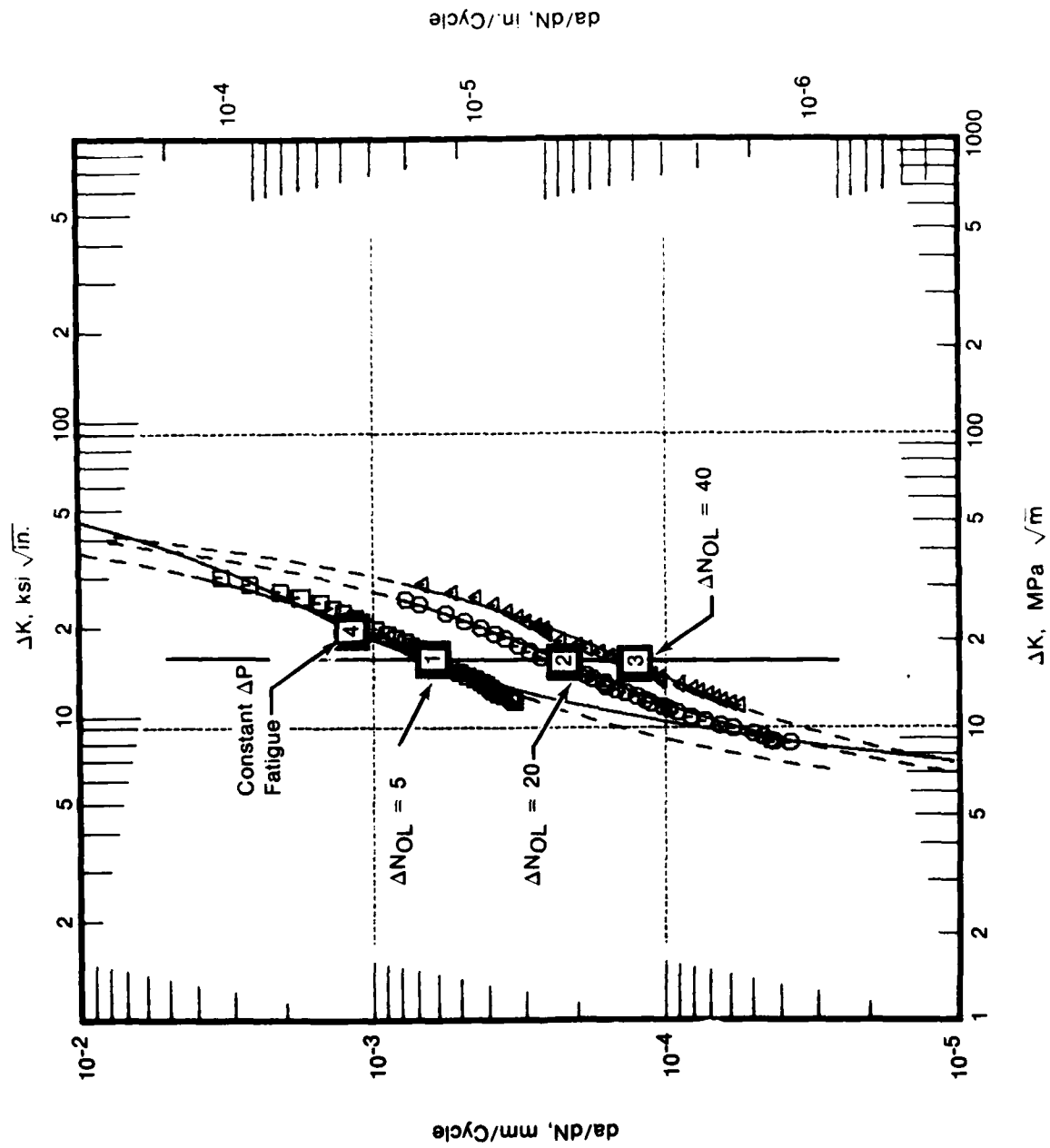
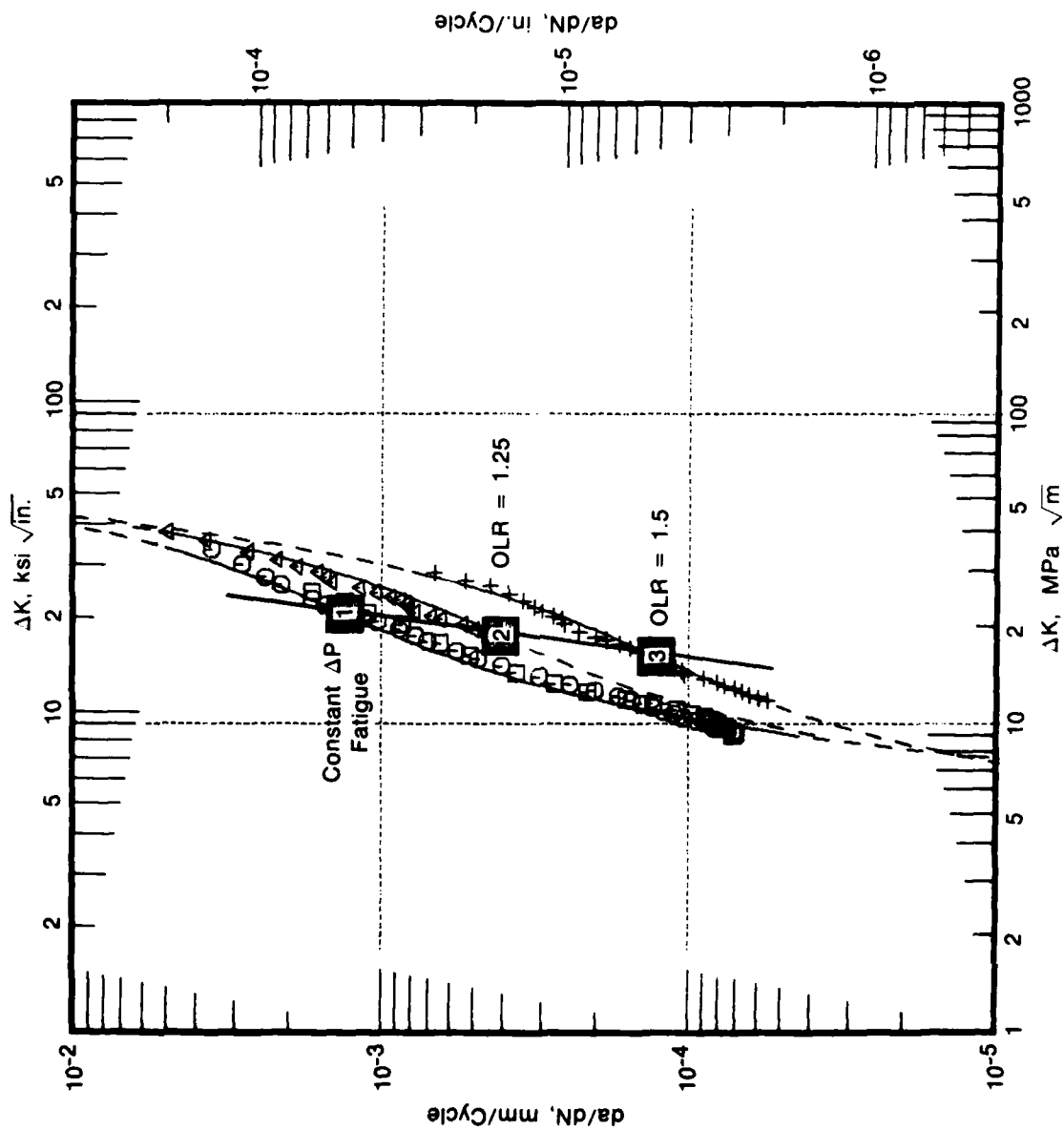


Figure A-5. Effect of Cycles Between Overloads on Fatigue of IN100, OLR = 1.5, 0.167 Hz, 649°C



10 162149

Figure A-6. Effect of Overload Ratio on Fatigue of IN100, $\Delta N_{OL} = 40$, 0.167 Hz, 649°C

This Interpolative SINH Model provides capability for prediction of fatigue crack propagation in IN100 as a function of overload ratio and the number of cycles between overloads. This interpolative model is limited to crack retardation effects under the frequently applied overloads which are characteristic of military gas turbine operation. The applicable range of OLR and ΔN_{OL} may be extended with additional testing.

Development of a similar interpolative model of crack propagation in Waspaloy has also been accomplished. As observed in Figure A-7, the beneficial influence of periodically applied overloads (OLR = 1.5) is much less pronounced in this material than in IN100. Crack growth in Waspaloy with $\Delta N_{OL} = 5$ (6 cycles per overload-fatigue mission) is considerably more severe than propagation under constant ΔP fatigue, and the average effect of the overloading becomes beneficial for $\Delta N_{OL} = 20$ and 40. In spite of the significantly different retardation behavior between Waspaloy and IN100, an interpolative function of the form of Equation (A2) is satisfactory representation of the effect of ΔN_{OL} on crack growth in this alloy.

The model of the effect of overload ratio ($\Delta N_{OL} = 40$) on crack propagation in Waspaloy, Figure A-8, also demonstrates a much more limited effect than was observed in IN100. A relationship of the form of Equation (A3) describes SINH coefficients for Waspaloy crack propagation as a function of overload ratio. Combining the models of the effects of cycles between overloads and overload ratio provides interpolative capability for both variables simultaneously (Equation A4).

The coefficients of Equation (A4) are given in Table A-1 for crack propagation of IN100 and Waspaloy at 649°C (1200°F), 0.167 Hz (10 cpm), and R = 0.5. Substitution into Equation (A1) gives crack propagation rate as a function of OLR and ΔN_{OL} .

POST-OVERLOAD CRACK RETARDATION

An Interpolative SINH Model representing crack growth under frequently applied periodic overloads is an effective method for prediction of crack growth resulting during a specific overload-fatigue sequence. However, the instantaneous response of a crack to the overload-fatigue block is not evident. From knowledge of the process of crack retardation resulting from application of a single overload, a hypothesis concerning crack growth in response to frequent periodic overloading may be established.

The crack growth curve is expected to range between two general extremes depending upon the form of post-overload crack retardation. For a given value of ΔN_{OL} , these curves are illustrated in Figure A-9. Assuming delayed retardation does not occur, the minimum crack growth rate should immediately follow the overload. If delayed retardation is present, the minimum crack growth rate should be observed some number of cycles following the overload. If ΔN_{OL} is less than the period of delayed retardation, N_{DR} , a subsequent overload interrupts the delayed retardation process, and the minimum crack growth rate should immediately precede the overload.

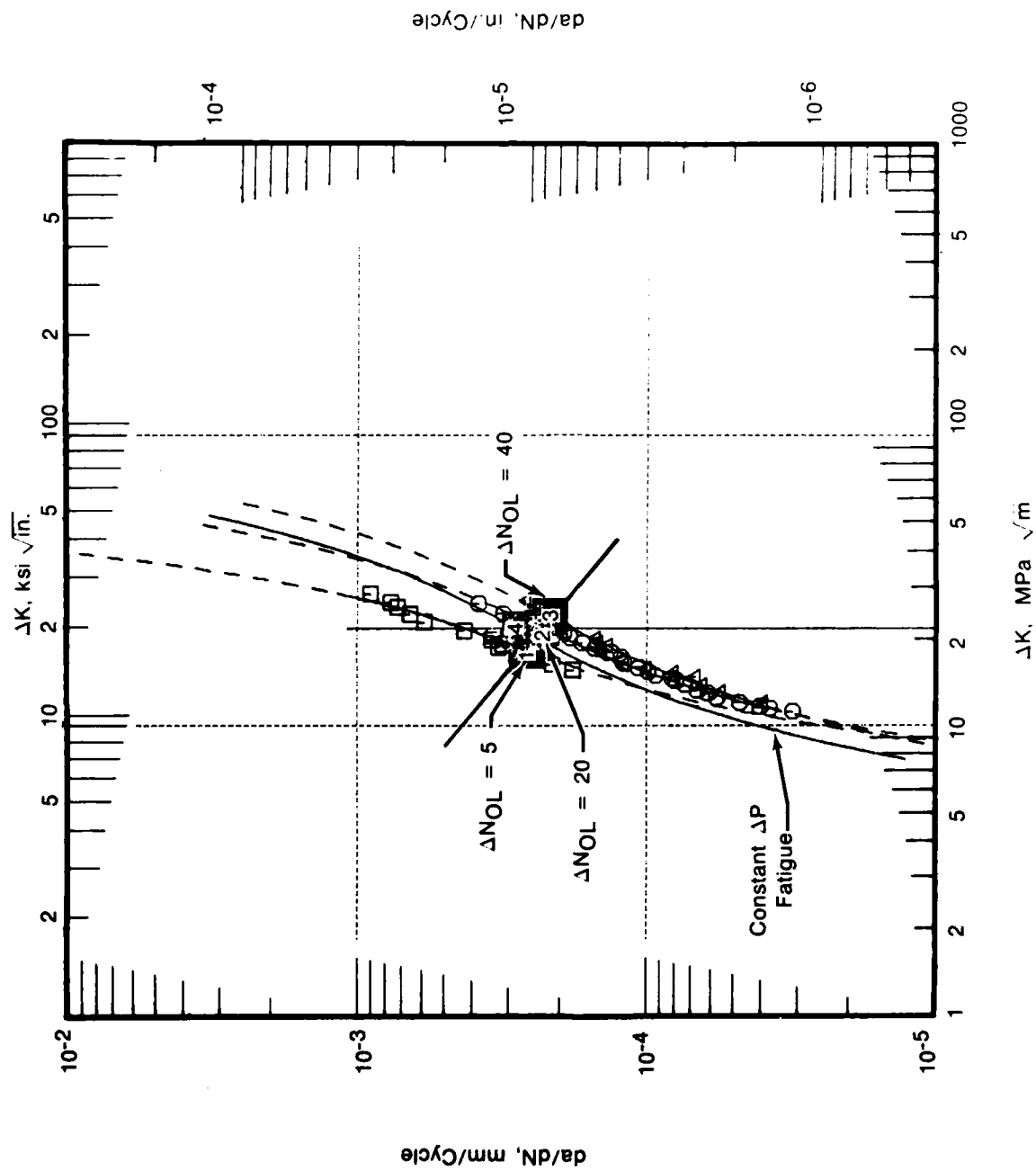
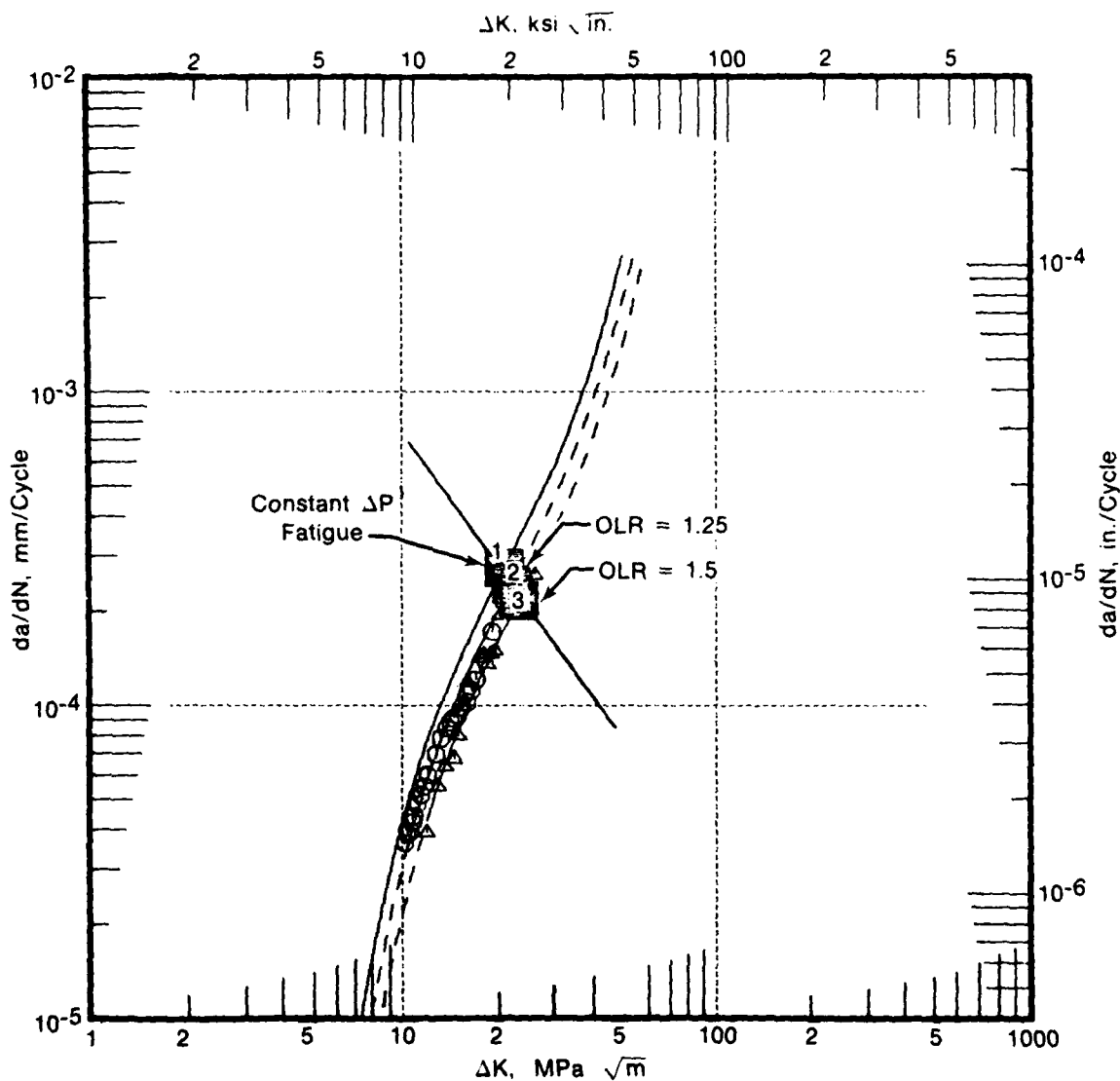


Figure A-7. Effect of Cycles Between Overloads on Fatigue of Waspaloy OLR = 1.5, 0.167 Hz, 649°C.

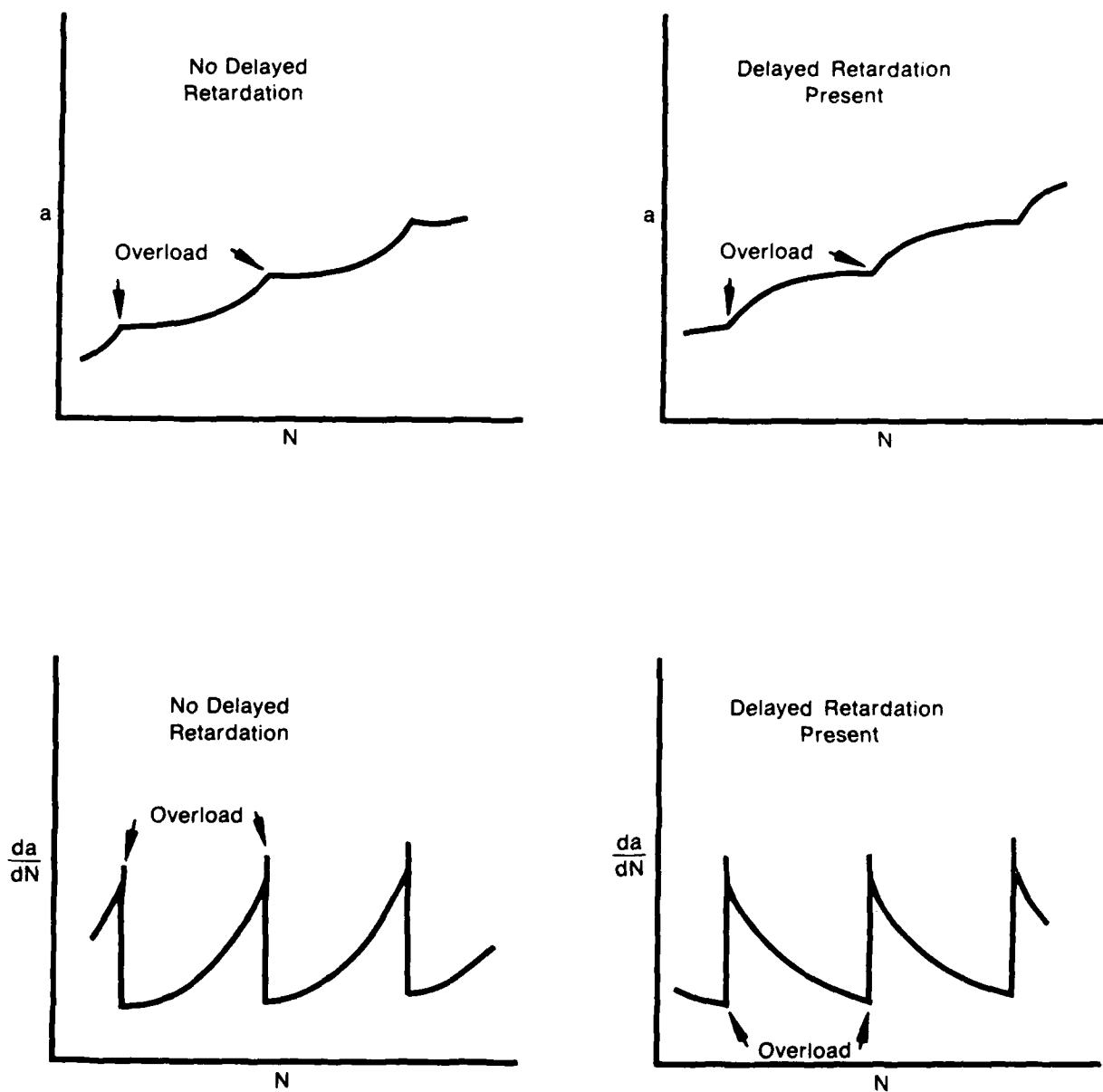


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Figure A-8. Effect of Overload Ratio on Fatigue of Waspaloy, $\Delta N_{OL} = 40$, 0.167 Hz, 649°C

TABLE A1. COEFFICIENTS OF EQUATION 4

	IN 100				Waspaloy			
	α	β	δ	ζ	α	β	δ	ζ
C_2	4.8410	-0.2140	0	0	-2.9984	6.8424	4.2414	-4.2414
C_3	-1.5448	0.1928	-0.0503	0.0503	-1.6853	0.3563	0.2780	-0.2780
C_4	-3.5196	0.6386	1.6534	-1.6534	-3.6536	0.0916	0.1845	-0.1845



FD 162146

Figure A-9. Fatigue Crack Propagation Under Periodic Overload Fatigue

Experimental determination of the nature of the instantaneous crack growth curve in response to periodic overloading is, however, a formidable task. As previously noted, it is extremely difficult to obtain accurate, meaningful measurement of crack advance between very frequent overloads using standard optical techniques. Additionally, measurement of crack length at the specimen surface is complicated by any discontinuities in crack advance due to microstructural variations. Such discontinuous fatigue crack growth is common in Waspaloy and to a lesser extent in IN100. Even if precise measurement of the surface crack length were accomplished without microstructural interference, a question would remain concerning the shape of the crack front. That is, does the crack front geometry remain constant during periodic overloading, or do periodic changes in crack curvature accompany the overloads? The latter phenomenon is certain to complicate data interpretation. Measurement of incremental crack growth by determination of fatigue striation spacing was prevented by formation of a heavy oxide on the crack face during elevated temperature testing.

It is possible, however, to determine the form of the instantaneous crack propagation curve indirectly. Unlike direct measurement, a SINH curve describing crack propagation under periodic overloading gives average behavior over the period of many overloads. The SINH representation also averages crack growth discontinuities due to variations in microstructure, crack front geometry, and judgment on the part of the technician. Thus, each curve represents a statistical mean of the microscopic crack growth rate as ΔK increases with crack length.

As noted earlier, increasing the number of fatigue cycles between successive overloads produces an increase in crack retardation and a corresponding reduction in average crack growth rate. Alternately, decreasing ΔN_{OL} reduces crack retardation, and, in the limit of zero cycles between overloads, the da/dN versus ΔK curve should approach the crack growth curve corresponding to constant overload fatigue. For the current example of constant ΔP fatigue ($R = 0.5$) interrupted by periodic overloads ($OLR = P_{OL}/P_{max} = 1.5$), the parameters defining constant overload fatigue are $R = P_{min}/P_{OL} = 0.33$ and

$$\Delta K_{OL} = \Delta K_{baseline} [(OLR - R)/(1 - R)] = 2\Delta K_{baseline} \quad (A5)$$

The propagation curve for $R = 0.333$ fatigue is obtained from an interpolative model of the effect of load ratio (Reference 13). Maintaining the convention of assigning the value of $\Delta K_{baseline}$ to all overload cycles, the $R = 0.333$ constant ΔP curve is translated by $\Delta K_{baseline} = \Delta K_{OL}/2$ in order to represent the case of constant overload fatigue. For IN100, this curve is presented in Figure A-10 and its relationship to the SINH curves representing periodic overload-fatigue is illustrated. A similar presentation of Waspaloy data appears in Figure A-11.

From the collection of curves for a single material, one may deduce an approximation to the instantaneous form of post-overload crack propagation due to periodic overloading. One assumption is required: the form of the post-overload crack propagation curve is similar for $\Delta N_{OL} = 5, 20$, and 40 . Noting that the increase in crack length between successive overloads is very small, the associated increase in ΔK is determined to be correspondingly small and of little significance. Calculating crack growth rate at a specific value of ΔK from each of the overload curves gives the average advance per cycle under the indicated load/r condition. The crack growth during each of the individual overload-fatigue missions is then calculated, and the difference in the crack growth for two different missions defines a point on the post-overload da/dN vs N curve. For example, by subtracting the crack advance due to a 21-cycle mission from the crack advance due to a 41-cycle mission, the Da corresponding to cycles 21 to 41 after the overload is obtained. The average value of da/dN for the cycle interval of 21 to 41 cycles after the overload may now be obtained by dividing $\Delta a_{21 \text{ to } 41}$ by the corresponding ΔN . This procedure is given by:

$$da/dN_{21 \text{ to } 41} = [41 (da/dN)_{41} - 21 (da/dN)_{21}]/(41-21) \quad (A6)$$

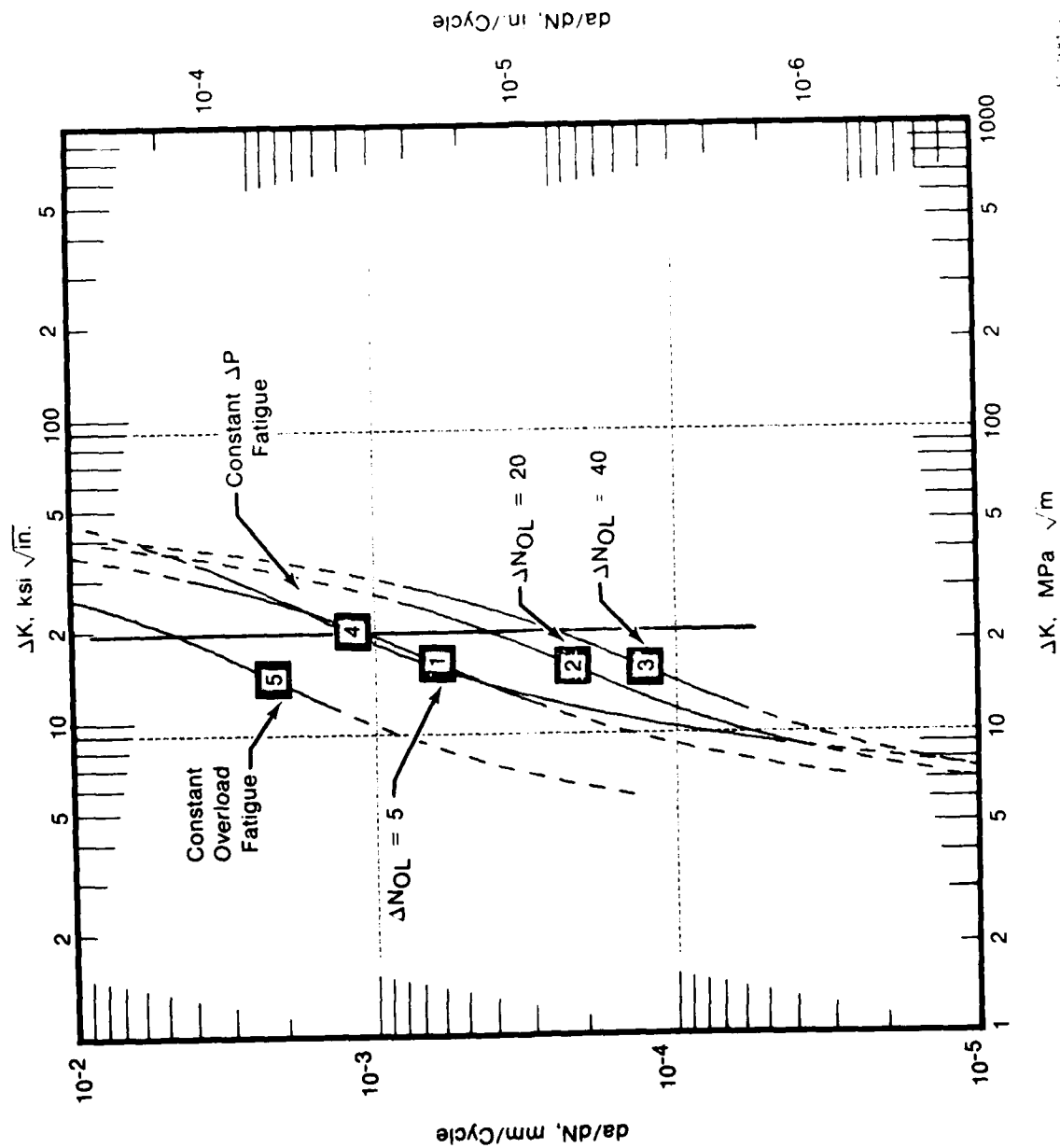


Figure A-10. Effect of Cycles Between Overloads on Fatigue of IN100, OLR = 1.5

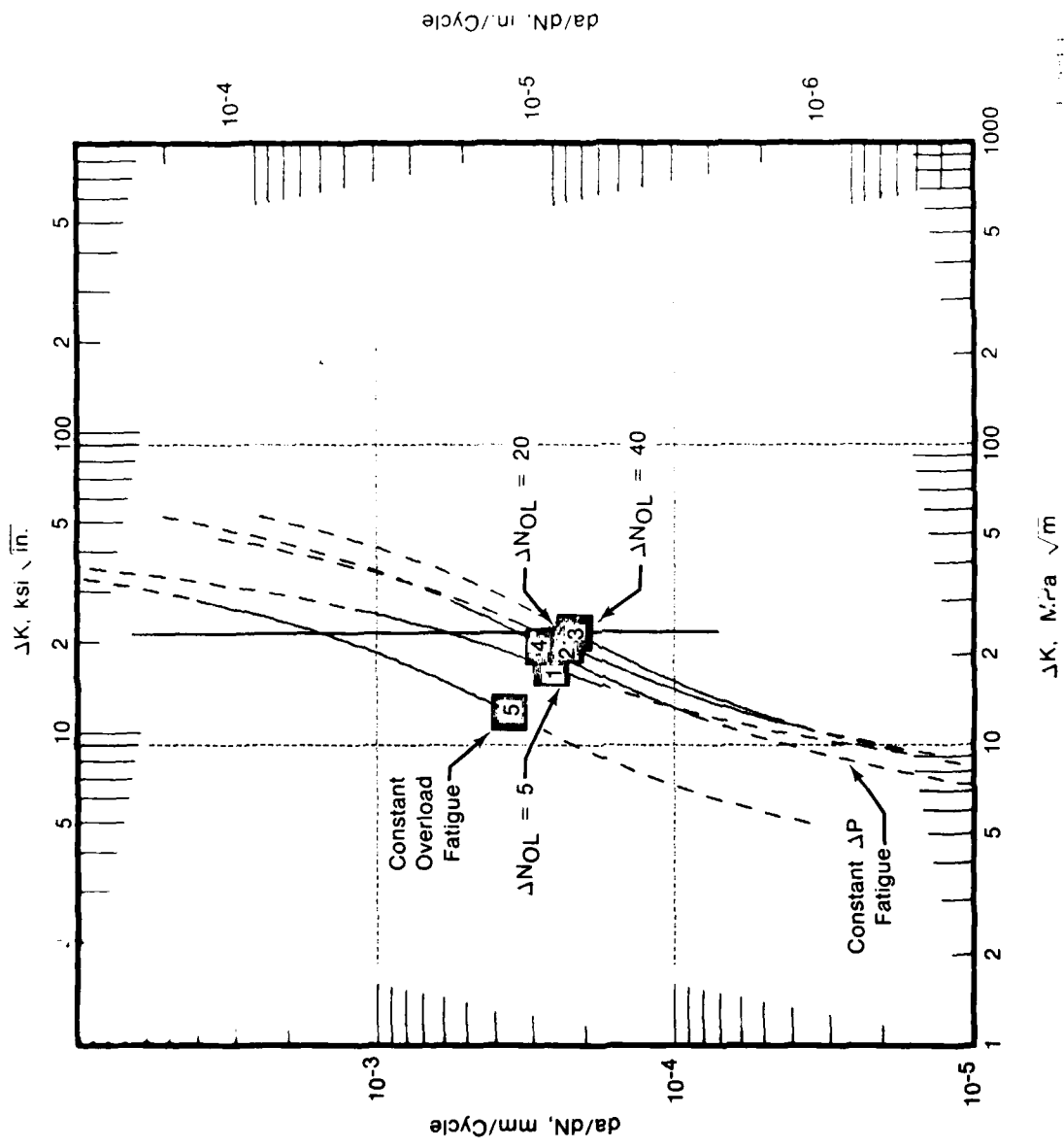
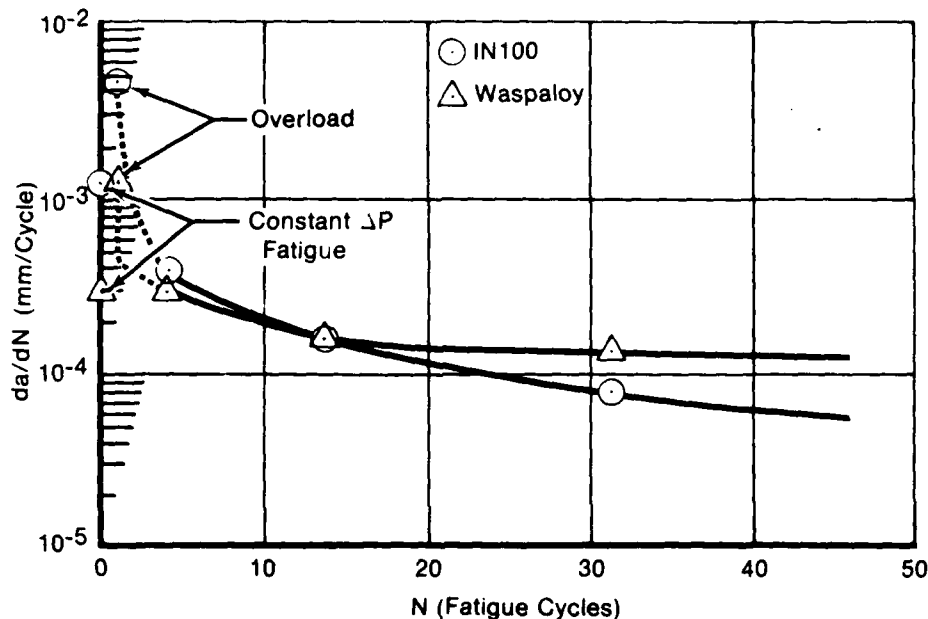


Figure A-11. Effect of Cycles Between Overloads on Fatigue of Waspaloy, OLR = 1.5

The value of $da/dN_{6 \text{ to } 21}$ may be obtained similarly, and $da/dN_{1 \text{ to } 6}$ may also be determined by subtracting the standard crack growth for one cycle of fatigue at the overload conditions from the 6-cycle mission data.

