NASA CR-72738
IITRI-B6078-38

FINAL REPORT

THERMAL FATIGUE DATA ON 15 NICKEL- AND COBALT-BASE ALLOYS

by

Maurice A.H. Howes
Metals Research Division

IIT RESEARCH INSTITUTE
10 West 35th Street
Chicago, Illinois 60616

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

May 15, 1970

CONTRACT NAS3-9411

NASA Lewis Research Center
Cleveland, Ohio
John P. Merutka, Project Manager
David A. Spera, Research Advisor

FOREWORD

This report describes the work performed under NASA Contract NAS3-9411 on the project entitled "Thermal Fatigue Data on 15 Nickel- and Cobalt-Base Alloys." The report covers the period March 24, 1967, to May 20, 1970.

The NASA personnel assigned to this contract were:

John H. Deford and Leonard Schopen - Contracting Officers
John P. Merutka - Project Manager
David A. Spera - Research Advisor
R. J. Paginton - Contract Administrator

The IITRI personnel who contributed to this project include Maurice Howes (Project Manager), E. R. Porlier (Administrative Supervisor), R. K. Nolen, E. Marozas, T. Harbrecht, L. Hopkins, D. Pitcairn, P. Santora, H. Konjevich, R. Dragen, and V. Johnson.

Data are contained in Logbooks No. C17551, C17552, C17793, C18644, C18959, C19283, C19290, C19440, C19720, and C19960.

The IITRI internal designation for this report is IITRI-B6078-38.

Maurice AH Howes.
Maurice A.H. Howes
Manager, Physical and
Ferrous Metallurgy

N M Parikh
N. M. Parikh, Director
Metals Research Division

TABLE OF CONTENTS

Page

SUMMARY. 1

INTRODUCTION 2

EXPERIMENTAL WORK. 3

Materials and Conditions 3

Heat Treatment 4

Thermal Fatigue Facility 4

Facility Performance 5

Thermal Fatigue Fixture--Development and Evaluation 6

Test Conditions. 8

Measurement of Transient Temperatures. 9

Inspection of Specimens During Testing 10

Metallography. 10

Scanning Electron Microscopy 10

RESULTS. 10

Thermal Fatigue Data 10

Metallography. 11

Scanning Electron Microscopy (SEM) 13

Hardness Measurements. 14

Oxidation. 14

DISCUSSION 15

CONCLUSIONS. 17

REFERENCES 18

ABSTRACT

The fluidized bed technique has been used to measure the relative thermal-fatigue resistance of 15 superalloys B1900, IN-100, PWA 1401, X-40, WI-52, MAR-M 200, PWA 664, MAR-M 302, IN-162, IN-713C, M22, TAZ-8A, Udimet 700 (cast and wrought), and TD-NiCr. PWA 1401 and PWA 664 were directionally solidified. B1900, IN-100, and PWA 1401 were also tested with aluminum-10% silicon coatings. Among the 15 alloys, cycles to cracking differed by several orders of magnitude. Coatings and directional solidification were of definite benefit. Some alloys experienced serious weight losses and internal oxidation. This investigation is part of a general study of thermal fatigue conducted by the NASA-Lewis Research Center.

LIST OF TABLES

Page

1 Alloys and Variations Used in Test Program. 19

2 Compositions of All Alloys Used in the Experimental Program. 20

3 Location of "As-Cast" Macrographs of the Directionally Solidified Alloys 21

4 Tensile Properties at 1400°F. 22

5 Creep-Rupture Properties at 1800°F. 23

6 Heat Treatments for Specimens 24

7 Calibration Data for Instrumented IN-100 Specimens When Cycled Into the High Temperature Bed 25

8 Calibration Data for Instrumented WI-52 Specimens When Cycled Into the High Temperature Bed 26

9 Calibration Data for Instrumented MAR-M 200 Specimens When Cycled Into the High Temperature Bed 27

10 Calibration Data for Instrumented MAR-M 302 Specimens When Cycled Into the High Temperature Bed 28

11 Calibration Data for Instrumented Udimet 700 Specimens When Cycled Into the High Temperature Bed . 29

12 Calibration Data for Instrumented IN-100 Specimens When Cycled Into the Intermediate Temperature Bed . . 30

13 Calibration Data for Instrumented WI-52 Specimens When Cycled Into the Intermediate Temperature Bed . . 31

14 Calibration Data for Instrumented MAR-M 200 Specimens When Cycled Into the Intermediate Temperature Bed 32

15 Calibration Data for Instrumented MAR-M 302 Specimens When Cycled Into the Intermediate Temperature Bed 33

16 Calibration Data for Instrumented Udimet 700 Specimens When Cycled Into the Intermediate Temperature Bed 34

17 Inspection Points and Total Thermal Cycles for Each Alloy 35

LIST OF TABLES (Continued)

Page

18 Summary of Crack Propagation for B1900. 36

19 Summary of Crack Propagation for B1900-coated 38

20 Summary of Crack Propagation for IN-100 40

21 Summary of Crack Propagation for IN-100-coated. . . . 42

22 Summary of Crack Propagation for PWA 1401 44

23 Summary of Crack Propagation for PWA 1401-coated. . . 45

24 Summary of Crack Propagation for X-40 46

25 Summary of Crack Propagation for WI-52. 48

26 Summary of Crack Propagation for MAR-M 200. 50

27 Summary of Crack Propagation for PWA 664. 53

28 Summary of Crack Propagation for MAR-M 302. 54

29 Summary of Crack Propagation for IN-162 56

30 Summary of Crack Propagation for IN-713C. 58

31 Summary of Crack Propagation for M22. 60

32 Summary of Crack Propagation for TAZ-8A 63

33 Summary of Crack Propagation for Udimet 700 (Cast). . 65

34 Summary of Crack Propagation for Udimet 700 (Wrought) 67

35 Summary of Crack Propagation for TD-NiCr. 70

36 Thermal Cycles Required to Initiate the First Crack in Each Edge. 71

37 Summarv of Specimens Sectioned for Metallography and SEM Fractography. 72

38 Surface Hardnesses (Rockwell C) of Thermal Fatigue Specimens 73

39 Microhardness Measurements in Thermal Fatigue Sample Sections. 76

LIST OF FIGURES

Page

1 Dimensions of Test Specimens Used in the Program. . . 77

2 Macrographs of Grain Patterns in PWA 664. 78

3 Macrographs of Grain Patterns in PWA 1401 81

4 Schematic View of Thermal Fatigue Facility. 85

5 Fluidized Bed Air Requirements. 86

6 Simulated Theraml Fatigue Specimen Utilized During Fixture Development 87

7 Temperature Gradient in Horizontally Held Specimens . 88

8 Temperature Gradient in Vertically Held Specimens . . 88

9 Distortion in a Stiffened Variation of the Fixture Shown in Figure 8 after 100 Cycles of Operation . . . 89

10 Use of Location Slots in the Test Pieces with Top and Bottom Plates in the Vertical Plane 89

11 Fixture with Welded Channel Sections after 580 Cycles 90

12 New Fixture with Rolled Channel Section Slide Members 90

13 Final Form of Fixture as Used in the Program with Increased Section Bottom Plate and Top Retaining Plates. 91

14 "C" Type Fixture After 100 Cycles 91

15 Calibration Curve for IN-100 Cycles under Set F Conditions. 92

16 Appearance of Test Specimens at the Conclusion of Thermal Fatigue Cycling 93

17 Thermal Cycles to Initiate the First Crack Formed in Either Test Edge Under Test Conditions A to F 98

18 Crack Propagation Data for the First Crack Formed in Uncoated and Coated IN-100 111

19 Crack Propagation Data for the First Crack Formed in Uncoated and Coated PWA 1401 112

LIST OF FIGURES (Continued)

Page

20 Appearance of Crack Propagation Path in Thermal Fatigue Specimen. 113

21 Root of Crack in Thermal Fatigue Specimens, Longitudinal Section. 119

22 B1900, Coated Sample. Transverse Section Showing Crack Through Coating 127

23 IN-100, Coated Sample. Transverse Section Showing Crack Through Coating 127

24 IN-100, Transverse Section Showing Possible Crack Nucleation Points 128

25 PWA 1401, Transverse Section Showing a Possible Crack Nucleation Point. 128

26 PWA 1401, Coated Sample, Showing Thermal Fatigue Crack Through Coating 129

27 IN-713C Sample Showing Possible Crack Nucleation Sites 129

28 X-40 Sample Showing Early Stages of Crack Propagation 130

29 WI-52 Longitudinal Section Showing Possible Crack Nucleation Sites. 130

30 MAR-M 200 Longitudinal Section Showing Possible Crack Nucleation Sites. 131

31 MAR-M 302 Longitudinal Section Showing Early Stages of Crack Propagation. 131

32 M22 Longitudinal Section Showing a Possible Crack Nucleation Site 132

33 TAZ-8A Longitudinal Section Showing the Early Stage of a Crack. 132

34 Cast Udimet 700 Longitudinal Section Showing Possible Crack Nucleation Sites. 133

35 Wrought Udimet 700 Logitudinal Section Showing. . . . Possible Crack Nucleation Site. 133

36 PWA 664 Longitudinal Section Showing Subsurface Porosity as Possible Crack Nucleation Site. 134

LIST OF FIGURES (Continued)

Page

37 Transverse Section through the Original 0.025 in. Radius after Thermal Fatigue Testing for the Cycles Indicated. 135

38 ThO_2 Dispersion in TD-NiCr Material Used in this Program. 137

39 ThO_2 Dispersion in TD-NiCr Material Known to Have Satisfactory Properties. 137

40 Appearance of Thermal Fatigue Fracture of IN-100 in the SEM 138

41 Appearance of Thermal Fatigue Fracture of MAR-M 200 in the SEM 138

42 Appearance of Thermal Fatigue Fracture of MAR-M 302 in the SEM 139

43 Appearance of Thermal Fatigue Fracture of TD-NiCr in the SEM 139

44 Appearance of Thermal Fatigue Fracture of Cast Udimet 700 in the SEM. 140

45 Appearance of Thermal Fatigue Fracture of Wrought Udimet 700 in the SEM. 140

46 Weight Loss after 1000-Cycle Exposure. 141

SUMMARY

This investigation is part of a general study of thermal fatigue conducted by the NASA-Lewis Research Center. This program used the fluidized bed heating and cooling technique to measure the relative thermal fatigue resistance of 15 superalloys. These alloys included B1900, IN-100, PWA 1401, X-40, WI-52, MAR-M 200, PWA 664, MAR-M 302, IN-162, IN-713C, M22, TAZ-8A, Udimet 700 (cast and wrought), and TD-NiCr. Two alloys--PWA 1401 and PWA 664--were directionally solidified. Three--B1900, IN-100, and PWA 1401--were also tested with a diffused aluminum-10% silicon slurry coating. The resistance to cracking was measured by cycling specimens between fluidized beds at 1990°F (1088°C) and 600°F (316°C), examining the specimens for cracks at intervals, and measuring the lengths of the first three cracks to be formed. When sufficient crack propagation data were obtained, the specimen was removed from the test.

The most crack-resistant materials were those coated or directionally solidified: PWA 664, PWA 1401, PWA 1401--coated, and B1900--coated. Among the conventionally cast and uncoated materials, the most crack-resistant nickel-base and cobalt-base alloys were TAZ-8A and X-40, respectively.

Two alloys--PWA 664 and MAR-M 200--had the same composition but different grain structure and radically different resistance to thermal fatigue. Directionally solidified PWA 664 had very high resistance to cracking, while MAR-M 200 showed poor resistance. This indicates that grain structure is at least as important as the composition of the superalloy.

Examination of the crack paths and fracture surface showed that the cracks tend to follow intergranular paths (with the possible exception of TAZ-8A and the cobalt-base alloys). Oxidation proceeds as cracks are formed, and the oxidation products are observed for the whole length of the crack. It is possible that oxidation at the surface grain boundaries occurs before cracking, particularly in the nickel-base alloys. The oxidation causes serious material loss during cycling on some alloys. However, it is shown that coatings can significantly reduce oxidation and metal loss.

INTRODUCTION

The purpose of the present work is to use the fluidized bed technique to measure the relative thermal fatigue cracking resistance of fifteen high-temperature superalloys that could be used for advanced air breathing engines. The study includes metallographic and hardness studies before and after thermal fatigue testing. The work was carried out in a facility designed and built by IIT Research Institute.

This investigation is part of a general study of thermal fatigue being undertaken by the NASA-Lewis Research Center. Other parts of the study and the possible use of the data are described by Spera.(1)

Thermal fatigue is a possible failure mechanism in any situation that involves fluctuating temperatures. If certain materials are heated or cooled rapidly, cracking sometimes occurs. The phenomenon, which is often called thermal shock, is caused by thermal gradients present during rapid temperature change. As a result, strain is produced which is related to the coefficient of expansion of the material. Failure occurs when thermally induced stresses exceed the strength of the material after starting as a crack in the most sensitive area. In metals, the thermal fatigue mechanism often results in the gradual formation of a network of cracks and is commonly referred to as craze cracking, heat checking, or fire cracking. Any part which undergoes temperature cycling during service is likely to fail by this mechanism.

Failures due to thermal fatigue can be found in brake drums, turbine blades, internal combustion engine pistons, rolls for forming hot steel, forging dies, railway wheels, furnace components, and in molds used for glass and metal molding. Thermal fatigue can become the dominant failure mode in aircraft gas turbine engines as the operating temperature and thermal gradients become more severe and the expected service life becomes longer.

Many methods of heating and cooling have been used to simulate the thermal cycles experienced in actual applications. Some of the earliest work used direct flame impingement on a surface. However, unless carefully controlled, the combustion products and variation in temperature conditions can introduce an arbitrary environment which can influence the cracking mechanism.

High-frequency heating and electrical resistance heating systems can be used to establish simulated thermal cycling conditions; however, they are generally expensive to construct for the multi-station test facilities which are needed to amass data quickly. In the consideration of thermal fatigue, the crack propagation rate is as important as the start of cracking. For instance, a material that cracks early might be satisfactory if the crack propagation rate is very slow. With high frequency and resistance heating, the formation of a crack alters the flux or current density in such a way that the crack is overheated and measurement of propagation rate becomes meaningless.

The fluidized bed heating system for thermal fatigue testing has many advantages and no significant disadvantages. The bed construction is simple and relatively inexpensive. The rate of heat transfer to a specimen or group of specimens is high. The heat content of a particulate solid fluidized media is also high, so that a large number of specimens or a large specimen can be rapidly and repeatedly heated without lowering the bed temperature significantly. The fluid bed system uses low-velocity air flows (in the order of 1 fps), and in this respect the high-velocity gas flows in a turbine engine are not simulated. The first reported use of fluidized beds for thermal fatigue testing was in 1958 by Glenny and co-workers.(2) Since that time there have been many reports of the use of this technique to evaluate thermal fatigue resistance.(3-11) A bibliography of the literature of thermal fatigue up to 1967 was compiled by Carden.(12)

The original high-temperature bed described by Glenny was 6 in. in diameter and was heated by wire-wound elements of 4 kw total input. For this program much heavier loads of test specimens had to be cycled, and a bed diameter of 11.5 in. with a power input of 55 kw was required. The low-temperature bed was controlled at an intermediate temperature instead of room temperature; thus the lower temperature beds were required to have provisions for both heating and cooling. These features are described in the section under Experimental Work which deals with the thermal fatigue facility.

EXPERIMENTAL WORK

Materials and Conditions

Eighteen variations of alloys and treatments were studied in this program. These are listed in Table 1. Thirteen different material compositions were used as shown in Table 2. The main variations, apart from composition, are directional solidification and surface coating.

Both IN-100 and MAR-M 200 were used in the directionally solidified condition. These were cast according to PWA 1401 and PWA 664 specifications, respectively.

The alloys coated were B1900, IN-100 and PWA 1401. The coating used was PWA 47 (Jo-Coat). This is a proprietary coating of Pratt and Whitney Aircraft Division, United Aircraft Corporation. The only information available is that Jo-Coat is a slurry-sprayed coating having a composition of aluminum-10% silicon. This coating is subsequently heat treated.

Two types of test pieces were produced:

1. A tapered thermal fatigue test piece for use in this program.
2. A uniaxial tensile and stress-rupture test piece for use by NASA-Lewis Research Center.

These test pieces are shown in Figure 1. The thermal fatigue test piece was produced in all eighteen variations of material and treatment. The uniaxial test piece was produced in all variations except PWA 664.

The two directionally solidified materials--PWA 1401 and PWA 664--were cast oversize and machined to size. The grain patterns in the as-cast condition are shown in Figures 2 and 3. The directionally solidified specimens were individually identified in order that the results might be considered in relationship to the original macro grain structure. The specimens used in each set and the figures giving the macrostructure are indicated in Table 3.

All other test pieces in cast materials were cast to size. The test pieces in wrought Udimet 700 and the TD-NiCr were machined to size. Owing to delivery difficulties the TD-NiCr material was supplied from two different heats. However, they are believed to have identical mechanical properties. Heat No. 2858 was used for sets A to D while heat No. 1852 was used for E and F. The identities of all test pieces were maintained throughout testing in case the heat was a source of variation of results. Tensile properties at 1400°F (760°C) and creep-rupture properties at 1800°F (982°C) were obtained by NASA-Lewis using the uniaxial specimens. The results are given in Table 4 and 5. The creep-rupture results for IN-713C, M22, and TD-NiCr are significantly lower than average published data.

Heat Treatment

The heat treatments used for all specimens are shown in Table 6. All heat treatment was carried out in an argon atmosphere.

Thermal Fatigue Facility

A schematic drawing of the thermal fatigue testing facility is shown in Figure 4. It consists of a 11.5 in.

diameter high-temperature bed situated between two 14 in. diameter intermediate-temperature beds.

The center high-temperature bed has either an Inconel retort or a silicon carbide retort, depending on the maximum temperature requirements, and a stainless steel air-diffuser box supplied with air from a low-pressure blower. The bed is heated by 12 silicon carbide elements with a total power of 55 kw. Heat insulation is provided by two layers of refractory insulating brick and 1 in. of Fiberfrax.

The intermediate beds are double walled, with a stainless steel liner and a 1 in. insulation of Fiberfrax. Heating is provided by three Calrod elements (total power of 12 kw for each bed) situated above the stainless steel air box. For cooling, the heat exchanger can be either a multi-tube, water-cooled copper assembly (left bed, Figure 4) for bed temperatures up to 400°F or an air-cooled stainless steel jacket (right bed, Figure 4) for bed temperatures above 400°F. These heat exchangers are interchangeable. For all work carried out on this program, the air-cooled heat exchanger was used.

The specimens are cycled by means of automatically controlled pneumatic cylinders which are sequenced by timers and limit switches. The facility will cycle automatically for the number of cycles selected.

The air supply for fluidization is controlled through flow-meters for each bed. The maximum fluidization air demand is about 3500 cu ft/sq ft/hr (3500 cfh) for each of the intermediate beds at 100°F and 900 cu ft/sq ft/hr (600 cfh) for the high-temperature bed at 2000°F. Less inlet air is required as the bed temperature is increased due to the expansion of the air as it passes through the bed. Tests show that the fluidization range is fairly narrow since the bed will rapidly empty if excessive air is used. For high heat transfer coefficients the bed should be worked at just below the maximum air flow curve in Figure 5.

Each bed is fitted with four thermocouples for control, over-temperature protection, low-temperature test cutoff, and recording purposes.

Facility Performance

The high-temperature bed will operate at 2300°F (1260°C) using a silicon carbide retort and could be run at this temperature for testing small samples. However, as the weight of the specimen load in pounds per hour is increased, the maximum permissible bed temperature must be decreased. Otherwise the temperature of the heating elements would exceed the maximum permissible value of 2750°F (1510°C). With a specimen load of 15 lb, the maximum bed temperature is about 2000°F (1204°C) with a constant input of about 45 kw. At below 200°F bed temperature, the Inconel retort may be used.

The intermediate beds will run at a maximum temperature of 800°F (427°C). When cooling a 15 lb load from 200°F every 4 min, the air-cooled and water-cooled heat exchangers will hold the bed temperatures at 400°F (204°C) and 200°F (83°C), respectively.

Thermal Fatigue Fixture--Development and Evaluation

A satisfactory fixture for holding the specimens must meet several requirements. It should have a reasonable degree of creep and thermal fatigue resistance, and be relatively simple to fabricate. The fixture should support the specimens in such a manner so as not to interfere with uniform heating and cooling of all specimens. The fixture design should ensure that its thermal expansion and contraction does not distort the test pieces. Therefore, several designs and materials were investigated to discover the best design.

Simulated specimens of type AISI 304 stainless steel were used throughout the initial fixture design study. Figure 6 shows the dimensions of the specimen. At the start of development, two fixtures were designed and fabricated--one to support the specimens horizontally (Figure 7), and the other to support them vertically (Figure 8). The material was AISI 304 stainless steel. Each fixture with 20 specimens was thermal-cycled in fluidized heating and cooling beds, with a 2 min dwell in each bed. The maximum bed temperature was 1950°F (1066°C) with a minimum temperature of 400°F (204°C). After 20 cycles, the fixture for holding the specimens horizontal showed little or no distortion. However, a temperature gradient in the specimens was observed (Figure 7), with the center 1 in. critical test area of the top specimen being considerably darker in heat color (1500°F) than the outer portions (1850°F). This dark region "fanned out," such that the entire bottom specimen was only approximately 1400°F-1500°F. This temperature gradient was probably due to the wide bottom plate of the fixture. The plate was an inch wider than the specimens, and this was sufficient to impair proper fluidization around the specimens. This design was discarded in favor of the one which held the specimens vertically.

The vertical-specimen fixture was tested in the manner described above, and it was found to cause a temperature gradient in the bottom inch of the specimens (Figure 8). Here again, the bottom plate shielded the specimens from the direct vertical action of the fluidizing media. With either fixture, thermal equilibrium (no thermal gradient) could only be attained by a longer heating cycle. In addition to the slight gradient produced, the top and bottom plates of the vertical fixture distorted, with the bottom distortion more severe. In an attempt to remedy this situation, triangular ribs were welded to the straightened bottom plate. Figure 9 shows the condition of the fixture and specimen after 100 thermal cycles. The end bolts bent, and one fractured in the threads. This fixture has two inherently undesirable features--namely, gross distortion occurs in a relatively few cycles, and the bottom plate restricts fluidization thus causing a temperature gradient from one specimen to another and along the span of a given specimen.

At this point in the fixture development program a new approach was taken. The primary concern was that of obtaining uniform heating and cooling of all specimens. Therefore, the top and bottom plates of the fixture had to be changed. A round notch was machined into the ends of the specimens (Figure 1) in order that they could be supported by plates in the vertical plane. This eliminated the shielding effect and produced more uniform heating of the fixture itself. Figure 10 shows the scheme used. Very uniform heating was attained in both the specimens and the fixture. However, after 100 cycles the side members were somewhat bowed.

After straightening the sides of the fixture shown in Figure 10, strips of the same width and thickness were welded to the sides to form channels and the fixture was bolted together as shown. Figure 11 shows this modification of the fixture after cycling the specimens 580 times. A very small amount of distortion is seen. The fracture through the top bolt hole is perhaps due to the lack of sufficient material above it. This fixture showed the most promise and therefore was further considered with some modifications.

Figure 12 shows the modified fixture prior to thermal cycling. The two vertical end pieces are standard 1 in. x 2 in. AISI 304 stainless steel channel sections. The top and bottom plates are wrought, heat-treated Udimet 700. After some 1000 thermal cycles this fixture too showed some distortion. The top and bottom plates had two-dimensional distortion, such that the plates had to be flame-straightened. Auxiliary plates were bolted to the top plate to restrain the specimens if the fixture became unduly distorted while cycling. These added plates did not affect the uniform heating. The maximum temperature to which the fixture is subjected is so severe that even the Udimet 700 superalloy has to be straightened after each 400-500 cycles. The latest design and the one which is the most satisfactory has a bottom plate machined from Inconel 600 stock. The top plate is identical to that shown in Figure 12. The added thickness and modified shape increased the rigidity. Figure 13 shows the fixture after

150 cycles with the auxiliary top plates and also the thicker bottom plate. The superalloy test specimens were cycled using this fixture.

During this fixture development phase and simultaneously with the design of other fixtures, a somewhat different approach was taken. On the theory that perhaps the previous fixtures may have been too bulky and constructed in such a manner as to induce distortion, a different shaped fixture was designed and tested. Figure 14 shows this fixture after 100 cycles. The distortion caused the end specimens to bend, and further cycling would cause all the specimens to fall from the fixture. This design was abandoned in favor of the fixture shown in Figure 13.

During the latter stages of testing, fewer samples were run at one time because sufficient data had been accumulated on the other samples. For these tests a fixture of the same design but holding 10 specimens (2 dummies + 8 actual test specimens) was used. This fixture was less subject to distortion and was more suited for long runs involving a high number of cycles. The smaller capacity fixture with 10 specimens weighed 9.9 lb as compared with 14.7 lb for the 20-specimen fixture. Since the difference in fixture weight is negligible compared with the weight of alumina used in the bed (approximately 250 lb); the heating and cooling conditions are not affected.

Test Conditions

Six sets of specimens were cycled. Each set consisted of 18 thermal fatigue test pieces, as listed in Table 1, with a dummy stainless steel sample at each end to eliminate end effects.

Specimens were always placed in the fixture in the same order--i.e., IN-713C, M22, TAZ-8A, WI-52, B1900 coated, B1900, MAR-M 302, In-162, PWA 664, MAR-M 200, wrought Udimet 700, cast Udimet 700, IN-100, PWA 1401 coated, PWA 1401, TD-NiCr, and X-40. The 0.025 in. radius edges were all on the same side of the fixture. These fixed positions were maintained for convenience in inspection. Previous investigations by IITRI have shown that position in the fixture does not have any particular effect on thermal fatigue life.

The following bed temperatures and fluidizing conditions were maintained constant through the entire test series:

	Temperature		Air Flow (Measured at 150°F, 2 psi pressure)	
	°F	°C	ft^3/ft^2/hr	m^3/m^2/hr
Hot bed	1990	1088	900	275
Intermediate bed	600	316	2100	640

The fluidized media was 28-48 mesh tabular alumina.

The time of immersion in each bed was varied in each set as follows:

	Time, min	
Set	Hot Bed	Intermediate Bed
A & B	2.0	2.0
C	2.5	2.5
D	3.0	3.0
E	3.5	3.5
F	4.0	4.0

Measurement of Transient Temperatures

The transient temperatures achieved during the cycling of sets A (or B), D, and F were established using instrumented specimens, each fitted with five thermocouples. The couple positions are shown in Figure 1. Five alloys were calibrated in this way: IN-100, WI-52, MAR-M 200, MAR-M 302, and Udimet 700 (wrought). The thermocouples were magnesium oxide insulated, Inconel 600 sheathed, ISA type K (Chromel/Alumel) with an outside sheath diameter of 0.020 in. These couples were fabricated to meet specifications MIL Q-9858 and ASTME-235. The couples were run in grooves milled in the surface of the specimen. Grooves were 0.022 in. wide and 0.020 in. deep. The thermocouples were secured in place using an air-setting two-part Allen P-1 ceramic cement. After curing at 600°F (316°C) an adherent bond is formed sufficient to hold the thermocouple in place. Temperatures were recorded on a multichannel high-speed recorder.

Typical curves obtained for IN-100 using a 4 min immersion time in each bed are shown in Figure 15. The effect of longer immersion times is to increase T_{max} and decrease T_{min}. Complete tabulated data are shown in Tables 7 to 16.

Inspection of Specimens During Testing

The specimens were removed at regular cycle intervals, and both edges were examined for cracks using a 30X microscope. When a crack was discovered, the length from crack tip to specimen edge was measured on both sides of the specimen and the average taken as the crack length. Measurement was made on a traveling microscope.

Table 17 summarizes the inspection points and total cycles that each specimen underwent during test.

When sufficient crack data were obtained, the specimen was removed from the fixture and replaced by a stainless steel dummy specimen.

At the later inspection points a Rockwell C hardness reading was taken on the surface of each specimen.

Metallography

At the end of the test program selected samples from sets C, D, and F were sectioned for metallography. The section containing the crack was cut from the specimen and ground carefully down to the center plane. The specimen was mounted in a thermo-setting plastic and prepared in the conventional way using automatic polishing, and finishing on a microcloth wheel with 0.05 micron abrasive powder. The nickel-base alloys were electrolytically etched in 10% phosphoric acid using about 1 1/2 v for 3 seconds. The cobalt-base alloys were etched electrolytically in a mixture of hydrochloric and acetic acid (approximately 6 v for 10 seconds).

Scanning Electron Microscopy

Selected fracture faces were separated by cutting through the tip of the crack so that one face could be viewed normally. The specimen was placed in a JSM-2 scanning electron microscope without further preparation. An operating voltage of 25 kw was used and examination made in the range 30 to 10,000X.

RESULTS

Thermal Fatigue Data

Complete crack propagation data are contained in Tables 18 to 35. Data are given as crack length versus cycle number for a maximum of three cracks. The appearance of the specimens after testing is shown in Figure 16.