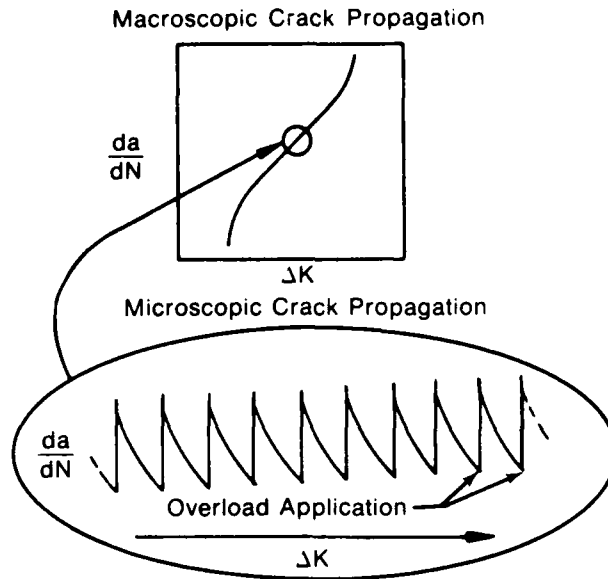
Plotting the calculated values of da/dN at the midpoints of the cycle intervals (e.g., $N = 31$ for the interval of 21 to 41 cycles) gives an approximation of the instantaneous crack propagation rate following an overload. For IN100 and Waspaloy at $\Delta K = 22 \text{ MPa} \sqrt{m}$ this data is presented in Figure A-12. While the exact path of the immediate post-overload crack propagation rate curve is unclear, as indicated by the broken line, the existence of delayed retardation is confirmed. In each alloy the crack growth rate is maximized at the time of the overload and the average crack growth rate decreases in each of the subsequent cycle intervals, i.e., 1 to 6, 6 to 21, and 21 to 41.



FD 162147

Figure A-12. Post Overload Crack Growth Exhibiting Delayed Retardation, $OLR = 1.5$, $\Delta K = 22 \text{ MPa} \sqrt{m}$

This finding is verification of the general crack behavior which was hypothesized earlier for mission crack growth subject to delayed retardation. That is, in IN100 and Waspaloy a crack subjected to constant load amplitude fatigue interrupted by periodic overloading will display a general decrease in the average macroscopic crack propagation rate, but, as illustrated in Figure A-13, the instantaneous response of a crack to such overloading is more complex. The full extent of crack retardation does not develop immediately following the application of an overload; rather, post-overload crack growth rate decelerates throughout the period of delayed retardation. Typically, this period is greater than the total number of baseline fatigue cycles applied between mission overload, and delayed retardation is responsible for all beneficial effects of the overloading. Since crack growth rate decelerates during the entire period of delayed retardation, fatigue cycles immediately following an overload are considerably more damaging than later cycles.



FD 132337A

Figure A-13. Fatigue Crack Propagation with Frequent Overloads

This behavior deviates significantly from the general long-term effects of an overload on FCP; therefore, mission crack growth in IN100 and Waspaloy is difficult to predict by any retardation model which is developed solely from experimental measurements of the total period of retardation N^* . Modeling of N^* addresses fatigue crack retardation as a steady-state process, while retardation under mission loading is dominated by delayed retardation which is a transient response. Only a model which contains this transient capability is expected to effectively predict the synergistic effects of the frequent overloading which is common to engine operation.

CONCLUSIONS

1. The rate of elevated temperature FCP of IN100 and Waspaloy subjected to constant load amplitude interrupted by periodic overloads, decreases with increasing overload ratio and number of cycles between overload.
2. The combined effects of overload ratio ($1.0 \leq \text{OLR} \leq 1.5$) and number of cycles between overloads ($5 \leq \Delta N_{\text{OL}} \leq 40$) on crack propagation of IN100 and Waspaloy are effectively described by an interpolative model based on the hyperbolic sine function.
3. Post-overload crack retardation resulting from frequently applied overloads ($\text{OLR} = 1.5$, $\Delta N_{\text{OL}} \leq 40$) exhibits delayed retardation in IN100 and Waspaloy. The delayed retardation is not exhausted between successive overloads and is entirely responsible for any reduction in crack growth rate in these alloys.

ACKNOWLEDGEMENT

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LIST OF SYMBOLS

a	crack length
C_1	SINH material coefficient = 0.5
C_2	SINH horizontal scaling coefficient
C_3	SINH horizontal inflection coefficient
C_4	SINH vertical inflection coefficient
da/dN	cyclic rate of crack growth
ΔK	applied stress intensity factor range
ΔN_{OL}	number of fatigue cycles applied between periodic overloads
K	stress intensity factor
K_{max}	maximum stress intensity factor
K_{min}	minimum stress intensity factor
K_{OL}	overload stress intensity factor
N	number of cycles
N^*	number of cycles during which crack growth rate is retarded following an overload application
N_{DR}	period of delayed retardation
P	applied load
P_{max}	maximum applied load
P_{min}	minimum applied load
P_{OL}	magnitude of applied overload
P	load ratio (P_{min}/P_{max})

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APPENDIX B. CUMULATIVE DAMAGE CRACK PROPAGATION TESTS

Specimen Number	Material	Test		Atmosphere	Frequency	Load Specimen		Thickness	Comment
		Temperature				Ratio	Geometry		
1000793	PMA 1073	427C		AIR	.167 HZ	R=-1.	CC ¹	7.62	
1001000	PMA 1007	427C		AIR	.167 HZ	R=.05	C ²	2.64	
1001001	PMA 1007	649C		AIR	.167 HZ	R=.05	C	2.59	
1001002	PMA 1007	427C		AIR	.167 HZ	R=.05	C	12.67	
1001003	PMA 1007	427C		AIR	.167 HZ	R=.05	CC	7.70	
1001004	PMA 1007	649C		AIR	.167 HZ	R=.05	CC	7.65	
1001005	PMA 1007	427C		AIR	.167 HZ	R=.05	CC	7.62	
1001006	PMA 1007	649C		AIR	.167 HZ	R=.55	CC	7.29	
1001007	PMA 1007	427C		AIR	.167 HZ	R=.8	CC	7.62	
1001008	PMA 1007	649C		AIR	.167 HZ	R=.8	CC	7.62	
1001009	PMA 1007	TMF		AIR	.0167 HZ	R=.05	CC	7.62	
1001010	PMA 1007	732C		AIR	.167 HZ	R=.05	CC	7.65	
1001011	PMA 1007	732C		AIR	.167 HZ	R=.05	C	2.72	
1001013	PMA 1007	649C		AIR	.167 HZ	R=.1	C	8.08	
1001014	PMA 1007	427C		AIR	.167 HZ	R=.05	C	7.62	
1001015	PMA 1007	732C		AIR	2 MDHL	R=.1	C	7.62	
1001017	PMA 1007	649C		AIR	.167 HZ	R=.8	C	7.62	
1001018	PMA 1007	427C		AIR	.167 HZ	R=.05	C	7.57	
1001019	PMA 1007	649C		AIR	.167 HZ	R=.5	C	7.59	
1001021	PMA 1007	649C		AIR	.167 HZ	R=.5	C	7.67	
1001022	PMA 1007	649C		AIR	.167 HZ	R=.5	C	7.62	
1001024	PMA 1007	649C		AIR	.167 HZ	R=.5	C	7.62	
1001025	PMA 1007	649C		AIR	.167 HZ	R=.5	C	7.62	
1001026	PMA 1007	649C		AIR	.167 HZ	R=.5	C	7.57	
1001027	PMA 1007	732C		AIR	2 MDHL	R=.1	C	7.59	
1001028	PMA 1007	649C		AIR	.167 HZ	R=.5	C	7.65	
1001029	PMA 1007	649C		AIR	.167 HZ	R=.5	C	7.62	
1001030	PMA 1007	649C		AIR	.167 HZ	R=.1	C	7.59	
1001031	PMA 1007	649C		AIR	DA/DT		C	12.75	
1001033	PMA 1007	649C		AIR	DA/DT		C	12.75	
1001034	PMA 1007	649C		AIR	DA/DT		C	12.73	
1001035	PMA 1007	649C		AIR	DA/DT		C	12.75	
1001036	PMA 1007	732C		AIR	DA/DT		C	12.80	
1001037	PMA 1007	732C		AIR	DA/DT		C	12.80	
1001039	PMA 1007	732C		AIR	DA/DT		C	12.80	
1001041	PMA 1007	732C		AIR	DA/DT		C	12.24	
1001042	PMA 1007	649C		AIR	DA/DT		C	12.29	
1001044	PMA 1073	732C		AIR	.0083 HZ	R=.1	C	7.67	
1001046	PMA 1073	732C		AIR	.167 HZ	R=.1	C	7.62	
1001047	PMA 1073	732C		AIR	.167 HZ	R=.1	C	7.65	
1001048	PMA 1073	649C		AIR	.167 HZ	R=.8	C	7.67	
1001052	PMA 1073	649C		AIR	.0083 HZ	R=.1	C	7.24	
1001053	PMA 1073	649C		AIR	.167 HZ	R=.1	C	7.59	
1001055	PMA 1073	649C		AIR	.167 HZ	R=.5	CC	7.82	

TMF800-1300F

PARTIAL
PARTIAL

011.50+5CY
011.50+40CY
011.25+5CY
011.25+40 PA
011.50+20CY
011.25+20CY

011.25+40CY
011.50+20CY
011.25+20CY

011.25+20CY
011.50+20CY

011.5-.3+20

APPENDIX B. CUMULATIVE DAMAGE CRACK PROPAGATION TESTS

Specimen Number	Material	Test Temperature	Atmosphere	Frequency	Load Ratio	Specimen Geometry	Thickness	Comment
1001058	PMA 1073	649C	AIR	.167 HZ	R=-.5	CC	7.85	
1001196	PMA 1007	649C	AIR	20 HZ	R=.05	C	19.13	
1001301	PMA 1007	649C	AIR	.167 HZ	R=.05	C	12.73	
1001302B	PMA 1007	649C	AIR	.167 HZ	R=.5	C	12.75	OL1.50+20CY
1001303	PMA 1007	649C	AIR	.167 HZ	R=.1	C	12.70	2MDWL+20CY
1001304	PMA 1007	649C	AIR	20 HZ	R=.1	C	12.70	
1001307	PMA 1007	427C	AIR	20 HZ	R=.1	C	7.80	
1001308	PMA 1007	649C	AIR	20 HZ	R=.1	C	7.67	
1001309	PMA 1007	649C	AIR	.167 HZ	R=.1	C	7.72	2MDWL+40CY
1001310	PMA 1007	649C	AIR	.167 HZ	R=.1	C	7.42	2MDWL+20CY
1001312	PMA 1007	649C	AIR	.167 HZ	R=.1	C	7.54	2MDWL+20CY
1001313	PMA 1007	732C	AIR	.167 HZ	R=.1	C	7.67	2MDWL+40CY
1001314	PMA 1007	732C	AIR	.167 HZ	R=.1	C	7.47	2MDWL+20CY
1001315	PMA 1007	732C	AIR	.167 HZ	R=.1	C	7.59	2MDWL+10CY
1001316	PMA 1007	732C	AIR	.167 HZ	R=.5	C	7.47	2MDWL+20CY
1001317	PMA 1007	649C	AIR	.167 HZ	R=.1	C	7.67	2MDWL+10CY
1001318	PMA 1007	732C	AIR	.167 HZ	R=.1	C	7.67	2MDWL+20CY
1001319	PMA 1007	732C	AIR	.167 HZ	R=.5	C	7.57	OL1.50+20CY
1001320	PMA 1007	732C	AIR	.167 HZ	R=.5	CC	7.59	OL1.50+20CY
1001321	PMA 1007	649C	AIR	.167 HZ	R=.1	CC	7.42	PRESTRAIN
1001323	PMA 1007	649C	AIR	.167 HZ	R=.1	CC	7.54	PRESTRAIN
1001324	PMA 1007	427C	AIR	.167 HZ	R=-.5	CC	7.57	
1001326	PMA 1007	649C	AIR	.167 HZ	R=-.5	CC	7.62	
1001327	PMA 1007	649C	AIR	.167 HZ	R=-.1	CC	7.59	
1001328	PMA 1007	649C	AIR	.0083 HZ	R=.1	CC	7.62	
1001329	PMA 1007	732C	AIR	.167 HZ	R=.1	CC	7.62	OL1.25+20CY
1001330	PMA 1007	732C	AIR	15 MDHL	R=.1	CC	7.59	PRESTRAIN
1001337	PMA 1073	649C	AIR	.167 HZ	R=.1	CC	7.32	
1001341	PMA 1073	649C	AIR	.167 HZ	R=.1	CC	7.52	
1001342	PMA 1073	649C	AIR	.167 HZ	R=-.1	CC	7.59	
1001343	PMA 1073	427C	AIR	.167 HZ	R=-.5	CC	5.79	HIGH STRESS
1001349	PMA 1007	649C	AIR	.167 HZ	R=.05	CC	7.59	
1001350	PMA 1007	427C	AIR	.167 HZ	R=-.1	CC	7.54	HIGH STRESS
1001426	PMA 1007	649C	AIR	.167 HZ	R=.05	CC	7.57	2MDWL+20CY
1001456	PMA 1007	649C	AIR	.167 HZ	R=.5	C	12.75	

1 CC = through thickness center crack specimen (figure 11a)

2 C = compact specimen (figure 11b)

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED

7AN0326A PMA 1073 1350F AIR 2 M7AN					
R= 0.10 THICKNESS=11.074 MM					
PMAX= 5.280 KN WIDTH=63.373 MM					
COMPACT SPECIMEN					
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)	
1	0.	27.08			
2	390.	28.17			
3	503.	28.48			
4	706.	29.20	14.58	3.156E-03	
5	841.	29.56	14.84	3.309E-03	
6	1074.	30.22	15.39	3.537E-03	
7	1254.	31.03	15.82	3.985E-03	
8	1374.	31.56	16.13	4.984E-03	
9	1569.	32.19	16.87	6.703E-03	
10	1749.	33.34	17.90	9.776E-03	
11	1894.	35.20	19.42	1.342E-02	
12	2014.	36.62	21.47	2.053E-02	
13	2089.	38.24			
14	2134.	39.13			
15	2254.	43.61			

1000330 PMA 1073 1350F AIR 10 CPM					
R= 0.10 THICKNESS=12.700 MM					
PMAX= 6.045 KN WIDTH=63.602 MM					
COMPACT SPECIMEN					
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)	
1	0.	26.81			
2	8040.	27.38	13.29	7.092E-05	

7AN0334 PMA 1073 1200F AIR 10 CPM					
R= 0.50 THICKNESS=12.725 MM					
PMAX= 8.976 KN WIDTH=63.409 MM					
COMPACT SPECIMEN					
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)	
1	0.	21.24			
2	2000.	21.51			
3	6000.	21.94			
4	14400.	22.33	9.15	7.141E-05	
5	21000.	22.80	9.30	6.987E-05	
6	28000.	23.30	9.47	7.156E-05	
7	34400.	23.77	9.64	7.415E-05	
8	41000.	24.25	9.82	7.610E-05	
9	48000.	24.79	10.03	8.041E-05	
10	55000.	25.35	10.25	8.480E-05	
11	62000.	25.93	10.51	8.894E-05	
12	69300.	26.68	10.78	9.756E-05	
13	76200.	27.32	11.03	1.096E-04	
14	84800.	28.14	11.53	1.303E-04	
15	92000.	29.22	12.01	1.597E-04	
16	99000.	30.38	12.62	2.125E-04	
17	105000.	31.53	13.40	2.718E-04	
18	111000.	33.13	14.53	3.630E-04	
19	117000.	35.61	16.48	5.140E-04	
20	120000.	37.10	18.08	6.410E-04	
21	123100.	39.12	20.78	8.549E-04	
22	124650.	40.64	22.71	1.107E-03	
23	125640.	41.71			
24	126500.	43.08			
25	127400.	44.33			

7AN0337 PMA 1073 1200F AIR 2 MOHL					
R= 0.10 THICKNESS=11.001 MM					
PMAX= 7.895 KN WIDTH=63.416 MM					
COMPACT SPECIMEN					
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)	
1	0.	21.08			
2	1011.	23.27			
3	1240.	23.72			
4	1460.	24.23	17.64	2.229E-03	
5	1700.	24.68	18.01	2.229E-03	
6	2000.	25.56	18.48	2.322E-03	
7	2200.	25.85	18.81	2.372E-03	
8	2665.	26.92	19.67	2.687E-03	
9	3110.	28.25	20.75	2.929E-03	
10	3500.	29.46	21.91	2.912E-03	
11	3900.	31.06	23.14	3.000E-03	
12	4200.	31.72	24.06	3.782E-03	
13	4397.	31.82	24.79	4.217E-03	
14	4710.	33.43	26.29	5.230E-03	
15	5100.	35.97	29.99	7.749E-03	
16	5200.	36.85	31.53	8.356E-03	
17	5360.	37.34	33.14	1.034E-02	
18	5400.	38.55	35.07	1.166E-02	
19	5500.	39.66	37.99	1.428E-02	
20	5640.	42.01	44.81	1.802E-02	
21	5650.	42.18	45.39	2.024E-02	
22	5665.	42.49	46.46	2.142E-02	
23	5680.	42.78			
24	5700.	43.28			
25	5720.	43.77			

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7AN0371 PWA 1073 1350F AIR 10CPM R= 0.10 THICKNESS=12.751 MM PMA= 9.016 KN WIDTH=63.469 MM COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)					
1	0	21.29							
2	500	21.73							
3	1340	22.19							
4	2210	22.61	16.68	5.382E-04					
5	3040	23.04	16.91	5.092E-04					
6	4000	23.62	17.20	5.185E-04					
7	5100	23.96	17.57	5.533E-04					
8	6500	24.26	18.11	6.473E-04					
9	7740	25.68	18.71	7.711E-04					
10	8340	26.15	19.09	8.301E-04					
11	9000	26.76	19.53	8.787E-04					
12	9650	27.34	20.00	9.611E-04					
13	10310	28.00	20.54	1.049E-03					
14	11110	28.78	21.29	1.190E-03					
15	11900	29.83	22.22	1.400E-03					
16	12400	30.53	22.94	1.582E-03					
17	12900	31.33	23.82	1.786E-03					
18	13400	32.25	24.85	2.016E-03					
19	13800	33.12	25.92	2.213E-03					
20	14100	33.80	26.84	2.364E-03					
21	14400	34.54	27.68	2.545E-03					
22	14660	35.20	28.85	2.840E-03					
23	14940	35.96	30.17	3.273E-03					
24	15200	36.77	31.72	3.806E-03					
25	15470	37.95	33.90	4.384E-03					
26	15580	38.51	35.00	4.459E-03					
27	15700	39.04	36.31	4.829E-03					
28	15920	39.76	37.80	4.700E-03					
29	15950	40.17	39.32	5.005E-03					
30	16070	40.99	40.89	6.278E-03					
31	16100	41.18	42.92	8.691E-03					
32	16290	42.14							
33	16350	43.28							
34	16400	44.20							

7AN0393 PWA 1073 1200F AIR 10 CPM R= 0.50 THICKNESS=12.700 MM PMA= 9.061 KN WIDTH=63.635 MM COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)					
1	26220	23.56							
2	32050	24.06							
3	36020	24.52							
4	44310	25.15	10.23	9.397E-05					
5	50210	25.80	10.45	1.038E-04					
6	55110	26.18	10.72	1.115E-04					
7	61100	26.86	10.96	1.204E-04					
8	66000	27.60	11.23	1.302E-04					
9	70600	28.10	11.56	1.425E-04					
10	75600	28.86	11.88	1.534E-04					
11	80300	29.58	12.25	1.694E-04					
12	85370	30.39	12.74	2.014E-04					
13	90330	31.47	13.34	2.425E-04					
14	95320	32.64	14.16	3.046E-04					
15	100000	34.17	15.31	4.044E-04					
16	102360	35.17	16.10	4.827E-04					
17	104540	36.18	17.10	5.683E-04					
18	106540	37.52	18.34	7.073E-04					
19	107450	38.10	19.07	7.707E-04					
20	109400	38.80	20.02	8.737E-04					
21	109350	39.83	21.15	1.026E-03					
22	109320	40.12	21.87	1.134E-03					
23	110420	40.91	22.96	1.346E-03					
24	110920	41.57	24.06	1.534E-03					
25	111270	42.11							
26	112043	43.59							
27	112390	44.40							

7AN0527 PWA 1073 1200F AIR 20 HZ R= 0.10 THICKNESS= 6.274 MM PMA= 4.448 KN WIDTH=63.703 MM COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)					
1	0	21.75							
2	5000	22.42							
3	9000	23.01							
4	13000	23.57	17.20	1.460E-04					
5	17000	24.12	17.59	1.508E-04					
6	21000	24.75	18.00	1.570E-04					
7	25000	25.41	18.45	1.644E-04					
8	29000	26.06	18.95	1.726E-04					
9	33000	26.78	19.49	1.816E-04					
10	36000	27.31	19.93	1.857E-04					
11	39000	27.89	20.41	1.979E-04					
12	42000	28.51	20.93	2.073E-04					
13	45000	29.13	21.51	2.190E-04					
14	48000	29.81	22.14	2.327E-04					
15	50000	30.27	22.60	2.431E-04					
16	52000	30.77	23.11	2.541E-04					
17	54000	31.30	23.66	2.638E-04					
18	56000	31.84	24.26	2.823E-04					
19	56043	31.84	24.26	2.829E-04					
20	58000	32.38	24.92	3.006E-04					
21	60000	33.04	25.70	3.200E-04					
22	61510	33.55	26.34	3.320E-04					
23	63000	34.04	27.02	3.466E-04					
24	64500	34.55	27.75	3.705E-04					
25	66000	35.09	28.59	3.960E-04					
26	67500	35.71	29.56	4.264E-04					
27	68500	36.21	30.30	4.499E-04					
28	69500	36.62	31.11	4.776E-04					
29	70500	37.10	31.99	5.075E-04					
30	71500	37.62	32.93	5.449E-04					
31	72500	38.18	34.19	5.788E-04					
32	73500	38.80	35.44	6.570E-04					
33	74500	39.48	37.05	7.184E-04					
34	75550	40.07	39.01	8.569E-04					
35	76350	41.07	40.93	9.477E-04					
36	77000	41.45	42.94	9.936E-04					
37	77700	42.46							
38	78300	42.99							
39	78600	43.47							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7A10528 FWA 1073 1000F AIR 10 CPM R= 0.10 THICKNESS=6.350 MM FMAX= 4.484 KN WIDTH=63.563 MM COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0.	20.63							
2	1000.	21.04							
3	3800.	21.49							
4	5810.	22.00							
5	7800.	22.53	16.23	2.441E-04					
6	10000.	23.04	16.52	2.537E-04					
7	12200.	23.60	16.86	2.661E-04					
8	14500.	24.28	17.23	2.818E-04					
9	16400.	24.89	17.65	2.967E-04					
10	18500.	25.60	18.08	3.152E-04					
11	20500.	26.22	18.57	3.337E-04					
12	22500.	26.96	19.07	3.504E-04					
13	24110.	27.58	19.63	3.702E-04					
14	26100.	28.37	20.12	3.877E-04					
15	28000.	29.16	20.80	4.182E-04					
16	29820.	29.98	21.53	4.429E-04					
17	30930.	30.56	22.84	4.731E-04					
18	31900.	31.01	23.37	5.092E-04					
19	33000.	31.59	24.01	5.163E-04					
20	34100.	32.20	24.65	5.249E-04					
21	35200.	32.78	25.36	5.442E-04					
22	36300.	33.30	26.09	5.743E-04					
23	37400.	33.97	26.95	6.025E-04					
24	38400.	34.59	27.83	6.412E-04					
25	39410.	35.33	28.87	6.835E-04					
26	40300.	35.86	29.88	7.179E-04					
27	41220.	36.56	31.02	7.708E-04					
28	42050.	37.20	32.19	8.330E-04					
29	42920.	37.92	33.73	9.104E-04					
30	43500.	38.78	35.53	1.017E-03					
31	44570.	39.62	37.48	1.149E-03					
32	45100.	40.13	39.08	1.267E-03					
33	45600.	40.85	40.89	1.409E-03					
34	46120.	41.60	43.17	1.610E-03					
35	46500.	42.29							
36	46950.	43.01							
37	47350.	43.92							

7A10534 FWA 1073 1200F AIR 10 CPM R= 0.10 THICKNESS=12.725 MM FMAX= 6.676 KN WIDTH=63.640 MM COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0.	22.73							
2	50000.	25.17							
3	60000.	26.86							
4	66000.	28.16	15.34	2.319E-04					
5	68000.	28.61	15.63	2.717E-04					
6	70000.	29.17	15.99	3.133E-04					
7	72000.	29.84	16.42	3.485E-04					
8	74000.	30.53	16.97	3.933E-04					
9	76000.	31.44	17.63	4.488E-04					
10	77280.	31.98	18.13	4.978E-04					
11	78600.	32.68	18.75	5.819E-04					
12	78770.	33.64	18.92	6.389E-04					
13	79570.	33.27	19.29	6.822E-04					
14	80170.	33.75	19.71	7.494E-04					
15	80770.	34.20	20.20	8.057E-04					
16	81330.	34.59	20.68	8.607E-04					
17	81900.	35.17	21.24	9.103E-04					
18	82400.	35.59	21.78	1.003E-03					
19	82900.	36.14	22.40	1.147E-03					
20	83400.	36.62	23.14	1.296E-03					
21	83900.	37.34	24.12	1.462E-03					
22	84400.	38.21	25.30	1.612E-03					
23	84800.	38.89	26.44	1.775E-03					
24	85100.	39.34	27.37	1.979E-03					
25	85400.	39.89	28.44	2.232E-03					
26	85700.	40.61	29.83	2.440E-03					
27	85700.	41.23	30.95	2.695E-03					
28	86100.	41.79	32.23	2.965E-03					
29	86300.	42.20							
30	86640.	43.45							
31	86800.	44.12							

7A10535 FWA 1073 1200F AIR 1 MOHL R= 0.10 THICKNESS=11.811 MM FMAX= 8.309 KN WIDTH=63.500 MM COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0.	25.97							
2	720.	26.71							
3	2100.	28.22							
4	2700.	29.04	21.41	1.489E-03					
5	3250.	29.93	22.21	1.651E-03					
6	3700.	30.79	22.99	1.842E-03					
7	4125.	31.64	23.84	2.088E-03					
8	4553.	32.35	24.88	2.481E-03					
9	4900.	33.25	25.94	2.992E-03					
10	5200.	34.15	27.22	3.977E-03					
11	5404.	34.95	28.38	4.808E-03					
12	5600.	35.78	29.89	6.040E-03					
13	5800.	37.31	32.14	7.909E-03					
14	6009.	38.71	35.13	1.107E-02					
15	6100.	39.97	38.80	1.376E-02					
16	6170.	40.99	41.55	1.813E-02					
17	6200.	41.66	43.31	1.817E-02					
18	6230.	42.24							
19	6260.	42.90							
20	6330.	44.19							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7A0536 PWA 1073 1200F AIR 10CPM					7A0537 PWA 1073 1200F AIR MIX					7A0540 PWA 1073 1200F AIR 20 HZ				
R= 0.10 THICKNESS=11.938 MM					R= 0.10 THICKNESS=12.027 MM					R= 0.10 THICKNESS=11.227 MM				
PMAX= 5.338 KN WIDTH=63.787 MM					PMAX= 6.672 KN WIDTH=63.906 MM					PMAX= 7.735 KN WIDTH=63.348 MM				
COMPACT SPECIMEN					COMPACT SPECIMEN					COMPACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)	NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)	NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	0.	26.92			1	0.	27.68			1	0.	19.99		
2	100.	27.06			2	100.	28.69			2	5000.	20.43		
3	200.	27.16			3	200.	28.51			3	5000.	20.82		
4	300.	27.27			4	300.	28.84			4	13000.	21.17		
5	487.	27.50	12.52	1.231E-03	5	400.	29.27	16.61	3.379E-03	5	17500.	21.64	15.46	9.820E-05
6	587.	27.66	12.64	1.345E-03	6	500.	29.59	16.76	3.154E-03	6	22000.	22.05	15.70	9.505E-05
7	687.	27.80	12.71	1.421E-03	7	600.	29.99	17.07	3.955E-03	7	26000.	22.53	15.75	1.007E-04
8	787.	27.95	12.79	1.557E-03	8	700.	30.43	17.38	4.127E-03	8	31000.	23.00	16.23	1.035E-04
9	887.	28.11	12.87	1.671E-03	9	800.	30.91	17.70	4.255E-03	9	35500.	23.47	16.50	1.054E-04
10	987.	28.32	12.96	1.829E-03	10	900.	31.32	18.05	4.506E-03	10	40000.	23.97	17.11	1.071E-04
11	1087.	28.52	13.07	1.985E-03	11	1000.	31.78	18.41	4.923E-03	11	44500.	24.49	17.44	1.083E-04
12	1187.	28.76	13.18	2.242E-03	12	1100.	32.30	18.64	5.235E-03	12	49000.	24.94	17.79	1.105E-04
13	1287.	28.97	13.31	2.535E-03	13	1200.	33.05	19.31	5.824E-03	13	53500.	25.51	18.16	1.131E-04
14	1387.	29.32	13.46	2.838E-03	14	1300.	33.57	19.88	6.632E-03	14	58000.	26.05	18.54	1.152E-04
15	1487.	29.66	13.62	3.317E-03	15	1400.	34.42	20.58	7.636E-03	15	62500.	26.62	18.97	1.173E-04
16	1587.	30.03	13.82	3.954E-03	16	1500.	35.37	21.38	9.121E-03	16	67000.	27.14	19.45	1.194E-04
17	1687.	30.54	14.08	4.690E-03	17	1600.	36.40	22.45	1.120E-02	17	71600.	27.83	20.00	1.214E-04
18	1887.	31.82	14.37	5.520E-03	18	1700.	38.03	24.01	1.409E-02	18	75900.	28.54	20.54	1.235E-04
19	1987.	32.59	15.20	8.753E-03	19	1750.	38.97	26.25	1.871E-02	19	79600.	29.19	21.14	1.256E-04
20	2087.	33.67			20	1800.	40.02	27.82	2.315E-02	20	83500.	29.84	21.79	1.277E-04
21	2187.	35.42			21	1850.	41.50	30.08	2.922E-02	21	87400.	30.59	22.52	1.298E-04
					22	1900.	43.45	33.12	3.933E-02	22	90600.	31.16	23.11	1.319E-04
					23	1925.	44.97	33.91	7.237E-02	23	92600.	31.83	23.78	1.340E-04
					24	1950.	46.95			24	95000.	32.33	24.47	1.361E-04
					25	1975.	51.99			25	97400.	32.97	25.20	1.382E-04
										26	99700.	33.61	26.01	1.403E-04
										27	101200.	34.24	26.97	1.424E-04
										28	103700.	35.03	28.14	1.445E-04
										29	106200.	35.79	29.50	1.466E-04
										30	108700.	36.53	30.70	1.487E-04
										31	105300.	36.26	29.70	1.508E-04
										32	106900.	36.53	30.70	1.529E-04
										33	107400.	37.17	31.63	1.550E-04
										34	108200.	37.70	32.50	1.571E-04
										35	109000.	38.42	33.70	1.592E-04
										36	109700.	39.75	35.17	1.613E-04
										37	110500.	39.59	37.27	1.634E-04
										38	111100.	40.43	39.07	1.655E-04
										39	111400.	40.93		
										40	111700.	41.63		
										41	112400.	42.72		

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7AN0541 PMA 1073 1200F AIR 10 CPM				
R = 0.10 THICKNESS=12.687 MM				
PMA= 11.978 KN WIDTH=63.393 MM				
CONTACT SPECIMEN				
NO.	CYCLES	A (MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	0.	20.52		
2	300.	20.84		
3	700.	21.20		
4	1200.	21.53	21.46	8.450E-04
5	1800.	22.05	21.83	8.421E-04
6	2550.	22.70	22.34	8.900E-04
7	3130.	23.24	22.78	9.461E-04
8	4000.	24.06	23.53	1.028E-03
9	4500.	24.62	24.01	1.085E-03
10	5000.	25.17	24.52	1.170E-03
11	5500.	25.73	25.11	1.255E-03
12	6000.	26.37	25.75	1.383E-03
13	6450.	27.05	26.42	1.554E-03
14	6850.	27.62	27.15	1.654E-03
15	7250.	28.36	27.96	1.746E-03
16	7600.	29.10	28.72	1.815E-03
17	7890.	29.50	29.41	1.896E-03
18	8220.	30.15	30.20	2.031E-03
19	8500.	30.70	30.97	2.120E-03
20	8800.	31.36	31.96	2.294E-03
21	9050.	32.07	32.87	2.315E-03
22	9250.	32.42	33.61	2.500E-03
23	9500.	33.11	34.64	2.822E-03
24	9700.	33.48	35.61	3.044E-03
25	9850.	34.15	36.54	3.099E-03
26	10000.	34.74	37.51	3.194E-03
27	10150.	35.12	38.54	3.389E-03
28	10330.	35.63	39.73	3.330E-03
29	10550.	36.38	41.42	3.592E-03
30	10700.	37.02	42.80	4.008E-03
31	10850.	37.58	44.46	4.359E-03
32	11020.	38.28	46.62	4.894E-03
33	11150.	39.06	48.59	5.466E-03
34	11250.	39.52	50.50	5.794E-03
35	11350.	40.18	52.64	6.297E-03
36	11450.	40.86	55.00	6.784E-03
37	11570.	41.59	58.57	7.597E-03
38	11650.	42.28	61.31	8.296E-03
39	11700.	42.72		
40	11750.	43.15		
41	11800.	43.62		

7AN0542 PMA 1073 1200F AIR 40HZ				
R = 0.10 THICKNESS=12.700 MM				
PMA= 5.693 KN WIDTH=63.500 MM				
CONTACT SPECIMEN				
NO.	CYCLES	A (MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	0.	27.69		
2	106.	28.45		
3	206.	29.25		
4	306.	30.14	14.27	9.255E-03
5	406.	31.06	14.83	1.053E-02
6	506.	32.07	15.65	1.237E-02
7	606.	33.36	16.63	1.545E-02
8	655.	34.20	17.34	1.840E-02
9	706.	35.07	18.21	2.247E-02
10	756.	36.17	19.31	2.825E-02
11	806.	37.61	21.03	3.722E-02
12	856.	39.49		
13	906.	42.17		
14	931.	44.13		

7AN0544 PMA 1073 1200F AIR .5 CPM				
R = 0.10 THICKNESS=11.913 MM				
PMA= 6.699 KN WIDTH=63.396 MM				
CONTACT SPECIMEN				
NO.	CYCLES	A (MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	0.	28.13		
2	500.	28.48		
3	1000.	28.76		
4	1500.	29.07	17.14	5.526E-04
5	2000.	29.32	17.33	5.211E-04
6	2500.	29.57	17.49	5.056E-04
7	3495.	30.01	17.88	5.323E-04
8	3995.	30.30	18.08	5.535E-04
9	6000.	31.55	19.17	7.141E-04
10	7357.	32.53	20.16	8.227E-04
11	8357.	33.54		
12	8357.	33.83		
13	9357.	34.42		

7AN0546 PMA 1073 1200F AIR 10 CPM				
R = 0.30 THICKNESS=12.776 MM				
PMA= 20.016 KN WIDTH=63.421 MM				
CONTACT SPECIMEN				
NO.	CYCLES	A (MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	32900.	26.66		
2	35000.	27.32		
3	32000.	28.22		
4	35500.	29.07	10.50	4.455E-04
5	40300.	29.34	10.75	4.691E-04
6	41500.	29.80	10.93	5.105E-04
7	42400.	30.16	11.16	5.517E-04
8	43500.	30.03	11.50	5.865E-04
9	44500.	31.50	11.83	5.938E-04
10	45300.	32.07	12.11	6.035E-04
11	46100.	32.46	12.40	6.244E-04
12	47300.	33.14	12.80	6.280E-04
13	48200.	33.70	13.17	6.671E-04
14	49000.	34.19	13.55	7.104E-04
15	49200.	34.69	13.97	7.625E-04
16	50500.	35.40	14.40	8.291E-04
17	51400.	36.13	15.06	9.411E-04
18	52100.	37.01	15.60	1.045E-03
19	52700.	37.42	16.22	1.184E-03
20	53500.	38.49	17.36	1.446E-03
21	53600.	39.12	18.04	1.697E-03
22	54300.	39.76	18.65	1.820E-03
23	54750.	40.51		
24	55130.	41.28		
25	55400.	42.00		

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1000602AF PWA 1073 1200F AIR 2 HDWL									
R= 0.10 THICKNESS= 6.350 MM									
P/Max= 5.604 KN WIDTH=61.874 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0	20.32							
2	51	20.39	19.81	1.295E-03					
3	200	20.64	19.92	1.713E-03					
4	500	21.24	20.22	1.998E-03					
5	800	21.52	20.69	2.261E-03					
6	1103	22.56	21.20	2.104E-03					
7	1400	23.19	21.72	2.108E-03					
8	1704	23.57	22.15	1.270E-03					
9	2054	24.28	22.63	2.021E-03					
10	2359	25.02	23.29	2.338E-03					
11	2625	25.60	23.92	2.268E-03					
12	2875	26.25	24.54	2.508E-03					
13	3100	27.09	25.32	3.759E-03					
14	3230	27.53	26.02	3.409E-03					
15	3355	28.12	26.61	4.684E-03					
16	3420	28.55	27.21	3.465E-03					
17	3510	28.76	27.60	6.774E-03					
18	3570	29.05	27.90	4.868E-03					
19	3691	29.44	28.34	3.243E-03					
20	3816	30.05	28.99	4.846E-03					
21	3936	30.84	29.95	6.593E-03					
22	4030	31.22	30.81	4.094E-03					
23	4113	31.58	31.37	4.300E-03					
24	4230	32.34	32.25	6.459E-03					
25	4326	32.63	33.12	3.095E-03					
26	4420	33.25	33.92	6.580E-03					
27	4512	34.01	35.19	8.283E-03					
28	4600	34.94	36.87	1.034E-02					
29	4650	35.61	38.59	1.331E-02					
30	4637	36.12	39.97	1.380E-02					
31	4720	36.60	41.21	1.474E-02					
32	4753	37.10	42.49	1.497E-02					
33	4733	37.65	43.94	1.578E-02					
34	4824	38.30	45.73	1.806E-02					
35	4853	39.69	47.68	1.711E-02					
36	4882	39.72	50.12	2.452E-02					
37	4910	40.04	52.25	1.771E-02					
38	4935	40.74	54.22	2.630E-02					
39	4925	41.33	57.60	2.715E-02					
40	4930	42.57	61.23	3.560E-02					

7AN0604AF PWA 1073 1200F AIR .5 CPM									
R= 0.10 THICKNESS= 6.350 MM									
P/Max= 6.214 KN WIDTH=61.900 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0	27.98							
2	200	28.43							
3	340	28.76							
4	660	29.44	31.64	2.317E-03					
5	900	29.94	32.43	2.414E-03					
6	1160	30.63	33.47	2.573E-03					
7	1360	31.27	34.42	2.783E-03					
8	1600	31.81	35.51	2.955E-03					
9	1810	32.45	36.64	3.357E-03					
10	2000	33.14	37.90	3.677E-03					
11	2150	33.64	39.10	3.903E-03					
12	2300	34.39	40.45	4.067E-03					
13	2400	34.72	41.41	4.204E-03					
14	2520	35.23	42.66	4.388E-03					
15	2640	35.74	43.95	4.486E-03					
16	2760	36.32	45.45	4.935E-03					
17	2870	36.86	47.04	5.459E-03					
18	2920	37.41	48.93	6.139E-03					
19	3020	38.10	51.03	6.736E-03					
20	3160	38.67	53.03	7.336E-03					
21	3340	39.30	55.41	7.834E-03					
22	3300	39.72	57.39	8.022E-03					
23	3370	40.36	59.66	8.335E-03					
24	3420	40.80	61.84	8.443E-03					
25	3490	41.53	64.74	9.017E-03					
26	3540	41.85							
27	3590	42.21							
28	3640	42.05							

7AN0605AF PWA 1073 1200F AIR .5 CPM									
R= 0.10 THICKNESS= 6.350 MM									
P/Max= 5.596 KN WIDTH=61.900 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	3560	28.53							
2	3760	28.83							
3	3970	29.27							
4	4160	29.54	28.67	1.693E-03					
5	4500	30.22	29.56	1.857E-03					
6	4900	30.78	30.41	2.193E-03					
7	5190	31.44	31.44	2.553E-03					
8	5450	32.19	32.51	3.122E-03					
9	5660	32.05	33.68	3.561E-03					
10	5860	33.48	35.04	4.041E-03					
11	6040	34.46	35.53	4.467E-03					
12	6130	34.75	37.39	4.903E-03					
13	6250	35.35	38.78	5.132E-03					
14	6360	35.85	40.02	5.650E-03					
15	6470	36.89	41.63	6.773E-03					
16	6540	36.94	42.91	7.746E-03					
17	6640	37.77	45.27	9.794E-03					
18	6700	39.46	47.04	1.113E-02					
19	6750	39.04	49.10	1.136E-02					
20	6790	39.63	50.66	1.233E-02					
21	6830	40.03	52.65	1.265E-02					
22	6870	40.53	54.73	1.368E-02					
23	6910	41.03							
24	6950	41.63							
25	7000	42.63							

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CUMULATIVE DAMAGE FRACTURE MECHANICS UNDER ENGINE SPECTRA.(U)

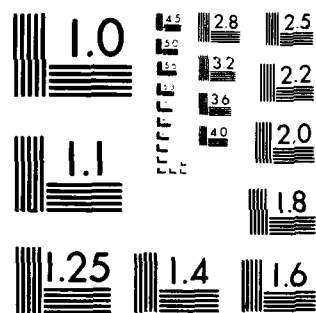
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APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1000613AF F/A 1073 1350F AIR 20MDWL									
R= 0.10 THICKNESS= 6.325 MM									
FMAX= 6.067 KN WIDTH=62.840 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)					
1	0.	29.04							
2	5.	31.67	31.49	5.260E-01					
3	7.	33.17	34.73	7.512E-01					
4	8.	34.48	37.30	1.304E+00					
5	9.	36.18	40.48	1.703E+00					
6	10.	37.99	44.09	1.815E+00					
7	11.	39.40	49.75	1.402E+00					
8	12.	43.85	61.26	4.453E+00					

1000600AF F/A 1073 1200F AIR .5 CFM									
R= 0.50 THICKNESS= 6.325 MM									
FMAX= 6.672 KN WIDTH=63.546 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)					
1	0.	28.15	17.13	8.890E-04					
2	50.	28.19	17.26	1.499E-03					
3	250.	28.49	17.40	5.418E-04					
4	400.	28.57	17.54	1.229E-03					
5	650.	28.80	17.85	1.455E-03					
6	1000.	29.39	18.27	1.611E-03					
7	1350.	29.95	18.72	1.513E-03					
8	1700.	30.48	19.16	1.723E-03					
9	2000.	31.00	19.62	1.757E-03					
10	2300.	31.53	20.21	2.476E-03					
11	2600.	32.27	20.78	2.051E-03					
12	2800.	32.68	21.24	2.377E-03					
13	3010.	33.19	21.70	1.754E-03					
14	3220.	33.55	22.24	2.482E-03					
15	3460.	34.14	22.82	2.848E-03					
16	3600.	34.54	23.46	2.318E-03					
17	3680.	35.19	24.25	2.632E-03					
18	4100.	35.77	25.23	4.288E-03					
19	4310.	36.67	26.86	4.064E-03					
20	4600.	37.85	27.82	1.538E-03					
21	4620.	37.82	28.38	4.808E-03					
22	4760.	38.49	29.29	5.440E-03					
23	4820.	38.81	30.66	5.976E-03					
24	5000.	39.89	32.80	9.106E-03					
25	5100.	40.80	35.16	5.376E-03					
26	5150.	41.16	36.34	9.758E-03					
27	5210.	41.43	37.92	9.208E-03					
28	5270.	42.07	39.89	1.295E-02					
29	5330.	42.62	41.83	1.089E-02					
30	5390.	43.40	43.13	8.255E-03					
31	5430.	43.83							
32	5470.	44.16							

1000607AF F/A 1073 1200F AIR .5 CFM									
R= 0.50 THICKNESS= 6.274 MM									
FMAX= 6.397 KN WIDTH=63.767 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)					
1	0.	28.05	16.18	7.112E-04					
2	100.	28.12	16.30	5.588E-04					
3	600.	28.40	16.50	6.425E-04					
4	1110.	28.72	16.73	5.424E-04					
5	1700.	29.04	16.98	6.160E-04					
6	2300.	29.41	17.27	5.350E-04					
7	3100.	29.84	17.65	6.408E-04					
8	3980.	30.41	18.12	5.927E-04					
9	5000.	31.01	18.71	8.115E-04					
10	6000.	31.82	19.44	8.510E-04					
11	6970.	32.65	20.12	9.390E-04					
12	7630.	33.27	20.78	1.031E-03					
13	8250.	33.95	21.49	1.073E-03					
14	8850.	34.59	22.22	1.127E-03					
15	9440.	35.21	23.09	1.442E-03					
16	10000.	36.02	23.95	1.340E-03					
17	10380.	36.53	24.76	1.698E-03					
18	10760.	37.17	25.61	2.053E-03					
19	11000.	37.67	26.39	1.998E-03					
20	11250.	38.17	27.10	1.540E-03					
21	11480.	38.52	27.88	2.013E-03					
22	11750.	39.06	28.71	2.302E-03					
23	11910.	39.43	29.41	2.254E-03					
24	12070.	39.79	30.57	2.916E-03					
25	12340.	40.53	31.87	2.603E-03					
26	12500.	41.00	32.98	3.235E-03					
27	12670.	41.55	34.42	3.713E-03					
28	12840.	42.18	35.25	4.747E-03					
29	13000.	42.94	37.91	2.984E-03					
30	13140.	43.36	39.91	5.596E-03					
31	13300.	44.25							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1000614AF PWA 1073 1200F AIR 20MDWL R= 0.10 THICKNESS= 6.401 MM PMA= 7.575 KN WIDTH=62.934 MM COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)					
1	0.	23.97	29.71	9.525E-03					
2	8.	24.05	29.86	6.585E-03					
3	35.	24.22	30.36	1.210E-02					
4	90.	24.89	31.06	1.101E-02					
5	135.	25.38	31.65	1.002E-02					
6	180.	25.84	32.19	8.365E-03					
7	226.	26.22	32.19	8.365E-03					
8	275.	26.95	32.92	1.488E-02					
9	310.	27.60	33.88	1.865E-02					
10	340.	28.20	34.78	2.007E-02					
11	385.	29.30	36.07	2.433E-02					
12	415.	30.08	37.58	2.591E-02					
13	442.	30.67	38.77	2.211E-02					
14	467.	31.36	39.93	2.753E-02					
15	488.	32.18	41.38	3.895E-02					
16	500.	32.48	42.52	2.540E-02					
17	515.	33.02	43.41	3.565E-02					
18	530.	33.70	44.76	4.521E-02					
19	545.	34.28	46.25	3.912E-02					
20	555.	34.89	47.75	6.032E-02					
21	565.	35.26	49.04	3.721E-02					
22	580.	35.78	50.29	3.505E-02					
23	595.	36.51	52.14	4.860E-02					
24	601.	36.85	53.82	5.694E-02					
25	611.	37.61	55.64	7.531E-02					
26	617.	38.02	57.70	6.816E-02					
27	623.	38.60	59.56	9.695E-02					
28	629.	39.24	62.00	1.063E-01					
29	634.	39.95	64.91	1.430E-01					
30	638.	40.42	67.66	1.172E-01					
31	642.	40.70	69.50	7.080E-02					
32	647.	41.38	71.96	1.351E-01					
33	651.	42.14	75.91	1.895E-01					
34	654.	42.92	80.55	2.616E-01					

7AN0621AF PWA 1073 1350F AIR MIX R= 0.10 THICKNESS= 6.020 MM PMA= 4.804 KN WIDTH=63.678 MM COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)					
1	0.	24.08	21.09	3.055E-02					
2	20.	24.54	21.63	3.195E-02					
3	40.	25.16	22.20	3.290E-02					
4	60.	25.79	22.81	3.437E-02					
5	80.	26.38	23.48	3.664E-02					
6	100.	27.10	24.02	3.914E-02					
7	120.	27.67	23.48	3.647E-02					
8	140.	28.40	24.66	4.288E-02					
9	155.	29.95	26.23	5.109E-02					
10	170.	29.54	27.02	5.422E-02					
11	185.	30.19	27.88	5.863E-02					
12	200.	30.92	28.86	6.400E-02					
13	212.	31.53	29.99	7.129E-02					
14	224.	32.35	30.67	7.631E-02					
15	236.	32.91	31.67	8.433E-02					
16	248.	33.69	32.61	8.395E-02					
17	256.	34.34	33.56	3.291E-02					
18	262.	34.84	34.49	8.501E-02					
19	268.	35.32	35.50	8.850E-02					
20	274.	35.78	35.62	9.359E-02					
21	280.	36.53	37.81	1.053E-01					
22	286.	36.78	37.95	1.162E-01					
23	292.	37.29	38.93	1.292E-01					
24	293.	37.95	40.12	1.404E-01					
25	302.	38.33	41.49	1.479E-01					
26	306.	38.81	43.25	1.549E-01					
27	310.	39.36	45.16	1.605E-01					
28	314.	39.92	47.23	1.690E-01					
29	318.	40.65	49.48	1.840E-01					
30	322.	41.31	51.93						
31	326.	41.80							
32	330.	42.50							
33	333.	43.10							
34	336.	43.71							
35	339.	44.41							

7AN0622AF PWA 1073 1200F AIR 20 HZ R= 0.80 THICKNESS= 5.220 MM PMA= 4.595 KN WIDTH=63.472 MM COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)					
1	0.	23.51							
2	23000.	23.92							
3	50000.	24.19							
4	80000.	24.31	4.92	9.209E-06					
5	120000.	24.67	4.93	8.795E-06					
6	197500.	25.42	5.13	1.182E-05					
7	242000.	26.05	5.27	1.379E-05					
8	303700.	26.55	5.45	1.594E-05					
9	353500.	27.82	5.65	1.750E-05					
10	390000.	28.39	5.81	1.936E-05					
11	426000.	29.16	5.93	1.936E-05					
12	466000.	29.50	6.05	2.032E-05					
13	470000.	30.05	6.22	2.132E-05					
14	494000.	30.53	6.36	2.199E-05					
15	518000.	31.07	6.52	2.397E-05					
16	532000.	31.42	6.62	2.467E-05					
17	556000.	31.93	6.82	2.647E-05					
18	590000.	32.98	7.12	2.894E-05					
19	600000.	33.30	7.25	3.001E-05					
20	630000.	34.33	7.67	3.227E-05					
21	653000.	34.97	7.90	3.373E-05					
22	660000.	35.51	8.12	3.541E-05					
23	683150.	35.97	8.39	3.791E-05					
24	698300.	36.56	8.65	4.031E-05					
25	713300.	37.18	8.97	4.595E-05					
26	727000.	37.84	9.34	5.116E-05					
27	742000.	38.53	9.76	5.500E-05					
28	751000.	39.22	10.17	5.960E-05					
29	752000.	39.61	10.45	6.366E-05					
30	766000.	40.05	10.83	6.397E-05					
31	775000.	40.73	11.30	7.002E-05					
32	782000.	41.30	11.76	8.432E-05					
33	793000.	41.65	12.51	9.576E-05					
34	796000.	42.59							
35	802000.	43.24							
36	807000.	43.69							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7A0625AF PMA 1073 1200F AIR MIX									
R= 0.10 THICKNESS= 6.452 MM									
PMA= 5.338 KN WIDTH=63.729 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} /M)	DA/DN (MM/CYCLE)					
1	0	23.75							
2	35	24.37							
3	70	24.86							
4	95	25.24	21.39	1.605E-02					
5	120	25.60	21.71	1.678E-02					
6	145	26.03	22.08	1.795E-02					
7	170	26.53	22.50	1.927E-02					
8	195	27.03	22.96	2.069E-02					
9	220	27.55	23.46	2.259E-02					
10	245	28.11	24.03	2.423E-02					
11	265	28.59	24.54	2.514E-02					
12	285	29.21	25.10	2.625E-02					
13	305	29.71	25.67	2.800E-02					
14	325	30.21	26.31	2.976E-02					
15	345	30.79	27.01	3.185E-02					
16	365	31.53	27.85	3.488E-02					
17	385	32.24	28.83	3.816E-02					
18	400	32.82	29.66	4.021E-02					
19	415	33.42	30.54	4.513E-02					
20	425	33.89	31.24	4.826E-02					
21	435	34.32	32.03	5.180E-02					
22	455	35.52	34.02	5.878E-02					
23	463	35.99	34.94	6.273E-02					
24	471	36.50	35.99	6.504E-02					
25	479	36.96	37.10	6.664E-02					
26	487	37.62	38.31	7.133E-02					
27	493	37.99	39.37	7.043E-02					
28	499	38.40	40.46	7.237E-02					
29	505	38.96	41.54	7.284E-02					
30	511	39.23	42.76	7.621E-02					
31	517	39.76	44.08	7.848E-02					
32	523	40.24	45.45	8.354E-02					
33	529	40.76	47.19	9.191E-02					
34	535	41.25	49.04	1.013E-01					
35	541	41.95	51.36	1.100E-01					
36	545	42.36	53.12	1.178E-01					
37	549	42.93							
38	553	43.34							
39	557	43.94							

7A0626AF PMA 1073 1350F AIR MIX									
R= 0.10 THICKNESS= 6.096 MM									
PMA= 4.955 KN WIDTH=61.951 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} /M)	DA/DN (MM/CYCLE)					
1	0	22.13							
2	10	22.26							
3	25	22.84							
4	40	23.41	20.33	3.579E-02					
5	55	23.87	20.78	4.051E-02					
6	70	24.42	21.29	4.436E-02					
7	85	25.23	21.69	4.960E-02					
8	100	26.00	22.63	5.599E-02					
9	110	26.56	23.13	5.944E-02					
10	120	27.15	23.76	6.472E-02					
11	130	27.60	24.46	6.861E-02					
12	140	28.53	25.24	7.350E-02					
13	150	29.40	26.12	8.442E-02					
14	155	29.63	26.64	8.410E-02					
15	160	30.11	27.17	8.792E-02					
16	165	30.75	27.73	9.149E-02					
17	170	30.99	28.41	9.716E-02					
18	175	31.57	28.99	1.101E-01					
19	180	32.08	29.78	1.234E-01					
20	185	32.58	30.87	1.420E-01					
21	190	33.67	32.13	1.514E-01					
22	195	34.39	33.61	1.732E-01					
23	198	34.82	34.69	1.748E-01					
24	201	35.23	35.66	1.849E-01					
25	203	35.96	36.48	1.939E-01					
26	205	36.13	37.41	2.031E-01					
27	207	36.55	38.40	2.119E-01					
28	209	37.00	39.31	2.098E-01					
29	211	37.43	40.49	2.378E-01					
30	213	37.92	41.75	2.637E-01					
31	215	38.39	43.26	3.009E-01					
32	217	39.04	45.22	3.334E-01					
33	219	39.80	47.57	3.639E-01					
34	220	40.25	48.95	3.858E-01					
35	221	40.48	50.40	4.079E-01					
36	222	40.91	51.98	4.064E-01					
37	223	41.42	53.70	4.109E-01					
38	224	41.88	55.49	4.573E-01					
39	225	42.21	57.34	5.166E-01					
40	226	42.61							
41	227	43.36							
42	228	44.22							

7A0629AF PMA 1073 1350F AIR MIX									
R= 0.10 THICKNESS= 6.375 MM									
PMA= 5.338 KN WIDTH=57.097 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} /M)	DA/DN (MM/CYCLE)					
1	0	20.25							
2	10	20.84							
3	20	21.50							
4	35	22.70	22.94	8.610E-02					
5	50	24.06	24.41	9.755E-02					
6	55	24.60	24.97	1.001E-01					
7	60	25.15	25.57	1.037E-01					
8	65	25.59	26.19	1.120E-01					
9	70	26.15	26.69	1.185E-01					
10	75	26.73	27.68	1.300E-01					
11	80	27.53	28.65	1.434E-01					
12	85	28.17	29.74	1.600E-01					
13	90	29.04	31.05	1.858E-01					
14	94	29.70	32.32	2.143E-01					
15	98	30.60	34.01	2.353E-01					
16	100	31.27	34.98	2.534E-01					
17	102	31.73	35.15	2.673E-01					
18	104	32.12	37.39	2.744E-01					
19	106	32.86	39.61	2.928E-01					
20	108	33.38	40.16	3.335E-01					
21	110	33.64	42.14	3.691E-01					
22	112	34.84	44.39	4.475E-01					
23	113	35.35	45.90	5.117E-01					
24	114	35.67	47.80	5.453E-01					
25	115	36.38	49.55	5.591E-01					
26	116	37.09	52.21	6.166E-01					
27	117	37.59	55.14	6.545E-01					
28	118	38.09	57.97	7.040E-01					
29	119	39.03	61.33	8.299E-01					
30	120	39.64							
31	121	40.75							
32	122	42.21							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1000630AF PWA 1073 1200F AIR MIX									
R= 0.50 THICKNESS=6.426 MM									
PMAx= 5.418 KN WIDTH=57.132 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{m}$)	DA/DN (MM/CYCLE)					
1	271.	21.11	12.13	7.057E-03					
2	350.	21.67	12.29	5.874E-04					
3	430.	21.71	12.37	3.411E-03					
4	516.	22.01	12.63	7.907E-03					
5	600.	22.67	12.86	1.786E-03					
6	696.	22.84	12.92	1.710E-04					
7	800.	22.86	13.19	6.166E-03					
8	952.	23.80	13.66	9.105E-03					
9	1023.	24.44	14.04	8.206E-03					
10	1088.	24.98	14.21	1.681E-04					
11	1156.	24.99	14.22	2.778E-04					
12	1220.	25.01	14.23	-1.633E-04					
13	1290.	24.99	14.46	1.001E-02					
14	1360.	25.70	14.98	1.297E-02					
15	1422.	26.50	15.27	-1.183E-04					
16	1465.	26.49	15.52	1.482E-02					
17	1510.	27.16	15.79	1.080E-03					
18	1550.	27.20	15.82	6.721E-04					
19	1601.	27.24	16.52	1.702E-02					
20	1700.	28.92	17.62	1.724E-02					
21	1745.	29.70	18.39	1.993E-02					
22	1784.	30.48	18.94	1.011E-02					
23	1810.	30.74	19.10	1.227E-03					
24	1840.	30.78	19.57	1.969E-02					
25	1880.	31.56	20.48	2.097E-02					
26	1915.	32.30	22.17	1.738E-03					
27	1941.	33.16	22.23	2.070E-03					
28	1960.	33.20	22.26	-4.999E-04					
29	1987.	33.23	23.26	3.312E-02					
30	2020.	33.23	26.06	4.661E-02					
31	2060.	34.56	28.95	5.817E-02					
32	2100.	36.42	32.05	6.482E-02					
33	2115.	37.30	35.94	8.583E-02					
34	2140.	38.92	38.77	1.092E-01					
35	2152.	39.95	40.50	7.303E-02					
36	2158.	40.60	42.03	1.257E-01					
37	2162.	40.89	44.41	1.651E-01					
38	2166.	41.40	47.52	1.867E-01					
39	2170.	42.06							
40	2174.	42.60							