The number of cycles required to initiate cracks was of primary interest in this study. There are several ways of determining this number which cannot be measured directly. Glenny(2) used the procedure of averaging the cycles between the last inspection cycle to show no crack and the first inspection when the crack was observed. A refinement of this method is to plot crack length versus cycle number and extrapolate to zero crack length. This later procedure is of particular value when the test section is of constant thickness and the crack length versus cycle number curves approximate to straight lines. The wedge section specimen used in this investigation results in curved crack propagation curves and maked it difficult to accurately extrapolate the curves to zero crack length. The averaging method of Glenny has been used in this investigation, and the cycles to initiate the first crack in each alloy are summarized in Table 36. Data from Table 36 are presented graphically in Figure 17.

One consideration beyond the initiation of crack cycles is the crack propagation rate. Inspection of Table 36 shows that crack propagation rates do vary in different materials. Crack propagation data for uncoated and coated IN-100 and PWA 1401 are shown in Figures 18 and 19. Crack propagation is particularly slow in the directionally solidified alloys (compare Figures 18 and 19). However, there is a tendency in these materials for small cracks to start from the locating grooves at the ends of the specimens. This results from the fact that the grain structure is highly directional. An extreme case of this is presented by some of the TD-NiCr samples which at the conclusion of testing were in danger of splitting into two parts. The presence of these splits would lower the stresses at the test edges.

In some cases the 0.040 in. test edge initiated cracks before the 0.025 in. edge. This was probably due to weaknesses in the 0.040 in. edge causing preferred initiation. Once a crack was well established, it is probable that the stresses were relieved sufficiently to delay crack initiation in the opposite edge. It was also noticeable that when several cracks propagated they did so at regular intervals along the specimen. When one crack formed, it relieved the stresses locally and thus prevented another crack forming within the immediate neighborhood of the first crack.

Metallography

A total of 50 specimens were sectioned for metallographic work. In most instances cracks between 0.100 and 0.300 in. in length (2.5-7.5 mm) were selected for examination. Cracks from both the 0.025 in. radius and the 0.040 in. radius were examined, as well as longitudinal sections parallel to the mid-chord plane of the specimen. All the sections containing cracks were made on the mid-thickness plane. In certain cases complete cross-sections were taken. Table 37 summarizes the specimens sectioned for metallography. All the photomicrographs presented are from specimens from set D with the exception of certain directionally solidified sections. Set D represents the intermediate time exposure in the fluidized beds. The other samples examined showed essentially the same metallographic features.

The appearance of typical thermal fatigue cracks in the 0.025 in. radius are shown in the Figure 20 series at low magnification (20X). It will be seen that the cracks in most of the nickel-base alloys appear to be following a predominantly intergranular path. The cobalt-base alloys (X-40, WI-52, and MAR-M 302) have straighter crack paths with less evidence of an intergranular path. WI-25 tends to form very wide cracks, as may be seen from an examination of the actual specimens (Figure 16).

The crack roots for the same sequence of samples in Figure 20 are shown in Figure 21 in the etched condition. All the nickel-base samples show areas of alloy depletion along the edge of the crack probably due to oxidation. All cracks show the presence of oxide within the crack usually extending to the end of the crack. Many of these photomicrographs show clearly that the crack is following a grain boundary or other structural discontinuity.

Perhaps the most significant series of micrographs are Figures 22 to 36. These figures show the edges of the longitudinal and some transverse sections of the thermal fatigue specimen surfaces including the coating, where present. The objective was to examine the surface of the specimens for sites of possible crack nucleation. In this way it was hoped to discover something of the mechanism that initiates cracks.

All the nickel-base alloys show a uniform layer of alloy depletion at the surface. At positions adjacent to grain boundaries, the depletion layer is deeper, tending to follow grain boundaries. This can be seen most clearly in Figures 24, 27, 30, 34, and 35. There is little doubt that this process continues with increased thermal cycling. If the material is weaker at one location than the surrounding material, a crack can initiate. Once the crack 's growing, depletion continues ahead of the crack and tends to follow grain boundaries.

Figures 22, 23, and 26 show coated samples. It appears that the coating is less effective on the B1900 (Figure 22) than on the IN-100 material in preventing surface oxidation.

Fissures develop through the coatings and allow oxidation of the base metal but at a much slower rate.

In general, the directionally solidified alloys show far fewer surface discontinuities to allow penetration of oxide (compare Figures 24 and 25). However, the PWA 664 specimen examined (Figure 36) showed subsurface porosity which could nucleate thermal cracks. The surface carbide in Figure 25 was not typical of this alloy but shows a feature that may start a crack after thermal cycling.

The photomicrographs of the cobalt alloys (Figures 28, 29, and 31) are more difficult to interpret. There is obvious surface penetration, but the structures are totally different. There is probably also some alloy depletion, but it is less visible in these alloys. The grain size of the X-40 specimens was much smaller than the other alloys.

Transverse sections through the 0.025 in. radius test edge of selected specimens are shown in Figures 30a-c. The coating on IN-100 and B1900 specimens shows definite deterioration (see Figures 37a and 37c). Erosion of the uncoated samples can be clearly seen (compare the edge radius of 37b and 37d with 37a and 37c). The metal loss from erosion has been significant; this will be discussed in the later section, "Oxidation."

Creep tests performed by NASA on the TD-NiCr (Table 5) indicated that the properties were much lower than expected when compared to the nominal properties of 0.060 in. (1.5 mm) sheet of the same alloy. This could be because the material was supplied in the relatively thick section of 0.250 in. (6.3 mm). Figure 38 shows the unetched structure of the TD-NiCr used in this program, while Figure 39 shows the structure of a 0.060 in. thick sample of TD-NiCr. The difference in ThO_2 distribution is immediately apparent.

Scanning Electron Microscopy (SEM)

Thermal fatigue fractures of six materials were examined using the SEM. Magnifications of 30 to 10,000X were used. A selection of electron micrographs is presented in Figures 40 to 45.

Many photographs give evidence of considerable crack branching and intergranular fracture (see Figures 40a, 41a, 41b, 42a, 42b, 44a, 45a, and 44b). At higher magnification the IN-100 (Figure 40b) shows evidence of particles, probably carbides, pulling out of the fracture. The MAR-M 200 (Figure 39b) shows the presence of a heavy oxide on the surface of the fracture probably mixed with carbide particles. The same effect is seen in the MAR-M 302 (Figure 42). The TD-NiCr gives evidence of large thoria particles (Figure 43), the structure having high ductility around these particles. The Udimet 700 samples show clearly the intergranular nature of the fracture (Figures 44a and 45a). At higher magnifications there are oxide particles on the fracture (Figures 44b and 45b).

All the fractures show a high degree of "dimple" type fracture indicative of a ductile fracture with the possible exception of the MAR-M 302 (Figure 42), which apparently has large areas of cleavage.

Hardness Measurements

Hardness measurements were made on the thermal fatigue samples using the Rockwell C hardness scale. The measurements were made along the mid-chord of the samples in the same area as thermocouple No. 3 (Figure 1). The hardness results are given in Table 38. In most instances there is a tendency for the hardness to decrease with extended thermal cycling.

Microhardness surveys were carried out on the sections of tested specimens prepared for metallographic analysis. Hardness readings on tested material were taken in five positions and are listed in Table 39:

1. Near the surface (approx. 0.003 in. from surface)
2. Near the surface and a major crack (approx. 0.003 in. from each)
3. 0.100-0.150 in. below the surface
4. Near crack tip (approx. 0.003 in. beyond the tip)
5. On nickel-base samples only, in the white-etching layer adjacent to the crack.

There is a tendency for the hardness to be lower near the surface than in the bulk of the material, the only major exception being MAR-M 302. The hardness near the crack does not differ significantly from that in areas away from the crack. The white-etching layer differs in hardness from the bulk material, but sometimes it is harder and other times softer than the nearby material.

Oxidation

It became obvious after prolonged cycling of the thermal fatigue specimens that considerable erosion of some specimens was occurring. The extent of this erosion is shown in Figures 37b and 37d, where the original profile has been drastically modified. In some of the alloys oxidation and erosion were so pronounced that it was decided to take weight-change data. Since this was not part of the original program, starting weights had not been measured. It was necessary to estimate these starting weights, using duplicate untested specimens as a guide. Weight change expressed as percent loss in 1000 cycles is shown in Figure 46. It will be seen that the percent loss increases with the maximum surface temperature reached during the thermal cycle.

The IN-100 and PWA 1401 showed the greatest loss, followed by PWA 664 and MAR-M 200. All other specimen weight losses were less than 1%. These oxidation results are for low-velocity air flow conditions.

DISCUSSION

The primary objective of this program was to measure the relative thermal fatigue cracking resistance of the 18 combinations of materials, casting conditions, and coating. Cracking resistance can be based on the projected number of cycles required to initiate the first crack (Table 36). For example, if the resistance after a 3 min exposure is selected, the following ranking is obtained as a measure of thermal fatigue crack resistance:

Rank	Alloy	Cycles to First Crack (3 min exposure)
1 (Highest)	PWA 664	4700
2-3	PWA 1401, coated PWA 1401	2400
4	B1900, coated	1190
5-6	TAZ-8A X-40	600
7-9	IN-100, coated B1900 IN-162	400
10-11	IN-713C TD-NiCr	250
12-14	WI-52 MAR-M 302 Udimet 700 (cast)	75
15	IN-100	38
16-18	Udimet 700 (wrought) M22 MAR-M 200	13

In considering this order, it should be noted that the number of cycles to cracking spread over a range of 2 to 2-1/2 orders of magnitude. But some results are close, and the difference of one or two places in the order may not be significant. One of the most important facts is that PWA 664 and MAR-M 200 are at or near the extremes of the table. These alloys have identical compositions, the difference being that PWA 664 is directionally solidified. It is probable that small changes in alloy composition are not as important for thermal fatigue resistance as is the structure. This observation has been made in several unpublished investigations by IITRI concerning medium carbon steel and tool steels. The structure that is under test is probably more important than minor compositional variations.

In considering individual results, the TD-NiCr sample probably did not fail in the 0.040 in. edge because the large, rapidly propagating cracks in the 0.025 in. edge relieve the stresses in the 0.040 in. edge.

In some cases the cycles to crack initiation for specimens tested at 3-1/2 min were higher than the general trend of data would indicate. Further analysis of the results will be attempted to verify the validity of these results although the effect is not believed to be due to experimental error.

The metallographic work, confirmed by the SEM, shows that the fractures are mainly intergranular and follow structural discontinuities. A significant feature seems to be the formation of the white-etching layer both on the specimen surface and on the side of the thermal cracks. This layer could be due to the loss of some elements by diffusion outwards or by the diffusion of oxygen inwards. The increase in hardness of this white layer suggests that some oxygen could be diffusing into the metal. This may produce a brittle layer which would aid crack propagation.

The results show that either directional solidification or coating can be very successful in delaying cracking--the former by producing fewer surface microscopic features that might nucleate a crack, and the latter by minimizing surface oxidation. It is interesting to note that the use of a coating on a directionally solidified alloy (PWA 1401) did not markedly delay thermal fatigue cracking. However, the coating substantially reduced weight loss by oxidation. In the absence of transverse grain boundaries, it is possible that as material is removed during thermal cycling by oxidation, crack nucleation sites are also removed. Since oxidation seems to be an important factor in the cracking mechanism, it is possible that tests in higher velocity airstreams might significantly change the number of cycles required to initiate a crack.

CONCLUSIONS

The purpose of this investigation was to use the fluidized bed heating and cooling technique to measure the relative thermal fatigue cracking resistance of 18 combinations of superalloy composition, casting technique, and coating.

The longest thermal fatigue lives were obtained with materials that had been either directionally solidified or coated: PWA 664, PWA 1401 (coated), PWA 1401, and B1900 (coated). Intermediate thermal fatigue lives were obtained with conventionally cast uncoated nickel-base alloy TAZ-8A and uncoated cobalt-base alloy X-40. These conclusions are based on preliminary examination of the raw data. A more complete analysis of the data is required before a final ranking can be made. This should be undertaken together with an analysis of new data on these alloys presently being generated.

The longest and shortest lives, as rated on the 3 min immersion time were obtained with materials which had the same composition (PWA 664 and MAR-M 200). Evidently, structure of the superalloy is more important than minor compositional changes.

Examination of the crack paths and fracture surfaces shows that the cracks tend to follow an intergranular path (with the possible exception of the cobalt alloys and TAZ-8A). There are many branching cracks found as propagation continues.

During thermal cycling, oxidation occurs resulting in a white-etching layer on the surface and along the sides of the cracks. This layer appears to precede the crack and to favor an intergranular penetration route. There is reason to believe that oxidation at a grain boundary at the surface precedes crack initiation particularly in the nickel-base alloys.

Cyclic oxidation occurs at the same time as thermal cycling, and some materials suffer considerable material loss. There is an indication that the directionally solidified materials oxidize to a greater extent than the same alloy in the conventionally cast form.

REFERENCES

1. Spera, D. A., Aerospace Structural Materials, NASA-SP-227, Nov. 1969, pp. 43-57.
2. Glenny, E., et al., J. Inst. Metals, 84, 1958-1959, 294.
3. Glenny, E., and Taylor, T. A., J. Inst. Metals, 88, 1959-1960, 449.
4. Glenny, E. and Cox, M., The Engineer, 210, 1960, 346.
5. Glenny, E. and Taylor, T. A., J. Inst. Metals, 89, 1960-1961, 439 (Discussion).
6. Glenny, E., Metals Rev., 24, 1961, 387-465.
7. Glenny, E., Ph.D. Dissertation, University of London, 1962.
8. Franklin, A. W., et al., J. Inst. Metals, 92, 1963-1964, 305
9. Glenny, E. and Northwood, J.E., Foundry Trade J., 119, 1965, 607.
10. Glenny, E. and Restall, J. E., J. Less-Common Metals, 9, 1965, 367.
11. Northwood, J. E., et al., J. Less-Common Metals, 14, 1968, 157.
12 Carden, A. E., Rep. MH67-AEC-3, NASA Grant NsG-381, Aug. 1967.

TABLE 1

ALLOYS AND VARIATIONS USED IN TEST PROGRAM

1. B1900
2. B1900 with Jo-Coat (PWA 47)
3. IN 100
4. IN-100 with Jo-Coat
5. PWA 1401 (directionally solidified IN-100)
6. PWA 1401 with Jo-Coat
7. X-40
8. WI-52
9. MAR-M 200
10. PWA 664 (directionally solidified MAR-M 200)
11. MAR-M 302
12. IN-162
13. IN-713C
14. M22
15. TAZ-8A
16. Udimet 700 (Cast)
17. Udimet 700 (Wrought)
18. TD-NiCr

TABLE 2

COMPOSITIONS OF ALL ALLOYS USED IN THE EXPERIMENTAL PROGRAM

Alloy	Cast Number	Composition, wt%												
		C	Mn	Si	Cr	Ni	Co	Mo	W	Al	Ti	Zr	B	Other
B1900	54V6335	0.10	0.10	<0.10	8.11	Bal.	10.15	6.11	<0.10	6.09	0.98	0.08	0.013	4.28Ta, 0.16Fe, 4.28V
IN-100 (also PWA 1401)	KJ2206	0.17	<0.02	0.11	10.30	Bal.	15.10	2.96	--	5.45	4.76	0.084	0.016	0.21Fe, 0.97V
X-40	12C6412	0.48	<0.05	0.33	25.59	10.52	Bal.	0.04	7.87	--	--	0.03	0.005	0.46Fe, 0.02N
WI-52	59-682	0.46	0.21	0.28	20.86	0.23	Bal.	<0.05	11.06	--	--	--	--	1.75Fe, 1.87Cb
MAR-M 200 (also PWA 664)	KD2012	0.15	<0.02	0.080	9.20	Bal.	10.25	--	12.55	5.05	2.13	0.048	0.017	0.36Fe, 0.96Cb, <0.01V
MAR-M 302	T272	0.88	<0.10	0.22	21.9	0.49	Bal.	<0.1	9.89	--	--	0.24	<0.01	8.80Ta, 1.11Fe
IN-162	96317	0.10	0.01	0.04	10.03	Bal.	0.03	4.05	2.03	6.35	0.93	0.11	0.018	1.97Ta, 0.17Fe, 0.88Cb
IN-713C	65611	0.11	<0.10	<0.10	13.40	Bal.	--	4.50	--	5.95	0.83	0.08	0.009	2.24Cb+Ta, 0.27Fe
M22	67-635	0.06	--	--	6.35	Bal.	--	1.96	11.37	6.24	--	0.65	--	2.87Ta
TAZ-8A	67-640	0.01	--	--	6.20	Bal.	--	3.86	3.86	5.96	--	0.88	--	8.01Ta, 2.44Cb
Udimet 700 (cast)	85V2416	0.08	<0.10	<0.10	14.24	Bal.	14.87	4.18	--	4.25	3.26	<0.01	0.012	0.30Fe
Udimet 700 (wrought)	6541	0.113	0.01	0.02	14.85	Bal.	17.50	5.10	--	4.55	3.45	<0.02	0.013	0.85Fe
TD-NiCr	1862	0.038	--	--	21.39	Bal.	--	--	--	--	--	--	--	2.5ThO_2, .0005N, .006 S
	2858	0.020	--	--	19.72	Bal.	--	--	--	--	--	--	--	1.9ThO_2, .004 N, .007 S

TABLE 3

LOCATION OF "AS-CAST" MACROGRAPHS OF THE DIRECTIONALLY SOLIDIFIED ALLOYS

Used in Experimental Set	PWA 1401				PWA 664	
	Not Coated		Coated			
	Specimen	Fig.	Specimen	Fig.	Specimen	Fig.
A	2	3b	13	3a	10	2b
B	11	3d	4	3a	2	2b
C	3	3b	9	3d	13	2b
D	10	3d	14	3b	7	2a
E	16	3c	6	3c	21	2c
F	12	3d	8	3a	14	2b
Unused	5 7 15	3b 3c 3c	1	3a	1 3 4 12 20 22	2a 2a 2a 2c 2c 2c

TABLE 4

TENSILE PROPERTIES AT 1400°F

Alloy (none coated)	Proportional Limit psi	Proportional Limit N/cm^2	Proportional Limit % of Nominal 0.2% YS	Ultimate Tensile Strength psi	Ultimate Tensile Strength N/cm^2	Ultimate Tensile Strength % of Nominal UTS	Reduction of Area, %
B1900	136,000	93,800	116	158,000	109,000	114	8
IN-100	115,000	79,300	92	140,000	96,500	90	13
PWA 1401	122,000	84,100	--	150,000	103,400	107	16
X-40	56,000	38,600	--	86,000	59,300	123	20
WI-52	84,000	57,900	168	111,000	76,500	126	7
MAR-M 200	124,000	85,500	102	145,000	100,000	107	5
PWA 664[(a)]							
MAR-M 302	101,000	69,600	180	117,000	80,700	115	3
IN-162	130,000	89,600	106	163,000	112,400	112	11
IN-713C	118,000	81,400	109	147,000	101,400	108	12
M22	139,000	95,800	124	153,000	105,500	116	8
TAZ-8A	150,000	103,400	--	174,000	120,000	134	2
Udimet 700 (cast)	108,000	74,500	--	148,000	102,000	114	16
Udimet 700 (wrought)	110,000	75,800	92	143,000	98,600	95	30
TD-NiCr	42,000	29,000	105	47,000	32,400	107	6

Each result is the average of two tests.

(a) No specimens available.

TABLE 5

CREEP-RUPTURE PROPERTIES AT 1800°F

Alloy (none coated)	Stress Life (nominal 100 hr) psi	N/cm^2	hours	% of Nominal	Reduction of Area, %
B1900	25,000	17,200	99, 95	97	11
IN-100	25,000	17,200	94, 70	82	16
PWA 1401	23,000	15,900	144, 164	154	62
X-40	11,000	7,600	183, >105	183	33
WI-52	13,000	9,000	158, 153	156	15
MAR-M 200	26,000	17,900	114, 73	94	10
PWA 664[a]					
MAR-M 302	14,000	9,700	69, 95	82	8
IN-162	24,000	16,500	115, 71	93	10
IN-713C[b]	21,000	14,500	75, 54	64	22
M22[b]	29,000	20,000	7.5, 11	9.3	4
TAZ-8A	18,000	12,400	89, 79	84	8
Udimet 700 (cast)	18,000	12,400	121, 118	120	22
Udimet 700 (wrought)	16,000	11,000	141, 133	137	32
TD-NiCr[b]	11,000	7,600	0.1	0.1	3
TD-NiCr[c]	5,000	3,400	1268	NA	6

[a] No specimens available.

[b] Rupture strength significantly lower than published data.

[c] Supplementary test.

TABLE 6

HEAT TREATMENTS FOR SPECIMENS

	Solution Treatment			Intermediate Aging			Final Aging		
	Temp.		Time,	Temp.		Time,	Temp.		Time,
Alloy	°F	°C	hr	°F	°C	hr	°F	°C	hr
B1900	--	--	-	--	--	-	1550	843	24
IN-100 & PWA 1401	2100	1149	2	--	--	-	1700	927	16
X-40	--	--	-	--	--	-	1400	760	50
MAR-M 200 & PWA 664	--	--	-	--	--	-	1500	816	50
MAR-M 302	2250	1232	8	--	--	-	1500	816	24
Udimet 700 (cast)	--	--	-	--	--	-	1400	760	16
Udimet 700 (wrought)	2050	1121	4	1550	843	24	1400	760	16

All other materials were used in the as-cast condition.

TABLE 7

CALIBRATION DATA FOR INSTRUMENTED IN-100 SPECIMENS WHEN CYCLED INTO THE HIGH TEMPERATURE BED

Time,		Temperature, °F, at Each Couple Position														
		2 min cycle					3 min cycle					4 min cycle				
min-sec		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	0	760	805	810	800	750	640	700	690	705	650	625	675	670	660	635
	3	1280				1310	1020				1125	1000				1100
	6	1340				1370	1140				1210	1120				1190
	9	1380				1420	1190				1280	1170				1250
	12	1405				1450	1240				1340	1270				1320
	15	1450	1090	1050	1110	1490	1280	935	880	1000	1380	1250	860	890	960	1370
	30	1580	1240	1230	1260	1600	1420	1140	1070	1150	1540	1375	1100	1060	1230	1525
	45	1660	1375	1365	1390	1670	1580	1265	1225	1290	1640	1570	1300	1210	1380	1630
1	0	1725	1490	1480	1495	1730	1680	1400	1365	1430	1725	1670	1450	1345	1500	1715
1	15	1780	1580	1570	1585	1780	1750	1505	1480	1555	1790	1740	1560	1460	1590	1780
1	30	1810	1640	1635	1645	1810	1800	1600	1580	1635	1830	1790	1640	1560	1665	1820
1	45	1855	1705	1700	1710	1850	1840	1680	1655	1705	1865	1830	1710	1645	1740	1855
2	0	1890	1745	1740	1755	1895	1880	1740	1710	1760	1890	1870	1775	1705	1790	1880
2	15						1900	1790	1765	1805	1905	1890	1820	1765	1835	1895
2	30						1915	1830	1800	1840	1925	1905	1850	1815	1860	1920
2	45						1930	1860	1830	1865	1935	1920	1880	1840	1890	1925
3	0						1940	1880	1855	1880	1945	1930	1900	1865	1905	1935
3	15											1940	1920	1885	1920	1945
3	30											1950	1930	1900	1930	1955
3	45											1955	1940	1915	1940	1957
4	0											1960	1945	1925	1945	1960

TABLE 8

CALIBRATION DATA FOR INSTRUMENTED WI-52 SPECIMENS WHEN CYCLED INTO THE HIGH TEMPERATURE BED

Time, min-sec		Temperature, °F, at Each Couple Position														
		2 min cycle					3 min cycle					4 min cycle				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	0	805	825	840	815	780	705	720	750	745	685	650	660	670	660	640
	3	1100				1140	1030				1090	980				1000
	6	1150				1240	1090				1170	1020				1120
	9	1200				1280	1130				1270	1070				1150
	12	1240				1310	1170				1255	1100				1190
	15	1280	1080	1050	1100	1340	1220	935	900	980	1290	1140	940	870	980	1230
	30	1420	1290	1250	1330	1525	1400	1095	1060	1180	1420	1310	1110	1040	1150	1380
	45	1550	1450	1430	1490	1635	1520	1265	1240	1350	1535	1470	1300	1210	1325	1510
1	0	1665	1590	1560	1606	1715	1615	1395	1370	1500	1630	1580	1450	1350	1475	1600
1	15	1745	1675	1670	1690	1775	1710	1530	1520	1590	1730	1670	1570	1500	1595	1690
1	30	1800	1745	1740	1765	1825	1770	1620	1610	1675	1780	1740	1670	1620	1680	1765
1	45	1840	1810	1805	1820	1855	1820	1700	1690	1740	1840	1800	1750	1700	1755	1815
2	0	1875	1850	1845	1860	1880	1855	1760	1740	1790	1860	1840	1800	1770	1805	1850
2	15						1880	1800	1780	1825	1885	1870	1835	1815	1845	1875
2	30						1905	1820	1800	1855	1910	1895	1865	1845	1875	1900
2	45						1920	1865	1855	1875	1925	1910	1890	1880	1900	1915
3	0						1935	1885	1875	1900	1940	1920	1910	1900	1910	1925
3	15											1930	1920	1915	1925	1935
3	30											1940	1935	1930	1930	1940
3	45											1945	1940	1935	1940	1950
4	0											1950	1945	1940	1950	1955

TABLE 9

CALIBRATION DATA FOR INSTRUMENTED MAR-M 200 SPECIMENS
WHEN CYCLED INTO THE HIGH TEMPERATURE BED

Time, min-sec	Temperature, °F, at Each Couple Position														
	2 min cycle					3 min cycle					4 min cycle				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	780	840	850	840	760	675	725	745	730	670	650	665	685	670	630
3	1070				1280	1080				1150	970				1020
6	1220				1340	1170				1240	1010				1110
9	1260				1385	1250				1310	1050				1160
12	1280				1410	1290				1360	1070				1200
15	1310	1060	1030	1100	1450	1330	940	890	950	1410	1100	890	840	910	1250
30	1510	1200	1170	1230	1570	1440	1100	1100	1180	1510	1220	1045	1020	1130	1460
45	1600	1335	1310	1360	1650	1540	1265	1245	1290	1605	1390	1195	1160	1285	1530
1 0	1680	1435	1415	1470	1710	1620	1390	1370	1415	1685	1530	1360	1340	1400	1640
1 15	1740	1515	1510	1565	1755	1670	1500	1475	1505	1740	1600	1490	1470	1500	1720
1 30	1760	1620	1600	1640	1790	1740	1590	1570	1595	1780	1665	1600	1580	1610	1775
1 45	1790	1680	1660	1690	1830	1780	1670	1665	1675	1830	1745	1680	1660	1690	1820
2 0	1820	1725	1710	1740	1860	1820	1725	1720	1740	1850	1795	1740	1725	1750	1850
2 15						1860	1775	1770	1790	1870	1835	1795	1785	1800	1875
2 30						1880	1815	1810	1835	1890	1860	1830	1820	1835	1895
2 45						1900	1845	1840	1865	1910	1880	1865	1855	1870	1910
3 0						1910	1875	1865	1880	1930	1895	1890	1880	1895	1920
3 15											1910	1910	1900	1915	1930
3 30											1925	1925	1915	1930	1940
3 45											1935	1935	1925	1935	1942
4 0											1940	1940	1935	1940	1945

TABLE 10

CALIBRATION DATA FOR INSTRUMENTED MAR-M 302 SPECIMENS WHEN CYCLED INTO THE HIGH TEMPERATURE BED

c

Time, min-sec		Temperature, °F, at Each Couple Position														
		2 min cycle					3 min cycle					4 min cycle				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	0	785	875	870	865	800	690	715	745	730	700	645	655	660	650	645
	3	1180				1090	1000				1040	950				960
	6	1250				1220	1060				1110	990				1100
	9	1290				1270	1110				1170	1030				1150
	12	1310				1320	1145				1220	1060				1200
	15	1340	1130	1085	1115	1360	1180	920	900	1000	1270	1100	825	925	955	1260
	30	1440	1310	1290	1310	1490	1300	1000	1070	1170	1420	1240	1115	1175	1245	1400
	45	1550	1460	1435	1470	1590	1430	1250	1200	1320	1535	1390	1340	1375	1415	1530
1	0	1640	1570	1560	1585	1675	1540	1340	1350	1430	1645	1535	1495	1305	1560	1635
1	15	1710	1655	1670	1670	1735	1630	1500	1470	1550	1715	1615	1605	1630	1660	1700
1	30	1770	1725	1745	1745	1785	1720	1605	1580	1640	1775	1690	1680	1710	1735	1755
1	45	1820	1790	1795	1800	1830	1775	1680	1650	1770	1870	1760	1750	1775	1795	1800
2	0	1855	1830	1825	1840	1865	1805	1750	1725	1775	1855	1825	1815	1830	1835	1840
2	15						1865	1790	1770	1820	1885	1860	1850	1865	1870	1875
2	30						1895	1840	1800	1860	1905	1880	1870	1890	1890	1900
2	45						1905	1860	1840	1885	1920	1900	1890	1905	1905	1915
3	0						1930	1890	1870	1910	1935	1910	1900	1920	1920	1930
3	15											1920	1915	1930	1930	1935
3	30											1930	1925	1933	1940	1945
3	45											1940	1935	1937	1945	1950
4	0											1950	1945	1940	1950	1955