1000631AF PWA 1073 1350F AIR MIX									
R= 0.50 THICKNESS=6.248 MM									
PMAx= 5.311 KN WIDTH=63.678 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{m}$)	DA/DN (MM/CYCLE)					
1	35.	23.43	11.65	2.810E-02					
2	75.	24.55	12.02	2.467E-02					
3	96.	25.07	12.27	2.718E-02					
4	116.	25.62	12.61	2.525E-02					
5	149.	26.45	13.01	2.755E-02					
6	175.	27.17	13.37	2.794E-02					
7	198.	27.81	13.75	3.397E-02					
8	218.	28.49	14.15	4.655E-02					
9	233.	29.19	14.54	4.250E-02					
10	246.	29.74	14.86	4.087E-02					
11	257.	30.19	15.19	3.973E-02					
12	271.	30.75	15.63	4.640E-02					
13	286.	31.44	16.07	5.283E-02					
14	296.	31.97	16.50	5.855E-02					
15	306.	32.56	16.92	4.995E-02					
16	315.	33.00	17.27	3.988E-02					
17	325.	33.40	17.71	5.403E-02					
18	336.	34.00	18.30	6.269E-02					
19	347.	34.69	18.97	6.756E-02					
20	357.	35.36	19.60	5.814E-02					
21	366.	35.89	20.23	1.031E-01					
22	372.	36.50	20.81	6.096E-02					
23	378.	36.87	21.34	6.931E-02					
24	385.	37.36	21.90	9.561E-02					
25	392.	38.03	22.09	9.271E-02					
26	399.	38.67	23.01	1.439E-01					
27	404.	39.21	23.90	1.074E-01					
28	410.	40.07	25.03	1.439E-01					
29	416.	40.53	26.17	7.556E-02					
30	426.	42.04	28.05	1.516E-01					
31	431.	42.99	30.71	1.890E-01					
32	435.	43.64	32.65	1.635E-01					

7AN0633AF PWA 1073 1200F AIR 10 CPM									
R= 0.10 THICKNESS=6.350 MM									
PMAx= 4.030 KN WIDTH=63.797 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{m}$)	DA/DN (MM/CYCLE)					
1	1490.	25.54	17.48	4.257E-04					
2	2570.	25.94	17.85	4.560E-04					
3	3700.	26.40	18.27	4.887E-04					
4	4930.	26.87	18.74	5.354E-04					
5	6150.	27.41	19.31	5.980E-04					
6	7350.	27.97	19.85	6.709E-04					
7	8550.	28.58	20.47	7.371E-04					
8	9840.	29.29	21.20	8.130E-04					
9	10900.	29.90	21.79	8.853E-04					
10	11900.	30.60	22.39	9.528E-04					
11	12900.	31.38	22.98	1.050E-03					
12	13600.	32.04	23.74	1.177E-03					
13	14230.	32.52	24.47	1.293E-03					
14	14800.	33.07	25.47	1.446E-03					
15	15420.	33.77	26.22	1.550E-03					
16	15900.	34.31	27.08	1.667E-03					
17	16460.	35.12	27.93	1.769E-03					
18	16820.	35.64	29.93	2.136E-03					
19	17180.	36.19	31.26	2.373E-03					
20	17510.	36.78	32.77	2.546E-03					
21	18130.	37.92	34.26	2.690E-03					
22	18450.	38.58	35.47	2.872E-03					
23	18750.	39.29	36.87	2.800E-03					
24	19000.	40.10	38.17	2.811E-03					
25	19180.	40.55	39.55	2.977E-03					
26	19360.	40.98							
27	19540.	41.54							
28	19720.	42.20							
29	20010.	42.78							
30	20160.	43.37							
31	20300.	44.01							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1000662AF PMA 1073 1350F AIR 20 HZ					1000663AF PMA 1073 1350F AIR MIX					1000664AF PMA 1073 1350F AIR MIX				
R= 0.80 THICKNESS= 6.375 MM					R= 0.80 THICKNESS= 6.350 MM					R= 0.80 THICKNESS= 6.325 MM				
PMA= 4.479 KN WIDTH=63.622 MM					PMA= 5.338 KN WIDTH=63.792 MM					PMA= 4.399 KN WIDTH=63.896 MM				
COMPACT SPECIMEN					COMPACT SPECIMEN					COMPACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)	NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)	NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	16540.	24.22			1	5285.	27.72	5.35	1.126E-03	1	0.	21.09	3.47	1.494E-02
2	18335.	25.17	4.16	4.655E-04	2	5505.	27.97	5.42	1.637E-03	2	50.	21.84	3.59	3.150E-02
3	19800.	25.96	4.23	4.694E-04	3	5730.	28.34	5.50	1.246E-03	3	90.	23.09	3.75	5.410E-02
4	20125.	26.02	4.31	4.920E-04	4	5945.	28.61	5.57	1.834E-03	4	110.	24.18	3.84	2.195E-02
5	21100.	26.39	4.40	5.640E-04	5	6150.	28.98	5.66	7.507E-04	5	117.	24.33	3.90	3.537E-02
6	22155.	26.86	4.51	6.334E-04	6	6600.	29.32	5.72	8.450E-04	6	137.	25.04	3.98	2.940E-02
7	23100.	27.40	4.63	6.892E-04	7	6860.	29.54	5.80	1.288E-03	7	150.	25.42	4.07	4.239E-02
8	24100.	28.01	4.79	7.337E-04	8	7150.	29.91	5.87	1.345E-03	8	166.	26.10	4.20	4.940E-02
9	25000.	28.57	4.93	8.100E-04	9	7412.	30.09	5.94	1.788E-03	9	185.	27.04	4.39	7.798E-02
10	26130.	29.40	5.08	8.895E-04	10	7683.	30.45	6.05	1.788E-03	10	200.	28.21	4.53	7.366E-02
11	27000.	30.10	5.22	1.006E-03	11	7960.	30.95	6.16	1.065E-03	11	206.	28.65	4.64	1.105E-01
12	27803.	30.74	5.40	1.137E-03	12	8245.	31.25	6.26	1.345E-03	12	212.	29.31	4.72	2.413E-02
13	28502.	31.23	5.50	1.243E-03	13	8550.	31.66	6.33	1.262E-03	13	218.	29.46	4.78	6.985E-02
14	29203.	32.10	5.75	1.440E-03	14	8860.	32.05	6.52	1.708E-03	14	225.	29.95	4.87	4.463E-02
15	29550.	32.47	5.87	1.495E-03	15	9150.	32.55	6.68	1.965E-03	15	232.	30.26	4.99	8.293E-02
16	30205.	33.34	6.22	1.625E-03	16	9437.	33.11	6.89	2.437E-03	16	242.	31.09	5.19	8.336E-02
17	30500.	33.70	6.40	1.715E-03	17	9720.	33.80	7.04	7.619E-04	17	253.	32.00	5.45	1.151E-01
18	31200.	34.91	6.61	1.865E-03	18	9920.	33.95	7.25	4.519E-03	18	263.	33.15	5.76	1.113E-01
19	31500.	35.44	6.78	2.020E-03	19	10144.	34.97	7.60	3.383E-03	19	273.	34.27	6.15	1.999E-01
20	31833.	36.00	7.03	2.334E-03	20	10364.	35.71	7.86	2.476E-03	20	280.	35.67	6.52	1.565E-01
21	32100.	36.34	7.29	2.640E-03	21	10564.	36.21			21	285.	36.45	6.78	1.943E-01
22	32400.	37.06	7.55	2.959E-03						22	288.	37.03	7.04	2.371E-01
23	32650.	37.67	7.77	3.146E-03						23	291.	37.74	7.32	2.978E-01
24	32850.	38.22	8.10	3.505E-03						24	293.	38.34	7.57	2.426E-01
25	33000.	38.68	8.52	4.122E-03						25	295.	38.82	7.81	1.626E-01
26	33200.	39.30	8.86	5.067E-03						26	298.	39.31	8.22	1.043E+00
27	33400.	40.08	9.28							27	299.	40.35	8.63	2.032E-01
28	33550.	40.63								28	301.	40.76	8.88	4.217E-01
29	33711.	41.38								29	302.	41.18	9.18	5.016E-01
30	33800.	41.57								30	303.	41.68	9.46	3.454E-01
31	34000.	42.75								31	304.	42.03	9.84	7.112E-01
32	34115.	43.96								32	305.	42.74	10.24	3.404E-01
										33	306.	43.08	10.61	5.944E-01
										34	307.	43.68		

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1000665AF PMA 1073 1350F AIR MIX					1000665AF PMA 1073 1350F AIR MIX					1000669AF PMA 1073 1200F AIR MIX				
R= 0.10 THICKNESS= 6.248 MM					R= 0.10 THICKNESS= 6.248 MM					R= 0.10 THICKNESS= 5.994 MM				
PHAX= 4.359 KN WIDTH=63.726 MM					PHAX= 4.359 KN WIDTH=63.726 MM					PHAX= 4.208 KN WIDTH=64.049 MM				
COMPACT SPECIMEN					COMPACT SPECIMEN					COMPACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)	NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)	NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	0.	22.35	16.20	1.439E-03	25	4700.	32.72	24.69	2.849E-03	1	100.	21.34	15.69	2.896E-03
2	30.	22.39	16.22	6.985E-04	26	4830.	33.32	25.25	4.591E-03	2	200.	21.63	15.84	2.743E-03
3	70.	22.42	16.22	1.825E-03	27	4930.	34.03	26.08	7.125E-03	3	300.	21.90	15.84	3.429E-03
4	157.	22.58	16.27	1.255E-03	28	5010.	34.45	26.84	5.191E-03	4	450.	22.41	16.06	4.801E-03
5	240.	22.68	16.35	1.255E-03	29	5090.	34.88	27.44	5.366E-03	5	600.	23.13	16.42	5.060E-03
6	400.	22.79	16.41	6.350E-04	30	5170.	35.51	28.22	7.874E-03	6	750.	23.90	16.87	5.060E-03
7	800.	23.51	16.66	1.800E-03	31	5250.	36.09	29.17	7.255E-03	7	850.	24.56	17.32	6.629E-03
8	1000.	23.71	16.95	1.041E-03	32	5330.	36.81	30.26	9.033E-03	8	950.	24.99	17.69	4.318E-03
9	1250.	24.24	17.19	2.098E-03	33	5412.	37.08	31.15	3.314E-03	9	1050.	25.48	18.00	4.877E-03
10	1500.	24.68	17.50	1.748E-03	34	5523.	38.01	32.29	8.421E-03	10	1150.	26.02	18.37	5.372E-03
11	1750.	25.36	17.88	2.718E-03	35	5624.	38.54	33.77	5.218E-03	11	1250.	26.80	18.85	7.849E-03
12	1920.	25.63	18.22	1.591E-03	36	5670.	39.28	35.16	1.612E-02	12	1350.	27.53	19.43	7.315E-03
13	2110.	25.94	18.43	1.638E-03	37	5700.	39.68	36.49	1.308E-02	13	1490.	28.57	20.15	7.411E-03
14	2300.	26.40	18.71	2.453E-03	38	5732.	40.10	37.49	1.318E-02	14	1550.	29.00	20.77	7.218E-03
15	2460.	27.18	19.18	4.842E-03	39	5760.	40.63	38.73	1.891E-02	15	1610.	29.46	21.17	7.535E-03
16	2615.	27.32	19.54	9.177E-04	40	5788.	40.96	39.90	1.175E-02	16	1670.	29.85	21.55	6.540E-03
17	2864.	27.67	19.74	1.408E-03	41	5818.	41.80	41.61	2.824E-02	17	1730.	30.33	21.96	8.065E-03
18	3112.	27.91	19.98	9.525E-04	42	5835.	42.32	43.74	3.063E-02	18	1790.	30.91	22.48	9.588E-03
19	3607.	29.56	20.79	3.346E-03	43	5850.	42.61	45.08	1.913E-02	19	1850.	31.67	23.17	1.270E-02
20	3809.	29.88	21.69	1.578E-03	44	5865.	42.98	46.22	2.489E-02	20	1910.	32.46	24.01	1.319E-02
21	4050.	30.68	22.23	3.325E-03	45	5880.	43.32	47.50	2.261E-02	21	1960.	32.85	24.69	7.849E-03
22	4253.	30.95	22.77	1.314E-03	46	5895.	43.92	49.26	3.979E-02	22	2010.	33.36	25.23	1.013E-02
23	4472.	31.92	23.42	4.431E-03	47	5910.	44.39	51.40	3.150E-02	23	2060.	33.81	25.82	8.992E-03
24	4585.	32.39	24.22	4.192E-03						24	2110.	34.31	26.44	9.957E-03
										25	2160.	34.89	27.19	1.173E-02
										26	2210.	35.75	28.24	1.717E-02
										27	2260.	36.41	29.43	1.316E-02
										28	2300.	37.08	30.56	1.680E-02
										29	2340.	37.92	31.94	2.105E-02
										30	2370.	38.33	33.16	1.346E-02
										31	2400.	38.96	34.24	2.095E-02
										32	2430.	39.59	35.64	2.100E-02
										33	2460.	40.38	37.35	2.654E-02
										34	2475.	40.85	38.98	3.090E-02
										35	2490.	41.21	40.11	2.396E-02
										36	2505.	41.82	41.51	4.089E-02
										37	2520.	42.29	43.18	3.166E-02
										38	2535.	42.99	45.09	4.640E-02
										39	2545.	43.50	47.19	5.118E-02
										40	2555.	43.95	48.97	4.470E-02
										41	2565.	44.40	50.72	4.508E-02

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APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1000670AF PMA 1073 1200F AIR MIX				
R= 0.50 THICKNESS= 6.375 MM				
PMA= 4.408 KN WIDTH=63.718 MM				
COMPACT SPECIMEN				
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	300.	22.31	8.91	3.701E-04
2	650.	22.44	8.96	4.431E-04
3	1100.	22.64	9.00	8.382E-04
4	1150.	22.68	9.07	4.914E-04
5	1902.	23.05	9.21	4.837E-04
6	2800.	23.48	9.37	5.618E-04
7	3720.	24.00	9.57	6.831E-04
8	4579.	24.59	9.83	8.218E-04
9	5585.	25.41	10.14	1.083E-03
10	6300.	26.19	10.41	1.065E-03
11	6801.	26.72	10.67	1.364E-03
12	7300.	27.40	10.96	1.534E-03
13	7700.	28.01	11.27	1.823E-03
14	8100.	28.74	11.59	1.964E-03
15	8400.	29.33	11.85	1.774E-03
16	8657.	29.79	12.15	2.371E-03
17	8950.	30.48	12.50	2.614E-03
18	9173.	31.07	12.83	2.342E-03
19	9404.	31.61	13.26	3.598E-03
20	9650.	32.49	13.65	1.965E-03
21	9820.	32.83	14.01	3.890E-03
22	10010.	33.57	14.48	3.088E-03
23	10200.	34.15	15.02	4.335E-03
24	10391.	34.98	15.61	4.330E-03
25	10535.	35.60	16.26	5.615E-03
26	10687.	36.46	16.91	6.845E-03
27	10790.	36.97	17.51	1.096E-02
28	10890.	37.65	18.30	6.007E-03
29	10960.	38.42	19.01	7.832E-03
30	11034.	38.86	19.61	1.020E-02
31	11100.	39.38	20.35	1.137E-02
32	11160.	39.99	21.52	1.659E-02
33	11250.	41.01	22.91	1.586E-02
34	11295.	41.76	24.14	1.131E-02
35	11338.	42.44	25.32	5.334E-02
36	11390.	43.03	26.43	2.087E-02
37	11400.	43.56	27.66	
38	11430.	44.19		

7AN0671AF PMA 1073 1200F AIR MIX				
R= 0.50 THICKNESS= 6.426 MM				
PMA= 4.390 KN WIDTH=64.206 MM				
COMPACT SPECIMEN				
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	455.	21.57	8.66	9.494E-04
2	605.	21.77	8.71	8.61E-04
3	805.	21.95	8.77	8.168E-04
4	1005.	22.31	8.85	7.850E-04
5	1205.	22.33	8.94	8.925E-04
6	1460.	22.50	9.05	9.246E-04
7	1760.	22.77	9.27	9.731E-04
8	2100.	23.12	9.52	1.044E-03
9	2450.	23.37	9.73	1.129E-03
10	3150.	24.08	9.95	1.217E-03
11	3850.	24.73	10.19	1.345E-03
12	4400.	25.38	10.47	1.512E-03
13	4900.	25.87	10.82	1.711E-03
14	5400.	26.53	11.23	2.044E-03
15	5900.	27.21	11.57	2.146E-03
16	6400.	27.97	12.09	2.346E-03
17	6900.	28.67	12.40	2.461E-03
18	7250.	29.64	12.75	2.627E-03
19	7490.	30.10	13.14	2.875E-03
20	7730.	30.61	13.44	3.084E-03
21	7970.	31.15	13.77	3.331E-03
22	8210.	31.75	14.14	3.410E-03
23	8450.	32.56	14.58	3.648E-03
24	8610.	32.88	15.03	3.852E-03
25	8770.	33.35	15.52	4.055E-03
26	8930.	33.97	16.08	4.436E-03
27	9090.	34.55	16.70	4.970E-03
28	9250.	35.22	17.33	5.635E-03
29	9410.	35.68	18.08	6.105E-03
30	9570.	36.35	18.96	6.721E-03
31	9720.	37.09	20.04	7.428E-03
32	9840.	37.68	20.87	8.086E-03
33	9960.	38.36	21.83	8.983E-03
34	10080.	39.13	22.94	1.027E-02
35	10200.	40.07		
36	10280.	40.54		
37	10360.	41.25		
38	10440.	41.95		
39	10520.	42.79		
40	10590.	43.67		
41	10625.	44.25		

7AN0673AF PMA 1073 1200F AIR MIX				
R= 0.50 THICKNESS= 6.274 MM				
PMA= 7.219 KN WIDTH=63.637 MM				
COMPACT SPECIMEN				
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	770.	25.91	18.25	1.630E-02
2	820.	26.70	18.75	1.702E-02
3	855.	27.21	19.33	1.865E-02
4	890.	27.59	20.01	2.038E-02
5	930.	28.32	20.76	2.209E-02
6	970.	29.01	21.64	2.608E-02
7	1010.	29.92	22.15	2.813E-02
8	1050.	30.60	22.78	3.183E-02
9	1090.	31.56	23.54	3.328E-02
10	1110.	32.04	24.18	3.406E-02
11	1130.	32.61	25.49	3.822E-02
12	1150.	33.41	26.33	4.246E-02
13	1165.	33.76	27.23	4.804E-02
14	1180.	34.50	28.49	5.914E-02
15	1195.	34.86	29.58	6.196E-02
16	1210.	35.39	30.79	6.585E-02
17	1225.	36.09	32.05	7.678E-02
18	1240.	36.90	33.74	8.964E-02
19	1250.	37.42	35.84	1.112E-01
20	1260.	38.10	38.91	1.419E-01
21	1270.	39.01		
22	1280.	39.47		
23	1290.	40.27		
24	1300.	41.71		
25	1305.	42.32		
26	1310.	43.28		
27	1315.	44.06		

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

74H0675AF PMA 1073 1200F AIR MIX									
R= 0.50 THICKNESS= 6.375 MM									
PHAX= 5.489 KN WIDTH=63.645 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)					
1	1790.	22.67							
2	2000.	23.04							
3	2250.	23.49							
4	2500.	24.09	11.84	2.271E-03					
5	2732.	24.60	12.09	2.435E-03					
6	2940.	25.15	12.34	2.611E-03					
7	3150.	25.71	12.62	2.749E-03					
8	3340.	26.21	12.89	2.907E-03					
9	3540.	26.35	13.19	3.120E-03					
10	3732.	27.43	13.53	3.310E-03					
11	3930.	28.09	13.92	3.640E-03					
12	4115.	28.66	14.33	3.835E-03					
13	4350.	29.28	14.65	4.210E-03					
14	4335.	29.97	15.03	4.585E-03					
15	4500.	30.86	15.74	4.951E-03					
16	4700.	31.49	16.12	5.305E-03					
17	4800.	32.12	16.53	5.632E-03					
18	4900.	32.44	17.01	5.951E-03					
19	5001.	33.27	17.50	6.343E-03					
20	5030.	33.69	17.94	6.635E-03					
21	5150.	34.22	18.49	7.584E-03					
22	5230.	34.80	18.97	8.183E-03					
23	5355.	35.43	19.65	9.289E-03					
24	5410.	36.38	20.85	1.040E-02					
25	5470.	37.21	21.65	1.054E-02					
26	5500.	37.51	22.08	1.130E-02					
27	5550.	37.98	22.85	1.226E-02					
28	5600.	38.52	23.69	1.305E-02					
29	5650.	39.31	24.63	1.419E-02					
30	5700.	40.12	26.13	1.560E-02					
31	5750.	40.97	27.69	1.814E-02					
32	5782.	41.27	28.78	2.178E-02					
33	5830.	42.18	30.60	2.755E-02					
34	5859.	42.62							
35	5882.	43.65							
36	5976.	44.09							

1000676AF PMA 1073 1200F AIR MIX									
R= 0.50 THICKNESS= 5.817 MM									
PHAX= 5.373 KN WIDTH=64.112 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)					
1	0.	22.38							
2	150.	22.59	11.87	1.448E-03					
3	553.	23.09	12.02	1.232E-03					
4	973.	23.59	12.24	1.197E-03					
5	1350.	24.04	12.46	1.189E-03					
6	1732.	24.57	12.69	1.393E-03					
7	2132.	25.18	12.97	1.508E-03					
8	2500.	25.69	13.25	1.394E-03					
9	2863.	26.29	13.54	1.641E-03					
10	3203.	26.83	13.85	1.587E-03					
11	3540.	27.53	14.20	2.099E-03					
12	3840.	28.12	14.58	1.994E-03					
13	4156.	28.78	14.96	2.082E-03					
14	4455.	29.47	15.39	2.373E-03					
15	4710.	30.06	15.81	2.252E-03					
16	4975.	30.77	16.27	2.679E-03					
17	5100.	31.24	16.70	3.729E-03					
18	5330.	31.55	16.99	2.364E-03					
19	5500.	32.43	17.46	3.260E-03					
20	5650.	32.90	18.03	3.166E-03					
21	5930.	33.53	18.51	4.182E-03					
22	5930.	33.97	19.00	3.351E-03					
23	6065.	34.51	19.48	4.064E-03					
24	6200.	35.19	20.10	5.014E-03					
25	6315.	35.67	20.73	4.160E-03					
26	6450.	36.34	21.39	4.985E-03					
27	6688.	37.22	22.34	5.586E-03					
28	6700.	37.82	23.33	6.502E-03					
29	6790.	38.54	24.27	7.930E-03					
30	6893.	39.17	25.31	6.177E-03					
31	6950.	39.91	26.45	7.566E-03					
32	7040.	40.50	27.64	9.527E-03					
33	7140.	41.27	28.96	9.541E-03					
34	7200.	41.80	30.30	8.626E-03					
35	7260.	42.62	31.63	1.378E-02					
36	7300.	43.20	33.53	1.441E-02					
37	7345.	43.75	35.00	1.315E-02					
38	7350.	44.43	36.71	1.775E-02					

74H0677AF PMA 1073 1200F AIR 10MDWL						
R= 0.10 THICKNESS= 6.401 MM						
PMAX= 7.117 KN WIDTH=63.609 MM						
COMPACT SPECIMEN						
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)		
1	0.	21.31				
2	60.	22.06				
3	112.	22.73				
4	150.	23.28	26.77	1.479E-02		
5	200.	24.05	27.55	1.601E-02		
6	240.	24.81	28.26	1.657E-02		
7	270.	25.15	28.63	1.694E-02		
8	300.	25.60	29.42	1.706E-02		
9	330.	26.26	29.99	1.799E-02		
10	360.	26.81	30.66	1.997E-02		
11	390.	27.29	31.39	2.185E-02		
12	420.	28.03	32.31	2.479E-02		
13	450.	28.88	33.39	2.892E-02		
14	470.	29.44	34.32	2.908E-02		
15	490.	30.04	35.24	2.942E-02		
16	510.	30.86	35.20	3.039E-02		
17	530.	31.20	37.18	3.206E-02		
18	550.	31.85	38.25	3.453E-02		
19	570.	32.56	39.49	3.811E-02		
20	590.	33.42	41.16	4.503E-02		
21	605.	34.11	42.65	4.915E-02		
22	620.	34.80	44.41	5.363E-02		
23	630.	35.49	45.74	5.633E-02		
24	640.	35.99	47.22	6.156E-02		
25	650.	36.61	49.02	6.888E-02		
26	660.	37.23	50.84	6.541E-02		
27	670.	38.09	53.00	7.127E-02		
28	676.	38.24	54.45	7.277E-02		
29	682.	39.20	55.96	8.072E-02		
30	688.	39.35	57.65	8.628E-02		
31	694.	39.73	59.91	1.006E-01		
32	700.	40.51	62.43	1.119E-01		
33	705.	41.10	65.56	1.324E-01		
34	711.	41.63	69.05	1.549E-01		
35	714.	42.06	71.35	1.776E-01		
36	717.	42.65				
37	720.	43.45				
38	723.	44.20				

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1000679AF FHA 1073 1350F AIR 10 CPM R= 0.50 THICKNESS= 6.350 MM FMAX= 4.395 KN WIDTH=63.605 MM									
COMPACT SPECIMEN		DEL K (MPA\N\ M)		DA/DN (MM/CYCLE)					
NO.	CYCLES	A(MM)							
1	425.	26.46							
2	475.	26.82	10.52		7.315E-03				
3	565.	27.74	10.80		1.023E-02				
4	645.	28.67	11.22		1.155E-02				
5	685.	29.46	11.63		1.969E-02				
6	725.	30.83	12.19		3.435E-02				
7	745.	31.17	12.67		1.664E-02				
8	765.	31.59	12.89		2.102E-02				
9	785.	32.78	13.39		5.975E-02				
10	800.	33.59	14.05		5.385E-02				
11	815.	34.91	14.82		8.839E-02				
12	830.	36.75	16.13		1.221E-01				
13	835.	37.26	17.25		1.019E-01				
14	840.	38.15	17.99		1.786E-01				
15	845.	38.94	18.96		1.580E-01				
16	850.	39.93	20.09		1.989E-01				
17	855.	41.32	21.79		2.776E-01				
18	862.	42.65	24.02		1.894E-01				
19	854.	43.27	25.85		3.124E-01				
20	866.	43.91	27.15		3.181E-01				

7100680AF FHA 1073 1200F AIR MIX R= 0.50 THICKNESS= 6.375 MM FMAX= 5.827 KN WIDTH=53.754 MM									
COMPACT SPECIMEN		DEL K (MPA\N\ M)		DA/DN (MM/CYCLE)					
NO.	CYCLES	A(MM)							
1	150.	22.49							
2	225.	22.60							
3	425.	23.04							
4	625.	23.41	12.23		1.960E-03				
5	825.	23.81	12.41		1.991E-03				
6	1025.	24.12	12.60		2.025E-03				
7	1250.	24.70	12.82		2.144E-03				
8	1475.	25.11	13.07		2.234E-03				
9	1700.	25.65	13.34		2.324E-03				
10	1925.	26.23	13.62		2.373E-03				
11	2150.	26.72	13.92		2.474E-03				
12	2375.	27.28	14.24		2.559E-03				
13	2600.	27.88	14.58		2.691E-03				
14	2825.	28.47	14.96		2.858E-03				
15	3050.	29.15	15.39		3.031E-03				
16	3275.	29.87	15.86		3.252E-03				
17	3475.	30.49	16.32		3.555E-03				
18	3675.	31.20	16.87		3.766E-03				
19	3850.	31.90	17.41		3.961E-03				
20	4025.	32.72	18.02		4.136E-03				
21	4150.	33.13	18.49		4.276E-03				
22	4275.	33.68	18.99		4.440E-03				
23	4400.	34.24	19.51		4.627E-03				
24	4525.	34.84	20.14		5.024E-03				
25	4650.	35.48	20.84		5.305E-03				
26	4775.	36.16	21.66		5.865E-03				
27	4900.	36.93	22.62		6.387E-03				
28	5000.	37.57	23.52		6.895E-03				
29	5100.	38.31	24.57		7.578E-03				
30	5175.	38.85	25.47		8.262E-03				
31	5250.	39.48	26.55		9.079E-03				
32	5325.	40.19	27.80		1.042E-02				
33	5355.	40.83	29.04		1.251E-02				
34	5445.	41.50	30.68		1.536E-02				
35	5495.	42.29	32.56		1.972E-02				
36	5530.	43.10							
37	5550.	43.70							
38	5570.	44.08							

1000681AF FHA 1073 1350F AIR 10 CPM R= 0.50 THICKNESS= 6.401 MM FMAX= 4.381 KN WIDTH=63.896 MM									
COMPACT SPECIMEN		DEL K (MPA\N\ M)		DA/DN (MM/CYCLE)					
NO.	CYCLES	A(MM)							
1	0.	22.19							
2	15.	22.24	8.74		3.302E-03				
3	100.	22.61	8.81		4.438E-03				
4	185.	22.97	8.92		4.228E-03				
5	270.	23.55	9.08		6.858E-03				
6	355.	23.80	9.22		2.943E-03				
7	450.	24.36	9.36		5.842E-03				
8	545.	25.13	9.60		8.128E-03				
9	620.	25.83	9.88		9.279E-03				
10	655.	26.09	10.06		3.471E-03				
11	770.	26.34	10.16		3.302E-03				
12	845.	26.91	10.33		7.654E-03				
13	920.	27.46	10.57		7.366E-03				
14	1053.	28.72	10.97		9.351E-03				
15	1130.	29.68	11.50		1.280E-02				
16	1190.	30.03	11.82		5.673E-03				
17	1265.	30.59	12.06		7.506E-03				
18	1330.	31.27	12.40		1.036E-02				
19	1395.	31.76	12.73		7.561E-03				
20	1456.	32.56	13.12		1.318E-02				
21	1521.	34.02	13.85		2.243E-02				
22	1556.	34.41	14.51		1.118E-02				
23	1590.	34.98	14.88		1.685E-02				
24	1635.	35.69	15.39		2.010E-02				
25	1655.	36.34	15.98		2.189E-02				
26	1685.	37.03	16.59		2.295E-02				
27	1715.	37.66	17.25		2.095E-02				
28	1745.	38.50	18.03		2.798E-02				
29	1775.	39.11	18.87		2.040E-02				
30	1805.	39.94	19.76		2.747E-02				
31	1835.	40.68	20.83		2.476E-02				
32	1855.	41.37	21.89		3.429E-02				
33	1870.	41.95	22.91		3.912E-02				
34	1855.	42.63	23.99		4.487E-02				
35	1893.	43.12	25.06		4.915E-02				
36	1905.	43.59	26.01		4.763E-02				