TABLE 11

CALIBRATION DATA FOR INSTRUMENTED UDIMET 700 SPECIMENS WHEN CYCLED INTO THE HIGH TEMPERATURE BED

Time, min-sec	Temperature, °F, at Each Couple Position														
	2 min cycle					3 min cycle					4 min cycle				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	770	840	845	830	760	665	715	720	700	650	640	660	665	650	630
3	1050				1290	1060				1200	1000				1170
6	1200				1350	1140				1260	1080				1240
9	1240				1390	1210				1320	1130				1300
12	1290				1415	1260				1360	1180				1340
15	1320	1100	1080	1130	1460	1290	980	900	1030	1400	1220	950	840	1000	1380
30	1515	1285	1270	1310	1580	1440	1190	1140	1240	1535	1370	1170	1055	1230	1520
45	1610	1440	1420	1460	1650	1580	1380	1340	1420	1640	1530	1360	1235	1400	1630
1 0	1690	1560	1540	1580	1715	1690	1520	1480	1560	1710	1620	1490	1390	1525	1700
1 15	1755	1645	1640	1655	1760	1750	1620	1580	1660	1780	1700	1600	1530	1630	1770
1 30	1795	1720	1710	1730	1790	1800	1700	1670	1730	1825	1750	1680	1630	1700	1820
1 45	1825	1770	1765	1780	1830	1840	1750	1720	1780	1860	1800	1750	1710	1770	1850
2 0	1850	1805	1800	1815	1860	1865	1795	1780	1830	1880	1840	1800	1770	1815	1875
2 15						1885	1830	1820	1860	1900	1870	1825	1815	1835	1895
2 30						1900	1860	1850	1890	1915	1895	1860	1845	1870	1910
2 45						1910	1880	1870	1900	1930	1905	1890	1880	1900	1925
3 0						1920	1895	1890	1910	1940	1915	1910	1900	1915	1935
3 15											1930	1920	1915	1925	1938
3 30											1940	1935	1930	1935	1942
3 45											1945	1940	1935	1940	1947
4 0											1950	1945	1940	1945	1950

TABLE 12

CALIBRATION DATA FOR INSTRUMENTED IN-100 SPECIMENS WHEN CYCLED INTO THE INTERMEDIATE TEMPERATURE BED

Time, min-sec	Temperature, °F, at Each Couple Position														
	2 min cycle					3 min cycle					4 min cycle				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	1790	1745	1745	1755	1770	1845	1880	1880	1855	1840	1900	1945	1925	1940	1870
3	1570				1380	1600				1570	1640				1590
6	1490				1320	1560				1500	1565				1520
9	1490				1290	1520				1470	1530				1480
12	1375				1270	1470				1430	1490				1440
15	1340	1510	1580	1460	1240	1430	1680	1740	1650	1380	1445	1790	1810	1700	1420
30	1210	1350	1400	1315	1130	1285	1520	1550	1465	1230	1300	1580	1600	1500	1240
45	1095	1210	1245	1180	1050	1150	1360	1380	1300	1090	1170	1420	1440	1330	1100
1 0	1000	1100	1130	1060	950	1025	1200	1235	1140	970	1055	1255	1290	1185	980
1 15	910	1010	1030	965	875	990	1070	1110	1050	880	960	1140	1155	1080	890
1 30	840	920	945	890	805	860	985	1005	955	820	880	1035	1060	980	830
1 45	790	860	885	830	750	800	910	925	885	770	820	960	970	910	775
2 0	750	805	815	800	730	760	845	855	830	730	790	900	910	860	750
2 15						720	800	810	780	690	740	840	855	820	715
2 30						685	760	770	750	670	700	805	810	770	690
2 45						665	730	740	720	650	685	775	775	740	675
3 0						650	705	710	690	640	675	745	745	725	665
3 15											655	720	720	695	655
3 30											645	705	700	680	645
3 45											635	685	780	670	635
4 0											630	670	675	660	630

TABLE 13

CALIBRATION DATA FOR INSTRUMENTED WI-52 SPECIMENS WHEN CYCLED INTO THE INTERMEDIATE TEMPERATURE BED

Time, min-sec	Temperature, °F, at Each Couple Position														
	2 min cycle					3 min cycle					4 min cycle				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	1800	1800	1830	1820	1810	1895	1875	1870	1875	1880	1910	1940	1940	1950	1900
3	1620				1535	1700				1635	1685				1700
6	1580				1470	1655				1570	1630				1570
9	1550				1440	1620				1520	1600				1500
12	1500				1410	1590				1475	1570				1470
15	1470	1620	1640	1570	1385	1550	1720	1760	1670	1430	1540	1770	1845	1720	1430
30	1300	1570	1590	1520	1210	1360	1540	1590	1490	1270	1430	1595	1620	1540	1300
45	1150	1310	1330	1270	1080	1230	1410	1460	1360	1130	1275	1425	1450	1390	1165
1 0	1050	1200	1220	1170	985	1110	1260	1300	1200	1010	1145	1260	1300	1240	1050
1 15	955	1090	1105	1070	900	1020	1150	1190	1100	910	1040	1140	1160	1120	970
1 30	900	990	1005	965	840	940	1050	1080	1000	865	970	1040	1065	1010	900
1 45	840	905	925	880	790	870	975	1000	950	810	875	965	960	940	830
2 0	785	820	835	810	765	820	900	925	870	780	840	900	900	880	800
2 15						790	830	840	810	730	795	835	850	865	765
2 30						765	790	800	775	710	765	795	800	765	740
2 45						720	750	760	730	685	740	755	770	725	710
3 0						695	725	730	705	675	710	735	740	705	685
3 15											685	710	725	695	665
3 30											670	690	710	680	650
3 45											655	680	690	670	645
4 0											640	665	670	660	640

TABLE 14

CALIBRATION DATA FOR INSTRUMENTED MAR-M 200 SPECIMENS WHEN CYCLED INTO THE INTERMEDIATE TEMPERATURE BED

Time,	Temperature, °F, at Each Couple Position														
	2 min cycle					3 min cycle					4 min cycle				
min-sec	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	1780	1725	1720	1750	1750	1840	1875	1875	1880	1835	1880	1905	1925	1920	1870
3	1420				1390	1590				1510	1660				1520
6	1350				1320	1550				1440	1615				1470
9	1310				1290	1510				1395	1590				1430
12	1280				1260	1460				1365	1550				1395
15	1290	1600	1615	1530	1230	1420	1680	1725	1660	1335	1520	1780	1790	1720	1365
30	1180	1440	1455	1370	1125	1280	1505	1560	1500	1190	1400	1610	1620	1530	1230
45	1090	1300	1320	1250	1040	1170	1360	1400	1350	1075	1240	1430	1435	1350	1110
1 0	990	1170	1180	1135	945	1070	1210	1260	1205	995	1130	1290	1300	1210	1000
1 15	900	1065	1075	1045	870	980	1100	1140	1095	910	1010	1170	1170	1120	920
1 30	850	985	990	970	800	900	1020	1045	1005	845	935	1065	1075	1020	855
1 45	790	920	925	900	750	850	955	970	940	790	870	985	990	940	800
2 0	750	850	855	845	730	805	885	910	870	755	825	925	925	885	750
2 15						780	830	855	815	725	790	860	870	830	725
2 30						740	780	810	780	700	760	810	830	790	705
2 45						700	755	775	750	630	730	780	795	755	685
3 0						670	730	750	730	660	690	750	765	725	665
3 15											675	725	740	710	650
3 30											665	705	720	690	645
3 45											655	685	700	675	640
4 0											650	670	685	665	635

TABLE 15

CALIBRATION DATA FOR INSTRUMENTED MAR-M 302 SPECIMENS WHEN CYCLED INTO THE INTERMEDIATE TEMPERATURE BED

Time,	Temperature, °F, at Each Couple Position														
	2 min cycle					3 min cycle					4 min cycle				
min-sec	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	1810	1830	1830	1840	1780	1905	1890	1870	1880	1845	1880	1940	1935	1945	1900
3	1610				1530	1690				1560	1630				1830
6	1520				1485	1400				1520	1580				1635
9	1460				1450	1550				1490	1540				1575
12	1415				1410	1500				1450	1500				1525
15	1390	1650	1655	1610	1385	1455	1720	1760	1670	1425	1470	1750	1780	1650	1490
30	1245	1480	1470	1420	1240	1320	1530	1540	1470	1260	1360	1550	1590	1470	1360
45	1120	1320	1320	1300	1120	1180	1365	1390	1315	1135	1220	1375	1410	1300	1215
1 0	1025	1180	1190	1175	1020	1050	1230	1250	1195	1040	1120	1230	1280	1170	1110
1 15	950	1080	1090	1080	940	975	1115	1130	1040	960	1030	1120	1155	1055	1000
1 30	890	1000	1005	995	860	910	1020	1020	1010	890	950	1025	1050	980	920
1 45	835	935	935	930	800	845	950	960	945	835	875	940	975	910	850
2 0	775	875	875	875	750	795	890	890	875	790	820	885	900	895	800
2 15						765	825	840	830	760	780	830	845	790	770
2 30						740	800	810	780	730	750	790	800	760	735
2 45						715	760	770	755	710	720	765	755	725	710
3 0						690	735	750	715	685	690	730	730	700	690
3 15											675	705	700	680	675
3 30											665	680	685	670	660
3 45											655	670	675	660	650
4 0											645	660	665	650	645

TABLE 16

CALIBRATION DATA FOR INSTRUMENTED UDIMET 700 SPECIMENS WHEN CYCLED INTO THE INTERMEDIATE TEMPERATURE BED

Time,	Temperature, °F, at Each Couple Position														
	2 min cycle					3 min cycle					4 min cycle				
min-sec	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	1795	1805	1805	1815	1780	1855	1895	1900	1880	1820	1900	1940	1950	1935	1860
3	1580				1400	1650				1450	1680				1470
6	1500				1340	1560				1420	1600				1450
9	1450				1300	1490				1380	1550				1400
12	1390				1280	1430				1340	1490				1370
15	1350	1630	1690	1600	1250	1400	1620	1700	1600	1300	1450	1750	1845	1700	1340
30	1215	1445	1500	1415	1140	1250	1425	1470	1410	1160	1240	1580	1660	1520	1200
45	1100	1320	1370	1290	1055	1110	1270	1300	1260	1040	1140	1410	1475	1370	1070
1 0	1010	1170	1205	1150	960	1000	1120	1150	1110	930	1030	1255	1325	1220	950
1 15	920	1065	1100	1050	880	920	1040	1060	1030	870	940	1125	1185	1100	870
1 30	850	980	1000	960	810	850	955	970	940	820	880	1030	1070	1000	830
1 45	800	920	950	890	760	800	890	900	880	780	800	955	980	930	780
2 0	760	840	850	820	740	765	850	860	840	750	770	890	905	870	745
2 15						730	800	815	790	720	740	825	860	815	720
2 30						700	770	790	760	685	720	790	805	770	700
2 45						680	750	765	735	660	700	750	770	735	680
3 0						655	725	740	710	640	680	730	740	710	660
3 15											660	710	720	690	650
3 30											650	690	705	675	640
3 45											645	680	685	665	635
4 0											640	665	670	650	630

TABLE 17

INSPECTION POINTS AND TOTAL THERMAL CYCLES FOR EACH ALLOY

Inspection Points / Alloy	Set A (2 min dwell) 50, 95, 132, 200, 300, 450, 625, 800, 1000, 1400, 2000, 3000, 4000, 5000	Set B (2 min dwell) 50, 95, 132, 200, 300, 450, 625, 800, 1000, 1400, 2000, 3000, 4000, 5000	Set C (2½ min dwell) 25, 50, 100, 200, 300, 500, 700, 1000, 1400, 2000	Set D (3 min dwell) 25, 50, 100, 200, 300, 500, 700, 980, 1400, 2000, 2800, 3500, 4000, 4400, 5000	Set E (3½ min dwell) 25, 50, 100, 200, 300, 500, 700, 1000, 1400	Set F (4 min dwell) 25, 50, 100 200, 300, 500, 700, 1000, 1500
B1900	5000	1000	2000	2000	700	500
B1900, coated	5000	5000	2000	4400	1400	1500
IN-100	1000	1000	1000	700	700	500
IN-100, coated	5000	1000	2000	2000	1400	1500
PWA 1401	5000	5000	2000	5000	1400	1500
PWA 1401, coated	5000	5000	2000	5000	1400	1500
X-40	2000	2000	2000	2000	1400	1500
WI-52	5000	1000	1000	700	700	500
MAR-M 200	1000	1000	1000	700	700	500
PWA 664	5000	5000	2000	5000	1400	1500
MAR-M 302	5000	1000	1000	700	700	500
IN-162	5000	1000	1000	3100	1400	1500
IN-713C	5000	1000	1000	700	700	500
M22	1000	1000	1000	700	700	500
TAZ-8A	5000	5000	2000	5000	1400	1500
Udimet 700 (cast)	1000	1000	1000	700	700	500
Udimet 700 (wrought)	1000	1000	1000	700	700	500
TD-NiCr	4000	4000	1000	700	700	500

TABLE 18

SUMMARY OF CRACK PROPAGATION FOR B1900

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance from bottom:			2.5 in.			1.95 in.			0.73 in.
		1000	.117	.108	.1125						
		1400	.121	.165	.143						
		2000	.204	.207	.2055	.194	.132	.188	.073	.040	.056
		3000	.220	.218	.219	.210	.198	.204	.095	.065	.030
		4000	.370	.363	.367	.373	.368	.371	.176	.136	.156
		5000	.380	.365	.373	.375	.377	.376	.135	.149	.167
	0.040	Distance from bottom:			3.00 in.			1.10 in.			
		4000	.240	.220	.230	.140	.186	.163			
		5000	.296	.240	.268	.223	.265	.244			
B (2 min dwell)	0.025	Distance from bottom:			1.50 in.			2.50 in.			
		800	--	.028	.014						
		1000	.211	.227	.219	.138	.155	.1465			
C (2 1/2 min dwell)	0.025	Distance from bottom:			2.55 in.			1.10 in.			3.20 in.
		500	.123	.101	.112						
		700	.214	.242	.228						
		1000	.327	.357	.342	.225	.204	.2145			
		1400	.335	.368	.352	.262	.275	.269	.204	.216	.210
		2000	.469	.409	.439	.330	.322	.326	.358	.364	.361
	0.040	Distance from bottom:			3.00 in.			2.30 in.			
		1400	.189	.220	.205	.160	.172	.166			
		2000	.241	.214	.228	.175	.173	.174			

TABLE 18 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
D (3 min dwell)	0.025	Distance from bottom:			1.60 in.			2.80 in.			2.10 in.
		500	.255	.265	.260						
		700	.270	.304	.287	.280	.260	.270	.163	.221	.192
		980	.303	.333	.321	.320	.308	.314	.236	.230	.233
		1400	.378	.388	.383	.372	.256	.364	.295	.308	.301
		2000	.444	.424	.434	.395	.399	.397	.298	.352	.325
	0.040	Distance from bottom:			1.20 in.			2.75 in.			
		980	.042	.035	.039						
		1400	.136	.140	.138	.104	.108	.106			
		2000	.165	.175	.170	.139	.165	.152			
E (3 1/2 min dwell)	0.025	Distance from bottom:			2.50 in.			2.00 in.			
		700	.134	.032	.083	.074	--	.037			
	0.040	Distance from bottom:			1.40 in.						
		700	.075	--	.0375						
F (4 min dwell)	0.025	Distance from bottom:			2.30 in.						
		500	.265	.277	.271	.248	.224	.235			
	0.040	Distance from bottom:			1.40 in.						
		500	.230	.218	.224						

TABLE 19

SUMMARY OF CRACK PROPAGATION FOR B1900 - COATED

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance from bottom:			1.08 in.			2.80 in.			2.20 in.
		2000	.152	.164	.158						
		3000	.163	.169	.166						
		4000	.306	.255	.281	.252	.213	.233	.203	.170	.187
		5000	.352	.318	.322	.291	.287	.289	.247	.243	.245
	0.040	Distance from bottom:			1.90 in.			0.90 in.			
		4000	.203	.185	.194	.170	.158	.164			
		5000	.220	.226	.223	.195	.170	.183			
B (2 min dwell)	0.025	Distance from bottom:			2.80 in.			1.00 in.			2.00 in.
		4000	.286	.280	.283	.260	.268	.264	.228	.256	.242
		5000	.295	.305	.300	.273	.297	.285	.305	.258	.282
	0.040	Distance from bottom:			2.20 in.						
		5000	.078	.074	.076						
C (2 1/2 min dwell)	0.025	Distance from bottom:			3.10 in.			2.80 in.			1.00 in.
		1400	.072	.048	.060	.066	.039	.053			
		2000	.192	.158	.175	.116	.134	.125	.286	.310	.298
D (3 min dwell)	0.025	Distance from bottom:			1.60 in.			2.75 in.			2.00 in.
		1400	.185	.177	.181						
		2000	.350	.340	.345	.280	.286	.283			
		2800	.370	.345	.358	.334	.390	.362			
		3500	.422	.414	.418	.445	.443	.444	.231	.240	.235
		4000	.439	.441	.440	.447	.452	.450	.265	.253	.259
		4400	.497	.493	.495	.495	.486	.490	.275	.273	.274

TABLE 19 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
	0.040	Distance from bottom:			1.25 in.			2.20 in.			1.70 in.
		2000	.174	.176	.175						
		2800	.325	.355	.340						
		3500	.336	.374	.355						
		4000	.345	.375	.360						
		4400	.413	.423	.418	.295	.315	.305	.175	.155	.165
F (4 min dwell)	0.025	Distance from bottom:			2.00 in.						
		1000	.168	.224	.196						
		1500	.368	.388	.378						

TABLE 20

SUMMARY OF CRACK PROPAGATION FOR IN 100

Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance from bottom:			2.60 in.			1.30 in.			0.97 in.
		1000	.318	.298	.308	.295	.305	.300	.280	.288	.284
B (2 min dwell)	0.025	Distance from bottom:			1.50 in.			1.00 in.			2.40 in.
		625	.245	.238	.242	.235	.229	.232	.154	.159	.157
		800	.279	.309	.294	.336	.336	.336	.290	.298	.294
		1000	.321	.329	.325	.341	.347	.344	.298	.310	.304
	0.040	Distance from bottom:			2.40 in.			1.80 in.			
		800	.167	.230	.199	.173	.146	.160			
		1000	.187	.223	.205	.198	.216	.207			
C (2 1/2 min dwell)	0.025	Distance from bottom:			2.75 in.			1.35 in.			2.00 in.
		100	.268	.198	.233	.180	.236	.208	.241	.130	.186
		200	.288	.294	.291	.270	.288	.279	.256	.277	.267
		300	.344	.315	.330	.290	.304	.297	.285	.299	.292
		500	.334	.330	.337	.320	.320	.320	.305	.299	.302
		700	.345	.340	.343	.336	.338	.337	.331	.328	.330
		1000	.355	.365	.360	.337	.343	.340	.350	.344	.347
	0.040	Distance from bottom:			2.80 in.			1.10 in.			1.80 in.
		500	.210	.217	.214	.190	.223	.206			
		700	.234	.232	.233	.216	.223	.220			
		1000	.282	.320	.301	.260	.240	.250	.185	.199	.192

TABLE 20 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
D (3 min dwell)	0.025	Distance from bottom:			3.00 in.			2.10 in.			1.25 in.
		50	.290	.268	.279	.285	.259	.267	.241	.231	.236
		100	.330	.334	.337	.304	.306	.305	.280	.340	.310
		200	.340	.346	.343	.337	.341	.339	.280	.346	.313
		300	.352	.372	.362	.337	.341	.339	.317	.347	.332
		500	.352	.372	.362	.337	.342	.340	.317	.348	.333
		700	.363	.372	.368	.345	.342	.344	.317	.348	.333
	0.040	Distance from bottom:			2.50 in.			1.40 in.			
		200	.220	.238	.229	.186	.168	.177			
		300	.220	.238	.229	.186	.168	.177			
		500	.245	.255	.250	.215	.225	.220			
		700	.281	.275	.278	.230	.237	.234			
E (3 1/2 min dwell)	0.025	Distance from bottom:			1.90 in.			2.60 in.			
		300	.049	.089	.069						
		500	.225	.217	.221						
		700	.323	.295	.309	.306	.265	.286			
	0.040	Distance from bottom:			3.00 in.			1.10 in.			1.80 in.
		100	.275	.275	.275	.236	.226	.231	.175	.185	.180
		200	.283	.285	.284	.265	.263	.264	.204	.209	.207
		300	.290	.292	.291	.272	.274	.273	.239	.243	.241
		500	.290	.315	.303	.276	.274	.275	.242	.262	.252
		700	.315	.325	.320	.276	.280	.278	.242	.274	.258
F (4 min dwell)	0.025	Distance from bottom:			1.60 in.			2.00 in.			3.10 in.
		50	.286	.276	.281	.277	.273	.275			
		100	.286	.307	.298	.290	.294	.292			
		200	.325	.305	.315	.295	.299	.297	.337	.327	.332
		300	.328	.310	.319	.297	.299	.298	.337	.327	.332
		500	.336	.338	.337	.319	.341	.330	.368	.379	.374
	0.040	Distance from bottom:			2.60 in.			1.40 in.			
		500	.260	.240	.250	.215	.203	.209			

TABLE 21

SUMMARY OF CRACK PROPAGATION FOR IN 100 - COATED

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance from bottom:			1.28 in.			2.34 in.			0.80 in.
		2000	.206	.238	.222	.246	.196	.221	.176	.192	.184
		3000	.212	.245	.229	.252	.221	.237	.182	.198	.190
		4000	.295	.291	.293	.275	.285	.280	.288	.286	.287
		5000	.312	.295	.303	.285	.297	.291	.289	.299	.294
	0.040	Distance from bottom:			2.80 in.			1.10 in.			
		4000	.210	.216	.213	.185	.175	.180			
		5000	.225	.220	.223	.186	.193	.190			
C (2 1/2 min dwell)	0.025	Distance from bottom:			2.20 in						
		1400	.279	.281	.280						
		2000	.338	.346	.342						
	0.040	Distance from bottom:			1.25 in.			2.90 in.			
		1400	.225	.279	.252						
		2000	.348	.336	.342	.324	.330	.327			
D (3 min dwell)	0.025	Distance from bottom:			2.45 in.			0.90 in.			1.40 in.
		700	.247	.251	.249						
		980	.293	.283	.288	.307	.265	.286	.230	.249	.240
		1400	.317	.307	.312	.356	.367	.362	.370	.363	.367
		2000	.320	.355	.338	.415	.392	.404	.370	.365	.368
	0.040	Distance from bottom:			3.00 in.			2.10 in.			
		500	.244	.270	.257	.260	.250	.255			
		700	.260	.308	.284	.280	.284	.282			
		980	.345	.330	.338	.283	.303	.293			
		1400	.375	.367	.371	.320	.316	.318			
		2000	.395	.370	.383	.343	.347	.345			

TABLE 21 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
E (3 1/2 min dwell)	0.025	Distance from bottom: 3.00 in.									
		300	.195	.199	.197						
		500	.291	.293	.292						
		700	.352	.308	.330						
		1000	.348	.346	.347						
		1400	.408	.420	.414						
F (4 min dwell)	0.025	Distance from bottom: 2.80 in.									
		1500	.375	.365	.370						
	0.040	Distance from bottom: 0.90 in.									
		500	.233	.219	.226						
		700	.290	.286	.288						
		1000	.360	.316	.338						
		1500	.420	.420	.420						

TABLE 22

SUMMARY OF CRACK PROPAGATION FOR PWA 1401

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
D (3 min dwell)	0.025	Distance from bottom:			0.80 in.			1.18 in.			
		2800	.065	.025	.045						
		3500	.065	.045	.055						
		4000	.066	.054	.066						
		4400	.075	.080	.078	.030	.030	.030			
		5000	.075	.080	.078	.035	.045	.040			

TABLE 23

SUMMARY OF CRACK PROPAGATION FOR PWA 1401 - COATED

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance from bottom:			1.3 in.			1.7 in.			
		1000	.050	--	.025						
		1400	.053	.046	.050	.035	.027	.031			
		2000	.060	.080	.070	.045	.035	.040	.030	.020	.025
		3000	.070	.082	.076	.050	.050	.050	.046	.020	.033
		4000	.093	.089	.091	.065	.059	.062	.049	.031	.040
		5000	.093	.089	.091	.065	.059	.062	.108	.092	.100
B (2 min dwell)	0.025	Distance from bottom:			0.87 in.			1.52 in.			3.26 in.
		2000	.052	.078	.065	--	.064	.032	.017	.047	.032
		3000	.058	.083	.071	--	.068	.034	.021	.049	.035
		4000	.110	.140	.125	.090	.127	.099	.074	.114	.094
		5000	.119	.140	.130	.098	.130	.114	.110	.114	.112
C (2 1/2 min dwell)	0.025	Distance from bottom:			0.80 in.						
		1400	.062	.021	.043						
		2000	.077	.062	.070						
D (3 min dwell)	0.025	Distance from bottom:			2.00 in.						
		2800	.030	.030	.030						
		3500	.130	.132	.131						
		4000	.130	.132	.131						
	0.040	Distance from bottom:			1.40 in.						
		2800	.050	.052	.051						
		3500	.055	.056	.056						
		4000	.057	.058	.058						

TABLE 24

SUMMARY OF CRACK PROPAGATION FOR X40

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance	from	bottom:	2.90 in.						
		800	.121	.112	.117						
		1000	.183	.190	.187						
		2000	.304	.285	.295						
	0.040	Distance	from	bottom:	2.62 in.						
		800	.054	--	.027						
		1000	.079	.036	.058						
		2000	.162	.182	.172						
B (2 min dwell)	0.025	Distance	from	bottom:	3.10 in.			1.20 in.			2.2 in.
		800	.116	.114	.115						
		1000	.204	.204	.204	.110	.207	.159			
		2000	.320	.320	.320	.295	.314	.304	.108	.158	.133
	0.040	Distance	from	bottom:	2.90 in.			3.25 in.			
		1000	.062	--	.031						
		2000	.062	.089	.076	.116	.077	.097			
C (2 1/2 min dwell)	0.025	Distance	from	bottom:	0.95 in.			2.25 in.			
		700	.115	.140	.128	.088	.075	.082			
		1000	.218	.222	.220	.198	.180	.189			
		1400	.255	.280	.268	.257	.290	.274	.202	.235	.219
		2000	.350	.366	.358	.324	.328	.326	.301	.287	.294
	0.040	Distance	from	bottom:	2.40 in.			2.10 in.			
		1400	.098		.049						
		2000	.110	.037	.074	.105	.115	.110			

TABLE 24 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
D (3 min dwell)	0.025	Distance	from bottom:		2.50 in.			1.20 in.			1.70 in.
		700	.137	.135	.136						
		980	.198	.208	.203	.105	.120	.113			
		1400	.271	.298	.284	.243	.247	.245			
		2000	.342	.322	.332	.328	.340	.334	.154	.162	.158
	0.040	Distance	from bottom:		2.80 in.			.080 in.			
		700	.048	.052	.050						
		980	.095	.113	.104						
		1400	.222	.196	.209	.145	.175	.160			
		2000	.222	.265	.244	.207	.175	.191			
E (3 1/2 min dwell)	0.025	Distance	from bottom:		2.25 in.			2.85 in.			1.65 in.
		700	.103	.117	.110						
		1000	.142	.156	.146	.122	.264	.193			
		1400	.241	.249	.245	.248	.268	.258	.188	.278	.233
	0.040	Distance	from bottom:		1.40 in.						
		1400	.094	.096	.095						
F (4 min dwell)	0.025	Distance	from bottom:		2.90 in.			2.25 in.			1.00 in.
		500	.083	.081	.082						
		700	.176	.196	.186	.165	.151	.158	.057	.067	.062
		1000	.285	.333	.309	.274	.286	.280	.186	.200	.193
		1500	.362	.388	.375	.341	.351	.346	.315	.301	.308
	0.040	Distance	from bottom:		2.70 in.			1.25 in.			
		700	--	.066	.033						
		1000	.110	.110	.110	.104	.044	.074			
		1500	.147	.133	.140	.122	.116	.119			

TABLE 25

SUMMARY OF CRACK PROPAGATION FOR WI-52

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in. First Crack Front	First Crack Back	First Crack Avg	Second Crack Front	Second Crack Back	Second Crack Avg	Third Crack Front	Third Crack Back	Third Crack Avg
A (2 min dwell)	0.025	Distance	from	bottom:	0.95 in.			2.96 in.			1.82 in.
		1000	.140	.125	.133	.096	.113	.109	.058	--	.029
		1400	.205	.191	.198	.206	.135	.170	.126	.099	.112
		2000	.242	.254	.248	.218	.270	.244	.140	.162	.151
		3000	.265	.271	.268	.225	.280	.252	.153	.168	.160
		4000	.312	.310	.311	.337	.331	.334	.269	.267	.268
		5000	.321	.313	.317	.337	.343	.340	.298	.280	.289
	0.040	Distance	from	bottom:	3.06 in.			1.20 in.			1.10 in.
		1000	.090	.059	.075	.051	.046	.049			
		1400	.144	.166	.155	.095	.125	.110	.128	.100	.114
		2000	.204	.210	.207	.156	.145	.150	.138	.178	.160
		3000	.212	.215	.214	.162	.152	.157	.152	.185	.168
		4000	.257	.248	.253	.162	.154	.158	.222	.206	.214
		5000	.252	.261	.257	.162	.165	.164	.225	.213	.219
B (2 min dwell)	0.025	Distance	from	bottom:	1.10 in.			0.95 in.			1.55 in.
		625	.070	.065	.068	.067	.064	.066			
		800	.124	.116	.120	.133	.123	.128	.105	.109	.107
		1000	.148	.128	.138	.168	.166	.167	.141	.139	.140
	0.040	Distance	from	bottom:	3.05 in.						
		800	.051	.053	.052						
		1000	.072	.076	.074						
C (2 1/2 min dwell)	0.025	Distance	from	bottom:	2.25 in.			1.50 in.			1.70 in.
		300	.060	.070	.065						
		500	.145	.160	.153	.091	.105	.098			
		700	.178	.222	.200	.133	.131	.132			
		1000	.242	.250	.246	.172	.170	.171	.152	.142	.147

TABLE 25 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
C (2 1/2 min dwell)	0.040	Distance	from	bottom:	1.25 in.			2.10 in.			
		500	.097	.070	.084						
		700	.122	.077	.100						
		1000	.122	.105	.114	.108	.108	.108			
D (3 min dwell)	0.025	Distance	from	bottom:	3.00 in.			1.90 in.			2.30 in.
		100	.053	.069	.061						
		200	.136	.138	.137						
		300	.178	.176	.177	.115	.115	.115	.087	.071	.079
		500	.245	.243	.244	.155	.160	.158	.140	.144	.142
		700	.267	.255	.261	.171	.185	.178	.162	.168	.165
	0.040	Distance	from	bottom:	1.40 in.			2.80 in.			
		500	.110	.108	.109	.067	.073	.070			
		700	.134	.122	.128	.115	.123	.119			
E (3 1/2 min dwell)	0.025	Distance	from	bottom:	2.75 in.			1.70 in.			2.40 in.
		300	.058	.064	.061						
		500	.140	.130	.135	.055	.045	.050			
		700	.225	.219	.222	.130	.091	.111	.145	.141	.143
	0.040	Distance	from	bottom:	1.10 in.						
		300	.039	.047	.043						
		500	.128	.116	.122						
		700	.130	.142	.136						
F (4 min dwell)	0.025	Distance	from	bottom:	1.60 in.			2.35 in.			1.90 in.
		200	.060	.036	.048						
		300	.085	.088	.087	.135	.131	.133	.092	.042	.067
		500	.134	.142	.138	.195	.185	.190	.155	.155	.155
	0.040	Distance	from	bottom:	1.00 in.			2.30 in.			
		500	.073	.093	.083	.065	.053	.059			

TABLE 26

SUMMARY OF CRACK PROPAGATION FOR MAR-M 200

(Specimens Cycles Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance	from	bottom:	3.00 in.			1.68 in.			1.10 in.
		200	.300	.300	.300	.041	.044	.043			
		300	.310	.310	.310	.043	.046	.045			
		450	.310	.310	.310	.068	.073	.072			
		625	.310	.310	.310	.107	.109	.108			
		800	.310	.310	.310	.107	.125	.116			
		1000	.395	.349	.372	.295	.298	.297	.386	.365	.376
	0.040	Distance	from	bottom:	2.65 in.			1.84 in.			
		1000	.249	.250	.250	.236	.186	.211			
B (2 min dwell)	0.025	Distance	from	bottom:	1.50 in.			1.75 in.			2.30 in.
		200	.180	.200	.190						
		300	.195	.210	.203						
		450	.205	.213	.209	.072	.065	.069			
		625	.227	.236	.232	.076	.080	.078	.086	.097	.092
		800	.283	.291	.287	.163	.212	.188	.280	.274	.277
		1000	.283	.291	.287	.175	.218	.197	.288	.278	.283
	0.040	Distance	from	bottom:	1.40 in.			2.50 in.			1.90 in.
		800	.246	.222	.234	.233	.250	.242	.221	.209	.215
		1000	.246	.222	.234	.257	.253	.255	.245	.237	.241
C (2 1/2 min dwell)	0.025	Distance	from	bottom:	1.50 in.			3.00 in.			2.25 in.
		50	.230	.240	.235						
		100	.350	.360	.355	.308	.298	.303			
		200	.355	.360	.358	.334	.325	.330			
		300	.355	.360	.358	.345	.343	.344	.297	.302	.300
		500	.355	.360	.358	.345	.345	.345	.351	.347	.349
		700	.355	.362	.359	.345	.345	.345	.352	.355	.354
		1000	.355	.362	.359	.362	.376	.369	.370	.364	.367

TABLE 26 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
C (2 1/2 min dwell)	0.040	Distance from bottom:			2.90 in.			1.60 in.			2.10 in.
		100	.280	.273	.277						
		200	.310	.317	.314						
		300	.310	.328	.319	.221	.226	.223			
		500	.325	.336	.330	.255	.255	.255			
		700	.360	.348	.354	.280	.256	.268			
		1000	.360	.348	.354	.280	.262	.271	.242	.230	.236
D (3 min dwell)	0.025	Distance from bottom:			1.70 in.			2.70 in.			
		25	.233	.278	.256	.207	.209	.208			
		50	.282	.280	.281	.290	.302	.296			
		100	.318	.288	.303	.307	.309	.308			
		200	.319	.288	.304	.311	.310	.311			
		300	.327	.303	.315	.317	.329	.323			
		500	.341	.340	.341	.322	.330	.326			
		700	.342	.340	.341	.330	.340	.335			
	0.040	Distance from bottom:			1.10 in.			2.80 in.			2.40 in.
		50	.239	.223	.231	.190	.198	.194	.105	.109	.107
		100	.283	.273	.278	.235	.205	.220	.166	.206	.186
		200	.286	.288	.287	.241	.239	.240	.227	.225	.226
		300	.286	.288	.287	.248	.241	.245	.235	.237	.236
		500	.295	.291	.293	.249	.245	.247	.237	.239	.238
		700	.341	.315	.328	.254	.245	.250	.276	.265	.271
E (3 1/2 min dwell)	0.025	Distance from bottom:			1.10 in.			3.20 in.			2.40 in.
		25	.280	.244	.262						
		50	.311	.309	.310	.325	.335	.330			
		100	.320	.310	.320	.333	.330	.332			
		200	.332	.318	.325	.333	.334	.334			
		300	.329	.323	.326	.338	.338	.338			
		500	.344	.330	.332	.355	.357	.356			
		700	.346	.336	.341	.375	.371	.373	.318	.308	.313

TABLE 26 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
E (3 1/2 min dwell)	0.040	Distance	from	bottom:	2.25 in.			1.80 in.			
		50	.285	.265	.275						
		100	.285	.267	.277						
		200	.297	.268	.283						
		300	.323	.331	.327	.257	.270	.264			
		500	.323	.337	.330	.257	.372	.315			
		700	.337	.340	.339	.328	.328	.328			
F (4 min dwell)	0.025	Distance	from	bottom:	2.45 in.			3.10 in.			1.35 in.
		25	.353	.333	.343						
		50	.360	.368	.364	.338	.326	.332	.300	.270	.285
		100	.374	.368	.371	.348	.329	.339	.312	.278	.295
		200	.374	.370	.372	.348	.338	.343	.312	.298	.305
		300	.376	.372	.374	.348	.340	.344	.312	.300	.306
		500	.380	.376	.378	.376	.394	.385	.348	.330	.339
	0.040	Distance	from	bottom:	1.25 in.			2.10 in.			
		25	.273	.275	.274						
		50	.292	.278	.285	.240	.238	.239			
		100	.370	.355	.363	.311	.276	.294			
		200	.370	.356	.363	.311	.276	.294			
		300	.370	.356	.363	.311	.280	.296			
		500	.370	.356	.363	.311	.291	.301			

TABLE 27

SUMMARY OF CRACK PROPAGATION FOR PWA 664

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in. First Crack Front	First Crack Back	First Crack Avg	Second Crack Front	Second Crack Back	Second Crack Avg	Third Crack Front	Third Crack Back	Third Crack Avg
D (3 min dwell)	0.025	Distance from bottom: 1.55 in.									
		5000	.010	.010	.010						
F (4 min dwell)	0.025	Distance from bottom: 3.50 in.									
		700	.036	.038	.307						
		1000	.040	.048	.044						
		1500	.060	.064	.062						

TABLE 28

SUMMARY OF CRACK PROGAGATION FOR MAR-M 302

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in. First Crack Front			Second Crack Front			Third Crack Front		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance	from	bottom:	1.00 in.			1.25 in.			1.55 in.
		1000	.054	.030	.042						
		1400	.164	.158	.161	.107	.094	.100	.090	.101	.095
		2000	.235	.253	.244	.120	.130	.125	.170	.160	.165
		3000	.246	.257	.252	.175	.152	.163	.180	.185	.182
		4000	.399	.379	.389	.176	.162	.169	.320	.314	.317
		5000	.410	.384	.394	.176	.162	.169	.320	.318	.319
	0.040	Distance	from	bottom:	1.60 in.			1.30 in.			2.80 in.
		3000	.168	.165	.167	.125	.127	.126			
		4000	.260	.238	.249	.136	.160	.148	.162	.174	.168
		5000	.260	.254	.257	.139	.161	.150	.187	.190	.189
B (2 min dwell)	0.025	Distance	from	bottom:	2.25 in.			1.10 in.			
		800	.225	.225	.225	.145	.150	.148			
		1000	.291	.288	.290	.224	.227	.226			
	0.040	Distance	from	bottom:	1.80 in.			1.20 in.			
		1000	.155	.147	.151	.091	.035	.063			
C (2 1/2 min dwell)	0.025	Distance	from	bottom:	1.80 in.			2.20 in.			1.00 in.
		300	.058	.068	.063	.018	.049	.034			
		500	.136	.136	.136	.105	.107	.106			
		700	.191	.196	.194	.157	.163	.160			
		1000	.257	.263	.260	.235	.243	.239	.324	.324	.324
	0.040	Distance	from	bottom:	1.90 in.			1.30 in.			
		300	.141	.115	.128						
		500	.205	.207	.206						
		700	.260	.260	.260						
		1000	.324	.302	.313	.113	.124	.129			

TABLE 28 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
D (3 min dwell)	0.025	Distance from bottom:			2.25 in.			1.40 in.			1.65 in.
		100	.134	.130	.132						
		200	.195	.193	.194						
		300	.231	.249	.240						
		500	.298	.325	.312						
		700	.356	.363	.360	.154	.156	.155	.145	.149	.147
	0.040	Distance from bottom:			1.80 in.			2.80 in.			2.50 in.
		300	.063	.033	.048						
		500	.103	.085	.094						
		700	.146	.138	.142	.167	.180	.174	.092	.086	.089
E (3 1/2 min dwell)	0.025	Distance from bottom:			1.30 in.			3.10 in.			
		500	.049	.029	.039						
		700	.101	.111	.106	.158	.160	.159			
	0.040	Distance from bottom:			1.1 in.			1.4 in.			
		700	.073	.110	.087	.044	.058	.051			
F (4 min dwell)	0.025	Distance from bottom:			0.90 in.			2.90 in.			
		500	.070	.076	.073	.060	.084	.072			
	0.040	Distance from bottom:			2.55 in.						
		500	.034	.076	.055						

TABLE 29

SUMMARY OF CRACK PROPAGATION FOR IN-162

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance from bottom:			1.80 in.			3.47 in.			2.50 in.
		2000	.155	.138	.147	.114	.144	.129			
		3000	.172	.143	.158	.120	.148	.134			
		4000	.308	.310	.309	.210	.224	.217	.347	.323	.330
		5000	.323	.331	.327	.243	.239	.241	.348	.329	.339
	0.040	Distance from bottom:			1.40 in.			2.20 in.			
		4000	.240	.198	.219	.196	.174	.185			
		5000	.240	.210	.225	.196	.182	.189			
B (2 min dwell)	0.025	Distance from bottom:			1.75 in.			2.35 in.			
		800	.048	.046	.047						
		1000	.065	.046	.056	.046	.060	.053			
C (2 1/2 min dwell)	0.025	Distance from bottom:			3.00 in.			1.45 in.			2.15 in.
		500	.207	.240	.224						
		700	.261	.265	.263	.198	.180	.189			
		1000	.330	.346	.338	.303	.283	.293	.246	.210	.228
	0.040	Distance from bottom:			2.10 in.						
		1000	.099	.039	.069						
D (3 min dwell)	0.025	Distance from bottom:			1.40 in.			2.70 in.			2.28 in.
		500	.187	.187	.187						
		700	.260	.258	.259	.241	.255	.248			
		1500	.368	.364	.366	.375	.337	.356	.280	.270	.275
		2200	.392	.398	.395	.378	.383	.380	.315	.313	.314
		2700	.439	.409	.419	.388	.419	.404	.330	.315	.323
		3100	.460	.470	.465	.410	.420	.415	.343	.353	.348

TABLE 29 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in. First Crack Front	First Crack Back	First Crack Avg	Second Crack Front	Second Crack Back	Second Crack Avg	Third Crack Front	Third Crack Back	Third Crack Avg
D (3 min dwell)	0.040	Distance	from	bottom:	1.70 in.						
		700	.052	.022	.037						
		1500	.172	.188	.180						
		2200	.214	.205	.210						
		2700	.230	.210	.220						
		3100	.240	.270	.255						
E (3 1/2 min dwell)	0.025	Distance	from	bottom:	2.10 in.			1.55 in.			2.65 in.
		500	.044	.030	.037						
		700	.250	.242	.246	.234	.238	.236	.224	.204	.214
		1000	.254	.304	.279	.268	.286	.277	.250	.273	.261
		1400	.285	.320	.303	.297	.295	.296	.261	.281	.271
	0.040	Distance	from	bottom:	1.80 in.			2.40 in.			2.50 in.
		700	.132	.106	.119	.070	.056	.064	.068	.058	.053
		1000	.204	.232	.218	.110	.110	.110	.063	.075	.069
		1400	.320	.361	.342	.110	.110	.110	.063	.075	.069
F (4 min dwell)	0.025	Distance	from	bottom:	1.00 in.			2.25 in.			2.90 in
		300	.131	.131	.131						
		500	.239	.257	.248						
		700	.296	.298	.297	.177	.236	.207			
		1000	.337	.351	.344	.279	.315	.297	.275	.281	.278
		1500	.410	.410	.410	.350	.360	.355	.370	.372	.371

TABLE 30

SUMMARY OF CRACK PROPAGATION FOR IN-713C

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance	from	bottom:	2.45 in.			1.15 in.			3.10 in.
		1000	.166	.202	.184						
		1400	.236	.228	.232	.293	.298	.295			
		2000	.271	.282	.276	.340	.342	.341	.160	.155	.157
		3000	.299	.285	.292	.341	.355	.348	.250	.237	.242
		4000	.320	.310	.315	.406	.384	.395	.284	.286	.285
		5000	.330	.344	.337	.406	.385	.396	.294	.290	.292
	0.040	Distance	from	bottom:	3.10 in.			2.00 in.			
		1400	.124	.144	.134						
		2000	.264	.268	.266						
		3000	.265	.268	.267						
		4000	.292	.314	.303	.216	.206	.211			
		5000	.294	.370	.332	.222	.224	.223			
B (2 min dwell)	0.025	Distance	from	bottom:	2.80 in.			1.70 in.			0.90 in.
		1000	.278	.312	.295	.269	.259	.264	.242	.213	.223
C (2 1/2 min dwell)	0.025	Distance	from	bottom:	1.70 in.			1.10 in.			2.80 in.
		500	.197	.160	.179						
		700	.264	.288	.276	.274	.300	.292	.193	.193	.196
		1000	.292	.298	.295	.320	.324	.322	.328	.326	.327
	0.040	Distance	from	bottom:	2.50 in.			1.30 in.			
		1000	.224	.214	.219	.166	.150	.158			

TABLE 30 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
D (3 min dwell)	0.025	Distance	from	bottom:	1.85 in.			2.75 in.			1.20 in.
		300	.174	.150	.162						
		500	.306	.308	.307						
		700	.375	.323	.359	.367	.375	.371	.318	.308	.313
	0.040	Distance	from	bottom:	2.10 in.						
		700	.075	.085	.080						
E (3 1/2 min dwell)	0.025	Distance	from	bottom:	2.25 in.			1.20 in.			2.70 in.
		700	.315	.335	.325	.319	.303	.311	.238	.194	.216
	0.040	Distance	from	bottom:	2.35 in.						
		700	.074	.098	.086						
F (4 min dwell)	0.025	Distance	from	bottom:	2.60 in.			1.70 in.			
		300	.125	.105	.115						
		500	.345	.303	.324	.330	.274	.302			

TABLE 31

SUMMARY OF CRACK PROPAGATION FOR M22

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance	from	bottom:	3.25 in.			2.60 in.			
		1000	.048	.055	.052	.051	.040	.046			
	0.040	Distance	from	bottom:	2.60 in.			1.55 in.			
		450	.210	.262	.236						
		625	.228	.267	.248						
		800	.240	.268	.254						
		1000	.250	.300	.275	.170	.016	.093			
B (2 min dwell)	0.025	Distance	from	bottom:	1.25 in.			2.35 in.			
		800	.307	.284	.296	.075	.093	.084			
		1000	.310	.295	.303	.244	.248	.246			
	0.040	Distance	from	bottom:	1.85 in.			2.65 in.			
		450	.040	.058	.049						
		625	.156	.161	.159						
		800	.215	.167	.191	.180	.170	.175			
		1000	.246	.207	.227	.222	.210	.216			
C (2 1/2 min dwell)	0.025	Distance	from	bottom:	2.80 in.			3.20 in.			2.15 in.
		25	.200	--	.100	.100	--	.050			
		50	.230	--	.115	.170	--	.085			
		100	.235	.175	.205	.170	.180	.175	.115	.055	.085
		200	.235	.220	.228	.170	.180	.175	.121	.072	.097
		300	.235	.265	.150	.222	.220	.221	.125	.160	.143
		500	.288	.165	.277	.223	.220	.221	.125	.183	.154
		700	.288	.302	.297	.240	.220	.230	.125	.185	.155
		1000	.310	.312	.311	.240	.220	.230	.155	.265	.210

TABLE 31 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
C (2 1/2 min dwell)	0.040	Distance	from	bottom:	2.70 in.			1.70 in.			1.30 in.
		100	.203	.135	.219	.160	.106	.133			
		200	.210	.136	.173	.170	.120	.148			
		300	.218	.142	.180	.125	.126	.151			
		500	.223	.232	.228	.198	.165	.182			
		700	.223	.232	.228	.210	.233	.222	.250	.265	.258
		1000	.241	.238	.240	.240	.244	.242	.305	.307	.306
D (3 min dwell)	0.025	Distance	from	bottom:	2.10 in.			0.90 in.			1.60 in.
		25	.220	.155	.188	.175	.143	.159	.155	.030	.093
		50	.268	.208	.238	.175	.158	.167	.170	.030	.100
		100	.268	.220	.244	.176	.168	.172	.170	.034	.102
		200	.268	.248	.258	.192	.198	.195	.170	.180	.175
		300	.268	.248	.258	.200	.198	.199	.177	.199	.188
		500	.269	.251	.260	.225	.223	.224	.199	.205	.202
		700	.272	.251	.262	.236	.223	.230	.217	.233	.225
	0.040	Distance	from	bottom:	1.90 in.			1.25 in.			
		100	.166	.210	.188						
		200	.166	.235	.201	.178	.162	.170			
		300	.199	.250	.225	.178	.172	.175			
		500	.199	.250	.225	.178	.176	.177			
		700	.206	.250	.228	.185	.187	.186			
E (3 1/2 min dwell)	0.025	Distance	from	bottom:	2.30 in.			2.75 in.			
		50	.160	.224	.192						
		100	.173	.224	.199						
		200	.175	.230	.203						
		300	.176	.260	.218						
		500	.233	.275	.254						
		700	.292	.275	.284	.197	.203	.200			

TABLE 31 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
E (3 1/2 min dwell)	0.040	Distance	from	bottom:	1.50 in.			2.25 in.			
		25	.161	.175	.168						
		50	.165	.175	.170						
		100	.190	.185	.190						
		200	.200	.185	.193						
		300	.200	.185	.193						
		500	.213	.185	.199	.205	.160	.183			
		700	.247	.230	.239	.235	.173	.204			
F (4 min dwell)	0.025	Distance	from	bottom:	1.60 in.						
		300	.074	.062	.068						
		500	.289	.255	.272						

TABLE 32

SUMMARY OF CRACK PROPAGATION FOR TAZ-8A

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance	from	bottom:	2.80 in.			2.00 in.			1.15 in.
		4000	.284	.266	.275	.258	.260	.259	.241	.265	.253
		5000	.325	.323	.324	.277	.286	.282	.292	.270	.281
	0.040	Distance	from	bottom:	1.25 in.						
		5000	.034	.038	.036						
B (2 min dwell)	0.025	Distance	from	bottom:	2.60 in.			1.15 in.			
		3000	.242	.239	.241						
		4000	.345	.347	.346	.330	.324	.327			
		5000	.358	.358	.358	.330	.346	.338			
C (2 1/2 min dwell)	0.025	Distance	from	bottom:	1.80 in.			2.65 in.			
		1000	.049	.003	.029						
		1400	.150	.180	.165						
		2000	.293	.302	.298	.215	.192	.204			
D (3 min dwell)	0.025	Distance	from	bottom:	1.55 in.			2.60 in.			1.00 in.
		700	.065	.077	.071						
		980	.225	.243	.234						
		1400	.280	.296	.288	.234	.288	.261			
		2000	.340	.346	.343	.343	.326	.335			
		2800	.408	.420	.414	.411	.421	.416			
		3500	.443	.458	.450	.442	.433	.437	.175	.178	.177
		4000	.445	.464	.455	.445	.464	.455	.232	.245	.239
		4400	.470	.480	.475	.490	.485	.488	.290	.285	.288
		5000	.470	.520	.495	.509	.491	.500	.295	.325	.310
	0.040	Distance	from	bottom:	1.28 in.			1.80 in.			
		5000	.070	.050	.060	.040	.042	.041			

TABLE 32 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
E (3 1/2 min dwell)	0.025	Distance	from	bottom:	2.10 in.						
		1400	.014	.018	.016						
F (4 min dwell)	0.025	Distance	from	bottom:	1.30 in.			2.35 in.			
		1000	.029	.025	.027						
		1500	.148	.156	.152	.166	.154	.160			
	0.040	Distance	from	bottom:	1.75 in.						
		1500	.068	.040	.054						

TABLE 33

SUMMARY OF CRACK PROPAGATION FOR UDIMET 700 (CAST)

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance from bottom:			1.95 in.			1.55 in.			
		1000	.255	.194	.225	.105	.103	.104			
B (2 min dwell)	0.025	Distance from bottom:			2.42 in.			1.45 in.			1.70 in.
		200	.022	--	.011						
		300	.025	.005	.015						
		450	.034	.018	.026						
		625	.040	.020	.030						
		800	.047	.088	.068	.199	.203	.201	.168	.166	.167
		1000	.218	.173	.196	.248	.246	.247	.190	.168	.179
	0.040	Distance from bottom:			1.60 in.			2.00 in.			
		800	.182	.090	.136						
		1000	.190	.132	.161	.132	.073	.103			
C (2 1/2 min dwell)	0.025	Distance from bottom:			2.15 in.			1.60 in.			2.60 in.
		200	.129	.120	.125						
		300	.193	.193	.193	.135	--	.068			
		500	.253	.253	.253	.246	.241	.243	.175	.195	.185
		700	.253	.279	.266	.281	.291	.286	.222	.234	.228
		1000	.317	.285	.301	.305	.315	.310	.292	.347	.320
	0.040	Distance from bottom:			1.40 in.			1.30 in.			
		500	.190	.183	.184	.164	.196	.180			
		700	.238	.196	.218	.225	.190	.208			
		1000	.245	.239	.242	.235	.198	.212			

TABLE 33 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
D (3 min dwell)	0.025	Distance	from	bottom:	2.70 in.			1.40 in.			1.70 in.
		100	.174	.090	.132	.086	.086	.086			
		200	.240	.258	.249	.204	.226	.215			
		300	.295	.291	.293	.235	.233	.234	.221	.242	.232
		500	.295	.292	.294	.235	.233	.234	.222	.242	.232
		700	.346	.320	.333	.239	.270	.255	.222	.278	.250
	0.040	Distance	from	bottom:	2.40 in.			1.40 in.			
		200	.098	.092	.095						
		300	.158	.136	.147	.173	.149	.161			
		500	.315	.310	.313	.330	.332	.331			
		700	.315	.310	.313	.330	.332	.331			
E (3 1/2 min dwell)	0.025	Distance	from	bottom:	2.60 in.			1.40 in.			1.70 in.
		300	.089	.093	.091	.074	.070	.072			
		500	.122	.127	.125	.150	.131	.141			
		700	.250	.149	.200	.290	.220	.255	.160	.120	.140
	0.040	Distance	from	bottom:	1.40 in.			1.80 in.			2.30 in
		700	.219	.195	.207	.080	.140	.110	.106	.080	.093
F (4 min dwell)	0.025	Distance	from	bottom:	1.30 in.			2.30 in.			1.75 in.
		200	.085	.065	.075						
		300	.242	.240	.241	.235	.227	.231			
		500	.289	.303	.296	.278	.280	.279	.255	.241	.248
	0.040	Distance	from	bottom:	1.70 in.			2.50 in.			
		300	.176	.161	.169						
		500	.228	.215	.222	.233	.227	.230			

TABLE 34

SUMMARY OF CRACK PROPAGATION FOR UDIMET 700 (WROUGHT)

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
A (2 min dwell)	0.025	Distance from bottom:			1.50 in.			1.00 in.			2.24 in.
		200	--	.032	.016						
		300	.009	.038	.024						
		450	.009	.038	.024						
		625	.037	.058	.048						
		800	.039	.058	.049						
		1000	.320	.243	.282	.300	.320	.310	.290	.286	.288
	0.040	Distance from bottom:			1.65 in.						
		1000	.050	.056	.053						
B (2 min dwell)	0.025	Distance from bottom:			2.30 in.			1.20 in.			2.00 in.
		200	.017	--	.009						
		300	.020	.008	.014						
		450	.020	.009	.015						
		625	.026	.039	.028						
		800	.157	.151	.154	.307	.297	.302	.196	.214	.205
		1000	.163	.183	.173	.362	.342	.352	.277	.255	.266
	0.040	Distance from bottom:			1.90 in.			2.45 in.			
		800	.163	.139	.151						
		1000	.196	.213	.205	.118	.128	.123			
C (2 1/2 min dwell)	0.025	Distance from bottom:			1.20 in.			0.80 in.			3.00 in.
		100	.194	.203	.199	.020	.020	.020			
		200	.260	.269	.265	.165	.205	.185	.307	.293	.300
		300	.273	.290	.282	.228	.218	.223	.318	.332	.325
		500	.320	.324	.322	.282	.305	.294	.368	.356	.362
		700	.343	.339	.341	.302	.310	.306	.372	.369	.371
		1000	.349	.335	.342	.315	.307	.311	.399	.355	.377

TABLE 34 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
C (2 1/2 min dwell)	0.040	Distance	from	bottom:	3.1 in.			1.00 in.			1.60 in.
		200	.208	.211	.210	.089	.060	.075	.053	.033	.043
		300	.231	.267	.249	.121	.114	.118	.102	.102	.102
		500	.293	.291	.292	.239	.233	.236	.238	.238	.238
		700	.310	.309	.310	.242	.245	.244	.255	.258	.257
		1000	.329	.219	.324	.262	.264	.263	.307	.285	.318
D (3 min dwell)	0.025	Distance	from	bottom:	2.75 in.			2.10 in.			1.00 in.
		25	.155	.170	.163						
		50	.293	.281	.287	.290	.278	.284	.289	.278	.284
		100	.314	.302	.308	.313	.303	.308	.320	.320	.320
		200	.349	.341	.345	.342	.346	.344	.344	.342	.343
		300	.371	.373	.372	.347	.349	.348	.366	.364	.365
		500	.375	.378	.377	.374	.376	.375	.370	.372	.371
		700	.392	.380	.386	.395	.380	.388	.391	.389	.390
	0.040	Distance	from	bottom:	2.90 in.			1.00 in.			2.05 in.
		100	.269	.265	.267	.234	.242	.246	.235	.233	.234
		200	.297	.299	.298	.275	.277	.276	.276	.275	.276
		300	.311	.309	.310	.295	.291	.293	.290	.292	.291
		500	.317	.315	.316	.309	.307	.308	.308	.305	.307
		700	.359	.323	.346	.353	.328	.341	.342	.340	.347
E (3 1/2 min dwell)	0.025	Distance	from	bottom:	2.90 in.			2.15 in.			1.80 in.
		50	.291	.291	.291						
		100	.292	.291	.292	.180	.210	.195			
		200	.292	.291	.292	.185	.210	.198			
		300	.312	.317	.315	.269	.281	.275			
		500	.328	.317	.323	.279	.281	.280			
		700	.360	.350	.355	.318	.320	.319	.297	.285	.286