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1000682AF PWA 1073 1300F AIR 10 CPM				
R= 0.10 THICKNESS= 6.426 MM				
PMA= 5.931 KN WIDTH=63.645 MM				
COMPACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	300.	22.61	21.89	1.032E-03
2	700.	23.03	22.26	9.881E-04
3	1200.	23.52	22.67	9.378E-04
4	1720.	24.01	22.67	9.378E-04
5	2200.	24.55	23.12	1.130E-03
6	2660.	25.05	23.58	1.077E-03
7	3130.	25.66	24.10	1.316E-03
8	3620.	26.30	24.70	1.301E-03
9	4060.	26.85	25.29	1.244E-03
10	4500.	27.55	25.94	1.588E-03
11	4870.	28.17	26.66	1.696E-03
12	5230.	28.76	27.34	1.630E-03
13	5580.	29.48	28.11	2.043E-03
14	5900.	30.40	29.13	2.889E-03
15	6150.	30.77	29.97	1.458E-03
16	6500.	31.52	30.74	2.159E-03
17	6750.	32.13	31.73	2.428E-03
18	7030.	32.92	32.80	2.812E-03
19	7200.	33.49	33.91	3.399E-03
20	7350.	34.00	34.84	3.361E-03
21	7500.	34.45	35.70	3.023E-03
22	7650.	34.94	36.59	3.260E-03
23	7800.	35.54	37.68	4.030E-03
24	7950.	36.16	38.97	4.115E-03
25	8090.	36.79	40.37	4.508E-03
26	8230.	37.45	41.92	4.690E-03
27	8330.	37.81	43.23	3.645E-03
28	8450.	38.63	44.83	6.784E-03
29	8550.	39.05	46.63	4.255E-03
30	8700.	39.88	48.59	5.537E-03
31	8800.	40.53	51.07	6.452E-03
32	8890.	41.16	53.40	7.906E-03
33	8930.	41.60	55.47	8.712E-03
34	9040.	42.30	57.83	6.335E-03
35	9140.	43.15	61.30	8.509E-03
36	9190.	43.42	64.01	5.385E-03

7A00685AF PWA 1073 1200F AIR 10 CPM				
R= 0.10 THICKNESS=22.098 MM				
PMA= 15.657 KN WIDTH=63.688 MM				
COMPACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	1400.	20.99	16.29	3.056E-04
2	2600.	21.34	16.56	3.115E-04
3	3300.	21.75	16.84	3.220E-04
4	5000.	22.10	17.20	3.473E-04
5	6500.	22.52	17.70	3.819E-04
6	8000.	22.98	18.24	4.221E-04
7	9760.	23.59	19.09	5.115E-04
8	11550.	24.31	19.65	5.678E-04
9	13500.	25.10	20.30	6.476E-04
10	15100.	25.66	20.81	7.218E-04
11	16400.	26.24	21.36	8.031E-04
12	17760.	26.95	22.01	9.059E-04
13	19100.	27.80	22.57	9.849E-04
14	19990.	28.36	23.93	1.139E-03
15	20530.	28.94	24.78	1.254E-03
16	21700.	29.68	25.33	1.297E-03
17	22300.	30.28	26.06	1.386E-03
18	23500.	31.49	26.70	1.445E-03
19	24130.	32.34	27.55	1.593E-03
20	24500.	32.74	28.72	1.762E-03
21	24940.	33.29	29.52	1.840E-03
22	25300.	33.81	30.42	1.940E-03
23	25700.	34.44	31.38	2.059E-03
24	26170.	35.19	32.43	2.205E-03
25	26550.	35.67	33.59	2.400E-03
26	26730.	36.25	35.39	2.682E-03
27	27000.	36.79	37.04	2.971E-03
28	27270.	37.35	38.45	3.252E-03
29	27540.	37.90	40.17	3.432E-03
30	27870.	38.72	40.58	3.782E-03
31	28120.	39.44	41.29	3.915E-03
32	28300.	40.06	42.22	4.245E-03
33	28490.	40.58	42.85	
34	28600.	41.29	43.25	
35	28930.	41.79	43.94	
36	29200.	42.22	44.01	
37	29050.	42.85		
38	29150.	43.25		
39	29200.	43.94		

1000687AF PWA 1073 1200F AIR 10MDHL				
R= 0.10 THICKNESS=21.742 MM				
PMA= 17.792 KN WIDTH=63.754 MM				
COMPACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	1300.	24.59	21.92	5.185E-03
2	1400.	25.09	22.35	5.445E-03
3	1500.	25.62	22.87	5.477E-03
4	1600.	26.10	23.40	5.517E-03
5	1700.	26.65	23.92	5.933E-03
6	1800.	27.19	24.34	6.054E-03
7	1900.	27.61	24.93	6.759E-03
8	2000.	28.45	25.57	7.264E-03
9	2070.	28.63	26.33	9.444E-03
10	2160.	29.19	27.59	9.644E-03
11	2250.	29.93	29.26	1.155E-02
12	2335.	30.45	30.39	1.333E-02
13	2430.	31.55	31.25	1.505E-02
14	2570.	32.76	33.07	1.779E-02
15	2632.	33.60	34.23	2.177E-02
16	2675.	34.10	35.63	2.790E-02
17	2700.	34.40	37.33	3.403E-02
18	2750.	35.25	40.65	4.673E-02
19	2735.	35.81	41.93	5.065E-02
20	2820.	36.58	43.65	5.645E-02
21	2845.	37.28	45.33	6.563E-02
22	2855.	38.00	47.61	7.773E-02
23	2930.	38.75	49.06	9.043E-02
24	2950.	39.21	52.01	1.017E-01
25	2901.	39.00		
26	2911.	40.29		
27	2921.	41.11		
28	2929.	41.66		
29	2935.	42.22		
30	2941.	42.90		
31	2945.	43.37		
32	2950.	44.01		

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7AN0703 PMA 1073 1200F AIR 20 HZ R= 0.05 THICKNESS= 6.325 MM PMA= 3.594 KN WIDTH=63.538 MM COMPACT SPECIMEN					7AN0730 PMA 1007 1200F AIR 20 CFM R= 0.05 THICKNESS=11.354 MM PMA= 14.935 KN WIDTH=63.566 MM COMPACT SPECIMEN					1000731 PMA 1007 1200F AIR 15NDHL R= 0.05 THICKNESS=10.592 MM PMA= 15.366 KN WIDTH=63.673 MM COMPACT SPECIMEN				
NO.	CYCLES	A(NM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)	NO.	CYCLES	A(NM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)	NO.	CYCLES	A(NM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	0.	21.73			1	0.	21.52			1	0.	19.74		
2	29000.	24.68			2	1160.	21.86			2	3.	19.77	32.54	7.197E-03
3	33000.	25.21			3	2400.	22.55			3	30.	19.84	32.59	2.569E-03
4	37000.	25.60	15.80	1.099E-04	4	3600.	23.13	33.31	5.003E-04	4	130.	19.93	32.70	1.531E-03
5	41000.	26.01	16.13	1.096E-04	5	4800.	23.68	34.13	5.293E-04	5	330.	20.47	33.03	2.491E-03
6	50500.	27.09	16.77	9.210E-05	6	6500.	24.68	35.33	5.546E-04	6	530.	20.69	33.41	1.111E-03
7	55100.	27.63	16.96	1.246E-04	7	7310.	25.15	35.96	5.699E-04	7	800.	21.43	33.93	2.916E-03
8	59500.	27.65	17.35	1.439E-04	8	8360.	25.70	36.83	5.852E-04	8	1050.	22.15	34.85	2.713E-03
9	64000.	28.15	17.83	1.462E-04	9	9420.	26.35	37.73	6.263E-04	9	1500.	22.96	35.78	3.231E-03
10	71000.	30.12	18.79	1.595E-04	10	10230.	26.85	38.51	6.812E-04	10	1500.	23.47	36.65	2.521E-03
11	74100.	30.62	19.35	1.594E-04	11	11060.	27.30	39.36	7.239E-04	11	1780.	24.01	37.37	2.711E-03
12	78600.	30.91	20.00	1.473E-04	12	11850.	28.03	40.43	7.639E-04	12	1900.	24.93	38.43	4.611E-03
13	83000.	31.57	20.34	1.359E-04	13	12520.	28.61	41.39	7.644E-04	13	2100.	25.55	39.59	3.111E-03
14	87000.	32.06	20.87	1.500E-04	14	13100.	29.01	42.20	7.868E-04	14	2300.	26.22	40.61	3.303E-03
15	91000.	32.69	21.56	1.679E-04	15	13860.	29.66	43.22	7.954E-04	15	2475.	27.10	41.03	5.645E-03
16	94000.	33.32	22.10	1.780E-04	16	14500.	30.00	44.15	8.250E-04	16	2595.	27.77	43.23	5.567E-03
17	97000.	33.78	22.73	1.949E-04	17	15300.	30.89	45.88	9.335E-04	17	2715.	28.67	44.65	7.451E-03
18	100000.	34.39	23.44	2.100E-04	18	16200.	31.64	47.30	1.022E-03	18	2815.	29.23	46.02	5.355E-03
19	103000.	35.01	24.23	2.297E-04	19	17040.	32.50	49.45	1.109E-03	19	2915.	30.07	47.44	3.697E-03
20	106000.	35.77	25.22	2.585E-04	20	17800.	33.17	51.02	1.183E-03	20	2990.	31.00	49.44	1.339E-02
21	109000.	36.53	26.40	2.899E-04	21	18000.	33.66	52.21	1.245E-03	21	3025.	31.52	51.09	1.266E-02
22	111000.	37.16	27.33	3.287E-04	22	18400.	34.09	53.58	1.312E-03	22	3060.	31.68	51.20	4.463E-03
23	113000.	37.80	28.43	3.739E-04	23	18800.	34.63	55.12	1.355E-03	23	3100.	32.17	52.59	1.232E-02
24	115000.	38.50	29.84	4.261E-04	24	19200.	35.28	56.67	1.480E-03	24	3140.	32.65	53.62	1.197E-02
25	117000.	39.49	31.63	5.000E-04	25	19600.	35.84	59.64	1.610E-03	25	3180.	33.18	55.15	1.335E-02
26	119000.	40.53	34.03	6.229E-04	26	20000.	36.31	60.83	1.777E-03	26	3220.	33.75	56.69	1.423E-02
27	120000.	41.08	35.60	6.811E-04	27	20400.	37.31	63.51	1.855E-03	27	3260.	34.60	58.75	2.111E-02
28	121000.	41.81	37.42	7.736E-04	28	20800.	37.57	65.08	1.916E-03	28	3290.	34.93	60.67	1.253E-02
29	122000.	42.76	39.76	8.332E-04	29	20900.	38.27	67.59	2.022E-03	29	3320.	35.92	62.35	3.133E-02
30	122500.	43.03	41.16	9.035E-04	30	21200.	38.73	69.76	2.427E-03	30	3340.	36.17	64.37	1.257E-02
31	123000.	43.60			31	21540.	39.46	74.07	3.305E-03	31	3355.	36.93	66.87	3.031E-02
32	123400.	43.82			32	21740.	40.10	77.54	4.816E-03	32	3385.	38.00	70.75	5.721E-02
33	123800.	44.42			33	21830.	41.03	81.58	6.559E-03	33	3395.	39.02	75.47	9.411E-02
					34	21930.	41.26			34	3400.	39.69	79.53	1.351E-01
					35	22000.	41.88			35	3405.	40.23	82.81	1.067E-01
					36	22660.	42.42			36	3410.	40.60	85.43	7.518E-02
										37	3415.	41.56	89.53	1.913E-01
										38	3417.	41.93	93.02	1.641E-01
										39	3419.	42.73	93.18	4.209E-01

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7A10732A PNA 1007 1200F AIR 15MDWL R= 0.05 THICKNESS=10.719 MM PNA= 14.336 KN WIDTH=63.741 MM COMPACT SPECIMEN					
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)	
1	0.	28.43			
2	75.	28.95			
3	253.	30.47			
4	315.	30.82	46.21	7.634E-03	
5	300.	31.46	47.27	8.028E-03	
6	457.	31.92	48.45	9.573E-03	
7	511.	32.36	49.73	1.063E-02	
8	567.	33.01	51.16	1.213E-02	
9	618.	33.95	52.99	1.330E-02	
10	660.	34.26	54.55	1.503E-02	
11	711.	35.15	55.79	1.694E-02	
12	751.	35.63	58.67	1.932E-02	
13	822.	37.24	64.37	2.755E-02	
14	847.	37.91	67.03	3.429E-02	
15	864.	38.58	69.67	4.150E-02	
16	892.	39.28	72.91	5.106E-02	
17	900.	40.11	77.82	6.652E-02	
18	912.	41.09	82.46	8.438E-02	
19	918.	41.63	85.62	1.144E-01	
20	924.	42.19			
21	930.	42.87			
22	934.	44.15			

7A10732 PNA 1007 1200F AIR 15MDWL R= 0.05 THICKNESS=10.719 MM PNA= 11.102 KN WIDTH=63.741 MM COMPACT SPECIMEN					
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)	
1	100.	23.19			
2	250.	23.24			
3	500.	23.32			
4	750.	23.50	26.36	4.282E-04	
5	1054.	23.57	26.54	5.242E-04	
6	1514.	23.74	26.84	6.047E-04	
7	2050.	24.36	27.19	6.271E-04	
8	2600.	24.59	27.52	6.578E-04	
9	3600.	25.20	28.25	6.821E-04	
10	4400.	25.73	28.77	6.814E-04	
11	6482.	27.33			
12	7099.	27.72			
13	7553.	28.43			

7A10736 PNA 1007 1200F AIR 20 HZ R= 0.05 THICKNESS=10.973 MM PNA= 7.210 KN WIDTH=63.551 MM COMPACT SPECIMEN					
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)	
1	0.	27.19			
2	3500.	27.71			
3	12700.	28.61			
4	18000.	29.12	21.18	1.060E-04	
5	25000.	29.89	21.80	1.074E-04	
6	32630.	30.25	22.17	1.126E-04	
7	32800.	30.75	22.65	1.196E-04	
8	39300.	31.44	23.46	1.276E-04	
9	49300.	32.85	25.06	1.531E-04	
10	52300.	33.40	25.65	1.608E-04	
11	55300.	33.80	26.30	1.720E-04	
12	58300.	34.36	26.96	1.816E-04	
13	64700.	35.53	28.83	2.180E-04	
14	68200.	36.33	30.17	2.436E-04	
15	71200.	37.22	31.53	2.652E-04	
16	73200.	37.63	32.62	2.745E-04	
17	75200.	38.26	33.77	2.946E-04	
18	77000.	38.77	34.83	3.125E-04	
19	78200.	39.29	36.27	3.398E-04	
20	80600.	39.99	37.75	3.764E-04	
21	82600.	40.75	39.69	4.262E-04	
22	84000.	41.29	41.67	4.732E-04	
23	86400.	42.58	45.60	5.787E-04	
24	86890.	42.81			
25	88000.	43.54			
26	89010.	44.25			

7A107373 PMA 1007 1200F AIR 2 MDHL									
R= 0.05 THICKNESS= 8.026 MM									
FMAX= 8.650 KN WIDTH=63.716 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K	DA/DN	(MPA\MM)	(MM/CYCLE)			
1	0.	21.31							
2	505.	21.57							
3	1511.	21.95							
4	2600.	22.22	27.12	4.862E-04					
5	3222.	22.63	27.40	5.651E-04					
6	3373.	23.13	27.82	5.618E-04					
7	4253.	23.41	28.27	5.678E-04					
8	5200.	24.10	28.61	5.702E-04					
9	5323.	24.16	29.03	6.050E-04					
10	6600.	24.66	29.56	6.339E-04					
11	7350.	25.27	30.04	6.917E-04					
12	8050.	25.67	30.69	8.357E-04					
13	8750.	26.19	31.42	9.411E-04					
14	9483.	27.00	32.32	1.042E-03					
15	9980.	27.53	33.10	1.062E-03					
16	10450.	28.15	33.89	1.092E-03					
17	11016.	28.77	34.76	1.063E-03					
18	11532.	29.21	35.51	1.099E-03					
19	12012.	29.60	36.28	1.226E-03					
20	12512.	30.31	37.23	1.414E-03					
21	13214.	31.31	39.13	1.815E-03					
22	13582.	32.17	40.32	2.068E-03					
23	13962.	32.76	41.61	2.369E-03					
24	14167.	33.48	43.35	2.555E-03					
25	14412.	34.10	44.59	2.807E-03					
26	14637.	34.93	46.15	3.091E-03					
27	14912.	35.20	47.66	2.937E-03					
28	15018.	36.07	49.29	3.260E-03					
29	15162.	36.53	50.47	3.735E-03					
30	15312.	36.70	52.25	4.361E-03					
31	15452.	37.64	54.19	5.282E-03					
32	15562.	38.30	55.99	6.431E-03					
33	15666.	39.83	59.79	8.252E-03					
34	15812.	39.97	63.85	1.109E-02					
35	15932.	40.89	67.34	1.224E-02					
36	15915.	41.66	69.49	1.435E-02					
37	15941.	41.75	71.45	1.635E-02					
38	15932.	42.08							
39	16032.	43.40							
40	16052.	44.04							

7A10739 PMA 1007 1200F AIR 5 MDHL									
R= 0.05 THICKNESS= 9.576 MM									
FMAX= 13.602 KN WIDTH=63.602 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K	DA/DN	(MPA\MM)	(MM/CYCLE)			
1	223.	30.57							
2	232.	30.61							
3	250.	30.75							
4	310.	30.93	49.49	5.699E-03					
5	335.	31.27	50.02	6.040E-03					
6	362.	31.36	50.54	6.574E-03					
7	422.	31.93	51.55	7.398E-03					
8	475.	32.02	52.17	7.412E-03					
9	515.	32.45	52.89	9.165E-03					
10	557.	32.80	53.67	1.170E-02					
11	582.	33.00	55.						

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7AN1000 PMA 1007 800F AIR 10 CPM R = 0.05 THICKNESS= 2.642 MM PMA= 2.473 KN WIDTH=63.602 MM COMPACT SPECIMEN									
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0	21.16							
2	6000	21.25							
3	12100	21.43							
4	24000	21.68	22.51	3.156E-05					
5	36000	22.23	22.86	3.557E-05					
6	48000	22.71	23.22	3.915E-05					
7	60000	23.11	23.65	4.319E-05					
8	72020	23.59	24.09	4.679E-05					
9	84000	24.25	24.63	5.170E-05					
10	93000	24.73	25.11	5.554E-05					
11	103000	25.31	25.70	5.817E-05					
12	113020	25.91	26.29	6.111E-05					
13	123000	26.54	26.95	6.458E-05					
14	131020	26.99	27.57	6.197E-05					
15	140000	27.69	28.19	6.446E-05					
16	148000	28.25	28.79	6.710E-05					
17	156990	28.47	29.42	7.583E-05					
18	164030	29.27	30.16	8.377E-05					
19	171060	29.80	30.94	1.010E-04					
20	178410	30.72	32.13	1.178E-04					
21	184000	31.20	33.11	1.338E-04					
22	189420	32.18	34.32	1.464E-04					
23	192150	32.45	34.98	1.496E-04					
24	194700	32.94	35.73	1.431E-04					
25	197200	33.28	36.25	1.489E-04					
26	199750	33.65	36.90	1.645E-04					
27	203350	34.01	38.03	1.897E-04					
28	206900	34.95	39.62	2.073E-04					
29	209900	35.74	41.11	2.174E-04					
30	212400	36.35	42.55	2.300E-04					
31	214400	36.48	43.52	2.478E-04					
32	217000	37.20	45.19	2.534E-04					
33	219000	37.80	46.58	2.922E-04					
34	221000	38.60	48.62	3.142E-04					
35	223100	38.88	50.88	3.023E-04					
36	225140	40.00	52.98	2.939E-04					
37	226500	40.15	54.30	2.931E-04					
38	228500	40.61	56.44	3.331E-04					
39	230460	41.26	58.39	3.743E-04					
40	233000	42.10							
41	234500	43.22							
42	236020	44.24							

7AN1002 PMA 1007 800F AIR 10 CPM R = 0.05 THICKNESS= 2.675 MM PMA= 11.449 KN WIDTH=63.622 MM COMPACT SPECIMEN									
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	7040	22.09							
2	11040	22.34							
3	16100	22.93							
4	20110	23.07	23.24	1.199E-04					
5	24210	24.09	23.65	1.316E-04					
6	28690	24.69	24.23	1.880E-04					
7	33020	25.13	24.73	1.266E-04					
8	38660	26.32	25.54	1.507E-04					
9	43200	26.51	26.37	1.150E-04					
10	48900	27.03	26.56	1.280E-04					
11	50450	27.44	26.73	1.193E-04					
12	57020	27.84	27.50	1.497E-04					
13	61250	28.94	28.71	1.810E-04					
14	66000	29.82	29.91	2.210E-04					
15	68540	30.63	30.72	2.337E-04					
16	70200	30.69	31.89	2.372E-04					
17	73240	31.43	32.03	2.427E-04					
18	74500	32.03	32.31	2.419E-04					
19	76700	32.37	33.70	2.639E-04					
20	81200	33.56	35.72	3.032E-04					
21	82500	34.03	36.37	3.144E-04					
22	83600	34.52	37.21	3.245E-04					
23	85350	34.93	38.59	3.553E-04					
24	87010	35.52	39.43	3.639E-04					
25	88250	36.19	41.12	4.007E-04					
26	89600	36.67	42.00	5.227E-04					
27	90300	36.99	42.93	5.600E-04					
28	91300	37.71	44.66	6.315E-04					
29	92350	38.26	46.04	6.150E-04					
30	93000	38.80	47.69	6.407E-04					
31	93800	39.35	48.53	6.521E-04					
32	94000	39.76	51.44	7.591E-04					
33	95000	40.49	53.60	8.151E-04					
34	96200	40.95	55.74	8.676E-04					
35	98000	41.64	58.29	8.995E-04					
36	97400	42.00	60.34	1.115E-03					
37	97700	42.33	61.76	1.235E-03					
38	98150	42.82							
39	98600	43.60							
40	99700	44.01							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7A1003 PMA 1007 800F AIR 10 CPM				
R = 0.05 THICKNESS= 7.696 MM				
PMA= 59.230 KN WIDTH=25.316 MM				
CENTER CRACK SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	0.	1.61		
2	2000.	1.79		
3	5000.	2.11		
4	8000.	2.37	25.41	1.213E-04
5	11000.	2.73	27.60	1.460E-04
6	14000.	3.17	30.09	1.816E-04
7	17000.	3.83	33.27	2.404E-04
8	19000.	4.23	35.90	3.022E-04
9	21500.	4.97	40.39	4.600E-04
10	23500.	5.84		
11	24500.	6.51		
12	25500.	7.74		
7A1004 PMA 1007 1200F AIR 10 CPM				
R = 0.05 THICKNESS= 7.645 MM				
PMA= 51.210 KN WIDTH=25.359 MM				
CENTER CRACK SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	0.	1.79		
2	4000.	2.64		
3	6000.	3.05		
4	7000.	3.32		
5	8000.	3.72	27.11	3.302E-04
6	9000.	4.18	28.55	3.826E-04
7	9800.	4.45	30.53	4.402E-04
8	11000.	5.11	32.17	5.053E-04
9	12000.	5.68	35.22	6.301E-04
10	13000.	6.57	38.52	8.197E-04
11	13500.	7.15	43.93	1.151E-03
12	14000.	7.87		
13	14200.	8.45		

1001005 PMA 1007 800F AIR 10 CPM				
R = 0.50 THICKNESS= 7.620 MM				
PMA= 63.473 KN WIDTH=25.293 MM				
CENTER CRACK SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	0.	2.59		
2	2000.	2.77	16.75	9.239E-05
3	3500.	2.80	17.25	7.112E-05
4	6000.	3.17	17.54	1.179E-04
5	8500.	3.50	18.99	1.321E-04
6	11000.	3.69	19.86	7.544E-05
7	13500.	4.10	20.84	1.610E-04
8	15300.	4.42	22.07	1.640E-04
9	17500.	4.68	23.06	1.267E-04
10	19500.	5.10	24.24	2.121E-04
11	21500.	5.52	25.75	2.093E-04
12	23500.	5.97	27.33	2.276E-04
13	25500.	6.69	29.75	3.597E-04
14	26500.	7.03	32.09	3.391E-04
15	27500.	7.49	34.01	4.534E-04
1001006 PMA 1007 1200F AIR 10 CPM				
R = 0.55 THICKNESS= 7.290 MM				
PMA= 64.838 KN WIDTH=25.314 MM				
CENTER CRACK SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	0.	1.62		
2	1000.	1.69	11.57	6.223E-05
3	5000.	2.19	12.57	1.264E-04
4	10500.	3.12	14.90	1.697E-04
5	13000.	3.65	17.12	2.103E-04
6	15500.	4.20	18.72	2.184E-04
7	18000.	5.01	20.77	3.244E-04
8	19500.	5.55	22.90	3.594E-04
9	21000.	6.17	24.87	4.191E-04
10	22300.	6.92	27.40	5.739E-04
11	23300.	7.70	30.62	7.817E-04

1001007 PMA 1007 800F AIR 10 CPM				
R = 0.00 THICKNESS= 7.600 MM				
PMA= 53.075 KN WIDTH=25.372 MM				
CENTER CRACK SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	1000.	1.69		
2	3000.	1.74	6.37	2.349E-05
3	10000.	1.87	6.53	1.932E-05
4	15000.	1.89	6.68	8.890E-07
5	20000.	1.97	6.77	1.854E-05
6	30000.	1.99	6.83	2.159E-05
7	40000.	2.16	7.06	1.740E-05
8	50000.	2.25	7.29	8.673E-06
9	60000.	2.46	7.55	2.044E-05
10	70000.	2.65	7.69	1.822E-05
11	80000.	2.65	8.22	1.991E-05
12	90000.	3.11	8.60	2.570E-05
13	100000.	3.30	8.76	1.567E-05
14	110000.	3.64	9.40	3.467E-05
15	120000.	3.07	9.86	2.542E-05
16	139000.	4.51	10.56	3.405E-05
17	148000.	4.96	11.46	4.515E-05
18	153000.	5.36	12.18	4.039E-05
19	162000.	5.81	12.94	4.413E-05
20	170000.	6.40	13.01	5.923E-05

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7AN1008 PWA 1007 1200F AIR 10 CPM R= 0.80 THICKNESS= 7.620 MM FMAX= 80.344 KN WIDTH=25.298 MM CENTER CRACK SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} /M)	DA/DN (MM/CYCLE)					
1	0.	1.62							
2	3000.	1.65							
3	5500.	1.72							
4	9000.	1.78	6.34	2.750E-05					
5	19000.	2.17	7.02	4.235E-05					
6	30000.	2.71	7.92	5.417E-05					
7	35000.	3.05	8.38	6.094E-05					
8	40000.	3.28	8.87	6.957E-05					
9	45000.	3.64	9.42	7.657E-05					
10	50000.	4.06	10.04	8.635E-05					
11	54000.	4.47	10.64	9.527E-05					
12	59000.	4.80	11.27	1.053E-04					
13	63000.	5.37	12.15	1.251E-04					
14	67000.	5.82							
15	71000.	6.44							
16	73500.	6.99							

1001009 PWA 1007 THF AIR 1 CPM R= 0.05 THICKNESS= 7.620 MM FMAX= 57.598 KN WIDTH=25.311 MM CENTER CRACK SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} /M)	DA/DN (MM/CYCLE)					
1	1600.	1.78	21.94	1.448E-04					
2	2600.	1.93	22.65	8.332E-05					
3	3600.	2.01	23.28	1.251E-04					
4	4600.	2.14	23.78	4.635E-05					
5	5600.	2.18	23.78	4.635E-05					
6	6100.	2.23	24.04	8.255E-05					
7	8000.	2.41	24.69	9.492E-05					
8	10000.	2.59	25.72	9.144E-05					
9	12000.	3.01	27.41	2.121E-04					
10	14000.	3.36	29.51	1.753E-04					
11	16000.	3.58	32.10	3.092E-04					
12	17500.	4.54	35.26	3.746E-04					
13	19000.	5.14	38.43	3.971E-04					
14	20000.	5.77	41.96	6.344E-04					
15	20800.	6.55	46.33	9.660E-04					
16	21400.	7.24	51.45	1.161E-03					

1001010 PWA 1007 1350F AIR 10 CPM R= 0.05 THICKNESS= 7.645 MM FMAX= 50.605 KN WIDTH=25.301 MM CENTER CRACK SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} /M)	DA/DN (MM/CYCLE)					
1	0.	1.76	20.81	2.616E-04					
2	3000.	2.55	24.99	3.642E-04					
3	5500.	3.46	29.52	5.109E-04					
4	7500.	4.43	33.10	9.741E-04					
5	8000.	4.97	35.43	9.487E-04					
6	8500.	5.44	37.93	9.365E-04					
7	9000.	5.91	40.83	1.154E-03					
8	9500.	6.49	44.68	1.556E-03					
9	9900.	7.11							

1001011 PWA 1007 1350F AIR 10 CPM R= 0.05 THICKNESS= 2.705 MM FMAX= 2.277 KN WIDTH=63.337 MM COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} /M)	DA/DN (MM/CYCLE)					
1	500.	27.72	25.74	2.286E-04					
2	1000.	27.84	26.03	3.247E-04					
3	2330.	28.27	26.66	4.086E-04					
4	4030.	28.96	27.35	4.915E-04					
5	5030.	29.46	27.90	5.095E-04					
6	5850.	29.87	28.45	6.181E-04					
7	6600.	30.34	28.98	5.183E-04					
8	7300.	30.70	29.51	5.765E-04					
9	8260.	31.14	30.05	4.634E-04					
10	8300.	31.48	30.66	6.081E-04					
11	9650.	32.00	30.66	6.081E-04					
12	10400.	32.16	31.16	2.184E-04					
13	11200.	32.52	31.56	4.493E-04					
14	12000.	33.25	32.41	9.160E-04					
15	12500.	33.56	33.26	6.070E-04					
16	13200.	34.04	33.93	6.915E-04					
17	13900.	34.44	34.72	5.715E-04					
18	14700.	34.99	35.60	6.691E-04					
19	15610.	35.47	36.61	5.408E-04					
20	16400.	35.77	37.41	3.794E-04					
21	17200.	36.39	33.40	7.779E-04					
22	18100.	36.72	39.47	3.627E-04					
23	18910.	37.12	40.33	4.907E-04					
24	19550.	37.64	41.46	8.136E-04					
25	20100.	38.07	42.69	7.805E-04					
26	20670.	38.35	43.66	4.991E-04					
27	21750.	38.94	44.89	5.421E-04					
28	22750.	39.76	47.02	8.217E-04					
29	23590.	40.23	49.14	5.624E-04					
30	24410.	41.06	51.43	1.013E-03					
31	25320.	41.79	54.41	9.000E-04					
32	26000.	42.46	57.30	8.515E-04					
33	26700.	43.15	60.35	9.906E-04					
34	27400.	44.12	64.44	1.353E-03					
35	27900.	44.37	67.69	6.319E-04					

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7A1013 PHA 1007 1200F AIR 10 CPM R= 0.10 THICKNESS= 8.064 MM PHAX= 5.609 KN WIDTH=63.094 MM COMPACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	0	24.61		
2	2000	24.93		
3	4540	25.65		
4	6800	25.96	18.78	1.831E-04
5	10300	26.61	19.27	1.873E-04
6	13920	27.07	19.71	1.920E-04
7	16560	27.72	20.23	2.224E-04
8	20000	28.62	20.83	2.572E-04
9	23000	29.11	21.64	2.714E-04
10	26000	30.21	22.47	2.861E-04
11	27690	30.84	22.97	2.908E-04
12	31080	31.57	24.13	3.115E-04
13	34130	32.62	25.16	3.357E-04
14	36500	33.35	26.19	3.981E-04
15	39410	34.09	27.30	4.468E-04
16	39500	34.65	27.99	4.918E-04
17	40640	35.33	28.93	5.119E-04
18	41600	35.74	29.82	5.285E-04
19	42630	36.39	30.74	5.461E-04
20	43500	36.80	31.69	5.618E-04
21	44680	37.41	32.95	5.876E-04
22	45700	38.13	34.03	6.818E-04
23	45710	38.76	35.72	7.906E-04
24	47700	39.31	37.78	8.644E-04
25	48700	40.69	40.28	9.575E-04
26	50000	41.99	44.52	1.080E-03
27	50500	42.23		
28	51500	43.53		
29	52000	44.19		