TABLE 34 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
E (3 1/2 min dwell)	0.040	Distance	from	bottom:	1.60 in.			2.30 in.			
		100	.186	.202	.194						
		200	.186	.206	.198						
		300	.222	.248	.235						
		500	.250	.273	.262	.210	.250	.230			
		700	.289	.289	.289	.274	.268	.271			
F (4 min dwell)	0.025	Distance	from	bottom:	2.90 in.			2.10 in.			1.20 in.
		25	.295	.283	.289	.287	.285	.286	.267	.261	.264
		50	.333	.333	.333	.326	.312	.319	.325	.335	.330
		100	.333	.333	.333	.331	.313	.322	.327	.335	.331
		200	.337	.355	.346	.334	.332	.333	.333	.349	.341
		300	.340	.360	.350	.347	.335	.341	.348	.350	.349
		500	.387	.415	.401	.374	.378	.376	.358	.368	.363
	0.040	Distance	from	bottom:	2.00 in.			2.40 in.			1.30 in.
		50	.214	.192	.203						
		100	.224	.205	.215	.240	.238	.239			
		200	.224	.220	.222	.246	.244	.245	.210	.188	.199
		300	.255	.253	.254	.248	.250	.249	.215	.195	.205
		500	.272	.296	.284	.303	.303	.303	.280	.292	.286

TABLE 35

SUMMARY OF CRACK PROPAGATION FOR TD-NiCr

(Specimens Cycled Between Fluidized Beds at 1990°F and 600°F)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.								
			First Crack			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg
C (2 1/2 min dwell)	0.025	Distance from bottom:			1.68 in.						
		500	.439	.431	.435						
		1000	.600	.600	.600						
D (3 min dwell)	0.025	Distance from bottom:			2.10 in.						
		300	.363	.380	.371						
		500	.525	.575	.550						
		700	.585	.590	.588						
E (3 1/2 min dwell)	0.025	Distance from bottom:			2.70 in.			1.20 in.			1.80 in.
		100	.160	.150	.155						
		200	.175	.200	.188						
		300	.395	.381	.388	.251	.253	.252			
		500	.420	.390	.405	.340	.335	.338	.307	.285	.296
		700	.465	.419	.442	.408	.384	.396	.407	.349	.376
F (4 min dwell)	0.025	Distance from bottom:			3.00 in.			1.15 in.			2.15 in.
		100	.213	.243	.230	.217	.213	.215			
		200	.360	.360	.360	.338	.350	.344			
		300	.405	.438	.422	.381	.425	.403	.325	.334	.330
		500	.455	.490	.473	.439	.467	.453	.383	.410	.397

TABLE 36

THERMAL CYCLES REQUIRED TO INITIATE THE FIRST CRACK IN EACH EDGE

Material and Condition	Set A (2 min dwell)		Set B (2 min dwell)		Set C (2½ min dwell)		Set D (3 min dwell)		Set E (3½ min dwell)		Set F (4 min dwell)	
	.025 edge	.040 edge	.025 edge	.040 edge	.025 edge	.040 edge	.025 edge	.040 edge	.025 edge	.040 edge	.025 edge	.040 edge
B1900	900	3500	713	>1000	400	1200	400	800	600	600	400	400
B1900, coated	1700	3500	3500	4500	1200	>2000	1190	1700	>1400	>1400	850	>1500
IN-100	900	>1000	537	713	75	400	38	150	250	75	38	400
IN-100, coated	1700	3500	>1000	>1000	1200	1200	600	400	250	>1400	1250	400
PWA 1401	>5000	>5000	>5000	>5000	>2000	>2000	2400	>5000	>1400	>1400	>1500	>1500
PWA 1401, coated	900	>5000	1700	>5000	1200	>2000	2400	2400	>1400	>1400	>1500	>1500
X-40	713	713	713	900	600	1190	600	600	600	1200	400	600
WI-52	900	900	537	713	250	400	75	400	250	250	150	400
MAR-M 200	166	900	166	713	38	75	13	38	13	38	13	13
PWA 664	>5000	>5000	>5000	>5000	>2000	>2000	4700	>5000	>1400	>1400	600	>1500
MAR-M 302	900	2500	713	900	250	250	75	250	400	600	400	400
IN-162	1700	3500	713	>1000	400	900	400	600	400	600	250	>500
IN-713C	900	1200	900	>1000	400	850	250	600	600	600	250	>500
M22	900	375	713	375	13	75	13	75	38	13	250	>500
TAZ-8A	3500	4500	2500	>5000	850	>2000	600	4500	1200	>1400	850	1250
Udimet 700 (cast)	900	>1000	166	713	150	450	75	150	250	600	150	250
Udimet 700 (wrought)	166	900	166	713	75	150	13	75	38	75	13	38
TD-NiCr	>4000	>4000	>4000	>4000	400	>1000	250	>1000	75	>700	75	>500

TABLE 37

SUMMARY OF SPECIMENS SECTIONED FOR METALLOGRAPHY AND SEM FRACTOGRAPHY

	As Received:	Set C (2½ min dwell):		Set D (3 min dwell):	Set F (4 min dwell):	
Alloy	Met.	Met.	SEM	Met.	Met.	SEM
B1900	X			X	X	
B1900, coated				X		
IN-100	X	X	X	X	X	X
IN-100, coated				X		
PWA 1401				X		
PWA 1401, coated				X		
X-40	X			X		
WI-52	X	X		X	X	
MAR-M 200	X	X	X	X	X	X
PWA 664				X		
MAR-M 302	X	X	X	X	X	
IN-162	X			X		
IN-713C	X	X		X		
M22	X	X		X	X	
TAZ-8A	X			X		
Udimet 700 (cast)	X	X	X	X	X	X
Udimet 700 (wrought)	X	X	X	X	X	X
TD-NiCr	X	X		X	X	X

TABLE 38

SURFACE HARDNESSES (ROCKWELL C) OF THERMAL FATIGUE SPECIMENS

Alloy	As Recd.	Set A (2 min dwell)		Set B (2 min dwell)		Set C ($2\frac{1}{2}$ min dwell)		Set D (3 min dwell)		Set E ($3\frac{1}{2}$ min dwell)		Set F (4 min dwell)	
		Cycles	R_C	Cycles	R_C	Cycles	R_C	Cycles	R_C	Cycles	R_C	Cycles	R_C
B1900	38	1000	37	1000	38	1000	38	700	37	700	38	500	38
		1400	35			1400	36	980	36				
		2000	35			2000	33	1400	35				
		3000	34					2000	36				
		4000	33										
		5000	33										
IN-100	38	1000	36	1000	36	1000	36	700	36	700	37	500	36
PWA 1401	39	1000	33	1000	35	1000	35	700	34	700	39	500	36
		1400	32	1400	30	1400	34	980	35	1000	35	700	36
		2000	32	2000	30	2000	33	1400	34	1400	33	1000	35
		3000	32	3000	30			2000	35			1500	35
		4000	33	4000	30			2800	33				
		5000	32	5000	30			3500	33				
								4000	32				
								4400	32				
								5000	32				
X-40	38	1000	36	1000	35	1000	35	700	36	700	37	500	36
		1400	--	1400	--	1400	32	980	35	1000	34	700	33
		2000	32	2000	35	2000	31	1400	34	1400	34	1000	33
								2000	33			1500	30
WI-52	36	1000	35	1000	34	1000	34	700	34	700	35	500	34
		1400	33										
		2000	32										
		3000	31										
		4000	30										
		5000	30										

TABLE 38 (Continued)

Alloy	As Recd.	Set A (2 min dwell)		Set B (2 min dwell)		Set C (2½ min dwell)		Set D (3 min dwell)		Set E (3½ min dwell)		Set F (4 min dwell)	
		Cycles	R_C	Cycles	R_C	Cycles	R_C	Cycles	R_C	Cycles	R_C	Cycles	R_C
MAR-M 200	41	1000	38	1000	38	1000	37	700	37	700	37	500	38
PWA 664	41	1000	36	1000	39	1000	37	700	38	700	38	500	38
		1400	36	1400	38	1400	36	980	37	1000	35	700	38
		2000	36	2000	38	2000	35	1400	37	1400	36	1000	37
		3000	36	3000	37			2000	37			1500	36
		4000	36	4000	35			2800	36				
		5000	36	5000	35			3500	36				
								4000	35				
								4400	35				
								5000	35				
MAR-M 302	49	1000	42	1000	42	1000	41	700	43	700	41	500	41
		1400	40										
		2000	42										
		3000	41										
		4000	38										
		5000	38										
IN-162	40	1000	37	1000	36	1000	37	700	38	700	37	500	38
		1400	35					980	--	1000	35	700	36
		2000	34.5					1500	37	1400	34	1000	36
		3000	34					2200	36			1500	35
		4000	33					2700	36				
		5000	32					3100	35				
IN-713C	40	1000	36	1000	37	1000	36	700	36	700	37	500	37
		1400	34										
		2000	33										
		3000	32										
		4000	30										
		5000	28										

TABLE 38 (Continued)

Alloy	As Recd.	Set A (2 min dwell)		Set B (2 min dwell)		Set C (2½ min dwell)		Set D (3 min dwell)		Set E (3½ min dwell)		Set F (4 min dwell)	
		Cycles	R_C	Cycles	R_C	Cycles	R_C	Cycles	R_C	Cycles	R_C	Cycles	R_C
M22	37	1000	38	1000	38	1000	39	700	39	700	38	500	39
TAZ-8A	46	1000	45	1000	45	1000	44	700	45	700	45	500	46
		1400	44	1400	45	1400	43	980	44	1000	42	700	44
		2000	44	2000	44	2000	43	1400	44	1400	42	1000	45
		3000	43	3000	43			2000	44			1500	45
		4000	43	4000	43			2800	43				
		5000	42	5000	43			3500	43				
								4000	43				
								4400	43				
								5000	42				
U700 (cast)	38	1000	35	1000	36	1000	37	700	36	700	35	500	37
U700 (wrought)	40	1000	37	1000	36	1000	36	700	36	700	38	500	36
TD-NiCr	30	1000	26	1000	26	1000	28	700	28	700	27	500	29
		1400	26	1400	25								
		2000	26	2000	25								
		3000	26	3000	25								
		4000	26	4000	25								

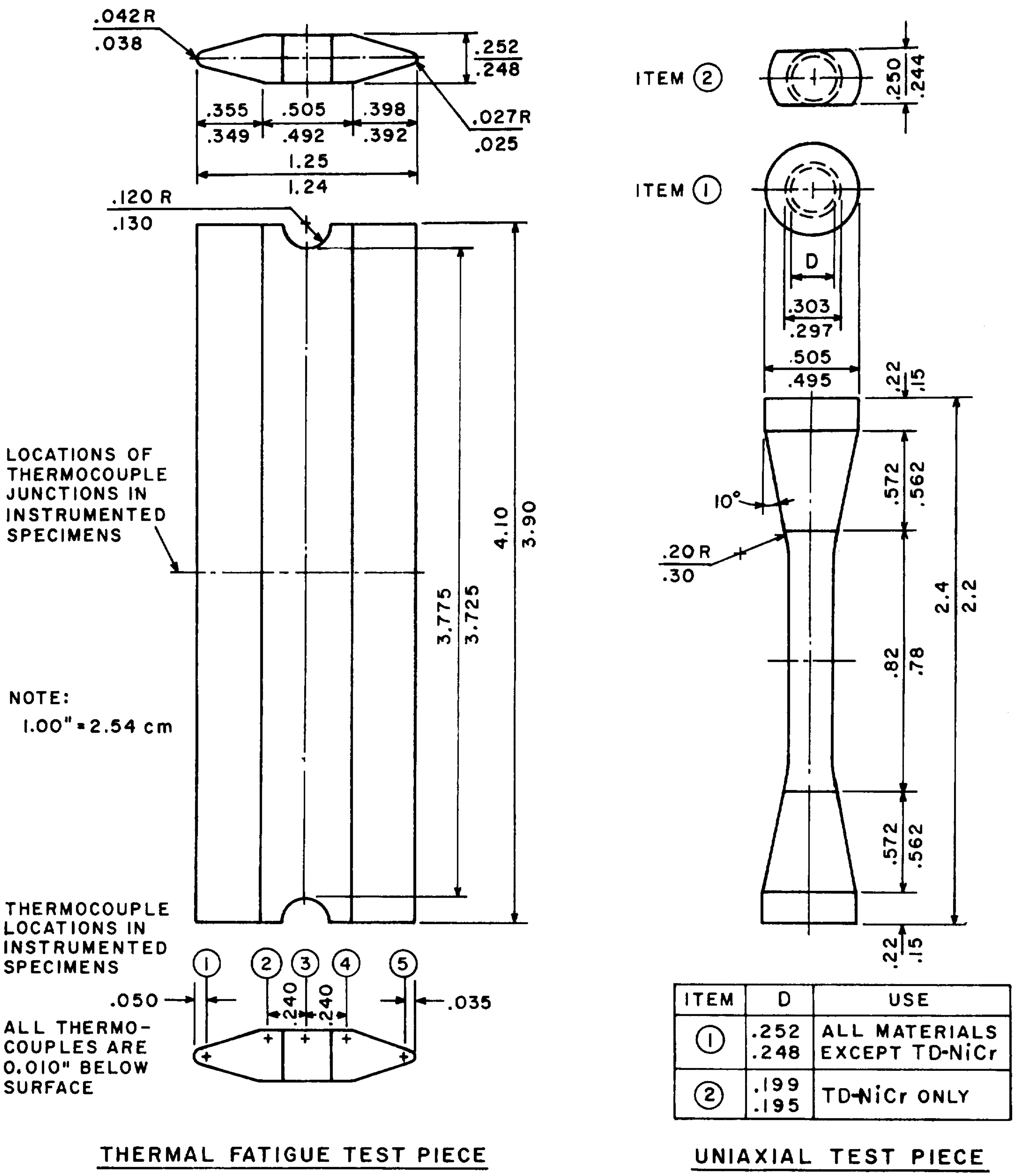
TABLE 39

MICROHARDNESS MEASUREMENTS IN THERMAL FATIGUE SAMPLE SECTIONS

			Microhardness, DPH (500 g)				
			Near Surface (.003 in.)		Below Surface		
Material	Set	Cycles	Removed from Crack	Near Crack (.003 in.)	.100-.150 in. Below Surface	Near Crack Tip (.003 in.)	White Layer Adjacent to Crack[*]
B1900	F	500	340	345	371	375	430
B1900, coated	D	4400	371	380	371	375	450
IN-100	F	500	340	332	357	371	409
IN-100, coated	D	2000	390	383	390	378	408
PWA 1401	D	5000	295	339	371	378	--
PWA 1401, coated	D	5000	390	390	386	371	--
X-40	D	2000	393	388	393	392	N.D.[†]
WI-52	F	500	464	371	480	503	N.D.[†]
MAR-M 200	F	500	312	308	371	378	330
PWA 664	D	5000	381	396	458	437	--
MAR-M 302	F	500	595	603	553	540	N.D.[†]
IN-162	D	3100	370	400	370	391	442
IN-713C	C	1000	282	286	333	348	464
M22	C	1000	328	321	371	371	348
TAZ-8A	D	5000	428	452	460	471	376
Udimet 700 (cast)	F	500	363	358	371	374	367
Udimet 700 (wrought)	F	500	371	316	371	367	340
TD-NiCr	C	1000	262	264	290	283	303

[*] Measured with 25 g load.

[†] Hardness in white-etching layer not determined on cobalt-base alloys.

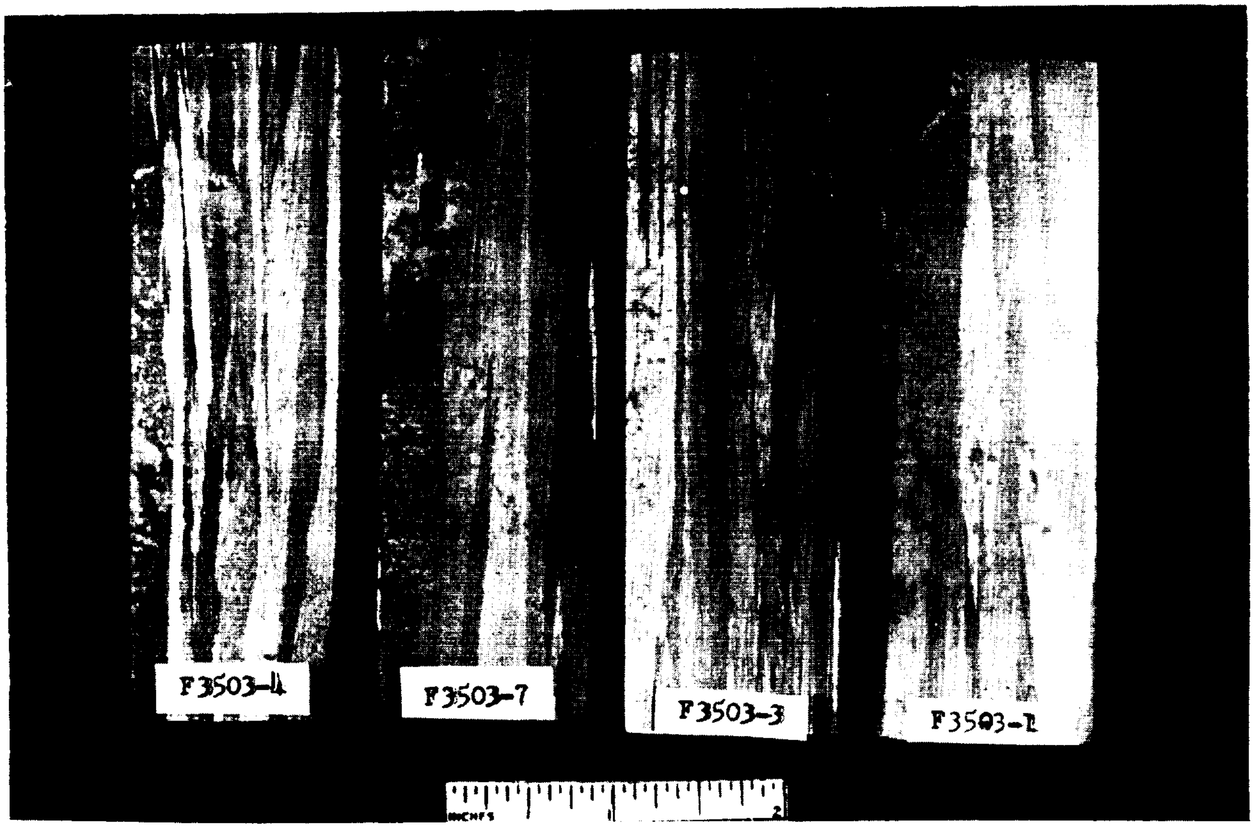


ITEM	D	USE
①	.252 .248	ALL MATERIALS EXCEPT TD-NiCr
②	.199 .195	TD-NiCr ONLY

THERMAL FATIGUE TEST PIECE

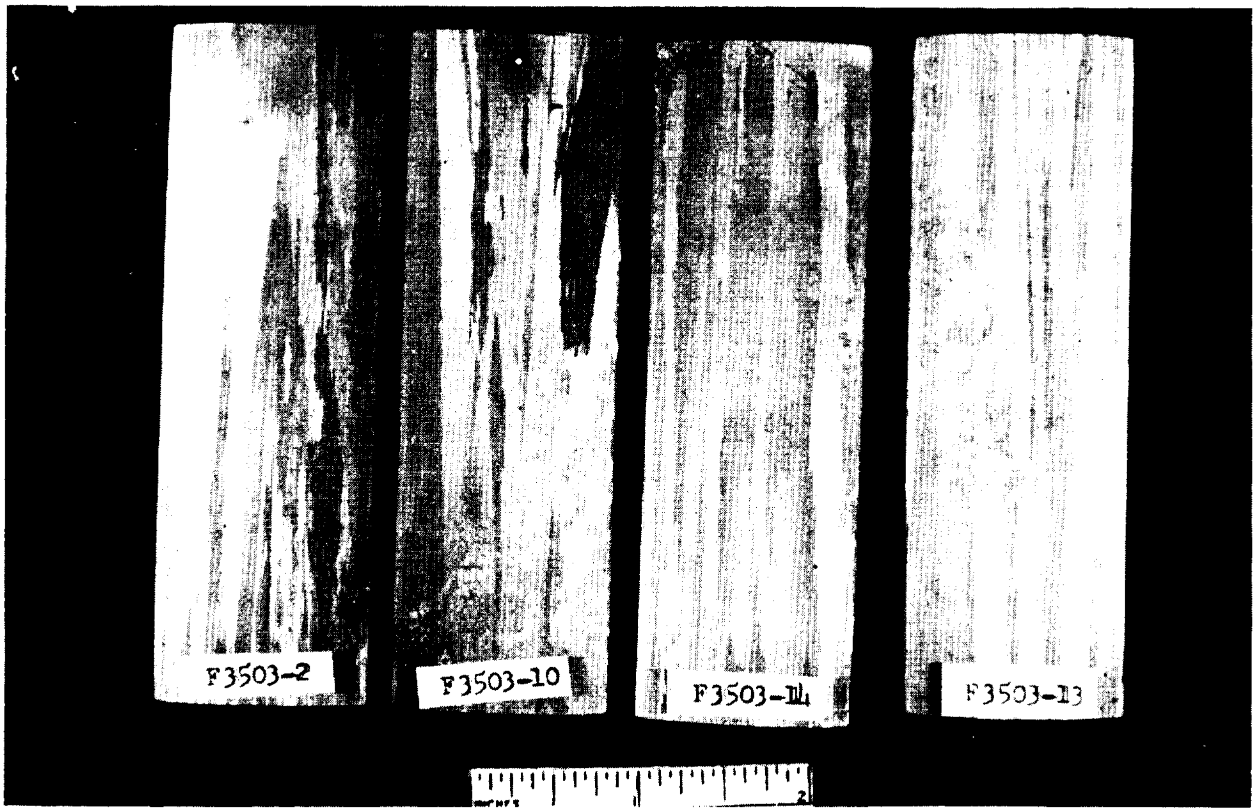
UNIAXIAL TEST PIECE

Fig. 1 - Dimensions of Test Specimens Used in the Program.



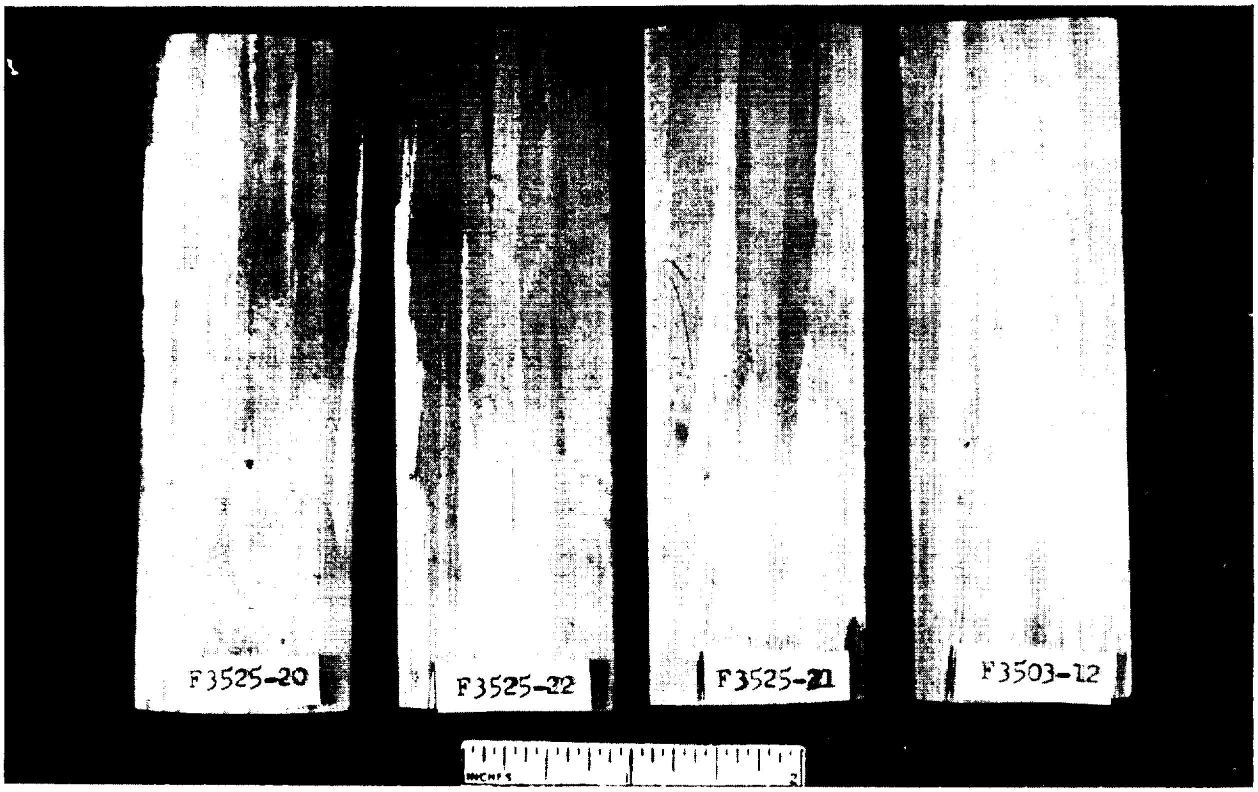
(a)

Fig. 2 - Macrographs of Grain Patterns in PWA 664.



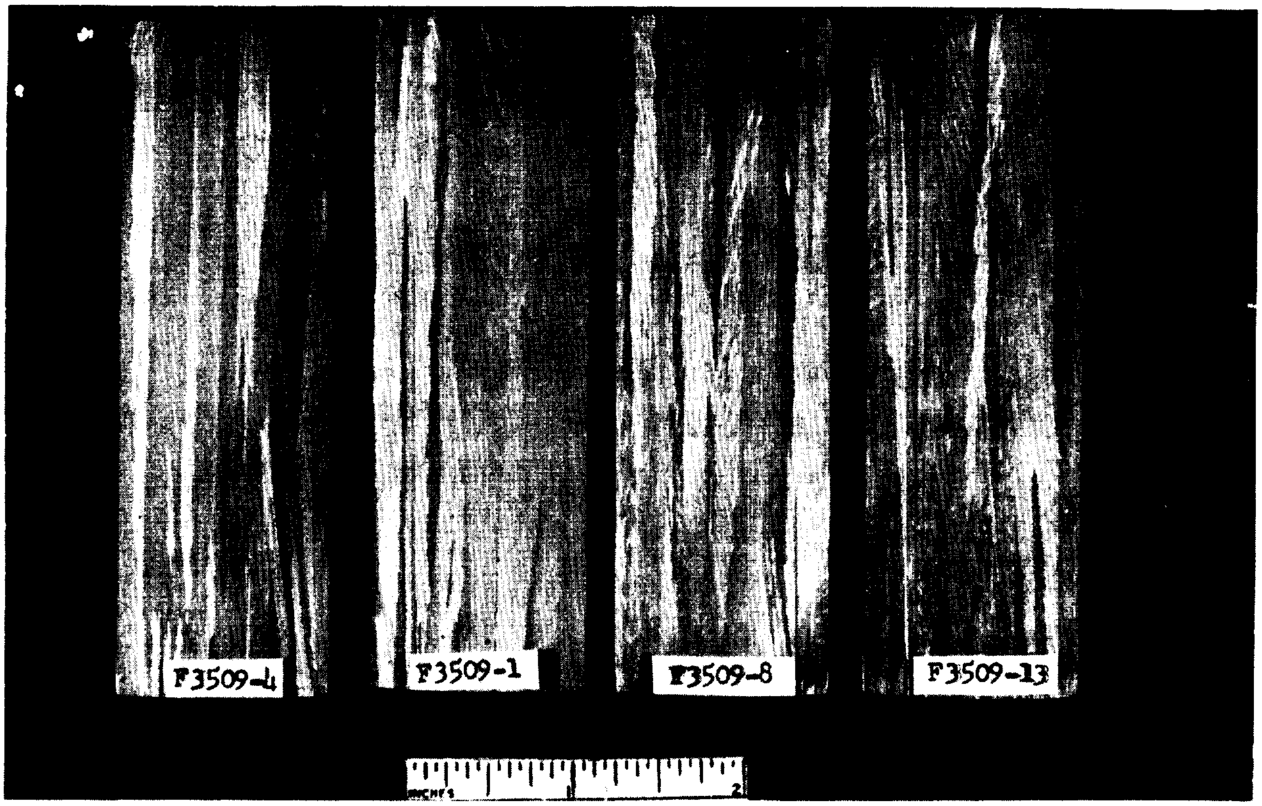
(b)

Fig. 2 (Continued) - Macrographs of Grain Patterns in PWA 664.



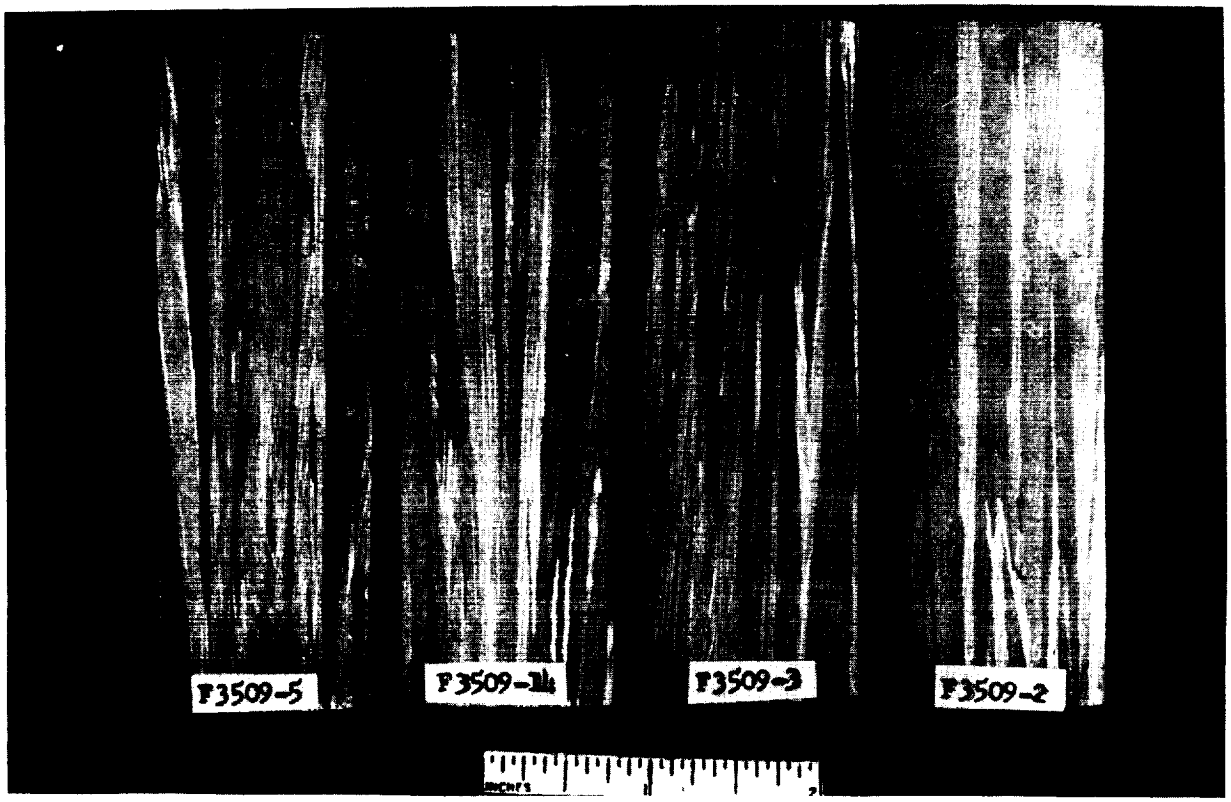
(c)

Fig. 2 (Continued) - Macrographs of Grain Patterns in PWA 664.



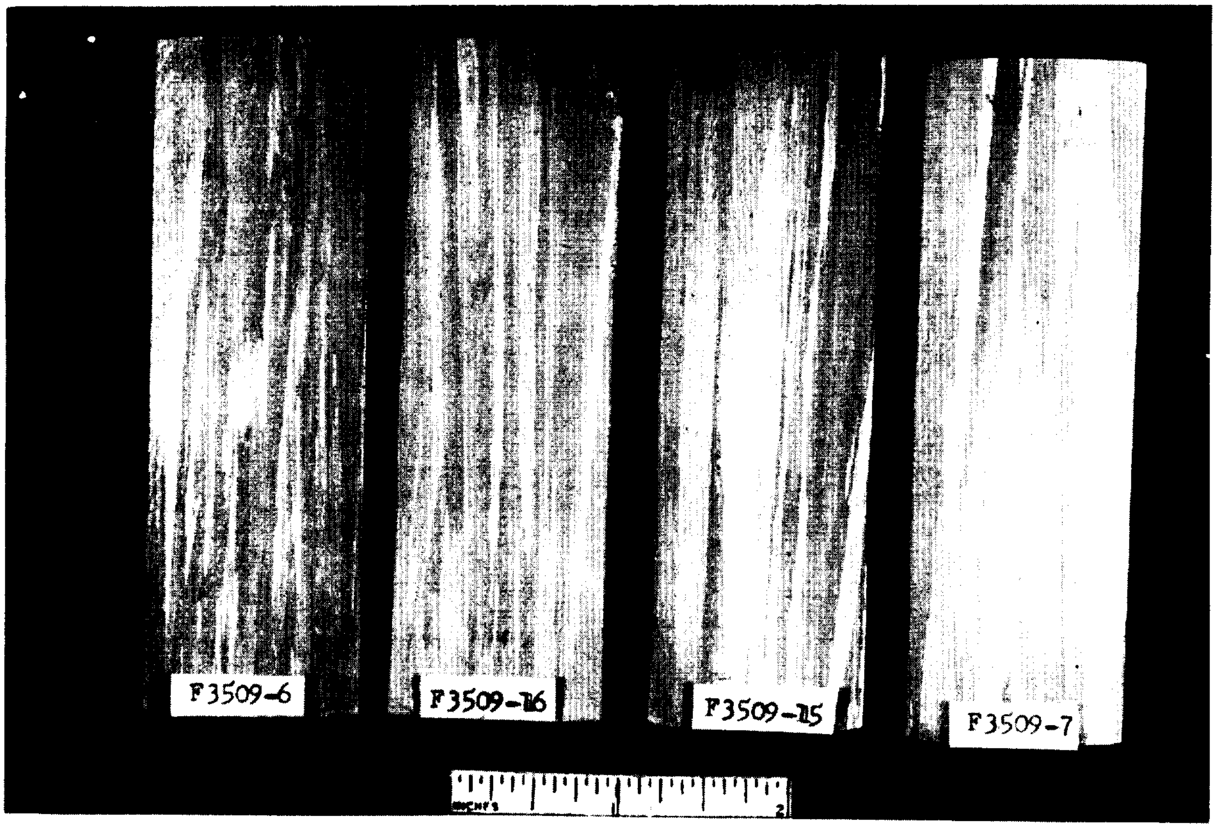
(a)

Fig. 3 - Macrographs of Grain Patterns in PWA 1401.



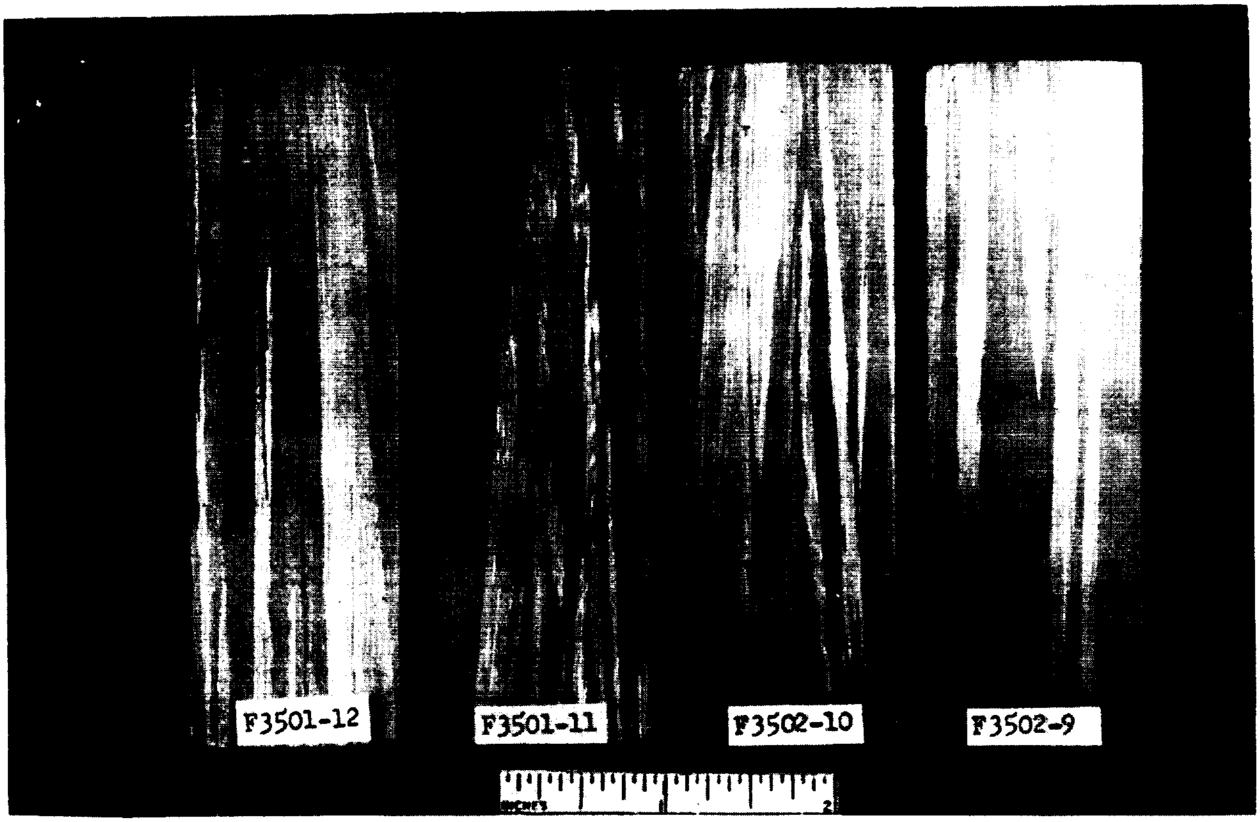
(b)

Fig. 3 (Continued) - Macrographs of Grain Patterns in PWA 1401



(c)

Fig. 3 (Continued) - Macrographs of Grain Patterns in PWA 1401



(d)

Fig. 3 (Continued) - Macrographs of Grain Patterns in PWA 1401

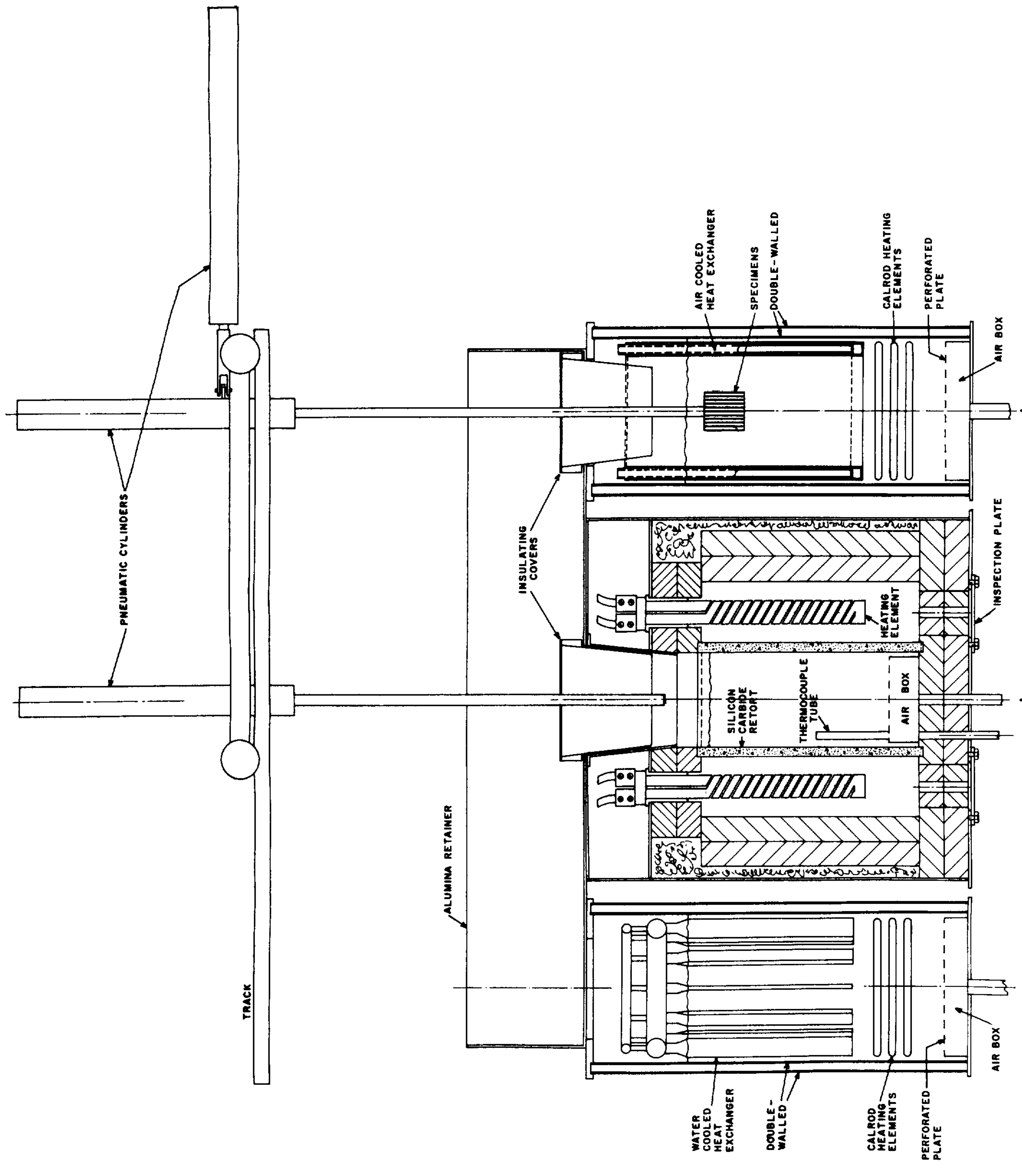


Fig. 4 - Schematic View of Thermal Fatigue Facility.

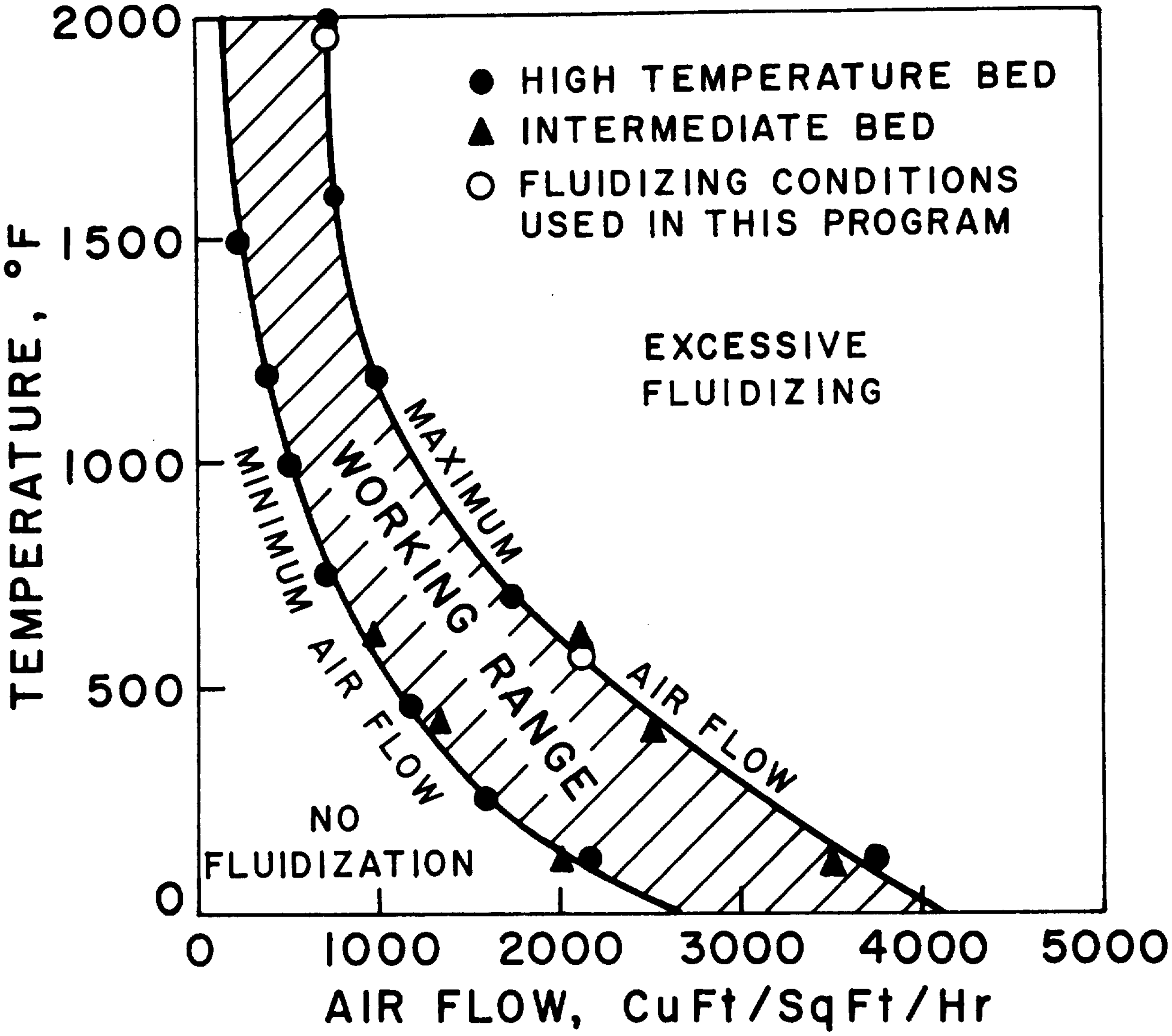


Fig. 5 - Fluidized Bed Air Requirements (28-48 mesh tabular alumina particles).

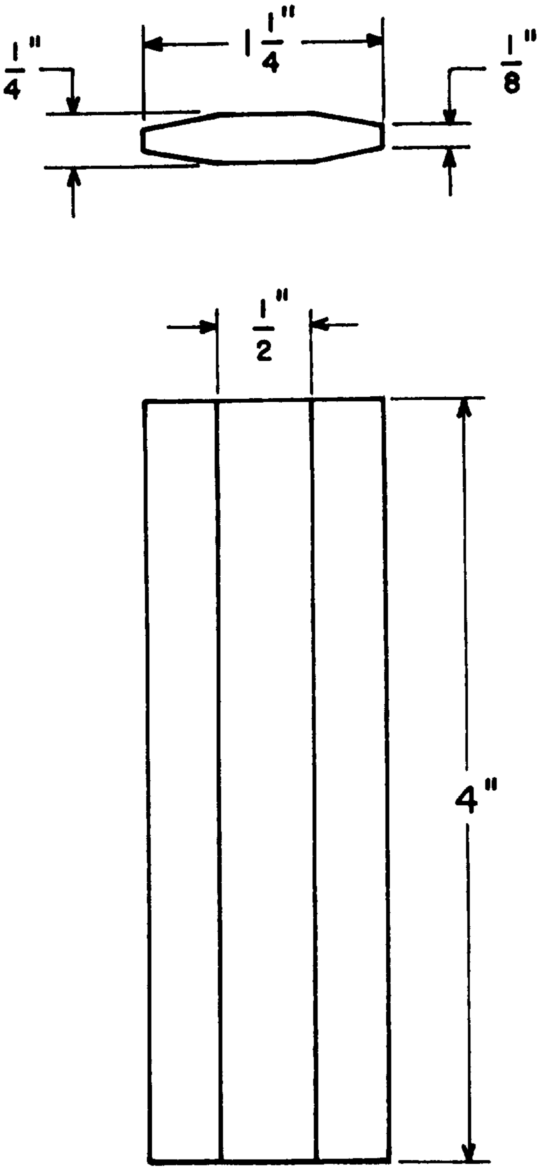
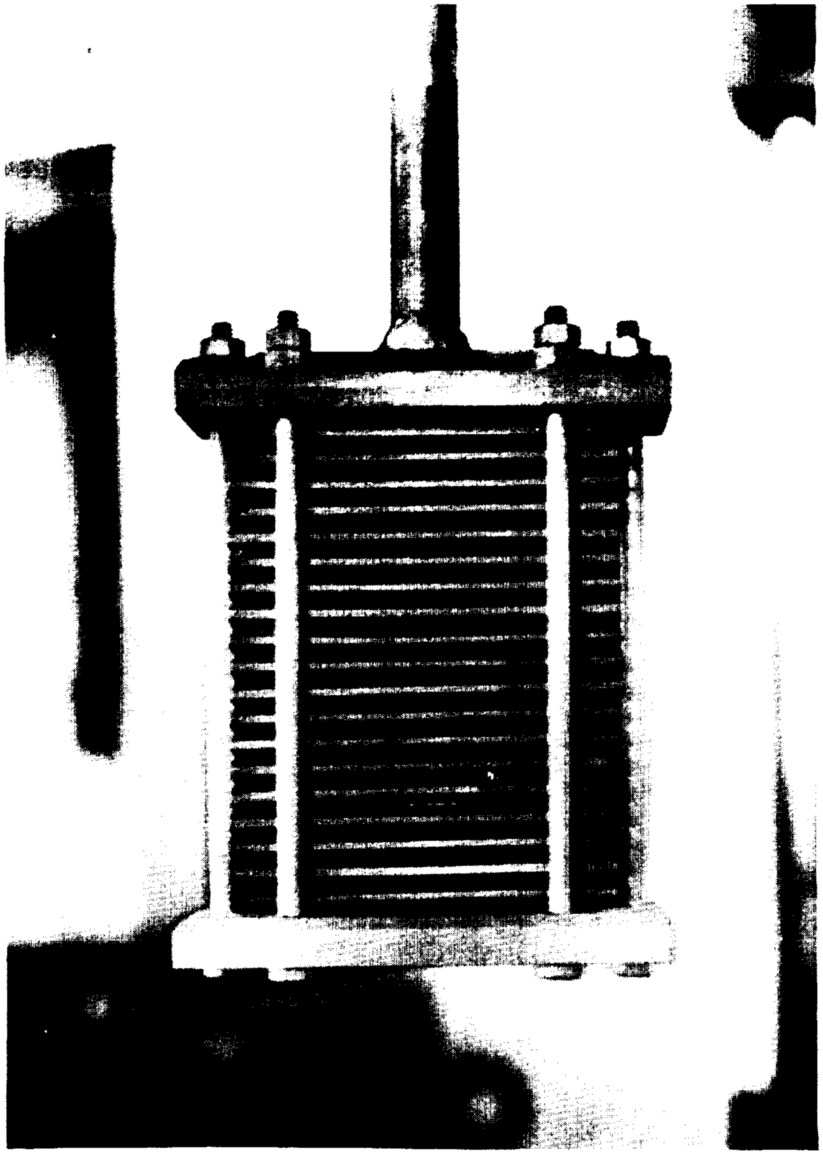
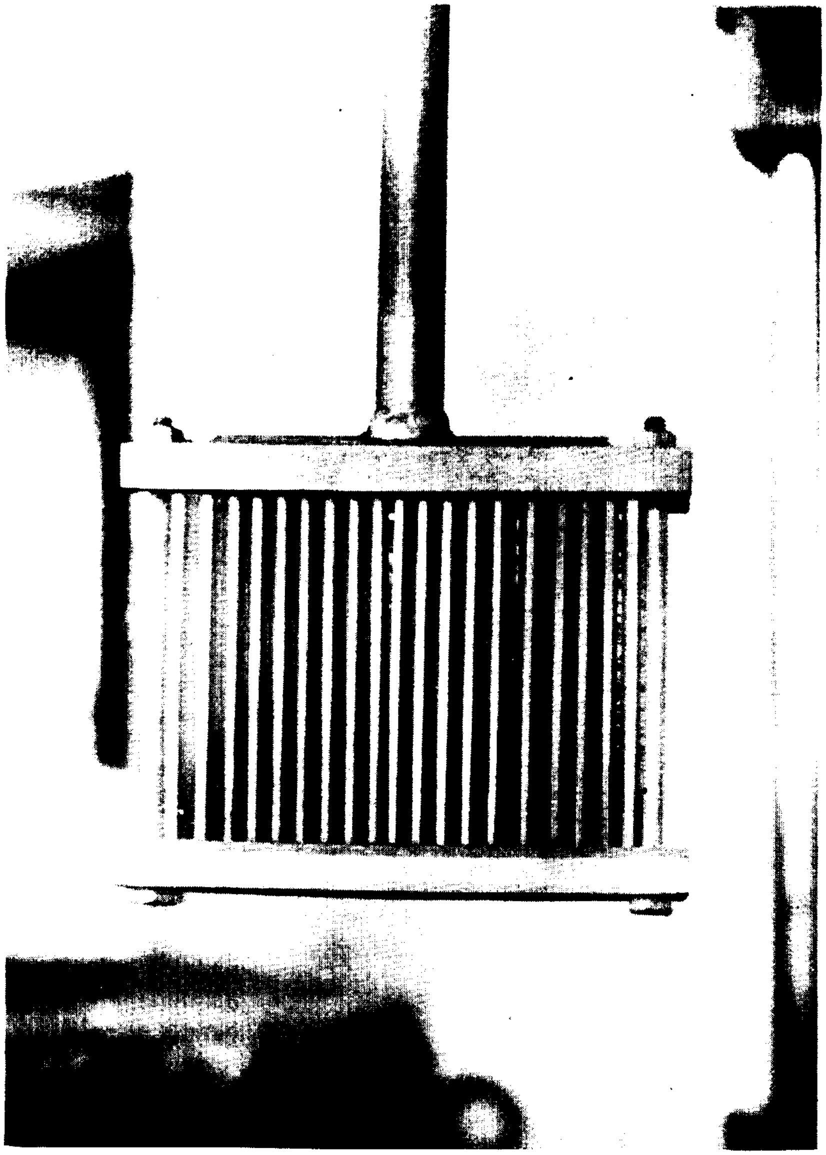


Fig. 6 - Simulated Thermal Fatigue Specimen
Utilized During Fixture Development.



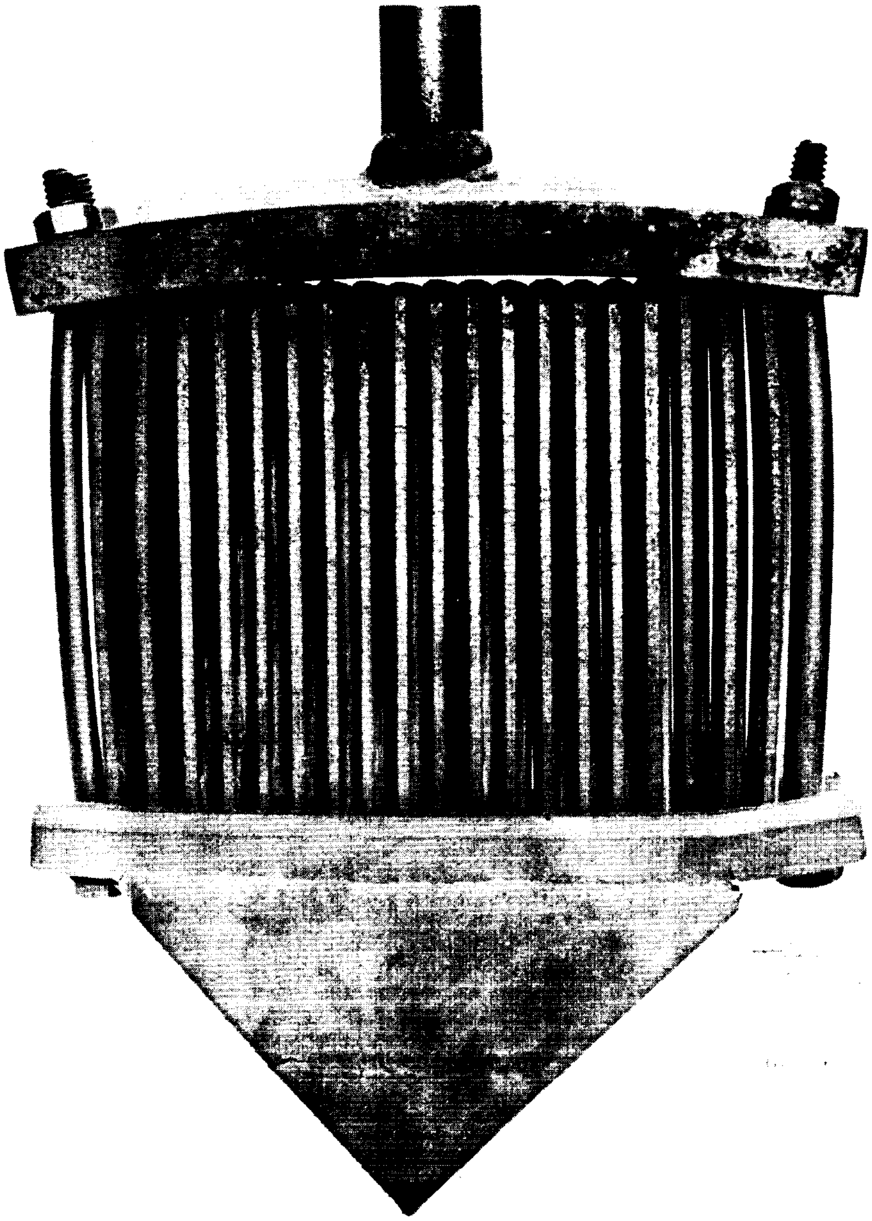
Neg. No. 37854

Fig. 7 - Temperature Gradient in Horizontally Held Specimens.