1001014 PHA 1007 800F AIR 10 CPM R= 0.05 THICKNESS= 7.620 MM PHAX= 4.853 KN WIDTH=63.165 MM COMPACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	0	26.84		
2	1500	26.88	18.79	2.794E-05
3	8540	27.19	18.93	4.402E-05
4	16070	27.37	19.12	2.429E-05
5	26000	28.00	19.45	6.382E-05
6	35000	28.61	19.96	6.689E-05
7	43500	28.98	20.33	4.348E-05
8	53300	29.24	20.66	2.606E-05
9	63200	30.00	21.13	7.983E-05
10	71750	30.50	21.73	5.878E-05
11	80200	31.03	22.25	6.328E-05

1001015 PHA 1007 1350F AIR 2 MDWL R= 0.10 THICKNESS= 7.620 MM PHAX= 8.883 KN WIDTH=63.602 MM COMPACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	604	28.59	34.83	3.793E-04
2	1200	28.82	35.27	4.576E-04
3	2016	29.19	35.98	5.627E-04
4	3000	29.75	36.66	3.316E-04
5	3900	30.04		

7A1017 PHA 1007 1200F AIR 20 HZ R= 0.80 THICKNESS= 7.620 MM PHAX= 9.528 KN WIDTH=63.576 MM COMPACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	0	24.39		
2	57920	25.17		
3	100000	26.23	7.61	1.995E-05
4	125000	26.59	7.91	2.114E-05
5	155000	27.09	8.03	2.231E-05
6	169000	27.37	8.21	2.140E-05
7	210000	28.44	8.37	2.179E-05
8	230000	28.87	8.51	2.140E-05
9	250000	29.33	8.63	2.352E-05
10	253570	30.16	9.06	2.517E-05
11	318000	30.59	9.28	2.701E-05
12	338000	31.29	9.52	2.769E-05
13	356000	31.76	9.74	2.764E-05
14	373000	32.20	9.97	2.767E-05
15	392000	32.80	10.23	2.886E-05
16	411000	33.20	10.55	3.099E-05
17	432000	33.64	10.87	3.239E-05
18	450000	34.44	11.19	3.408E-05
19	466000	34.96	11.50	3.425E-05
20	480000	35.50	11.80	3.768E-05
21	495000	35.97	12.19	4.204E-05
22	510300	36.55	12.66	4.443E-05
23	525000	36.99	13.23	4.689E-05
24	540000	38.00	13.62	5.619E-05
25	550000	38.51	14.14	6.403E-05
26	560000	38.78	14.72	6.957E-05
27	570250	39.33	15.46	8.312E-05
28	580000	40.48		
29	585000	40.83		
30	596300	41.67		
31	606000	42.93		

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7A11018	PWA 1007	800F AIR	10 CPM				
R=	0.05	THICKNESS=	7.556 MM				
PHAX=	6.303 KN	WIDTH=	63.635 MM				
COMPACT SPECIMEN				DEL K	DA/DN		
NO.	CYCLES	A(MM)	(MPA $\sqrt{M}$)	(MM/CYCLE)			
1	0.	25.74					
2	1355.	25.87					
3	3353.	26.22					
4	5400.	26.30					
5	10088.	26.99					
6	14140.	27.97					
7	17116.	28.25					
8	20000.	28.47					
9	23207.	28.77					
10	26220.	29.25					
11	29210.	29.82					
12	32420.	30.31					
13	35745.	30.92					
14	43347.	32.17					
15	47000.	32.87					
16	49500.	33.12					
17	52036.	33.51					
18	55000.	34.69					
19	58540.	34.91					
20	59070.	35.45					
21	59532.	35.76					
22	61000.	36.22					
23	62517.	36.41					
24	64000.	36.87					
25	65500.	37.46					
26	69700.	39.31					
27	71250.	39.98					
28	72500.	40.73					
29	73500.	41.18					
30	74800.	41.77					
31	75800.	43.37					
32	76114.	43.53					
33	76710.	44.15					

7A11019	PWA 1007	1200F AIR	10 CPM				
R=	0.50	THICKNESS=	7.595 MM				
PHAX=	6.316 KN	WIDTH=	63.660 MM				
COMPACT SPECIMEN				DEL K	DA/DN		
NO.	CYCLES	A(MM)	(MPA $\sqrt{M}$)	(MM/CYCLE)			
1	2200.	25.82					
2	6200.	29.00					
3	7700.	30.50					
4	8700.	31.30					
5	9700.	32.42					
6	10800.	33.48					
7	11500.	35.01					
8	11700.	35.64					
9	12000.	36.22					
10	12300.	36.56					
11	12700.	37.31					
12	13100.	38.42					
13	13350.	39.11					
14	13550.	40.51					
15	13650.	40.75					
16	13950.	41.50					
17	14050.	42.63					
18	14150.	43.18					
19	14250.	44.37					

7A11021	PWA 1007	1200F AIR	10 CPM				
R=	0.50	THICKNESS=	7.658 MM				
PHAX=	5.911 KN	WIDTH=	63.612 MM				
COMPACT SPECIMEN				DEL K	DA/DN		
NO.	CYCLES	A(MM)	(MPA $\sqrt{M}$)	(MM/CYCLE)			
1	2600.	25.29					
2	3400.	25.95					
3	4000.	26.39					
4	4600.	26.82					
5	5600.	28.91					
6	6100.	30.80					
7	6600.	31.74					
8	6850.	32.11					
9	7100.	33.35					
10	7275.	33.73					
11	7575.	35.38					
12	7675.	35.29					
13	7750.	36.80					
14	7925.	35.90					
15	7925.	37.58					
16	8025.	38.00					
17	8125.	39.03					
18	8200.	39.73					
19	8260.	40.71					
20	8320.	40.86					
21	8360.	41.17					
22	8440.	41.96					
23	8490.	42.42					
24	8540.	43.27					
25	8590.	43.07					

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1001022 PWA 1007 1200F AIR 10 CPM R= 0.50 THICKNESS= 7.607 MM P/AX= 5.537 KN WIDTH=63.500 MM COMPACT SPECIMEN NO. CYCLES A(MM) DEL K (MPA$\sqrt{M}$) DA/DN (MM/CYCLE)									
1	2706.	27.24			12.04	4.229E-04			
2	5000.	27.52			12.34	4.884E-04			
3	7000.	28.00			12.64	5.239E-04			
4	8599.	28.69			12.64	5.606E-04			
5	9812.	29.31			12.96	5.902E-04			
6	10830.	29.94			13.39	6.558E-04			
7	11889.	30.26			13.68	6.878E-04			
8	13134.	31.18			14.00	7.098E-04			
9	13960.	31.56			14.46	7.825E-04			
10	14786.	32.19			14.90	8.299E-04			
11	15611.	32.64			15.31	8.663E-04			
12	16436.	33.81			16.10	9.008E-04			
13	17133.	33.81			16.57	1.011E-03			
14	18213.	34.75			17.08	1.098E-03			
15	18828.	35.46			17.62	1.233E-03			
16	19414.	36.02			18.25	1.603E-03			
17	20000.	36.44			20.08	1.749E-03			
18	20600.	37.03			21.05	1.923E-03			
19	21684.	38.53			22.13	2.056E-03			
20	22100.	39.42			24.07	2.149E-03			
21	22500.	40.22							
22	22795.	40.44							
23	23115.	41.29							
24	23715.	42.69							
25	24015.	43.51							
26	24315.	44.35							
1001024 PWA 1007 1200F AIR 10 CPM R= 0.50 THICKNESS= 7.620 MM P/AX= 4.595 KN WIDTH=63.627 MM COMPACT SPECIMEN NO. CYCLES A(MM) DEL K (MPA$\sqrt{M}$) DA/DN (MM/CYCLE)									
1	100.	28.78			10.08	1.391E-03			
2	300.	29.05			10.19	1.986E-03			
3	433.	29.32							

7ANI025 PWA 1007 1200F AIR 10 CPM R= 0.50 THICKNESS= 7.607 MM P/AX= 5.702 KN WIDTH=63.597 MM COMPACT SPECIMEN NO. CYCLES A(MM) DEL K (MPA$\sqrt{M}$) DA/DN (MM/CYCLE)									
1	0.	25.14			11.16	6.566E-04			
2	300.	25.28			11.46	7.875E-04			
3	800.	25.47			11.59	8.514E-04			
4	1800.	26.16			11.93	1.003E-03			
5	2700.	26.55			12.49	1.208E-03			
6	3045.	27.12			12.89	1.288E-03			
7	3945.	27.86			13.20	1.497E-03			
8	4845.	28.74			13.84	1.545E-03			
9	5445.	29.53			14.25	1.655E-03			
10	5945.	30.10			14.51	1.716E-03			
11	6545.	31.20			14.35	1.950E-03			
12	6945.	31.64			15.34	2.072E-03			
13	7175.	32.22			15.81	2.235E-03			
14	7475.	32.64			16.41	2.507E-03			
15	7775.	33.25			17.14	2.570E-03			
16	8075.	33.80			17.91	2.794E-03			
17	8375.	34.84			18.43	3.171E-03			
18	8675.	35.19			19.22	3.506E-03			
19	8975.	36.25			19.99	3.853E-03			
20	9175.	36.89			21.05	4.038E-03			
21	9375.	37.17			21.61	4.295E-03			
22	9575.	38.06			21.87	4.558E-03			
23	9775.	39.04			22.71	4.921E-03			
24	9859.	39.25			24.09	6.587E-03			
25	9916.	39.47			26.12	7.989E-03			
26	10056.	39.97							
27	10205.	40.85							
28	10356.	42.02							
29	10431.	42.60							
30	10506.	43.35							
31	10581.	43.95							

7ANI026 PWA 1007 1200F AIR 10 CPM R= 0.50 THICKNESS= 7.556 MM P/AX= 4.568 KN WIDTH=63.506 MM COMPACT SPECIMEN NO. CYCLES A(MM) DEL K (MPA$\sqrt{M}$) DA/DN (MM/CYCLE)									
1	466.	28.93			10.81	1.027E-03			
2	974.	29.70			10.93	1.040E-03			
3	1314.	29.86			11.18	1.145E-03			
4	1654.	30.34			11.42	1.167E-03			
5	2593.	30.97			11.54	1.361E-03			
6	2450.	31.07			11.71	1.501E-03			
7	2850.	31.49			11.90	1.511E-03			
8	3054.	31.93			12.10	1.543E-03			
9	3264.	32.16			12.36	1.669E-03			
10	3464.	32.29			12.64	1.699E-03			
11	3722.	32.92			12.95	1.738E-03			
12	3969.	33.32			13.17	1.738E-03			
13	4219.	33.53			13.54	1.891E-03			
14	4520.	34.26			13.95	2.146E-03			
15	4726.	34.53			14.52	2.268E-03			
16	5030.	35.00			15.17	2.048E-03			
17	5330.	35.53			15.32	2.363E-03			
18	5630.	35.25			15.65	2.468E-03			
19	5941.	37.18			16.41	2.853E-03			
20	6011.	37.31			16.93	3.132E-03			
21	6170.	37.40			17.49	3.204E-03			
22	6329.	37.71			18.12	3.156E-03			
23	6491.	38.49			18.83	3.700E-03			
24	6630.	38.82			19.87	4.165E-03			
25	6784.	39.20							
26	6973.	39.93							
27	7164.	40.44							
28	7355.	41.08							
29	7550.	41.92							
30	7900.	44.10							
31	8000.	44.35							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7A1027 FMA 1007 1350F AIR 2 MDXL R= 0.10 THICKNESS= 7.595 MM FMAX= 9.950 KN WIDTH=63.800 MM COMPACT SPECIMEN NO. CYCLES A(MM) DEL K (MPA ^{1/2} M) DA/DN (MM/CYCLE)									
1	150.	26.04							
2	460.	26.27							
3	1070.	26.66							
4	1690.	27.02	36.26	5.776E-04					
5	2308.	27.33	36.76	5.683E-04					
6	2827.	27.58	37.16	6.077E-04					
7	3400.	27.97	37.73	6.382E-04					
8	3880.	28.25	38.26	6.802E-04					
9	4303.	29.03	39.35	7.182E-04					
10	5600.	29.53	40.30	7.470E-04					
11	6400.	30.12	41.37	7.870E-04					
12	6990.	30.55	42.15	8.124E-04					
13	8400.	31.79	44.61	1.024E-03					
14	9100.	32.47	46.21	1.236E-03					
15	9400.	32.83	47.03	1.259E-03					
16	9700.	33.34	47.89	1.503E-03					
17	10000.	33.80	48.96	1.700E-03					
18	10300.	34.06	50.30	1.835E-03					
19	10750.	35.27	52.84	2.089E-03					
20	10950.	35.75	54.14	2.263E-03					
21	11170.	36.16	55.82	2.462E-03					
22	11400.	36.55	57.44	2.504E-03					
23	11645.	37.38	59.59	2.937E-03					
24	11775.	37.81	61.06	3.144E-03					
25	11931.	38.11	63.09	3.452E-03					
26	12103.	38.91							
27	12275.	39.48							
28	12421.	40.12							

10C1028 FMA 1007 1200F AIR 10 CPM R= 0.50 THICKNESS= 7.645 MM FMAX= 5.275 KN WIDTH=63.721 MM COMPACT SPECIMEN NO. CYCLES A(MM) DEL K (MPA ^{1/2} M) DA/DN (MM/CYCLE)									
1	0.	25.15							
2	135.	25.26	9.90	7.902E-04					
3	300.	25.57	9.98	1.909E-03					
4	559.	25.88	10.10	1.172E-03					
5	859.	26.39	10.27	1.710E-03					
6	1159.	26.89	10.48	1.676E-03					
7	1459.	27.37	10.69	1.609E-03					
8	1604.	27.65	10.86	1.874E-03					
9	1906.	28.12	11.02	1.573E-03					
10	2213.	28.78	11.29	2.159E-03					
11	2500.	29.57	11.64	2.744E-03					
12	2750.	30.09	11.98	2.068E-03					
13	3283.	31.28	12.44	2.230E-03					
14	3550.	32.12	13.03	3.144E-03					
15	3817.	33.16	13.62	3.924E-03					
16	3956.	33.54	14.10	2.677E-03					
17	4110.	34.16	14.46	4.016E-03					
18	4260.	34.63	14.87	3.166E-03					
19	4411.	35.33	15.34	4.634E-03					
20	4563.	35.91	15.69	3.802E-03					
21	4711.	36.52	16.41	4.136E-03					
22	4859.	37.22	17.05	4.754E-03					
23	5200.	38.82	18.27	4.669E-03					
24	5390.	40.41	20.24	8.819E-03					
25	5450.	41.21	21.95	9.938E-03					
26	5510.	41.56	22.87	7.010E-03					
27	5561.	42.10	23.63	1.076E-02					
28	5609.	42.55	24.51	9.207E-03					
29	5659.	42.92	25.28	7.442E-03					
30	5709.	43.32	26.04	8.128E-03					
31	5760.	44.25	27.44	1.823E-02					

1001029 FMA 1007 1200F AIR 10 CPM R= 0.10 THICKNESS= 7.620 MM FMAX= 5.564 KN WIDTH=63.739 MM COMPACT SPECIMEN NO. CYCLES A(MM) DEL K (MPA ^{1/2} M) DA/DN (MM/CYCLE)									
1	0.	23.73							
2	250.	23.96	17.90	9.144E-04					
3	504.	24.14	18.04	7.200E-04					
4	1000.	25.45	18.56	2.637E-03					
5	1300.	26.21	19.32	2.515E-03					
6	1500.	26.63	19.73	2.127E-03					
7	1750.	27.44	20.28	3.236E-03					
8	1950.	28.36	21.01	4.378E-03					
9	2152.	28.87	21.65	2.692E-03					
10	2348.	29.79	22.32	4.651E-03					
11	2500.	30.12	22.93	2.164E-03					
12	2700.	30.68	23.33	2.813E-03					
13	2900.	31.80	24.28	5.607E-03					
14	3050.	32.16	25.13	2.338E-03					
15	3207.	32.94	25.82	4.991E-03					
16	3330.	33.65	26.78	5.792E-03					
17	3550.	34.62	27.94	4.405E-03					
18	3876.	35.42	29.26	5.463E-03					
19	3840.	36.50	30.80	7.489E-03					
20	3915.	36.98	32.20	6.384E-03					
21	4000.	37.68	33.34	8.262E-03					
22	4039.	38.33	34.79	7.802E-03					
23	4194.	39.30	36.60	8.757E-03					
24	4273.	40.51	39.26	1.532E-02					
25	4310.	41.03	41.67	1.407E-02					
26	4353.	41.62	43.34	1.373E-02					
27	4412.	42.38	45.53	1.292E-02					
28	4462.	43.87	49.58	2.987E-02					

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1001030 PMA 1007 1200F AIR 10 CPM R= 0.10 THICKNESS= 7.582 MM PMA= 5.467 KN WIDTH=63.754 MM COMPACT SPECIMEN									
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0.	24.04	17.66	6.646E-04					
2	300.	24.24	18.07	8.029E-04					
3	803.	24.65	18.75	2.060E-03					
4	1533.	26.15	19.66	1.876E-03					
5	2017.	27.06	20.37	2.023E-03					
6	2622.	27.69	21.13	2.815E-03					
7	2759.	28.83	21.89	2.397E-03					
8	3662.	29.55	22.55	3.245E-03					
9	3662.	30.20	23.08	2.022E-03					
10	3663.	30.61	23.55	2.458E-03					
11	3665.	31.11	24.41	6.551E-03					
12	3829.	32.10	25.28	2.471E-03					
13	3994.	32.59	26.09	5.986E-03					
14	4154.	33.49	27.12	1.792E-03					
15	4249.	33.67	28.16	7.705E-03					
16	4417.	33.97	29.80	5.906E-03					
17	4567.	35.13	31.23	6.193E-03					
18	4730.	36.09	32.40	5.160E-03					
19	4843.	36.79	33.52	5.499E-03					
20	4954.	37.35	34.74	5.531E-03					
21	5057.	37.93	35.93	6.233E-03					
22	5154.	38.52	37.73	9.904E-03					
23	5240.	38.99	40.16	1.276E-02					
24	5344.	40.02	42.43	1.383E-02					
25	5403.	40.84	44.25	8.306E-03					
26	5452.	41.59	46.22	1.527E-02					
27	5512.	42.00							
28	5552.	42.77							

1001044 PMA 1073 1350F AIR .5 CPM R= 0.10 THICKNESS= 7.671 MM PMA= 10.337 KN WIDTH=63.782 MM COMPACT SPECIMEN									
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0.	20.87	30.19	1.017E-02					
2	100.	21.89	30.90	5.249E-03					
3	160.	22.20	31.61	7.334E-03					
4	259.	23.15	32.50	7.165E-03					
5	370.	23.73	33.32	9.141E-03					
6	451.	24.47	34.02	7.122E-03					
7	502.	24.83	34.60	9.489E-03					
8	555.	25.34	35.19	8.184E-03					
9	600.	25.70	35.85	9.504E-03					
10	660.	26.28	36.67	9.377E-03					
11	720.	26.84	37.61	1.160E-02					
12	780.	27.53	38.57	1.079E-02					
13	830.	28.07	39.42	1.251E-02					
14	870.	28.57	40.33	1.161E-02					
15	920.	29.15	41.41	1.318E-02					
16	970.	29.81	42.80	1.590E-02					
17	1024.	30.67	44.50	2.203E-02					
18	1056.	31.55	45.83	1.308E-02					
19	1094.	31.95	46.61	1.109E-02					
20	1124.	32.28	48.27	2.816E-02					
21	1164.	33.40	50.21	2.394E-02					
22	1184.	33.88	51.43	2.324E-02					
23	1204.	34.35	52.75	2.578E-02					
24	1224.	34.86	54.29	2.832E-02					
25	1244.	35.43	55.83	2.330E-02					
26	1264.	35.90	57.62	3.315E-02					
27	1284.	36.56	59.98	3.689E-02					
28	1304.	37.30	62.25	2.553E-02					
29	1324.	37.81	65.60	5.963E-02					
30	1344.	39.00	69.44	5.817E-02					
31	1354.	39.58	71.68	2.532E-02					
32	1369.	39.96	74.26	4.420E-02					
33	1384.	40.62	83.75	1.813E-01					
34	1399.	43.34							

1001046 PMA 1073 1350F AIR 10 CPM R= 0.10 THICKNESS= 7.620 MM PMA= 6.120 KN WIDTH=63.810 MM COMPACT SPECIMEN									
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0.	21.08	18.87	1.119E-02					
2	300.	24.43	21.07	1.641E-02					
3	451.	26.91	22.61	1.993E-02					
4	503.	27.95	23.47	2.066E-02					
5	540.	28.71	24.31	2.555E-02					
6	575.	29.61	25.10	2.352E-02					
7	600.	30.19	26.18	4.403E-02					
8	630.	31.52	27.21	2.72E-02					
9	645.	31.89	27.93	4.961E-02					
10	660.	32.63	28.98	4.609E-02					
11	677.	33.41							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1001047 PMA 1073 1350F AIR 10 CPM R= 0.10 THICKNESS= 7.645 MM PHAX= 6.036 KN WIDTH=63.690 MM COMPACT SPECIMEN									
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0	21.50	17.89	6.960E-03					
2	50	21.85	18.04	2.591E-03					
3	100	21.98	18.12	1.507E-03					
4	175	22.09	18.28	5.148E-03					
5	250	22.48	18.63	1.305E-02					
6	301	23.14	19.21	5.914E-03					
7	467	24.12	19.73	5.572E-03					
8	547	24.57	20.11	8.106E-03					
9	615	25.12	20.56	7.603E-03					
10	690	25.69	21.06	8.527E-03					
11	767	26.35	21.68	1.029E-02					
12	844	27.14	22.41	1.272E-02					
13	910	27.98	23.02	6.314E-03					
14	980	28.42	23.68	1.791E-02					
15	1030	29.32	24.47	1.540E-02					
16	1071	29.95	25.38	9.531E-03					
17	1180	30.99	27.67	1.354E-02					
18	1380	33.59	30.30	3.846E-02					
19	1405	34.65	32.28	5.476E-02					
20	1431	36.08	33.90	1.367E-02					
21	1456	36.42	35.18	3.610E-02					
22	1482	37.36	37.58	4.064E-02					
23	1513	38.62	40.06	3.791E-02					
24	1533	39.38	43.33	6.935E-02					
25	1556	40.97	46.62	2.716E-02					
26	1574	41.46							

1001048 PMA 1073 1200F AIR 10 CPM R= 0.80 THICKNESS= 7.671 MM PHAX= 8.180 KN WIDTH=63.589 MM COMPACT SPECIMEN									
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	30330	24.12	5.99	7.081E-05					
2	42221	24.96	6.14	7.237E-05					
3	49100	25.46	6.24	6.220E-05					
4	54000	25.76	6.34	7.775E-05					
5	60060	26.23	6.45	6.371E-05					
6	66000	26.61	6.56	7.529E-05					
7	73000	27.14	6.72	8.745E-05					
8	80000	27.75	6.88	8.596E-05					
9	86000	28.27	7.03	8.361E-05					
10	92000	28.77	7.16	9.596E-05					
11	97400	29.29	7.36	1.270E-04					
12	102400	29.92	7.51	5.439E-05					
13	107000	30.17	7.62	8.776E-05					
14	111820	30.59	7.77	1.342E-04					
15	115000	31.02	7.91	1.312E-04					
16	118000	31.41	8.04	9.380E-05					
17	121060	31.70	8.17	9.799E-05					
18	125000	32.09	8.32	1.006E-04					
19	129000	32.49	8.51	1.394E-04					
20	133000	33.05	8.71	9.430E-05					
21	137000	33.43	8.95	1.554E-04					
22	141560	34.13	9.30	2.125E-04					
23	145170	34.90	9.62	1.194E-04					
24	149200	35.38	9.93	2.992E-04					
25	151450	36.06	10.31	3.393E-04					
26	153430	36.73	10.66	2.462E-04					
27	155400	37.22	10.98	2.476E-04					
28	157400	37.71	11.31	2.337E-04					
29	159400	38.18	11.74	3.615E-04					
30	161350	38.88	12.25	3.725E-04					
31	163000	39.50	12.77	3.961E-04					
32	164600	40.13	13.70	4.989E-04					
33	167400	41.53	15.42	8.429E-04					
34	168400	42.02	16.55	1.429E-03					
35	169420	42.83							
36	170100	43.85							

7AN1052 PMA 1073 1200F AIR .5 CPM R= 0.10 THICKNESS= 7.239 MM PHAX= 10.751 KN WIDTH=63.358 MM COMPACT SPECIMEN									
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0	20.57							
2	150	21.11							
3	300	21.80							
4	450	22.08	34.39	3.448E-03					
5	650	22.61	35.21	3.798E-03					
6	828	23.44	36.09	4.356E-03					
7	960	24.09	36.97	4.769E-03					
8	1060	24.59	37.72	5.127E-03					
9	1150	24.97	38.33	5.400E-03					
10	1250	25.53	39.22	5.676E-03					
11	1360	26.23	40.25	6.113E-03					
12	1463	26.90	41.35	6.552E-03					
13	1555	27.46	42.41	6.930E-03					
14	1630	28.00	43.34	7.244E-03					
15	1700	28.53	44.23	7.664E-03					
16	1770	29.09	45.33	8.373E-03					
17	1840	29.64	46.52	9.065E-03					
18	1900	30.19	47.72	9.320E-03					
19	1980	31.06	49.43	9.613E-03					
20	2020	31.49	50.35	1.012E-02					
21	2060	31.73	51.29	1.043E-02					
22	2120	32.37	52.76	1.087E-02					
23	2183	33.16	54.67	1.216E-02					
24	2225	33.67	56.20	1.322E-02					
25	2265	34.19	57.90	1.336E-02					
26	2305	34.75	59.57	1.410E-02					
27	2330	35.19	60.72	1.475E-02					
28	2375	35.83	62.99	1.593E-02					
29	2415	36.36	65.29	1.711E-02					
30	2460	37.22	68.39	1.946E-02					
31	2502	38.07	72.14	2.291E-02					
32	2530	38.70	75.34	2.372E-02					
33	2535	39.41	78.45	2.431E-02					
34	2570	39.82	80.57	2.535E-02					
35	2593	40.09	82.03	2.707E-02					
36	2601	40.54	85.03	2.612E-02					
37	2615	40.93	87.49	3.050E-02					
38	2635	41.62	91.63	3.517E-02					
39	2650	42.13	95.68	3.750E-02					
40	2665	42.73							
41	2690	43.73							
42	2690	43.73							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7AN1053 PMA 1073 1200F AIR 10 CPM									
R= 0.10 THICKNESS= 7.595 MM									
PHAX= 6.593 KN WIDTH=63.330 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0.	21.63							
2	1000.	22.41							
3	2000.	23.01							
4	2000.	23.69	21.27	7.580E-04					
5	3300.	23.95	21.57	7.655E-04					
6	3800.	24.42	21.91	8.197E-04					
7	4300.	24.85	22.25	8.441E-04					
8	4800.	25.26	22.55	9.082E-04					
9	5300.	25.71	23.06	9.195E-04					
10	5800.	26.18	23.49	9.701E-04					
11	6200.	26.63	23.87	1.041E-03					
12	6600.	26.95	24.27	1.119E-03					
13	7000.	27.44	24.75	1.164E-03					
14	7400.	27.96	25.26	1.184E-03					
15	7800.	28.51	25.79	1.269E-03					
16	8200.	28.93	26.33	1.337E-03					
17	8600.	29.37	26.94	1.420E-03					
18	9000.	30.07	27.62	1.602E-03					
19	9400.	30.74	28.49	1.690E-03					
20	9600.	31.04	28.97	1.681E-03					
21	9800.	31.50	29.42	1.721E-03					
22	10000.	31.71	29.90	1.766E-03					
23	10200.	32.08	30.41	1.793E-03					
24	10400.	32.49	30.92	1.834E-03					
25	10600.	32.87	31.55	1.885E-03					
26	10800.	33.21	32.12	1.928E-03					

7AH1053 PMA 1073 1200F AIR 10 CPM									
R= 0.10 THICKNESS= 7.595 MM									
PHAX= 6.593 KN WIDTH=63.330 MM									
COMPACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
27	11000.	33.66	32.73	2.018E-03					
28	11200.	33.94	33.43	2.036E-03					
29	11400.	34.45	34.17	2.282E-03					
30	11600.	34.96	35.02	2.502E-03					
31	11800.	35.34	36.08	2.677E-03					
32	12000.	36.01	37.19	2.926E-03					
33	12100.	36.33	37.83	3.084E-03					
34	12200.	36.53	38.59	2.982E-03					
35	12300.	36.92	39.23	2.930E-03					
36	12450.	37.33	40.25	2.949E-03					
37	12700.	37.97	42.17	3.180E-03					
38	12800.	38.40	42.97	3.521E-03					
39	12900.	38.72	43.96	3.642E-03					
40	13000.	39.10	45.17	3.832E-03					
41	13100.	39.57	46.32	3.809E-03					
42	13200.	39.88	47.55	4.160E-03					
43	13300.	40.28	48.93	4.307E-03					
44	13400.	40.73	50.45	4.718E-03					
45	13500.	41.28	52.34	5.159E-03					
46	13600.	41.79	54.46	5.605E-03					
47	13750.	42.22	56.19	6.250E-03					
48	13750.	42.64	58.21	6.892E-03					
49	13825.	43.16							
50	13900.	43.86							
51	13950.	44.27							

Continued Next Column

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7AH1058	PMA 1073	1200F AIR	10 CPH
R= 0.0	THICKNESS= 7.849 MM		
PHAX= 29.437 KN	WIDTH= 26.378 MM		
CENTER CRACK SPECIMEN			
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)
1	0.	2.54	DA/DN (MM/CYCLE)
2	2000.	2.88	
3	3500.	3.14	
4	4500.	3.68	
5	5200.	3.92	
6	6000.	4.31	
7	6300.	4.49	
8	6600.	4.80	
9	6900.	4.97	
10	7200.	5.21	
11	7800.	5.56	
12	8100.	5.86	
13	8300.	6.07	
14	8500.	6.22	
15	8700.	6.66	
16	8900.	6.91	
17	9050.	7.07	
18	9200.	7.34	
19	9350.	7.59	
20	9450.	7.93	
21	9550.	8.08	
22	9650.	8.35	
23	9750.	8.62	
24	9850.	8.93	
25	9900.	9.10	
26	9950.	9.33	
27	10000.	9.61	
28	10050.	9.88	

7AH1196	PMA 1007	1200F AIR	20 HZ
R= 0.05	THICKNESS= 19.126 MM		
PHAX= 13.344 KN	WIDTH= 63.627 MM		
COMPACT SPECIMEN			
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)
1	498000.	35.79	DA/DN (MM/CYCLE)
2	501000.	36.08	
3	504000.	37.18	
4	507000.	37.87	
5	509000.	38.64	
6	511000.	39.24	
7	513000.	39.89	
8	515000.	40.85	
9	516500.	41.33	
10	519000.	42.12	
11	519000.	42.79	
12	520000.	43.65	
13	521000.	44.41	

7AH1301	PMA 1007	1200F AIR	10 CPH
R= 0.05	THICKNESS= 12.725 MM		
PHAX= 7.869 KN	WIDTH= 63.993 MM		
COMPACT SPECIMEN			
NO.	CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)
1	0.	28.12	DA/DN (MM/CYCLE)
2	500.	28.19	
3	4845.	28.71	
4	10016.	29.77	
5	13000.	30.26	
6	16415.	30.95	
7	19000.	31.56	
8	21000.	31.98	
9	23000.	32.49	
10	25000.	32.91	
11	27500.	33.47	
12	30358.	34.40	
13	33045.	34.94	
14	35812.	36.02	
15	37800.	36.77	
16	39300.	37.39	
17	40300.	37.79	
18	41300.	38.28	
19	42300.	38.59	
20	43555.	39.32	
21	45241.	40.07	
22	46240.	40.69	
23	47241.	41.30	
24	48240.	42.20	
25	48740.	42.77	
26	49240.	43.42	