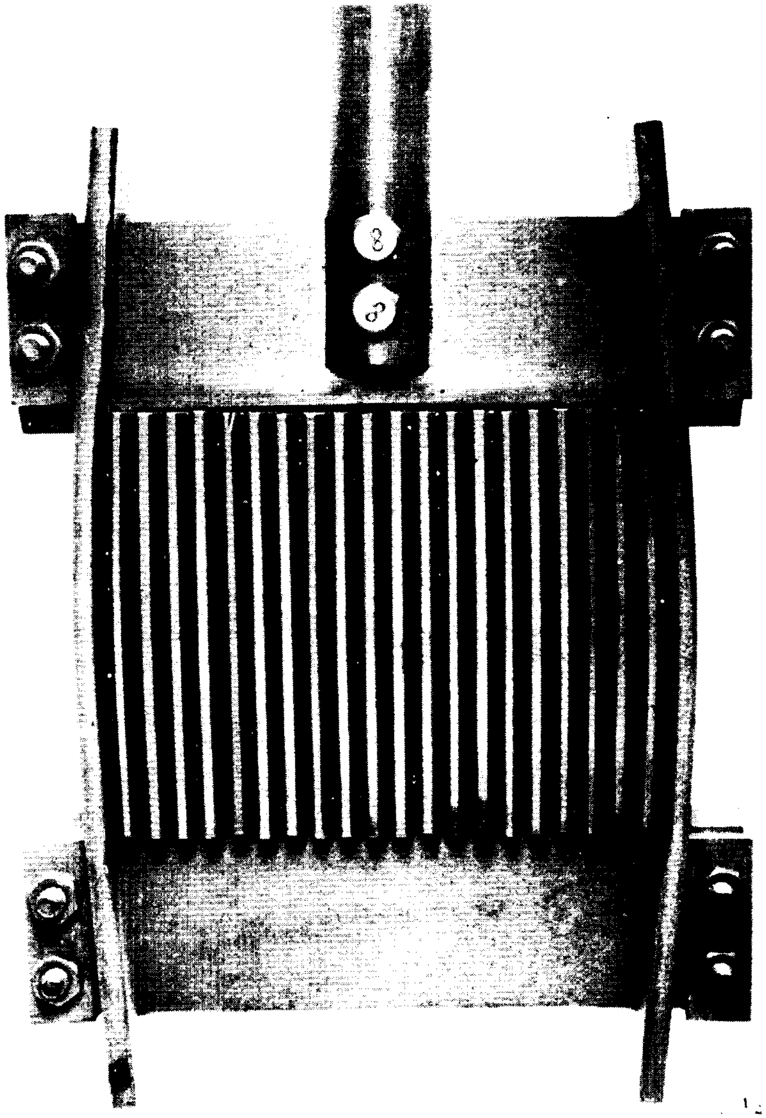
Neg. No. 37853

Fig. 8 - Temperature Gradient in Vertically Held Specimens.



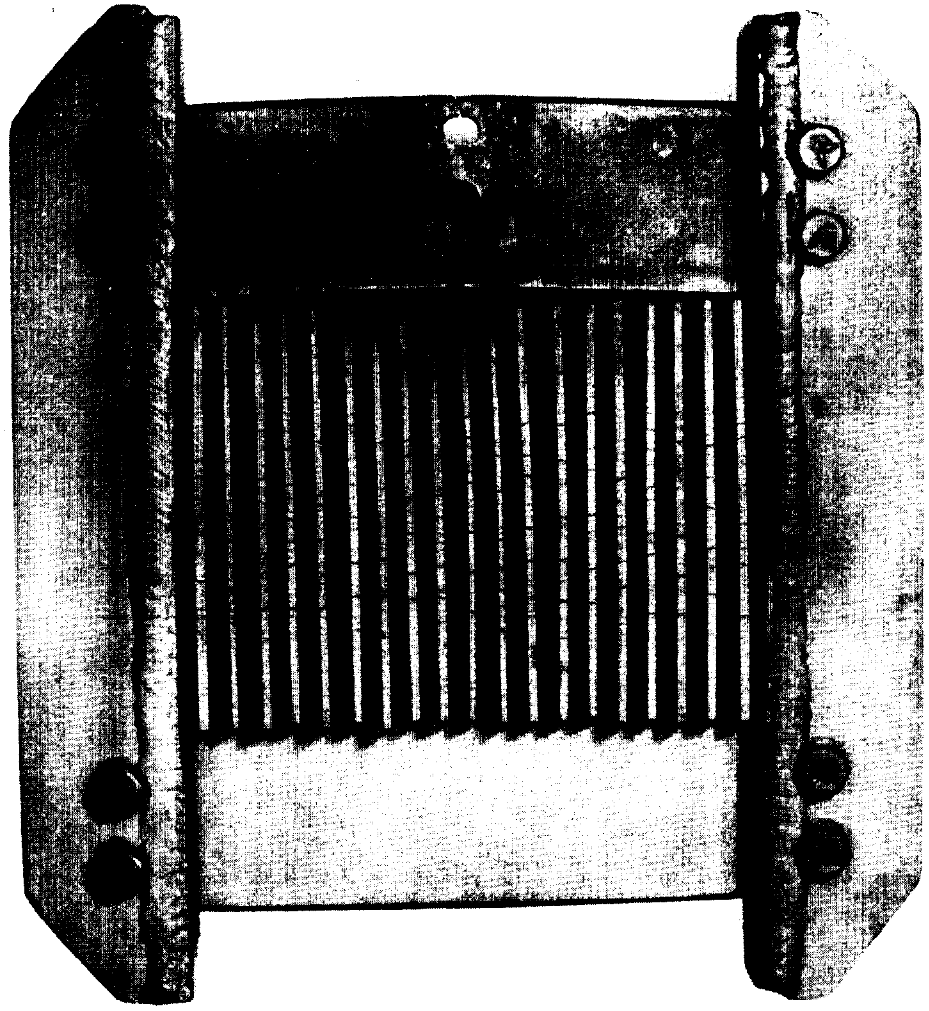
Neg. No. 33484

Fig. 9 - Distortion in a Stiffened Variation of the Fixture Shown in Fig. 8 after 100 Cycles of Operation.



Neg. No. 33847

Fig. 10 - Use of Location Slots in the Test Pieces with Top and Bottom Plates in the Vertical Plane.

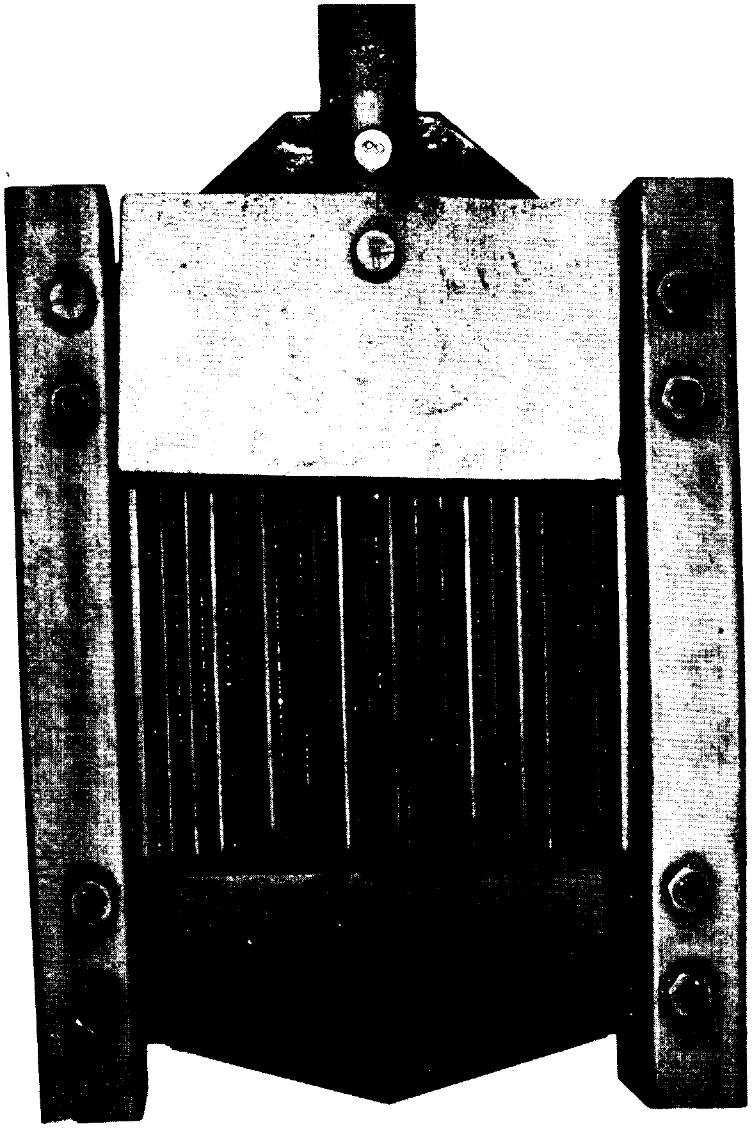


Neg. No. 33949

Fig. 11 - Fixture with Welded Channel Sections after 580 Cycles.

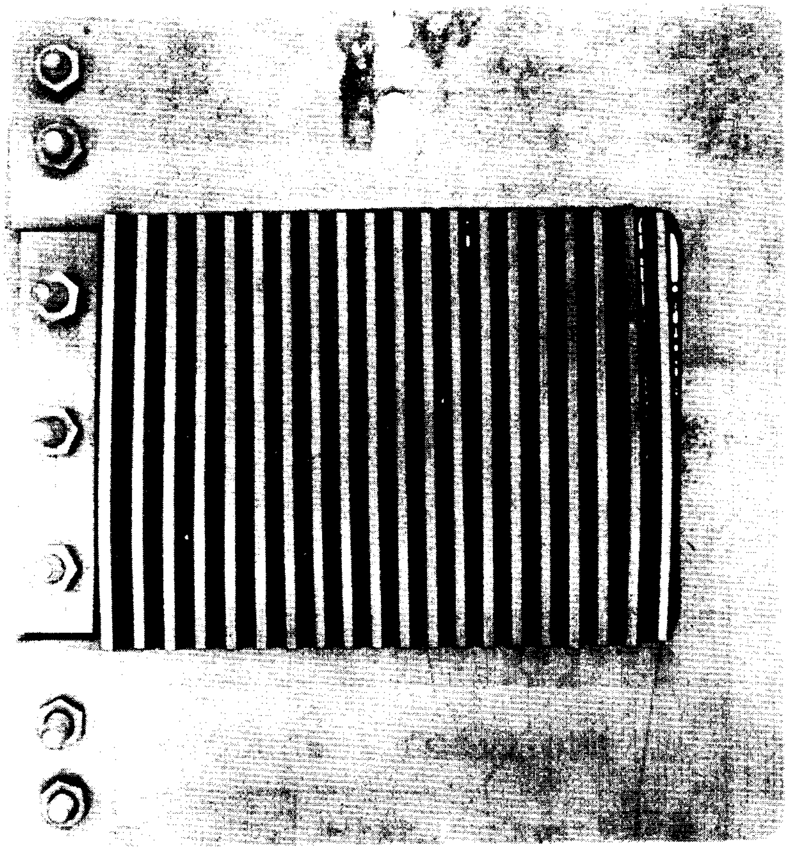
Neg. No. 34825

Fig. 12 - New Fixture with Rolled Channel Section Side Members.



Neg. No. 36377

Fig. 13 - Final Form of Fixture as Used in the Program with Increased Section Bottom Plate and Top Retaining Plates.



Neg. No. 34064

Fig. 14 - "C" Type Fixture after 100 Cycles.

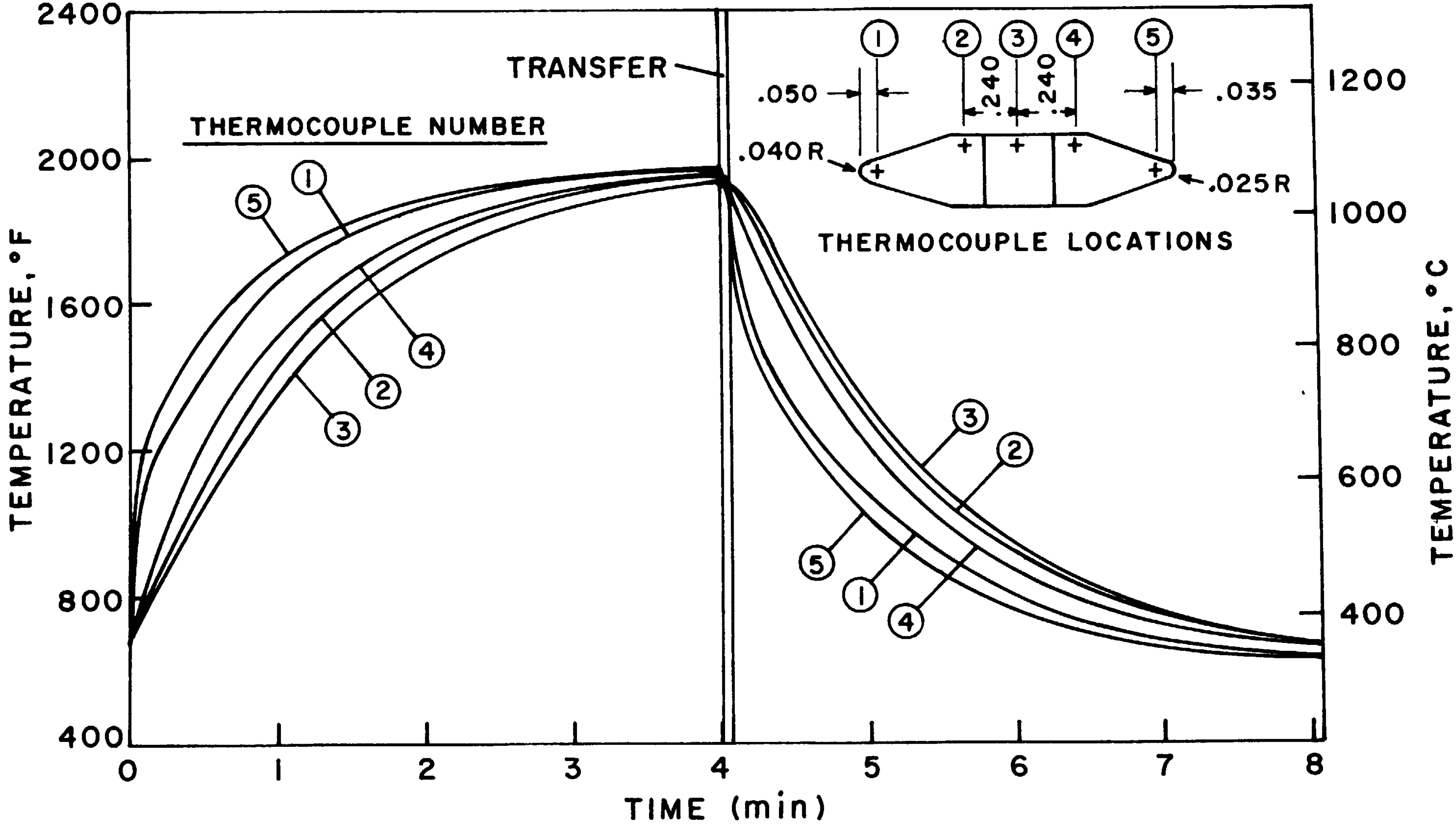
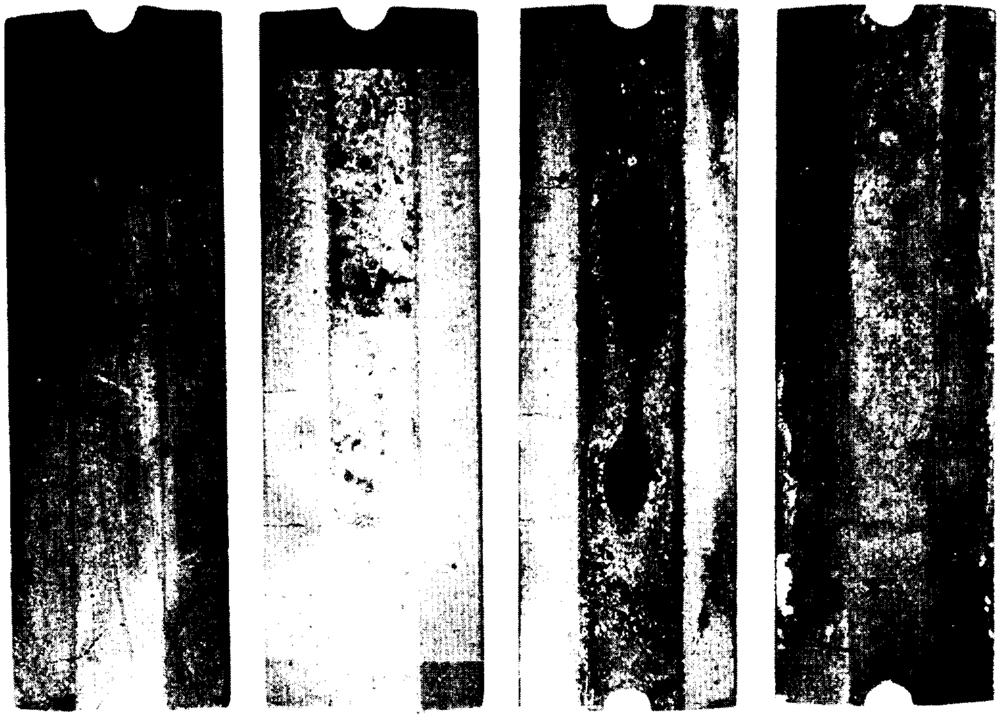


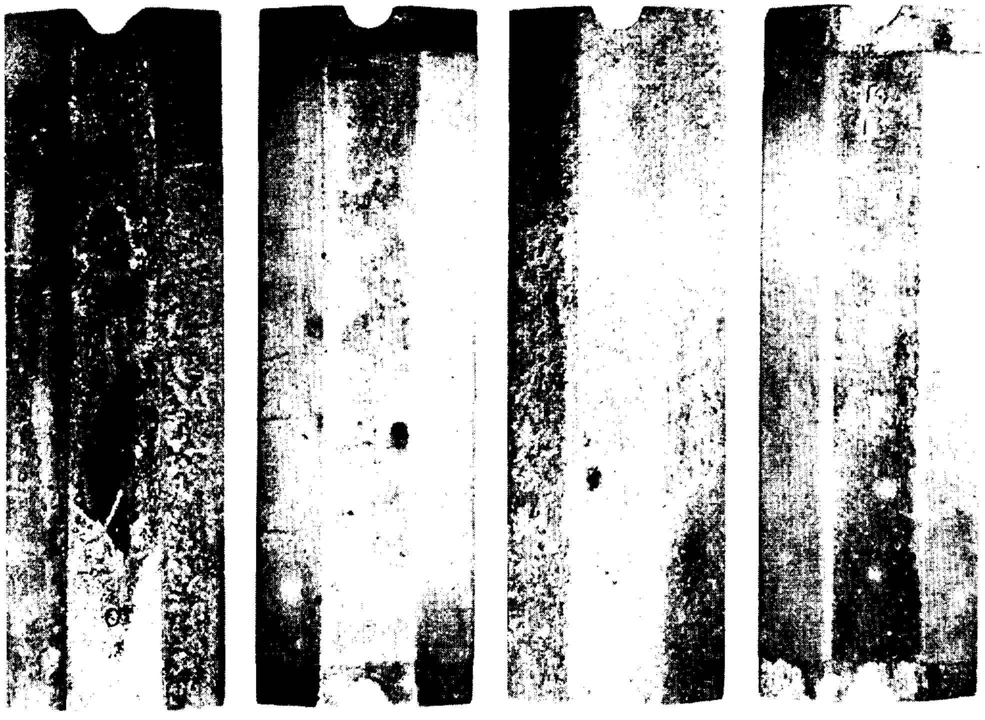
Fig. 15 - Temperature Calibration Curves for IN-100 Cycled under Set F Conditions



Neg. No. 37994

B1900 (5000 Cycles) B1900 Coated (5000 Cycles) MAR-M 200 (1000 Cycles) PWA 664 (5000 Cycles)

(a) Set A Specimens (2 min exposure)



Neg. No. 37995

IN-100 (1000 Cycles) IN-100 Coated (5000 Cycles) PWA 1401 (5000 Cycles) PWA 1401 Coated (5000 Cycles)

(b) Set A Specimens (2 min exposure)

Fig. 16 - Appearance of Test Specimens at the Conclusion of Thermal Fatigue Cycling.

Neg. No. 37992

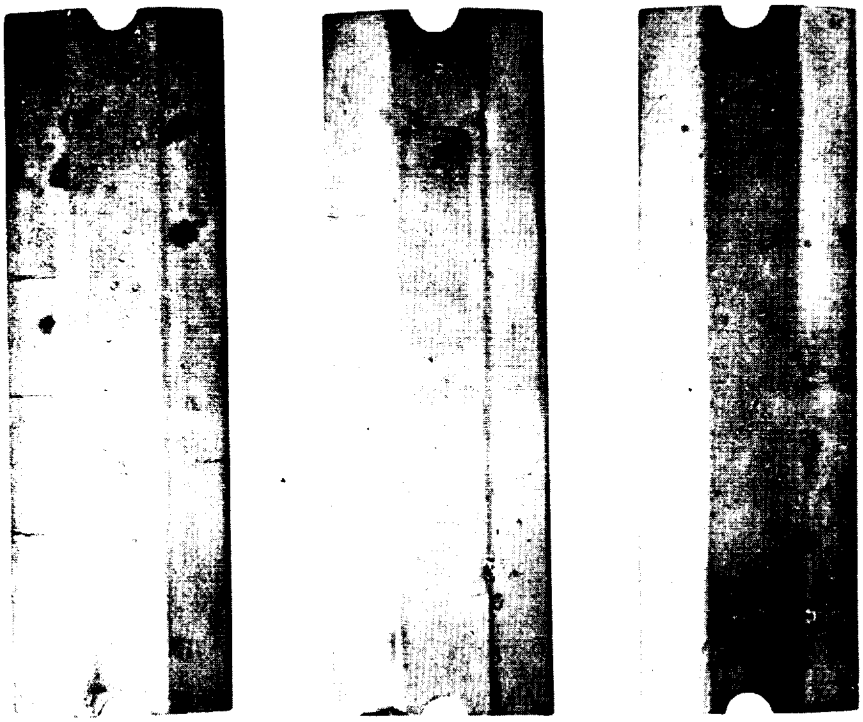
Udimet 700 (Wrought) (1000 Cycles)

Udimet 700 (cast) (1000 Cycles)

TD-NiCr (400 Cycles)

IN-713C (500 Cycles)

(c) Set A Specimens (2 min exposure)



Neg. No. 37993

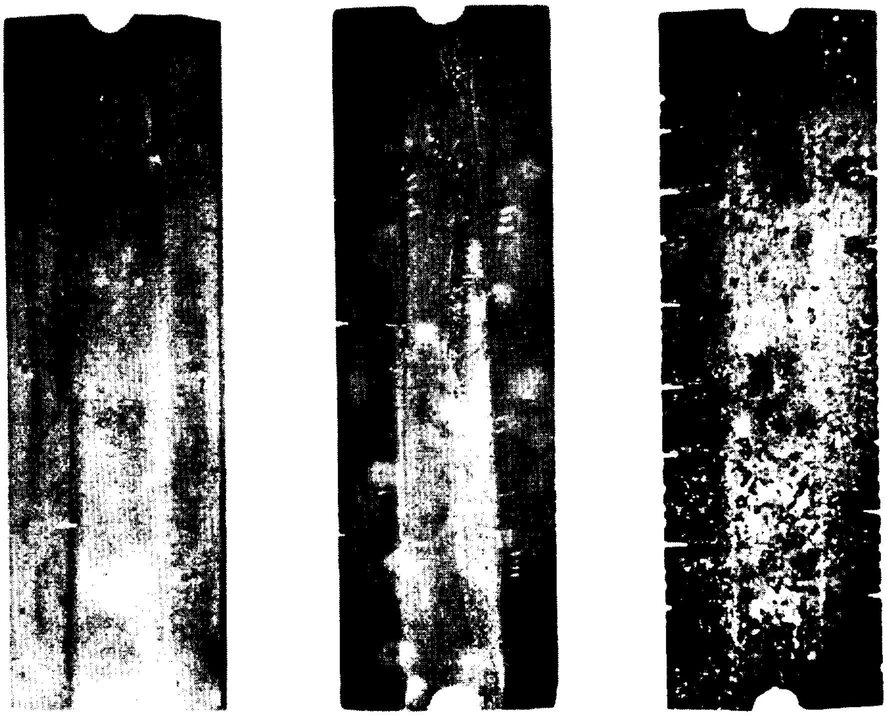
IN-162 (5000 Cycles)

TAZ-8A (5000 Cycles)

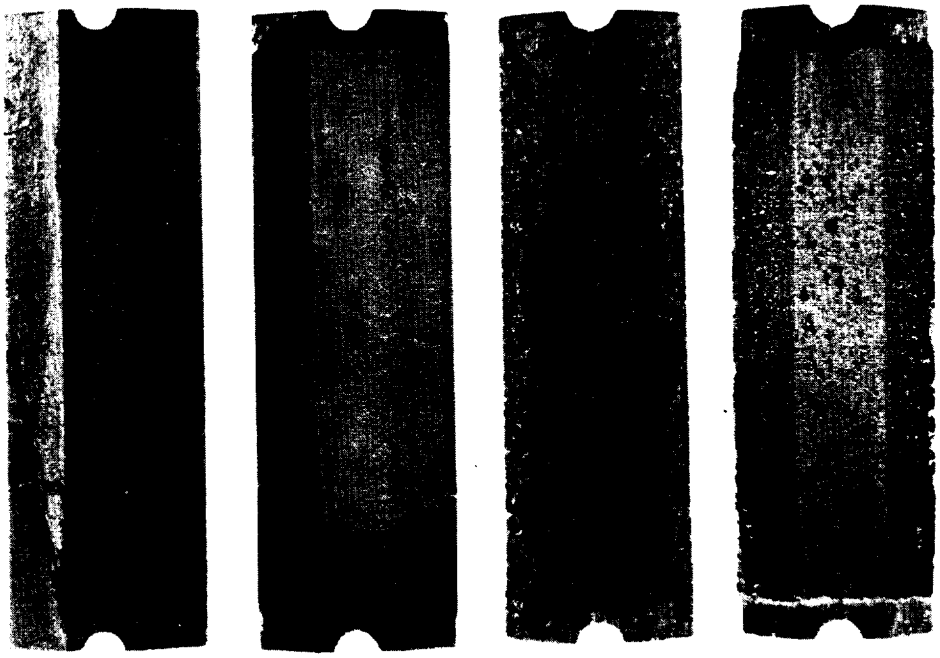
M22 (1000 Cycles)

(d) Set A Specimens (2 min exposure)

Fig. 16 (Continued) - Appearance of Test Specimens at the Conclusion of Thermal Fatigue Cycling.

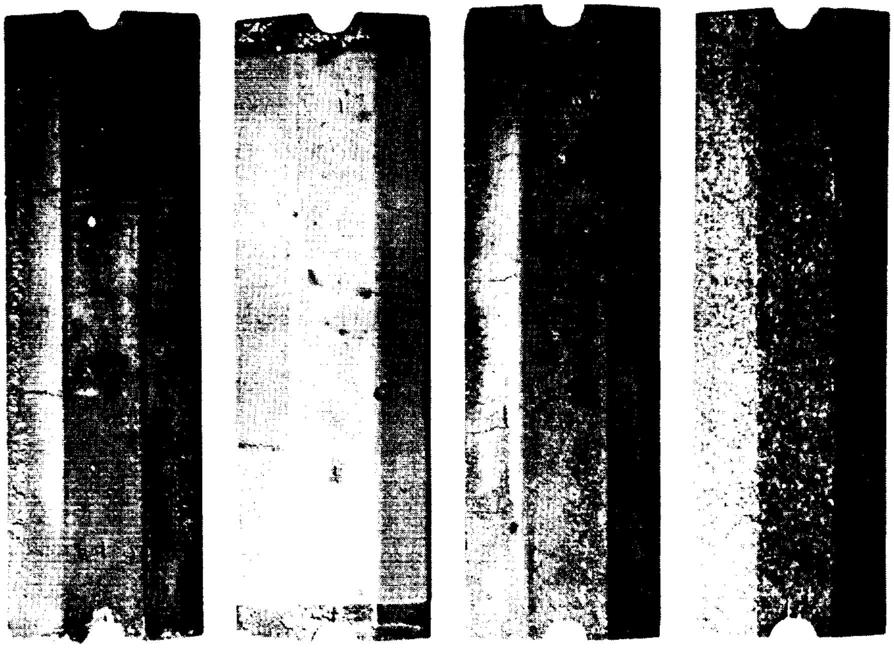


Neg. No. 37996
X-40 MAR-M 302 WI-52
(2000 Cycles) (5000 Cycles) (5000 Cycles)
(e) Set A Specimens (2 min exposure)

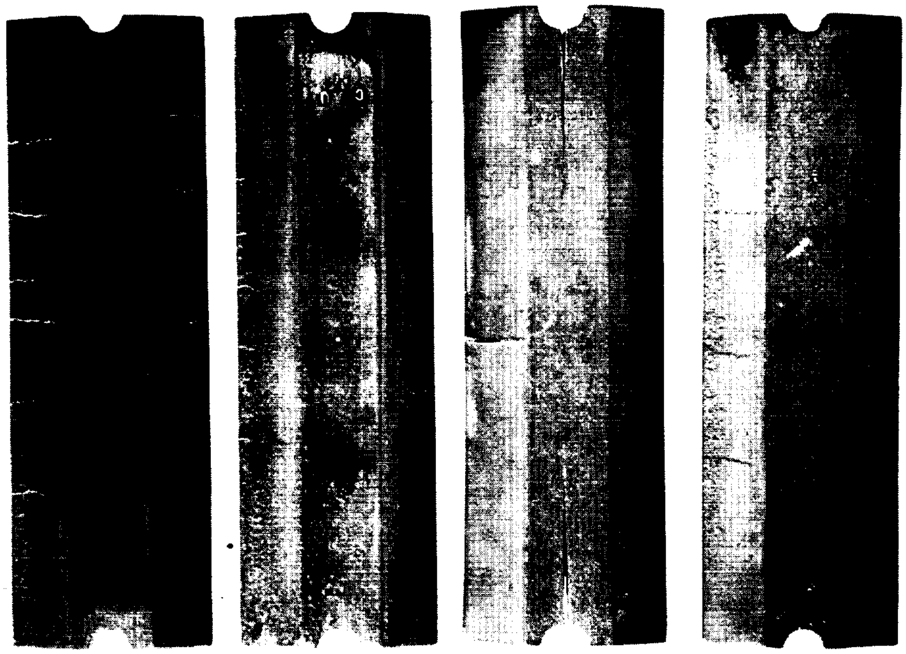


Neg. No. 37776
B1900 B1900 Coated MAR-M 200 PWA 664
(2000 Cycles) (4400 Cycles) (700 Cycles) (5000 Cycles)
(f) Set D Specimens (3 min exposure)

Fig. 16 (Continued) - Appearance of Test Specimens at the Conclusion of Thermal Fatigue Cycling.