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1031303D P/A 1007 1200F AIR 10 CPM R= 0.50 THICKNESS=12.738 MM P/AX= 10.057 KN WIDTH=64.018 MM CONTACT SPECIMEN					7AN1303 P/A 1007 1200F AIR 10 CPM R= 0.10 THICKNESS=12.700 MM P/AX= 10.396 KN WIDTH=63.840 MM CONTACT SPECIMEN					7AN1304 P/A 1007 1200F AIR 20 HZ R= 0.10 THICKNESS=12.700 MM P/AX= 10.066 KN WIDTH=63.726 MM CONTACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)	NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)	NO.	CYCLES	A(MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)
1	0	38.64			1	100	21.20			1	0	21.44		
2	50	38.70			2	202	21.43			2	60220	27.51		
3	100	39.00			3	294	21.80			3	63060	27.93		
4	150	39.16	22.13	4.881E-03	4	400	22.09	18.77	3.229E-03	4	66830	28.31	23.21	1.223E-04
5	250	39.81	23.00	6.821E-03	5	520	22.51	19.03	3.365E-03	5	70000	28.68	23.51	1.363E-04
6	350	40.37	24.25	8.184E-03	6	640	22.94	19.30	3.572E-03	6	73500	29.04	23.97	1.599E-04
7	450	41.53	25.84	8.640E-03	7	760	23.29	19.62	3.772E-03	7	78500	29.86	24.92	2.012E-04
8	500	42.02	26.74	8.318E-03	8	880	23.79	19.93	3.730E-03	8	81000	30.68	25.51	2.051E-04
9	550	42.35	27.68	8.064E-03	9	1000	24.37	20.32	3.889E-03	9	85500	30.96	25.91	1.956E-04
10	570	42.57			10	1120	24.79	20.68	4.144E-03	10	84000	31.10	26.32	1.931E-04
11	670	43.26			11	1240	25.10	21.06	4.333E-03	11	85500	31.40	26.56	1.744E-04
12	720	43.52			12	1400	25.91	21.65	4.833E-03	12	85000	31.79	27.01	1.890E-04
					13	1500	26.49	22.10	5.057E-03	13	89000	32.03	27.39	2.087E-04
					14	1600	27.00	22.61	5.095E-03	14	92000	32.72	28.24	2.430E-04
					15	1700	27.54	23.10	4.804E-03	15	94670	33.34	29.21	2.651E-04
					16	1800	28.03	23.54	4.729E-03	16	96000	33.77	29.75	2.732E-04
					17	1900	28.43	23.97	4.880E-03	17	97000	34.14	30.19	2.704E-04
					18	2000	28.83	24.42	5.451E-03	18	98000	34.25	30.62	2.846E-04
					19	2100	29.33	25.01	5.952E-03	19	99500	34.75	31.30	2.768E-04
					20	2200	30.05	25.74	5.817E-03	20	101000	35.11	32.01	2.766E-04
					21	2250	30.59	26.03	6.289E-03	21	102500	35.67	32.75	3.010E-04
					22	2300	30.67	26.42	6.317E-03	22	104000	35.99	33.54	3.145E-04
					23	2450	31.48	27.49	6.827E-03	23	105500	36.44	34.42	3.548E-04
					24	2600	32.70	28.95	8.789E-03	24	107000	37.28	36.14	3.984E-04
					25	2675	33.34	29.98	9.424E-03	25	109000	37.83	37.43	4.081E-04
					26	2750	34.14	31.16	9.269E-03	26	110000	38.47	38.44	4.250E-04
					27	2825	35.02	32.33	1.014E-02	27	111500	38.92	40.06	4.468E-04
					28	2875	35.38	33.27	1.033E-02	28	112600	39.34	41.29	4.752E-04
					29	2925	35.63	34.28	1.033E-02	29	113600	39.89	42.56	4.983E-04
					30	2975	36.59	35.27	1.051E-02	30	114600	40.44	44.15	5.703E-04
					31	3005	36.94	36.03	1.059E-02	31	115600	41.03		
					32	3064	37.28	37.48	9.770E-03	32	116500	41.60		
					33	3084	37.62	37.70	1.254E-02	33	117500	42.35		
					34	3104	37.77	38.26	1.382E-02					
					35	3124	38.13	39.10	1.571E-02					
					36	3160	38.77	40.51	1.708E-02					
					37	3190	39.34	41.94	1.893E-02					
					38	3220	39.72	43.54	2.062E-02					
					39	3250	40.49	45.34	2.417E-02					
					40	3280	41.19	47.95	2.679E-02					
					41	3310	42.04							
					42	3340	43.25							
					43	3370	43.98							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1001307 PWA 1007 800F AIR 20 HZ				74N1309 PWA 1007 1200F AIR 10 CPM			
R= 0.10 THICKNESS= 7.798 MM				R= 0.10 THICKNESS= 7.709 MM			
PMA= 6.539 KN WIDTH=63.772 MM				PMA= 6.432 KN WIDTH=64.021 MM			
COMPACT SPECIMEN				COMPACT SPECIMEN			
NO.	CYCLES	A (MM)	DEL K (MPA ^{1/2} M)	NO.	CYCLES	A (MM)	DEL K (MPA ^{1/2} M)
1	0	25.01	22.00	1	400	24.40	22.06
2	17000	26.28	22.80	2	506	24.62	22.51
3	25000	26.80	23.32	3	609	25.15	23.10
4	32000	27.39	23.74	4	713	26.22	23.62
5	37000	27.68	24.22	5	774	26.44	24.26
6	44000	28.37	24.85	6	850	27.12	24.66
7	50000	28.89	25.45	7	920	27.67	24.66
8	56000	29.50	26.01	8	990	28.44	25.00
9	61000	29.91	26.56	9	1060	29.01	25.00
10	66000	30.45	27.32	10	1135	29.82	25.96
11	71000	31.18	28.08	11	1195	30.85	26.80
12	76000	31.66	28.84	12	1225	31.05	27.26
13	81000	32.32	29.74	13	1275	31.65	29.03
14	86000	32.94	30.59	14	1312	31.94	29.59
15	90000	33.49	31.47	15	1350	32.75	29.54
16	94000	34.08	32.52	16	1375	33.48	30.26
17	97000	34.77	33.89	17	1392	33.63	30.79
18	102000	35.64	35.20	18	1417	33.99	31.46
19	105000	36.16	36.38	19	1442	34.49	32.03
20	108000	36.61	37.69	20	1517	35.76	34.66
21	110000	37.37	38.89	21	1530	36.23	35.22
22	113000	37.86	40.71	22	1543	36.52	35.80
23	116000	38.86	43.18	23	1557	36.86	36.61
24	118000	39.70	44.74	24	1572	37.18	37.15
25	119000	39.93	45.90	25	1597	37.45	37.97
26	120500	40.45	47.73	26	1602	37.79	38.93
27	122000	41.06	49.83	27	1617	38.60	40.36
28	123500	41.70	52.67	28	1627	38.86	41.55
29	125000	42.55	57.27	29	1637	39.52	42.66
30	126500	43.91		30	1647	39.62	43.53
				31	1657	39.78	43.97
				32	1657	39.96	44.40
				33	1677	40.27	45.51
				34	1687	40.72	46.59
				35	1697	41.40	48.49
				36	1707	41.70	49.85
				37	1717	41.90	51.33
				38	1727	42.40	52.93
				39	1737	43.14	
				40	1747	43.55	
				41	1757	44.26	

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7AN1310 PHA 1007 1200F AIR 10 CPM R= 0.10 THICKNESS= 7.417 MM PHAX= 6.281 KN WIDTH=63.922 MM									
COMPACT SPECIMEN		DEL K (MPA ^{1/2} /M)	DA/DN (MM/CYCLE)						
NO.	CYCLES								
1	100.	20.69							
2	204.	20.85							
3	725.	21.57							
4	925.	22.49	19.57	3.176E-03					
5	1025.	22.79	19.80	3.191E-03					
6	1102.	22.95	20.05	3.347E-03					
7	1250.	23.45	20.36	3.056E-03					
8	1400.	23.56	20.73	3.149E-03					
9	1553.	24.33	21.10	3.333E-03					
10	1700.	24.93	21.49	3.462E-03					
11	1850.	25.35	21.94	3.605E-03					
12	2012.	26.06	22.45	4.153E-03					
13	2125.	26.48	22.89	4.254E-03					
14	2290.	27.09	23.60	4.681E-03					
15	2460.	28.24	24.37	5.150E-03					
16	2630.	28.86	25.36	5.525E-03					
17	2812.	29.94	26.54	5.903E-03					
18	2953.	31.04	27.47	6.840E-03					
19	3082.	31.60	28.67	8.161E-03					
20	3186.	32.36	29.84	8.482E-03					
21	3284.	33.59	31.11	9.429E-03					
22	3357.	34.46	32.42	1.039E-02					
23	3500.	35.52	35.22	1.062E-02					
24	3550.	36.39	36.17	1.206E-02					
25	3585.	36.82	37.01	1.319E-02					
26	3620.	37.14	38.10	1.471E-02					
27	3668.	37.87	39.71	1.530E-02					
28	3710.	38.59	41.56	1.596E-02					
29	3758.	39.56	43.68	1.779E-02					
30	3804.	40.29	45.97	2.076E-02					
31	3843.	40.70							
32	3890.	42.08							
33	3930.	43.53							

1001312 PHA 1007 1200F AIR 10 CPM R= 0.10 THICKNESS= 7.544 MM PHAX= 6.521 KN WIDTH=63.435 MM									
COMPACT SPECIMEN		DEL K (MPA ^{1/2} /M)	DA/DN (MM/CYCLE)						
NO.	CYCLES								
1	0.	20.73							
2	81.	21.01	19.13	3.465E-03					
3	181.	21.06	19.24	5.080E-04					
4	381.	21.79	19.50	3.664E-03					
5	581.	22.22	19.90	2.153E-03					
6	731.	22.77	20.26	2.737E-03					
7	931.	23.28	20.65	3.412E-03					
8	1031.	23.71	21.02	2.863E-03					
9	1206.	24.24	21.40	4.185E-03					
10	1340.	24.75	21.83	3.848E-03					
11	1460.	25.03	22.17	5.307E-03					
12	1580.	25.45	22.47	3.514E-03					
13	1720.	26.07	22.94	4.409E-03					
14	1820.	26.22	23.29	1.499E-03					
15	1982.	26.79	23.63	3.543E-03					
16	2150.	27.64	24.32	5.019E-03					
17	2270.	28.15	25.01	4.276E-03					
18	2390.	28.67	25.56	4.560E-03					
19	2510.	29.39	26.25	6.023E-03					
20	2610.	29.99	27.01	5.569E-03					
21	2710.	30.62	27.76	6.312E-03					
22	2813.	31.07	28.44	4.539E-03					
23	2913.	32.11	29.43	1.031E-02					
24	2979.	32.34	30.32	3.463E-03					
25	3080.	33.01	30.99	8.310E-03					
26	3130.	33.35	31.77	4.662E-03					
27	3200.	34.04	32.61	9.924E-03					
28	3250.	34.17	33.30	2.464E-03					
29	3350.	34.79	33.55	7.731E-03					
30	3411.	35.81	35.49	1.270E-02					
31	3451.	36.30	37.02	1.213E-02					
32	3500.	36.99	38.29	1.407E-02					
33	3540.	37.53	39.72	1.353E-02					
34	3580.	38.08	41.06	1.568E-02					
35	3620.	38.69	42.58	1.537E-02					
36	3660.	39.65	44.81	2.397E-02					
37	3700.	39.94	46.72	7.303E-03					
38	3757.	40.64	48.33	1.217E-02					
39	3802.	42.62	53.19	4.420E-02					
40	3836.	43.83	60.05	3.552E-02					

7AN1313 PHA 1007 1350F AIR 10 CPM R= 0.10 THICKNESS= 7.671 MM PHAX= 6.272 KN WIDTH=63.541 MM									
COMPACT SPECIMEN		DEL K (MPA ^{1/2} /M)	DA/DN (MM/CYCLE)						
NO.	CYCLES								
1	0.	21.14							
2	103.	21.57							
3	260.	22.32							
4	303.	23.09	19.50	7.392E-03					
5	390.	23.40	19.93	7.622E-03					
6	460.	24.32	20.39	7.976E-03					
7	512.	24.66	20.74	8.120E-03					
8	582.	25.25	21.30	8.535E-03					
9	672.	26.01	21.81	9.289E-03					
10	717.	26.30	22.19	1.001E-02					
11	737.	27.02	22.83	1.044E-02					
12	850.	27.90	23.52	1.127E-02					
13	800.	28.35	23.99	1.220E-02					
14	930.	28.56	24.48	1.272E-02					
15	1010.	29.75	25.60	1.304E-02					
16	1050.	30.47	26.28	1.474E-02					
17	1090.	30.99	27.03	1.476E-02					
18	1144.	31.70	28.04	1.601E-02					
19	1180.	32.43	29.51	1.500E-02					
20	1215.	32.72	29.65	1.561E-02					
21	1260.	33.92	30.62	1.807E-02					
22	1285.	33.99	31.21	2.017E-02					
23	1333.	34.69	32.97	2.705E-02					
24	1333.	36.41	35.58	3.093E-02					
25	1405.	37.42	37.52	4.005E-02					
26	1421.	39.17	39.19	3.607E-02					
27	1433.	39.40	40.47	3.259E-02					
28	1445.	39.87	41.27	3.155E-02					
29	1459.	39.21	42.15	3.066E-02					
30	1475.	39.52	43.79	3.545E-02					
31	1492.	40.37	45.70	3.901E-02					
32	1505.	40.93	47.62	3.023E-02					
33	1517.	41.41	49.26	4.358E-02					
34	1529.	41.92							
35	1545.	42.31							
36	1560.	43.51							
37	1572.	44.39							

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7A11314 PWA 1007 1350F AIR 10 CPM			
R = 0.10 THICKNESS= 7.468 MM			
FMAX= 6.432 KN WIDTH=63.421 MM			
CONTACT SPECIMEN			
NO.	CYCLES	A(MM)	DEL K (MPA\ M) DA/DN (MM/CYCLE)
1	931.	20.66	
2	1050.	21.13	
3	1100.	21.45	
4	1150.	21.43	19.53 3.775E-03
5	1250.	21.88	19.79 4.055E-03
6	1350.	22.40	20.09 4.270E-03
7	1450.	22.74	20.42 4.965E-03
8	1550.	23.31	20.84 4.872E-03
9	1650.	23.74	21.26 4.541E-03
10	1750.	24.53	21.59 4.600E-03
11	1900.	24.92	22.13 4.300E-03
12	1975.	24.97	22.38 4.243E-03
13	2150.	26.05	22.95 5.262E-03
14	2300.	26.58	23.78 6.892E-03
15	2375.	27.05	24.37 5.935E-03
16	2450.	28.08	24.85 5.917E-03
17	2500.	28.23	25.27 6.804E-03
18	2700.	29.12	26.46 5.589E-03
19	2775.	29.53	26.83 5.285E-03
20	2850.	30.03	27.31 6.055E-03
21	2925.	30.59	27.89 6.774E-03
22	3000.	30.75	28.52 7.595E-03
23	3100.	31.79	29.60 8.865E-03
24	3175.	32.48	30.57 1.083E-02
25	3250.	33.32	32.01 1.218E-02
26	3325.	34.14	33.59 1.282E-02
27	3375.	35.22	34.69 1.191E-02
28	3425.	35.65	35.94 1.349E-02
29	3475.	36.27	37.00 1.527E-02
30	3525.	36.51	38.41 1.707E-02
31	3625.	37.70	43.98 2.531E-02
32	3675.	40.80	48.24 2.547E-02
33	3700.	41.25	50.81 2.153E-02
34	3725.	41.46	53.29 2.335E-02
35	3750.	42.01	
36	3775.	42.35	
37	3800.	43.54	

7A11315 PWA 1007 1350F AIR 10 CPM			
R = 0.10 THICKNESS= 7.595 MM			
FMAX= 6.338 KN WIDTH=62.161 MM			
CONTACT SPECIMEN			
NO.	CYCLES	A(MM)	DEL K (MPA\ M) DA/DN (MM/CYCLE)
1	1009.	22.12	
2	1201.	22.49	
3	1401.	23.49	
4	1502.	23.77	20.91 2.453E-03
5	1756.	23.88	21.37 2.182E-03
6	1900.	24.14	21.50 1.975E-03
7	2150.	24.93	21.98 2.587E-03
8	2296.	25.19	22.43 2.906E-03
9	2601.	26.20	23.32 3.110E-03
10	2756.	26.88	23.79 3.413E-03
11	2900.	27.09	24.32 3.340E-03
12	2996.	27.50	24.66 3.242E-03
13	3120.	28.11	25.05 3.418E-03
14	3220.	28.24	25.47 3.632E-03
15	3323.	28.55	25.04 3.665E-03
16	3423.	29.10	26.30 3.730E-03
17	3723.	30.12	27.87 4.407E-03
18	3811.	30.90	29.41 4.368E-03
19	3920.	31.36	29.42 4.393E-03
20	4080.	31.97	30.08 4.822E-03
21	4120.	32.29	30.75 4.793E-03
22	4280.	32.77	31.65 4.624E-03
23	4331.	33.54	32.44 4.644E-03
24	4460.	33.77	32.94 5.039E-03
25	4546.	33.93	33.66 5.205E-03
26	4641.	34.29	34.58 5.166E-03
27	4740.	35.42	35.73 6.005E-03
28	4900.	35.59	36.61 6.504E-03
29	4900.	35.98	38.03 6.751E-03
30	5000.	36.83	39.42 6.752E-03
31	5100.	37.53	41.37 7.644E-03
32	5200.	38.28	43.69 8.531E-03
33	5277.	39.02	45.54 1.057E-02
34	5347.	39.59	48.05 1.233E-02
35	5420.	40.25	50.54 1.403E-02
36	5493.	41.38	53.33 1.503E-02
37	5475.	41.69	55.53 1.449E-02
38	5513.	42.05	
39	5533.	42.79	
40	5609.	43.41	

1001316 PWA 1007 1350F AIR 10 CPM			
R = 0.50 THICKNESS= 7.468 MM			
FMAX= 6.249 KN WIDTH=62.202 MM			
CONTACT SPECIMEN			
NO.	CYCLES	A(MM)	DEL K (MPA\ M) DA/DN (MM/CYCLE)
1	754.	23.82	11.87 2.032E-03
2	954.	24.23	12.08 1.900E-03
3	1200.	24.70	12.35 2.617E-03
4	1446.	25.34	12.59 6.402E-04
5	1939.	25.66	12.81 1.463E-03
6	2300.	26.18	13.24 3.012E-03
7	2650.	27.24	13.68 2.914E-03
8	2823.	27.74	13.97 2.732E-03
9	2995.	28.21	14.09 3.626E-03
10	3154.	28.79	14.09 3.307E-03
11	3313.	29.32	14.65 3.307E-03
12	3463.	29.66	14.94 5.300E-03
13	3613.	30.53	15.36 4.216E-03
14	3735.	31.05	15.87 2.848E-03
15	3953.	31.41	16.20 5.275E-03
16	3993.	32.10	16.62 4.741E-03
17	4123.	32.74	17.18 4.687E-03
18	4250.	33.29	17.71 4.687E-03
19	4370.	33.85	18.23 4.139E-03
20	4490.	34.53	18.89 6.139E-03
21	4511.	34.79	19.33 2.261E-03
22	4753.	35.93	20.17 6.948E-03
23	4841.	36.62	21.31 7.255E-03
24	5021.	37.63	22.42 5.531E-03
25	5075.	38.18	23.53 1.030E-02
26	5126.	38.66	24.40 9.328E-03
27	5189.	39.15	25.22 7.721E-03
28	5325.	39.65	26.11 7.356E-03
29	5325.	40.25	27.16 6.815E-03
30	5355.	40.91	28.44 9.471E-03
31	5450.	41.73	30.08 1.427E-02
32	5503.	42.54	32.05 1.524E-02
33	5540.	43.01	33.74 1.287E-02
34	5577.	43.96	35.76 2.557E-02
35	5604.	44.27	37.70 1.167E-02

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

74H1317 FMA 1007 1200F AIR 10 CPM R= 0.10 THICKNESS= 7.671 MM FMA= 5.022 KN WIDTH=62.212 MM									
CONTACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0.	21.78							
2	200.	22.20							
3	400.	22.54							
4	600.	22.79	18.52	1.678E-03					
5	800.	23.31	18.25	1.608E-03					
6	1200.	23.89	19.21	1.634E-03					
7	1500.	24.23	19.59	1.676E-03					
8	1900.	24.93	20.12	1.693E-03					
9	2300.	25.70	20.68	1.777E-03					
10	2600.	26.18	21.16	1.841E-03					
11	2900.	26.73	21.66	1.842E-03					
12	3200.	27.35	22.16	1.926E-03					
13	3500.	27.90	22.73	2.065E-03					
14	3800.	28.41	23.35	2.245E-03					
15	4200.	29.00	23.82	2.346E-03					
16	4500.	29.46	24.34	2.590E-03					
17	4800.	29.99	24.97	2.700E-03					
18	4800.	30.47	25.57	2.892E-03					
19	4800.	31.22	26.31	3.115E-03					
20	4800.	31.49	26.94	3.261E-03					
21	5250.	32.70	28.38	3.574E-03					
22	5450.	33.58	29.45	3.705E-03					
23	5800.	33.91	30.42	3.835E-03					
24	5700.	34.55	31.37	4.050E-03					
25	5800.	35.19	32.55	4.702E-03					
26	6020.	35.71	33.65	5.315E-03					
27	6140.	36.40	34.93	5.894E-03					
28	6260.	37.09	36.67	6.279E-03					
29	6360.	37.90	39.29	6.702E-03					
30	6460.	38.41	39.64	7.770E-03					
31	6520.	38.83	41.36	8.493E-03					
32	6600.	39.54	43.29	9.947E-03					
33	6670.	40.55	45.70	1.144E-02					
34	6720.	40.83	47.91	1.257E-02					
35	6770.	41.67	50.26	1.439E-02					
36	6820.	42.31							
37	6870.	43.09							
38	6910.	44.07							

1001318 FMA 1007 1350F AIR 10 CPM R= 0.10 THICKNESS= 7.671 MM FMA= 6.374 KN WIDTH=62.065 MM									
CONTACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	0.	19.93							
2	300.	20.60	18.54	2.079E-03					
3	500.	20.77	18.80	3.695E-04					
4	900.	21.90	19.24	2.813E-03					
5	1332.	23.07	20.07	2.699E-03					
6	1433.	23.47	20.68	2.636E-03					
7	1635.	23.76	20.96	1.913E-03					
8	1835.	24.60	21.43	3.370E-03					
9	2035.	25.38	22.14	3.030E-03					
10	2254.	25.83	22.70	2.660E-03					
11	2400.	26.72	23.34	6.105E-03					
12	2600.	28.08	24.47	3.383E-03					
13	3000.	29.06	25.74	4.900E-03					
14	3200.	29.70	26.70	3.226E-03					
15	3350.	30.55	27.63	5.666E-03					
16	3500.	31.47	28.81	6.147E-03					
17	3650.	32.22	30.01	5.004E-03					
18	3757.	33.47	31.57	1.154E-02					
19	3857.	34.48	33.52	1.007E-02					
20	3910.	35.02	34.99	1.023E-02					
21	3960.	35.91	36.47	1.783E-02					
22	4010.	36.44	39.05	1.052E-02					
23	4077.	37.24	39.64	1.138E-02					
24	4127.	37.71	41.28	9.576E-03					
25	4180.	38.64	43.24	1.743E-02					
26	4220.	39.27	45.60	1.587E-02					
27	4260.	39.58	47.14	7.747E-03					
28	4305.	40.55	49.38	2.161E-02					
29	4352.	41.63	53.31	2.286E-02					
30	4392.	42.94	53.51	3.267E-02					
31	4412.	43.49	63.12	2.781E-02					
32	4432.	44.11	66.29	3.036E-02					

1001319 FMA 1007 1350F AIR 10 CPM R= 0.50 THICKNESS= 7.569 MM FMA= 6.033 KN WIDTH=63.332 MM									
CONTACT SPECIMEN									
NO.	CYCLES	A(MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)					
1	100.	21.06							
2	300.	21.21	9.91	7.176E-04					
3	701.	21.63	10.00	1.055E-03					
4	1100.	22.00	10.14	9.135E-04					
5	1503.	22.50	10.30	1.264E-03					
6	1934.	22.96	10.48	1.134E-03					
7	2300.	23.60	10.70	1.610E-03					
8	2722.	24.26	10.96	1.562E-03					
9	3030.	24.51	11.16	8.609E-04					
10	3411.	25.58	11.45	2.733E-03					
11	3611.	26.16	11.83	2.877E-03					
12	3811.	26.33	12.01	8.381E-04					
13	4013.	26.69	12.13	1.792E-03					
14	4255.	27.07	12.32	1.791E-03					
15	4435.	27.20	12.45	6.531E-04					
16	4736.	28.33	12.78	3.755E-03					
17	4900.	28.57	13.16	1.448E-03					
18	5100.	29.41	13.46	4.210E-03					
19	5252.	29.63	13.77	1.337E-03					
20	5452.	30.07	13.97	2.203E-03					
21	5600.	30.65	14.29	2.790E-03					
22	5850.	31.84	14.83	5.950E-03					
23	6072.	32.61	15.59	3.648E-03					
24	6497.	34.26	16.55	4.409E-03					
25	6550.	34.59	17.42	3.144E-03					
26	6570.	34.71	17.63	1.016E-03					
27	6800.	35.22	17.93	3.947E-03					
28	6930.	35.66	18.40	3.361E-03					
29	7151.	37.08	19.40	6.436E-03					
30	7288.	37.97	20.79	7.628E-03					
31	7358.	38.67	21.85	6.974E-03					
32	7418.	39.79	23.18	2.235E-02					
33	7483.	40.19	24.41	1.621E-02					
34	7473.	40.48	25.00	9.609E-03					
35	7548.	41.08	25.80	8.043E-03					
36	7623.	42.27	27.54	1.578E-02					
37	7649.	42.90	29.49	2.437E-02					
38	7670.	43.47	30.91	2.728E-02					
39	7692.	43.62	31.80	6.639E-03					

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1001320 PHA 1007 1350F AIR 10 CPM
R = 0.50 THICKNESS= 7.595 MM
PHAX= 39.107 KN WIDTH=25.336 MM
CENTER CRACK SPECIMEN
NO. CYCLES A(MM) DEL K (MPA $\sqrt{M}$) DA/DN (MM/CYCLE)

1	125.	2.74	9.78	4.128E-04
2	325.	2.82	10.68	8.522E-04
3	1325.	3.67	12.55	1.130E-03
4	2300.	4.77	14.27	2.550E-03
5	2550.	5.41	16.08	1.053E-02
6	2650.	6.46		

7AN1321 PHA 1007 1200F AIR 10 CPM
R = 0.10 THICKNESS= 7.417 MM
PHAX= 29.424 KN WIDTH=24.714 MM
CENTER CRACK SPECIMEN
NO. CYCLES A(MM) DEL K (MPA $\sqrt{M}$) DA/DN (MM/CYCLE)

1	0.	2.08		
2	2500.	2.18		
3	7000.	2.40		
4	11170.	2.79		
5	16200.	2.95		
6	20200.	3.48		
7	22260.	3.67		
8	25530.	4.32		
9	27200.	4.55		
10	28630.	4.85		
11	30060.	5.22		
12	31020.	5.52		
13	32010.	5.89		
14	33000.	6.09		
15	34000.	6.54		
16	36750.	6.76		
17	39400.	7.11		
18	39800.	7.45		
19	38220.	7.75		
20	36520.	7.95		
21	37730.	9.30		

13.65	7.080E-05
14.70	9.903E-05
15.84	1.275E-04
16.49	1.473E-04
18.05	1.824E-04
18.90	2.116E-04
19.83	2.467E-04
20.83	2.702E-04
21.70	3.007E-04
22.72	3.201E-04
23.79	3.496E-04
25.02	4.210E-04
26.18	5.220E-04
27.66	6.167E-04
28.66	7.246E-04

7AN1323 PHA 1007 1200F AIR 10 CPM
R = 0.10 THICKNESS= 7.544 MM
PHAX= 60.471 KN WIDTH=25.349 MM
CENTER CRACK SPECIMEN
NO. CYCLES A(MM) DEL K (MPA $\sqrt{M}$) DA/DN (MM/CYCLE)

1	0.	2.33		
2	300.	2.58		
3	960.	2.83		
4	2000.	3.39		
5	2500.	3.63		
6	3000.	3.96		
7	3510.	4.30		
8	4010.	4.63		
9	4400.	5.04		
10	4670.	5.63		
11	4900.	5.96		
12	5120.	6.26		
13	5320.	6.64		
14	5520.	7.20		
15	5620.	7.52		
16	5750.	7.68		
17	5800.	8.01		

7AN1324 PHA 1007 800F AIR 10 CPM
R = 0.0 THICKNESS= 7.569 MM
PHAX= 32.204 KN WIDTH=25.298 MM
CENTER CRACK SPECIMEN
NO. CYCLES A(MM) DEL K (MPA $\sqrt{M}$) DA/DN (MM/CYCLE)

1	31530.	3.11		
2	34350.	3.25		
3	37600.	3.37		
4	40300.	3.47		
5	47000.	3.72		
6	49000.	3.90		
7	52710.	4.22		
8	55200.	4.40		
9	57851.	4.85		
10	60710.	5.30		
11	62951.	5.90		
12	64440.	6.18		
13	66000.	6.52		
14	67500.	6.70		
15	69000.	7.41		
16	70300.	7.69		
17	70570.	8.15		
18	71200.	8.25		

18.29	4.274E-05
19.29	6.235E-05
19.81	8.356E-05
20.64	1.045E-04
21.48	1.346E-04
22.75	1.650E-04
24.49	1.987E-04
26.23	1.937E-04
27.41	2.29CE-04
28.37	2.555E-04
30.27	3.014E-04
32.47	3.750E-04

7AN1326 PHA 1007 1200F AIR 10 CPM
R = 0.0 THICKNESS= 7.556 MM
PHAX= 39.338 KN WIDTH=25.349 MM
CENTER CRACK SPECIMEN
NO. CYCLES A(MM) DEL K (MPA $\sqrt{M}$) DA/DN (MM/CYCLE)

1	0.	2.22		
2	1000.	2.32		
3	3050.	2.56		
4	5300.	2.96		
5	6300.	3.16		
6	7100.	3.41		
7	7800.	3.45		
8	8825.	3.85		
9	9400.	3.87		
10	10000.	4.08		
11	11275.	4.34		
12	11900.	4.53		
13	12500.	4.74		
14	13100.	4.90		
15	13735.	5.03		
16	14500.	5.18		
17	15608.	6.17		
18	17445.	7.51		

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7AN1327 PMA 1007 1200F AIR 10 CPM R= 0.0 THICKNESS= 7.620 MM FMAX= 32.639 KN WIDTH=25.336 MM CENTER CRACK SPECIMEN NO. CYCLES A(MM) DEL K (MPA√M) DA/DN (MM/CYCLE)				7AN1328 PMA 1007 1200F AIR .5 CPM R= 0.10 THICKNESS= 7.595 MM FMAX= 55.600 KN WIDTH=25.349 MM CENTER CRACK SPECIMEN NO. CYCLES A(MM) DEL K (MPA√M) DA/DN (MM/CYCLE)				7AN1337 PMA 1073 1200F AIR 10 CPM R= 0.10 THICKNESS= 7.315 MM FMAX= 41.115 KN WIDTH=18.351 MM CENTER CRACK SPECIMEN NO. CYCLES A(MM) DEL K (MPA√M) DA/DN (MM/CYCLE)				1001329 PMA 1007 1350F AIR 10 CPM R= 0.10 THICKNESS= 7.559 MM FMAX= 38.733 KN WIDTH=25.339 MM CENTER CRACK SPECIMEN NO. CYCLES A(MM) DEL K (MPA√M) DA/DN (MM/CYCLE)				1001370 PMA 1007 1350F AIR 15 CPM R= 0.10 THICKNESS= 7.507 MM FMAX= 65.077 KN WIDTH=25.349 MM CENTER CRACK SPECIMEN NO. CYCLES A(MM) DEL K (MPA√M) DA/DN (MM/CYCLE)							
1	0.	1.67		1	1800.	1.91		1	73.	1.68		1	0.	2.40		1	73.	1.68		1	0.	2.40	
2	1000.	1.74		2	3000.	2.27		2	3000.	2.45		2	200.	2.45		2	93.	1.92		2	200.	2.45	
3	3100.	1.78		3	3930.	2.49		3	5030.	2.85		3	500.	2.47		3	133.	1.99		3	500.	2.47	
4	6960.	2.12	9.865E-05	4	5030.	3.38	25.61	4	5970.	3.38	27.24	4	1000.	2.53	13.13	4	253.	2.10	30.77	4	1000.	2.53	13.13
5	10100.	2.64	1.231E-04	5	5970.	3.38	27.24	5	6400.	3.55	29.03	5	1700.	2.54	13.22	5	303.	2.27	33.94	5	1700.	2.54	13.22
6	14000.	3.00	1.530E-04	6	6400.	3.55	29.03	6	7000.	4.09	31.10	6	2750.	2.59	13.40	6	403.	2.45	35.97	6	2750.	2.59	13.40
7	15800.	3.33	1.789E-04	7	7000.	4.09	31.10	7	7650.	4.55	33.52	7	4170.	2.70	13.64	7	503.	2.69	38.63	7	4170.	2.70	13.64
8	17630.	3.63	1.974E-04	8	7650.	4.55	33.52	8	7900.	4.62	34.33	8	6013.	2.96	14.43	8				8	6013.	2.96	14.43
9	19200.	4.00	2.316E-04	9	7900.	4.62	34.33	9	8300.	5.05	36.26	9	7410.	3.03	14.93	9				9	7410.	3.03	14.93
10	20900.	4.45	2.560E-04	10	8300.	5.05	36.26	10	8500.	5.23	37.09	10	8700.	3.27	15.63	10				10	8700.	3.27	15.63
11	22000.	4.62	2.776E-04	11	8500.	5.23	37.09	11	8750.	5.52	39.63	11	9400.	3.59	16.53	11				11	9400.	3.59	16.53
12	24000.	5.34	3.370E-04	12	8750.	5.52	39.63	12	9010.	5.71	40.15	12	9560.	6.60	20.44	12				12	9560.	6.60	20.44
13	25025.	5.59	3.605E-04	13	9010.	5.71	40.15	13	9400.	6.39	43.63	13	9720.	7.03	24.43	13				13	9720.	7.03	24.43
14	26066.	5.98	4.201E-04	14	9400.	6.39	43.63	14	9560.	6.60	45.52	14	9940.	7.37		14				14	9940.	7.37	
15	26600.	6.31	4.796E-04	15	9560.	6.60	45.52	15	9720.	7.03	46.12	15	9950.	7.61		15				15	9950.	7.61	
16	27200.	6.56	5.443E-04	16	9720.	7.03	46.12	16	9940.	7.37		16	10000.	7.75		16				16	10000.	7.75	
17	27800.	6.86	5.870E-04	17	9940.	7.37		17	9950.	7.61													
18	28500.	7.36		18	9950.	7.61		18	10000.	7.75													
19	29000.	7.72		19				19															
20	29400.	7.93		20				20															
21	29930.	8.17		21				21															

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

7A11341 PWA 1073 1200F AIR 10 CPM						
R = 0.10 THICKNESS = 7.518 MM						
P _{MAX} = 31.883 KN WIDTH = 25.044 MM						
CENTER CRACK SPECIMEN						
NO.	CYCLES	A (MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)		
1	0.	2.24				
2	1000.	2.37				
3	3000.	2.62				
4	5140.	2.93	15.12	2.088E-04		
5	6640.	3.20	16.10	2.536E-04		
6	8000.	3.68	17.15	2.834E-04		
7	9520.	4.17	18.55	3.321E-04		
8	10000.	4.29	19.06	3.819E-04		
9	10700.	4.43	19.73	4.684E-04		
10	11400.	4.83	20.65	6.382E-04		
11	11900.	5.18	21.72	7.783E-04		
12	12200.	5.45	22.55	8.599E-04		
13	12500.	5.72	23.41	9.778E-04		
14	12800.	5.98	24.42	1.095E-03		
15	13100.	6.32	25.62	1.273E-03		
16	13400.	6.75	27.15	1.488E-03		
17	13560.	6.97	28.17	1.757E-03		
18	13700.	7.23	29.23	2.016E-03		
19	13820.	7.42	30.31	2.188E-03		
20	13940.	7.79	31.70	2.346E-03		
21	14030.	8.01	32.69	2.552E-03		
22	14120.	8.20				
23	14210.	8.42	34.03	2.575E-03		
24	14300.	8.60				
25	14390.	8.98				

7A11342 PWA 1073 1200F AIR 10 CPM						
R = 0.0 THICKNESS = 7.595 MM						
P _{MAX} = 38.595 KN WIDTH = 25.285 MM						
CENTER CRACK SPECIMEN						
NO.	CYCLES	A (MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)		
1	0.	2.84				
2	500.	3.01				
3	1000.	3.45				
4	1300.	3.77	23.00	1.106E-03		
5	1400.	3.82	23.47	1.137E-03		
6	1600.	4.14	24.35	1.225E-03		
7	1800.	4.34	25.34	1.300E-03		
8	2000.	4.62	26.41	1.424E-03		
9	2200.	4.92	27.49	1.522E-03		
10	2400.	5.23	28.76	1.772E-03		
11	2575.	5.52	30.05	2.010E-03		
12	2750.	5.87	31.64	2.251E-03		
13	2925.	6.34	33.57	2.464E-03		
14	3000.	6.54	34.53	2.616E-03		
15	3075.	6.70	35.54	2.666E-03		
16	3150.	6.88	36.81	2.926E-03		
17	3225.	7.16	37.84	3.114E-03		
18	3300.	7.45	39.23	3.502E-03		
19	3375.	7.62	40.83	3.651E-03		
20	3450.	7.92	42.75	4.152E-03		
21	3525.	8.32	45.35	5.106E-03		
22	3555.	8.55				
23	3505.	8.83				
24	3645.	9.10				

7A11343 PWA 1073 800F AIR 10 CPM						
R = 0.0 THICKNESS = 5.791 MM						
P _{MAX} = 20.799 KN WIDTH = 25.108 MM						
CENTER CRACK SPECIMEN						
NO.	CYCLES	A (MM)	DEL K (MPA ^{1/2} M)	DA/DN (MM/CYCLE)		
1	0.	2.57				
2	1800.	2.59				
3	5700.	2.62				
4	6930.	2.67	13.47	2.562E-05		
5	13000.	2.84	13.89	4.426E-05		
6	17800.	2.99	14.48	5.408E-05		
7	20350.	3.25	15.00	6.033E-05		
8	23900.	3.50	15.54	6.932E-05		
9	25400.	3.55	16.05	7.535E-05		
10	29945.	3.76	16.54	7.661E-05		
11	31400.	4.03	17.01	8.992E-05		
12	33700.	4.21	17.66	1.042E-04		
13	34600.	4.39	18.30	1.190E-04		
14	35360.	4.79	19.11	1.357E-04		
15	40500.	4.99	19.61	1.432E-04		
16	42600.	5.41	21.03	1.661E-04		
17	43100.	5.55	21.42	1.745E-04		
18	45100.	5.70	22.71	2.116E-04		
19	46100.	6.15	23.11	2.401E-04		
20	47100.	6.49	24.17	2.764E-04		
21	47400.	6.70	25.44	2.914E-04		
22	47800.	7.23	26.00	2.610E-04		
23	48100.	7.32	27.13	3.556E-04		
24	48400.	7.58	27.77	4.024E-04		
25	48700.	7.79	28.35	4.149E-04		
26	49000.	7.94	29.17	4.207E-04		
27	49300.	8.14	29.77	4.346E-04		
28	49600.	8.44	30.41	4.545E-04		
29	49900.	8.74	31.11	4.745E-04		
30	50200.	9.04	31.81	4.945E-04		
31	50500.	9.34	32.51	5.145E-04		
32	50800.	9.64	33.21	5.345E-04		
33	51100.	9.94	33.91	5.545E-04		
34	51400.	10.24	34.61	5.745E-04		
35	51700.	10.54	35.31	5.945E-04		
36	52000.	10.84	36.01	6.145E-04		
37	52300.	11.14	36.71	6.345E-04		
38	52600.	11.44	37.41	6.545E-04		
39	52900.	11.74	38.11	6.745E-04		
40	53200.	12.04	38.81	6.945E-04		
41	53500.	12.34	39.51	7.145E-04		
42	53800.	12.64	40.21	7.345E-04		
43	54100.	12.94	40.91	7.545E-04		
44	54400.	13.24	41.61	7.745E-04		
45	54700.	13.54	42.31	7.945E-04		
46	55000.	13.84	43.01	8.145E-04		
47	55300.	14.14	43.71	8.345E-04		
48	55600.	14.44	44.41	8.545E-04		
49	55900.	14.74	45.11	8.745E-04		
50	56200.	15.04	45.81	8.945E-04		
51	56500.	15.34	46.51	9.145E-04		
52	56800.	15.64	47.21	9.345E-04		
53	57100.	15.94	47.91	9.545E-04		
54	57400.	16.24	48.61	9.745E-04		
55	57700.	16.54	49.31	9.945E-04		
56	58000.	16.84	50.01	1.014E-03		
57	58300.	17.14	50.71	1.034E-03		
58	58600.	17.44	51.41	1.054E-03		
59	58900.	17.74	52.11	1.074E-03		
60	59200.	18.04	52.81	1.094E-03		
61	59500.	18.34	53.51	1.114E-03		
62	59800.	18.64	54.21	1.134E-03		
63	60100.	18.94	54.91	1.154E-03		
64	60400.	19.24	55.61	1.174E-03		
65	60700.	19.54	56.31	1.194E-03		
66	61000.	19.84	57.01	1.214E-03		
67	61300.	20.14	57.71	1.234E-03		
68	61600.	20.44	58.41	1.254E-03		
69	61900.	20.74	59.11	1.274E-03		
70	62200.	21.04	59.81	1.294E-03		
71	62500.	21.34	60.51	1.314E-03		
72	62800.	21.64	61.21	1.334E-03		
73	63100.	21.94	61.91	1.354E-03		
74	63400.	22.24	62.61	1.374E-03		
75	63700.	22.54	63.31	1.394E-03		
76	64000.	22.84	64.01	1.414E-03		
77	64300.	23.14	64.71	1.434E-03		
78	64600.	23.44	65.41	1.454E-03		
79	64900.	23.74	66.11	1.474E-03		
80	65200.	24.04	66.81	1.494E-03		
81	65500.	24.34	67.51	1.514E-03		
82	65800.	24.64	68.21	1.534E-03		
83	66100.	24.94	68.91	1.554E-03		
84	66400.	25.24	69.61	1.574E-03		
85	66700.	25.54	70.31	1.594E-03		
86	67000.	25.84	71.01	1.614E-03		
87	67300.	26.14	71.71	1.634E-03		
88	67600.	26.44	72.41	1.654E-03		
89	67900.	26.74	73.11	1.674E-03		
90	68200.	27.04	73.81	1.694E-03		
91	68500.	27.34	74.51	1.714E-03		
92	68800.	27.64	75.21	1.734E-03		
93	69100.	27.94	75.91	1.754E-03		
94	69400.	28.24	76.61	1.774E-03		
95	69700.	28.54	77.31	1.794E-03		
96	70000.	28.84	78.01	1.814E-03		
97	70300.	29.14	78.71	1.834E-03		
98	70600.	29.44	79.41	1.854E-03		
99	70900.	29.74	80.11	1.874E-03		
100	71200.	30.04	80.81	1.894E-03		

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1001349 FIA 1007 1200F AIR 10 CPM R= 0.05 THICKNESS= 7.582 MM P1AX=108.175 KN WIDTH=25.336 MM CENTER CRACK SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	900.	3.39	53.00	3.140E-04
2	1000.	3.45	59.10	1.639E-03
3	1180.	3.61	60.63	1.175E-03
4	1300.	3.75	62.83	1.973E-03
5	1450.	4.05		
7A11350 FIA 1007 800F AIR 10 CPM R= 0.0 THICKNESS= 7.531 MM P1AX= 32.737 KN WIDTH=25.336 MM CENTER CRACK SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	15000.	2.51	17.12	5.198E-05
2	18000.	2.56	17.82	5.820E-05
3	22000.	2.87	18.57	6.775E-05
4	25000.	2.93	19.53	8.595E-05
5	29000.	3.15	20.53	1.034E-04
6	33333.	3.42	21.60	1.208E-04
7	37600.	3.71	22.89	1.438E-04
8	41000.	3.99	23.90	1.489E-04
9	44032.	4.36	24.96	1.682E-04
10	47647.	4.74	26.34	2.072E-04
11	49300.	5.02	27.22	2.320E-04
12	51300.	5.34	28.32	2.620E-04
13	53210.	5.78	29.62	2.820E-04
14	54354.	5.84	31.19	3.110E-04
15	55550.	6.24	32.59	3.256E-04
16	56700.	6.60	33.67	3.645E-04
17	57800.	6.89	35.03	4.264E-04
18	58800.	7.24	35.14	4.952E-04
19	59500.	7.39	37.77	5.683E-04
20	60200.	7.71	39.48	7.208E-04
21	60700.	7.87		
22	61209.	8.16		
23	61726.	8.46		
24	62200.	8.33		
25	62707.	9.17		
26	63320.	10.09		

1001426 FIA 1007 1200F AIR 10 CPM R= 0.05 THICKNESS= 7.569 MM P1AX=120.096 KN WIDTH=25.349 MM CENTER CRACK SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	0.	1.82	46.02	7.366E-04
2	100.	1.89	47.20	5.461E-04
3	300.	2.00	48.64	7.916E-04
4	450.	2.12	51.16	1.926E-03
5	600.	2.41	54.37	1.548E-03
6	750.	2.66	57.84	2.495E-03
7	900.	3.01		

1001456 FIA 1007 1200F AIR 10 CPM R= 0.50 THICKNESS=12.751 MM P1AX= 8.273 KN WIDTH=63.309 MM COMPACT SPECIMEN				
NO.	CYCLES	A(MM)	DEL K (MPA√M)	DA/DN (MM/CYCLE)
1	350.	30.36	11.68	7.622E-04
2	425.	30.42	11.78	2.057E-03
3	575.	30.73	11.95	2.100E-03
4	725.	31.04	12.13	2.371E-03
5	875.	31.40	12.41	3.513E-03
6	1050.	32.01	12.64	1.075E-03
7	1200.	32.18	12.89	3.232E-03
8	1400.	32.82	13.26	2.736E-03
9	1575.	33.30	13.59	2.961E-03
10	1750.	33.82	13.98	3.259E-03
11	1925.	34.39	14.42	3.971E-03
12	2075.	34.98	14.86	4.145E-03
13	2200.	35.50	15.29	4.003E-03
14	2325.	36.00	15.99	8.544E-03
15	2450.	37.07	16.58	2.083E-03
16	2525.	37.23	16.96	7.721E-03
17	2600.	37.81	17.46	4.886E-03
18	2675.	38.17	18.10	1.009E-02
19	2750.	38.93	18.97	9.026E-03
20	2825.	39.60	19.83	1.267E-02
21	2875.	40.24	20.65	1.517E-02
22	2910.	40.77	21.53	1.818E-02
23	2945.	41.40	22.40	1.747E-02
24	2970.	41.64	23.32	2.586E-02
25	2995.	42.49	24.43	2.826E-02
26	3015.	43.05	25.66	3.454E-02
27	3035.	43.74	27.01	3.954E-02
28	3050.	44.34		

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1000784 PWA 1073 1310F AIR MISSION
R= 0.10 THICKNESS=10.282 MM
P/AX= 17.792 KN WIDTH=63.424 MM
COMPACT SPECIMEN
NO. CYCLES A(MM)

1	1.	20.60
2	10.	21.09
3	20.	21.47
4	30.	21.75
5	40.	22.19
6	50.	22.54
7	60.	22.93
8	70.	23.33
9	80.	23.83
10	90.	24.25
11	100.	24.58
12	110.	24.93
13	120.	25.52
14	130.	26.26
15	138.	26.69
16	146.	27.05
17	154.	27.35
18	163.	27.96
19	172.	28.59
20	180.	29.31
21	186.	29.68
22	192.	30.17
23	198.	30.69
24	203.	31.25
25	208.	31.70
26	213.	32.30

Continued Next Column

1000784 PWA 1073 1310F AIR MISSION
R= 0.10 THICKNESS=10.282 MM
P/AX= 17.792 KN WIDTH=63.424 MM
COMPACT SPECIMEN
NO. CYCLES A(MM)

27	217.	32.74
28	221.	33.08
29	225.	33.68
30	229.	34.08
31	233.	34.86
32	237.	35.40
33	241.	36.08
34	244.	36.69
35	246.	37.11
36	248.	37.60
37	250.	37.99
38	252.	38.44
39	254.	39.07
40	256.	39.65
41	258.	40.32
42	260.	41.04
43	261.	41.38
44	262.	41.91

1001333 PWA 1073 1275F AIR MISSION
R= 0.10 THICKNESS=12.692 MM
P/AX= 16.235 KN WIDTH=63.594 MM
COMPACT SPECIMEN
NO. CYCLES A(MM)

1	1.	21.97
2	25.	22.29
3	50.	22.53
4	85.	22.90
5	125.	23.44
6	165.	23.96
7	205.	24.59
8	245.	25.44
9	275.	25.79
10	305.	26.44
11	335.	27.09
12	365.	27.87
13	385.	28.31
14	405.	28.85
15	425.	29.61
16	440.	29.93
17	455.	30.44
18	470.	30.99
19	485.	31.44
20	500.	32.07
21	510.	32.46
22	520.	33.00
23	530.	33.51
24	540.	34.02
25	550.	34.57
26	560.	35.08
27	570.	35.73
28	580.	36.13
29	590.	36.83
30	600.	37.53
31	610.	38.67
32	625.	40.06
33	630.	41.09
34	635.	41.63
35	640.	43.11
36	643.	43.60

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1001335 PHA1073 1310F MISSION
R= 0.10 THICKNESS=12.824 MM
PHAX= 22.240 KN WIDTH=63.269 MM
COMPACT SPECIMEN
NO. CYCLES A(MM)

1	1.	20.03
2	10.	20.13
3	22.	20.45
4	30.	20.74
5	38.	21.35
6	46.	21.76
7	56.	21.89
8	68.	22.40
9	78.	22.83
10	89.	23.53
11	96.	23.69
12	106.	24.13
13	116.	24.63
14	125.	25.23
15	134.	25.71
16	143.	26.29
17	152.	27.07
18	157.	27.39
19	164.	27.94
20	171.	28.56
21	176.	29.03
22	181.	29.43

Continued Next Column

1001335 PHA1073 1310F MISSION
R= 0.10 THICKNESS=12.824 MM
PHAX= 22.240 KN WIDTH=63.269 MM
COMPACT SPECIMEN
NO. CYCLES A(MM)

23	165.	29.78
24	190.	30.28
25	195.	30.66
26	200.	31.17
27	205.	31.64
28	209.	32.39
29	212.	32.72
30	215.	33.17
31	218.	33.70
32	221.	34.14
33	224.	34.75
34	227.	35.47
35	230.	35.95
36	233.	36.91
37	235.	36.98
38	238.	37.20
39	242.	38.29
40	245.	39.13
41	246.	39.61
42	247.	40.19
43	248.	40.80
44	249.	41.48

1001473 PHA1074 1310 AIR MISSION
R= 0.10 THICKNESS= 9.017 MM
PHAX= 80.064 KN WIDTH=23.660 MM
SURFACE FLAW SPECIMEN
NO. CYCLES A(MM)

1	1.	1.77
2	100.	1.88
3	187.	2.48
4	245.	2.92
5	275.	3.12
6	305.	3.48
7	330.	3.80
8	345.	4.08
9	780.	4.54
10	395.	4.74
11	410.	5.18
12	420.	5.53
13	431.	5.82
14	436.	6.21
15	441.	6.42
16	446.	6.52
17	456.	6.63
18	466.	6.89
19	476.	7.61
20	480.	8.12
21	482.	8.36
22	484.	8.46
23	486.	8.74
24	489.	9.01
25	490.	8.71
26	493.	9.30
27	494.	9.81
28	495.	10.13
29	496.	10.22
30	497.	10.46
31	498.	10.65
32	499.	11.47

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1001498	PHA 1007	1150F	MISSION
R=	0.05	THICKNESS=	8.979 MM
PHAX=	88.960	KN	WIDTH=23.673 MM
SURFACE FLAW SPECIMEN			
NO. CYCLES	A(MM)		
1	1.	3.47	
2	100.	3.59	
3	204.	3.75	
4	304.	4.15	
5	354.	4.99	
6	406.	5.09	
7	464.	5.29	
8	502.	4.89	
9	555.	5.36	
10	629.	5.32	
11	649.	5.57	
12	699.	5.69	
13	729.	5.93	
14	761.	6.23	
15	808.	6.59	
16	839.	6.98	
17	854.	7.20	
18	869.	7.51	
19	887.	7.93	
20	905.	8.42	
21	918.	8.64	
22	926.	8.83	
23	937.	9.21	

1001500	PHA 1007	1150F	AIR	MISSION
R=	0.10	THICKNESS=	8.979 MM	
PHAX=	88.960	KN	WIDTH=23.711 MM	
SURFACE FLAW SPECIMEN				
NO. CYCLES	A(MM)			
1	1.	3.27		
2	80.	3.35		
3	170.	3.51		
4	260.	3.55		
5	360.	3.75		
6	460.	3.87		
7	560.	4.07		
8	680.	4.27		
9	760.	4.66		
10	840.	5.06		
11	855.	5.21		
12	905.	5.38		
13	955.	5.58		
14	1005.	5.49		
15	1055.	5.92		
16	1105.	6.22		
17	1155.	6.36		
18	1285.	7.01		
19	1320.	7.49		
20	1385.	7.98		
21	1390.	8.26		
22	1418.	8.73		
23	1431.	9.09		

1001501	PHA 1074	1310F	AIR	MISSION
R=	0.10	THICKNESS=	12.675 MM	
PHAX=	22.240	KN	WIDTH=63.388 MM	
COMPACT SPECIMEN				
NO. CYCLES	A(MM)			
1	1.	20.52		
2	8.	20.75		
3	20.	21.20		
4	32.	21.54		
5	44.	21.89		
6	56.	22.48		
7	66.	22.55		
8	78.	22.83		
9	90.	23.23		
10	102.	23.65		
11	114.	23.79		
12	126.	24.16		
13	139.	24.82		
14	149.	25.11		
15	159.	25.49		
16	169.	26.08		
17	179.	26.56		
18	189.	26.83		
19	199.	27.06		
20	209.	27.55		
21	218.	28.09		
22	227.	28.44		
23	237.	28.74		

Table Data Continued on Next Page

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1001501 PWA 1074 1310F AIR MISSION
R= 0.10 THICKNESS=12.675 MM
PHAX= 22.240 KN WIDTH=63.308 MM
COMPACT SPECIMEN
NO. CYCLES A(MM)

24	247.	29.37
25	257.	29.84
26	266.	30.37
27	274.	30.90
28	282.	31.50
29	290.	31.97
30	298.	32.73
31	305.	33.28
32	311.	33.78
33	317.	34.25
34	323.	34.95
35	328.	35.53
36	333.	36.16
37	338.	36.86
38	343.	37.45
39	347.	38.29
40	350.	38.88
41	353.	39.71
42	355.	40.17
43	357.	40.83
44	358.	41.02
45	360.	41.93
46	361.	43.01

1001503 PWA 1073 1310F MISSION
R= 0.10 THICKNESS=12.700 MM
PHAX= 22.240 KN WIDTH=64.018 MM
COMPACT SPECIMEN
NO. CYCLES A(MM)

1	1.	21.40
2	6.	21.84
3	13.	22.26
4	20.	22.87
5	26.	23.16
6	32.	23.37
7	38.	24.10
8	44.	24.53
9	50.	25.10
10	55.	25.63
11	60.	25.89
12	66.	26.38
13	72.	27.15
14	77.	27.27
15	82.	28.14
16	88.	28.79
17	93.	29.50
18	97.	29.97
19	101.	30.46
20	105.	31.01
21	109.	31.68
22	112.	32.13
23	115.	32.72
24	118.	33.29
25	121.	33.77
26	124.	34.52
27	127.	35.27
28	130.	35.66
29	133.	36.46
30	136.	37.55
31	138.	38.51
32	139.	39.35
33	141.	39.85
34	142.	40.42
35	143.	41.61

1001504 PWA 1073 1310F AIR MISSION
R= 0.10 THICKNESS=12.700 MM
PHAX= 22.240 KN WIDTH=63.431 MM
COMPACT SPECIMEN
NO. CYCLES A(MM)

1	1.	20.50
2	15.	21.36
3	27.	22.13
4	35.	22.65
5	45.	23.36
6	52.	23.68
7	59.	24.55
8	66.	25.13
9	71.	25.44
10	77.	26.10
11	82.	26.65
12	87.	27.43
13	91.	27.95
14	95.	28.11
15	101.	28.51
16	107.	29.19
17	113.	29.98
18	118.	30.70
19	122.	31.21
20	126.	32.00
21	129.	32.54
22	132.	33.18
23	135.	33.85
24	139.	34.68
25	142.	35.52
26	144.	35.91
27	146.	36.42
28	148.	37.09
29	151.	37.97
30	153.	38.36
31	155.	39.47
32	157.	40.24
33	158.	40.95

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1001563 PWA 1007 1150F AIR MISSION
R= 0.10 THICKNESS=12.848 MM
P_{MAX}= 22.240 KN WIDTH=63.500 MM
COMPACT SPECIMEN
NO. CYCLES A(MM)

1	1.	22.73
2	40.	23.17
3	80.	23.50
4	120.	23.80
5	160.	24.26
6	200.	24.62
7	240.	25.12
8	280.	25.59
9	320.	26.21
10	355.	26.19
11	390.	27.15
12	420.	27.20
13	450.	27.56
14	475.	27.66
15	500.	28.05
16	525.	28.45
17	550.	28.69
18	575.	29.63
19	595.	29.94
20	615.	30.02
21	635.	30.54
22	655.	30.71
23	675.	31.34

1001563 PWA 1007 1150F AIR MISSION
R= 0.10 THICKNESS=12.848 MM
P_{MAX}= 22.240 KN WIDTH=63.500 MM
COMPACT SPECIMEN
NO. CYCLES A(MM)

24	695.	31.57
25	705.	31.98
26	715.	32.60
27	755.	33.41
28	770.	33.32
29	785.	34.11
30	800.	34.26
31	815.	34.87
32	825.	35.05
33	835.	35.46
34	845.	35.99
35	855.	36.30
36	865.	36.97
37	873.	37.20
38	891.	37.67
39	895.	38.61
40	901.	39.01
41	907.	39.85
42	910.	40.54
43	913.	40.41
44	914.	40.88
45	917.	42.44
46	921.	43.51

1001565 PWA1007 1150F AIR MISSION
R= 0.10 THICKNESS=12.695 MM
P_{MAX}= 26.688 KN WIDTH=63.515 MM
COMPACT SPECIMEN
NO. CYCLES A(MM)

1	1.	21.23
2	40.	21.43
3	80.	21.46
4	130.	21.68
5	180.	22.05
6	240.	22.18
7	310.	22.57
8	380.	23.10
9	430.	23.41
10	490.	23.75
11	530.	24.06
12	590.	24.56
13	650.	24.92
14	730.	25.53
15	810.	26.21
16	880.	26.86
17	940.	27.65
18	1000.	27.65
19	1040.	28.58
20	1100.	29.04
21	1140.	29.59
22	1180.	29.74
23	1210.	30.69
24	1240.	31.11
25	1265.	31.53
26	1290.	31.83
27	1305.	32.14
28	1340.	32.40
29	1355.	35.69
30	1380.	37.43
31	1385.	37.99
32	1460.	38.94

Continued Next Column

APPENDIX C. CRACK PROPAGATION DATA FOR SPECIMENS TESTED (Continued)

1001575 PNA 1073 1275F AIR MISSION			
R= 0.05 THICKNESS= 9.017 MM			
FRIAX= 80.064 KN WIDTH=23.647 MM			
SURFACE FLAW SPECIMEN			
NO. CYCLES	A (MM)	DEL K (MPA $\sqrt{M}$)	DA/DN (MM/CYCLE)
1	1.97	22.19	3.135E-03
2	80.	22.79	-1.123E-04
3	227.	23.67	6.075E-03
4	287.	24.94	1.638E-03
5	387.	26.30	4.230E-03
6	487.	28.02	4.078E-03
7	577.	30.87	1.067E-02
8	677.	34.07	3.499E-02
9	697.	35.52	6.252E-03
10	723.	36.88	1.349E-01
11	728.	37.58	-2.311E-02
12	739.	37.75	2.269E-02
13	753.	38.52	1.626E-02
14	763.	39.04	1.842E-02
15	773.	40.84	4.000E-02
16	799.	42.65	4.106E-02
17	805.	43.15	2.921E-02
18	809.	43.53	4.191E-02
19	813.	44.16	7.525E-02
20	817.	44.85	7.408E-02
21	820.	45.40	6.773E-02
22	823.	45.95	7.406E-02
23	826.	46.56	8.721E-02
24	829.	47.19	8.043E-02
25	832.	47.94	3.658E-01
26	833.		

LIST OF SYMBOLS

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>	
		<u>Metric (SI)</u>	<u>English</u>
a	crack length	mm	in.
B	specimen thickness	mm	in.
C ₁	SINH material coefficient = 0.5	dimensionless	dimensionless
C ₂	SINH horizontal scaling coefficient	dimensionless	dimensionless
C ₃	SINH horizontal inflection coefficient	log (ΔK)	log (ΔK)
C ₄	SINH vertical inflection coefficient	log (da/dN)	log (da/dN)
CC	center crack specimen		
CS	compact specimen		
d	differential		
da/dN	cyclic rate of crack growth	mm/cycle	in./cycle
da/dt	sustained load rate of crack growth	mm/hr	in./hr
Δ	algebraic difference		
Δa/ΔN	growth rate determined from direct secant	mm/cycle	in./cycle
ΔK	applied stress intensity = $K_{max} - K_{min}$	MPa√m	ksi√in.
ΔN _{OL}	number of fatigue cycles applied between periodic overloads	cycles	cycles
ΔN _{Dwell}	number of fatigue cycles applied between period load dwells		
f(subscript)	final value of parameter subscripted		
f,g	functions		
i(subscript)	initial value of parameter subscripted		
K	stress intensity factor	MPa√m	ksi√in.
LCF	low cycle fatigue		
LEFM	linear elastic fracture mechanics		
N	number of cycles	cycle	cycle
N _A	number of cycles to specimen failure (actual)		
N _c	number of cycles to specimen failure (calculated)		
N*	period of crack retardation	cycle	cycle
N _{DR}	period of delayed retardation	cycle	cycle
ν	test frequency	Hz	Hz, cpm (cycles/minute)
P	load	N	Kips
P _{max}	maximum load	N	Kips
P _{min}	minimum load	N	Kips
P _{ol}	magnitude of overload	N	Kips
R	load ratio = P _{min} /P _{max}		

LIST OF SYMBOLS (Continued)

<i>Symbol</i>	<i>Definition</i>	<i>Units</i>	
		<i>Metric (SI)</i>	<i>English</i>
σ	stress	MPa	ksi
t	time	seconds	seconds
T	temperature	°C	°F
W	specimen width	mm	in.

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