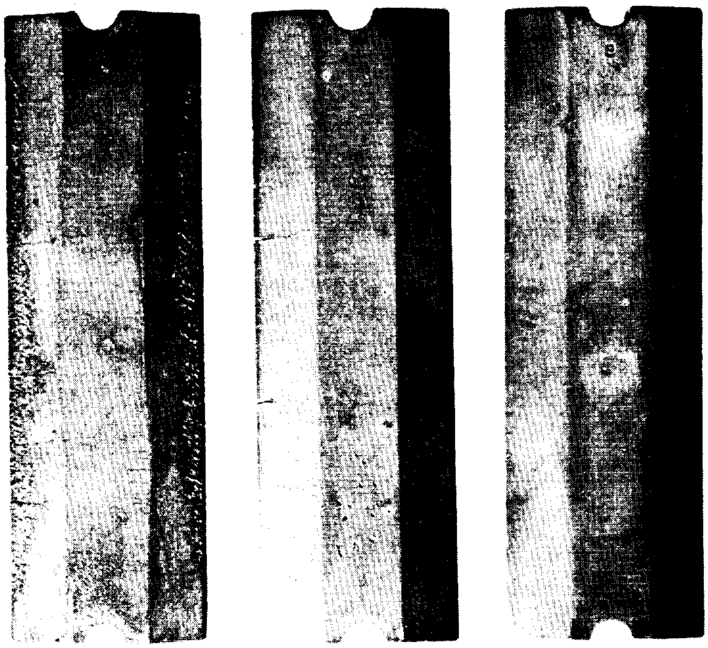


Neg. No. 37778
IN-100 IN-100 Coated PWA 1401 PWA 1401 Coated
(700 Cycles) (2000 Cycles) (5000 Cycles) (5000 Cycles
(g) Set D Specimens (3 min exposure)

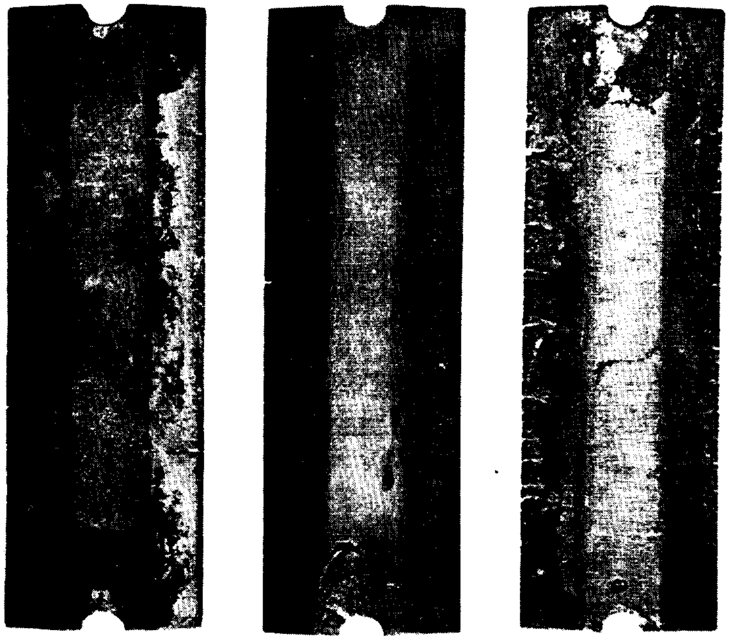


Neg. No. 37775
Udimet 700 Udimet 700 TD-NiCr Inconel 713C
(Wrought) (Cast) (700 Cycles) (700 Cycles)
(700 Cycles) (700 Cycles)
(h) Set D Specimens (3 min exposure)

Fig. 16(Continued) - Appearance of Test Specimens at the Conclusion of Thermal Fatigue Cycling.



Neg. No. 37774
Inconel 162 (3100 Cycles) | TAZ-8A (5000 Cycles) | M22 (700 Cycles)
(i) Set D Specimens (3 min exposure)



Neg. No. 37777
X-40 (2000 Cycles) | MAR-M 302 (700 Cycles) | WI-52 (700 Cycles)
(j) Set D Specimens (3 min exposure)

Fig. 16 (Continued) - Appearance of Test Specimens at the Conclusion of Thermal Fatigue Cycling.

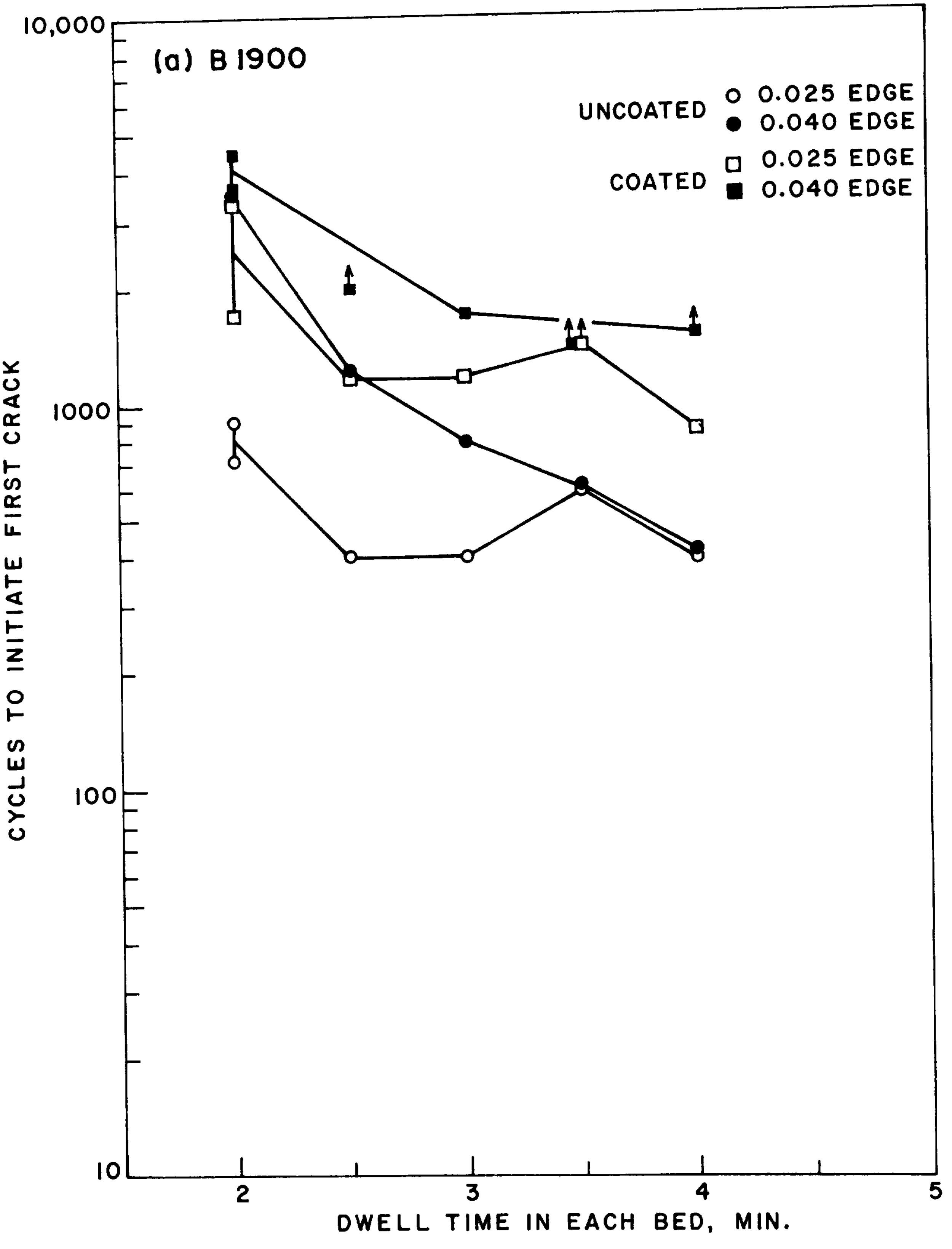


Fig. 17(a) - Thermal Cycles to Initiate the First Crack in B1900 Test Specimens in Either Test Edge under Test Conditions A to F.

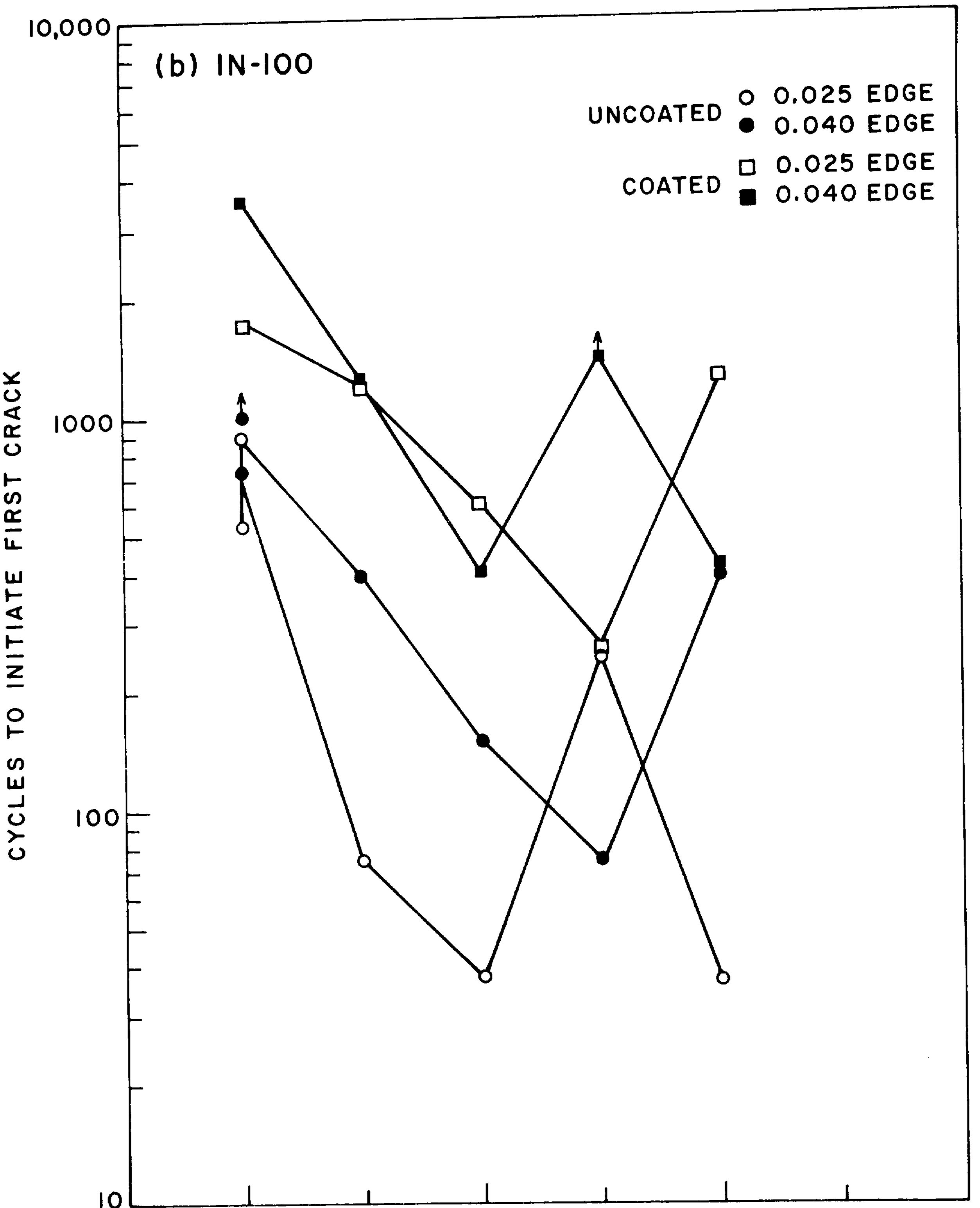


Fig. 17(b) - Thermal Cycles to Initiate the First Crack in IN-100 Test Specimens in Either Test Edge under Test Conditions A to F.

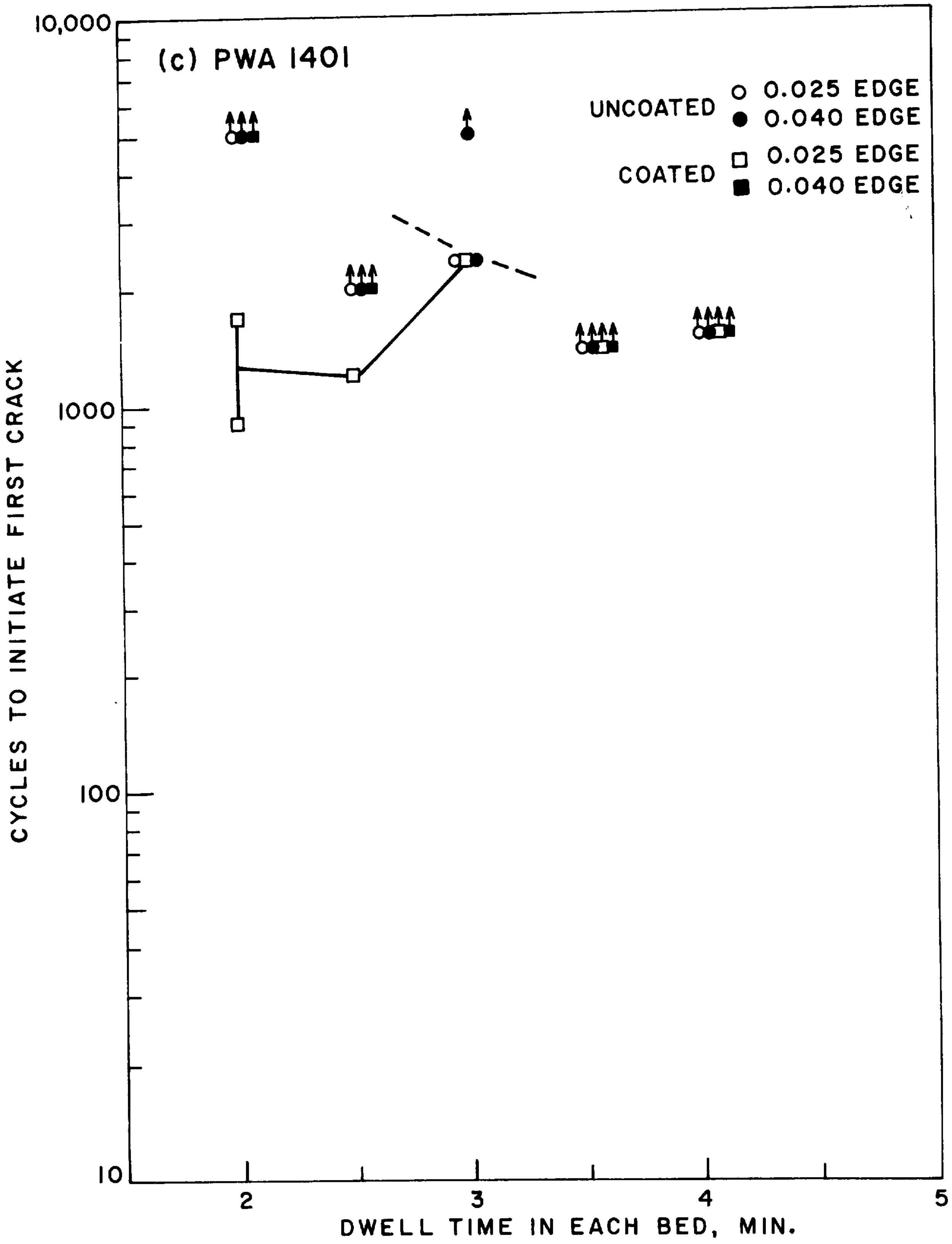


Fig. 17(c) - Thermal Cycles to Initiate the First Crack in PWA 1401 Test Specimens in Either Test Edge under Test Conditions A to F.

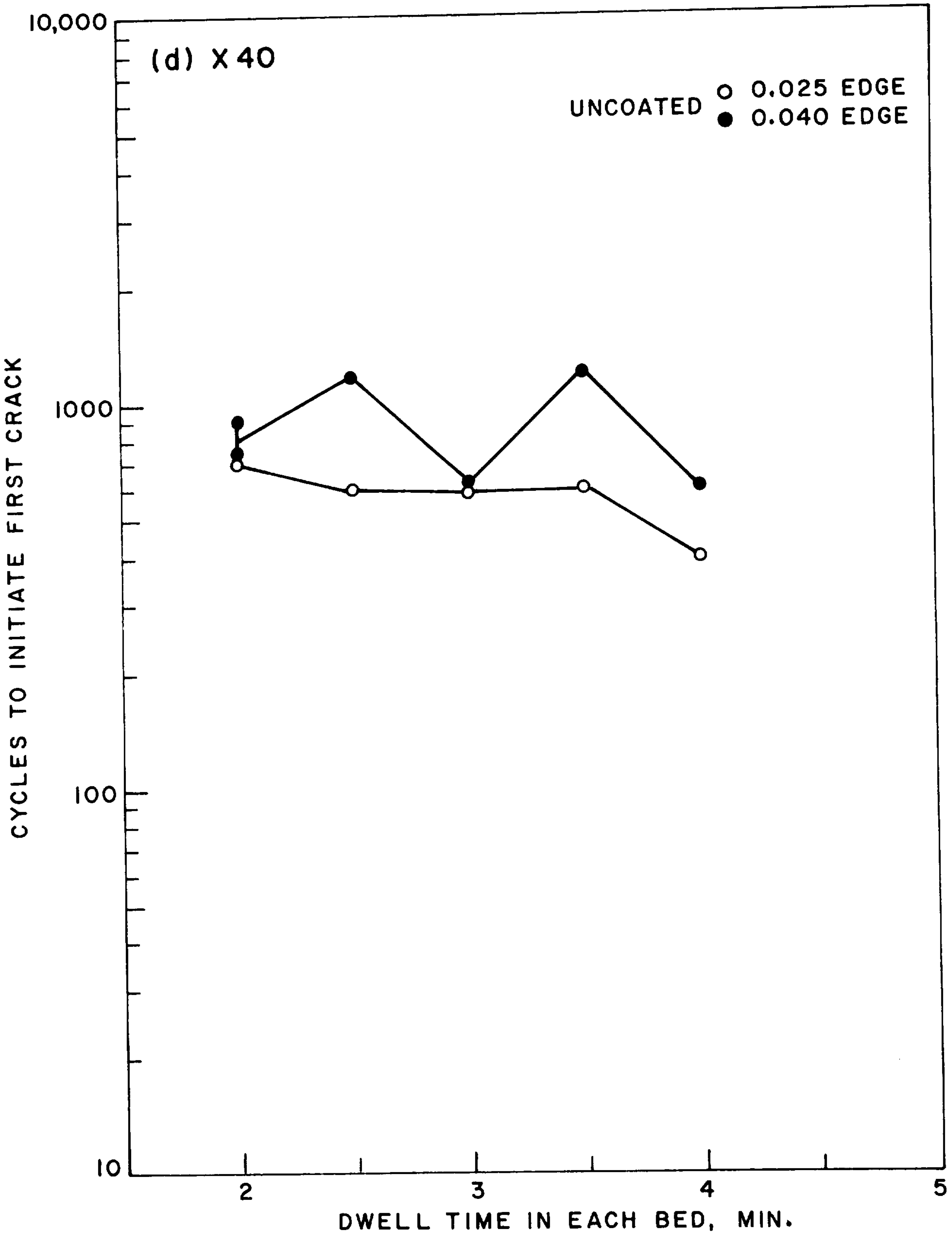


Fig. 17(d) - Thermal Cycles to Initiate the First Crack in X-40 Test Specimens in Either Test Edge under Test Conditions A to F.

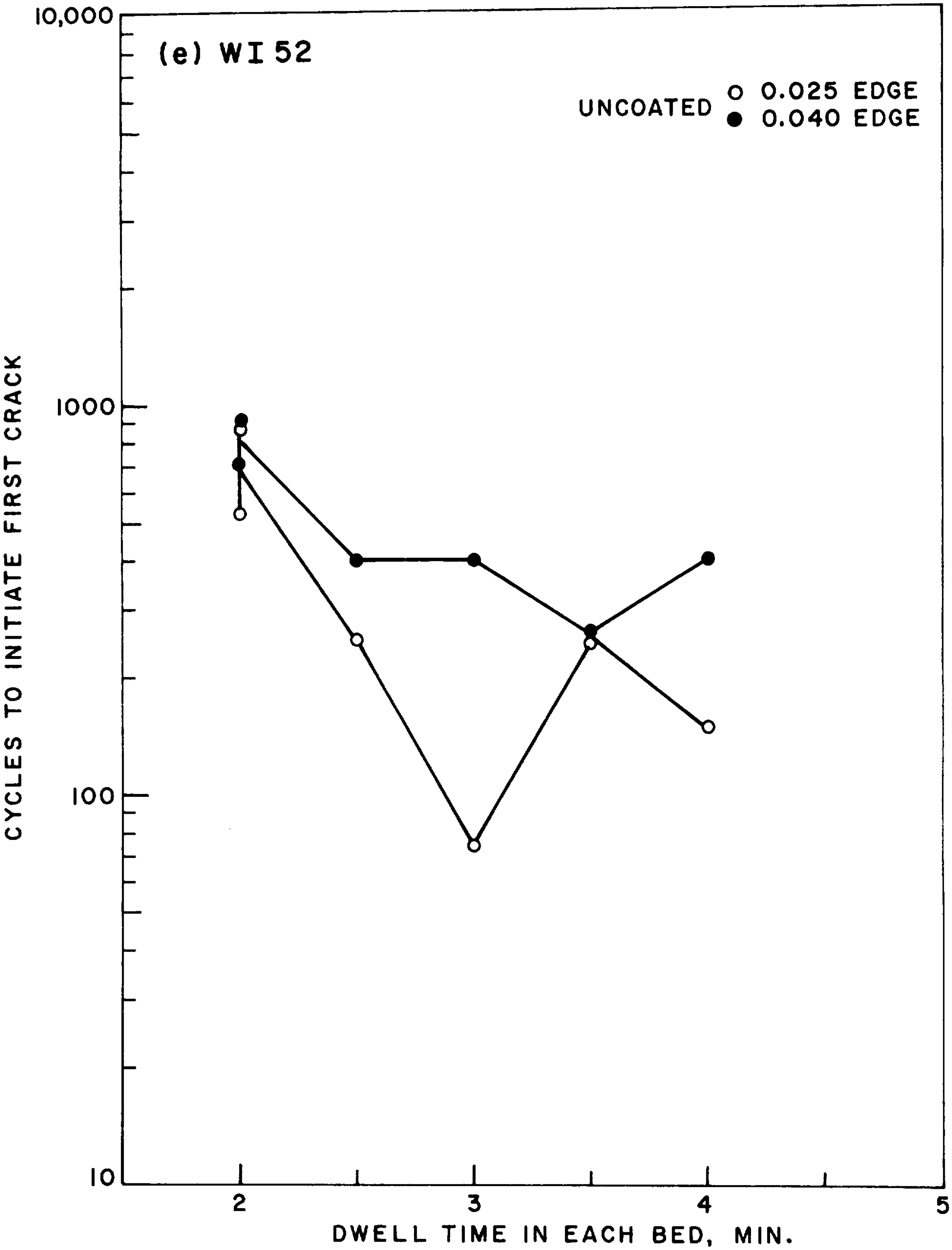


Fig. 17(e) - Thermal Cycles to Initiate the First Crack in WI-52 Test Specimens in Either Test Edge under Test Conditions A to F.

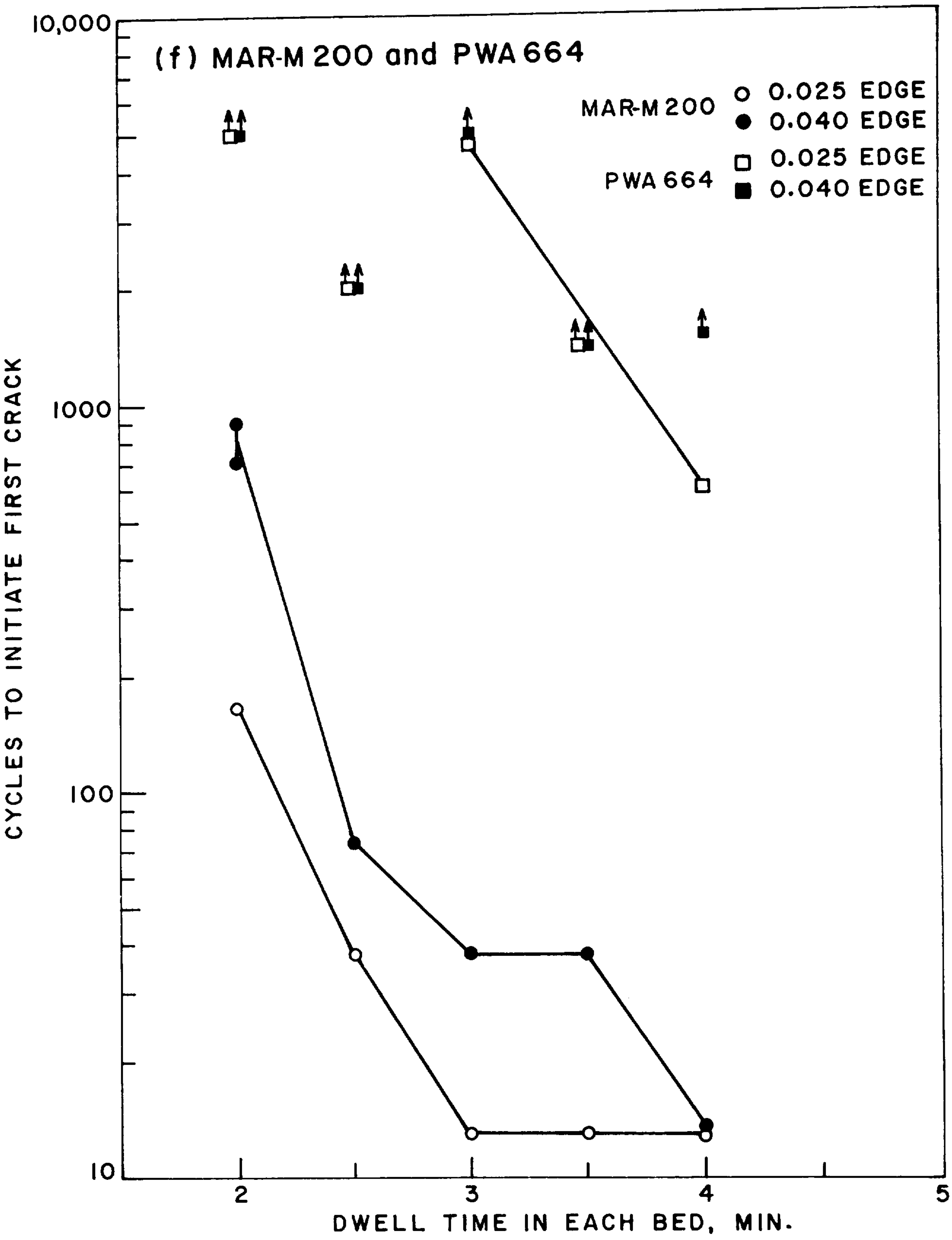


Fig. 17(f) - Thermal Cycles to Initiate the First Crack in MAR-M 200 and PWA 664 Test Specimens in Either Test Edge under Test Conditions A to F.

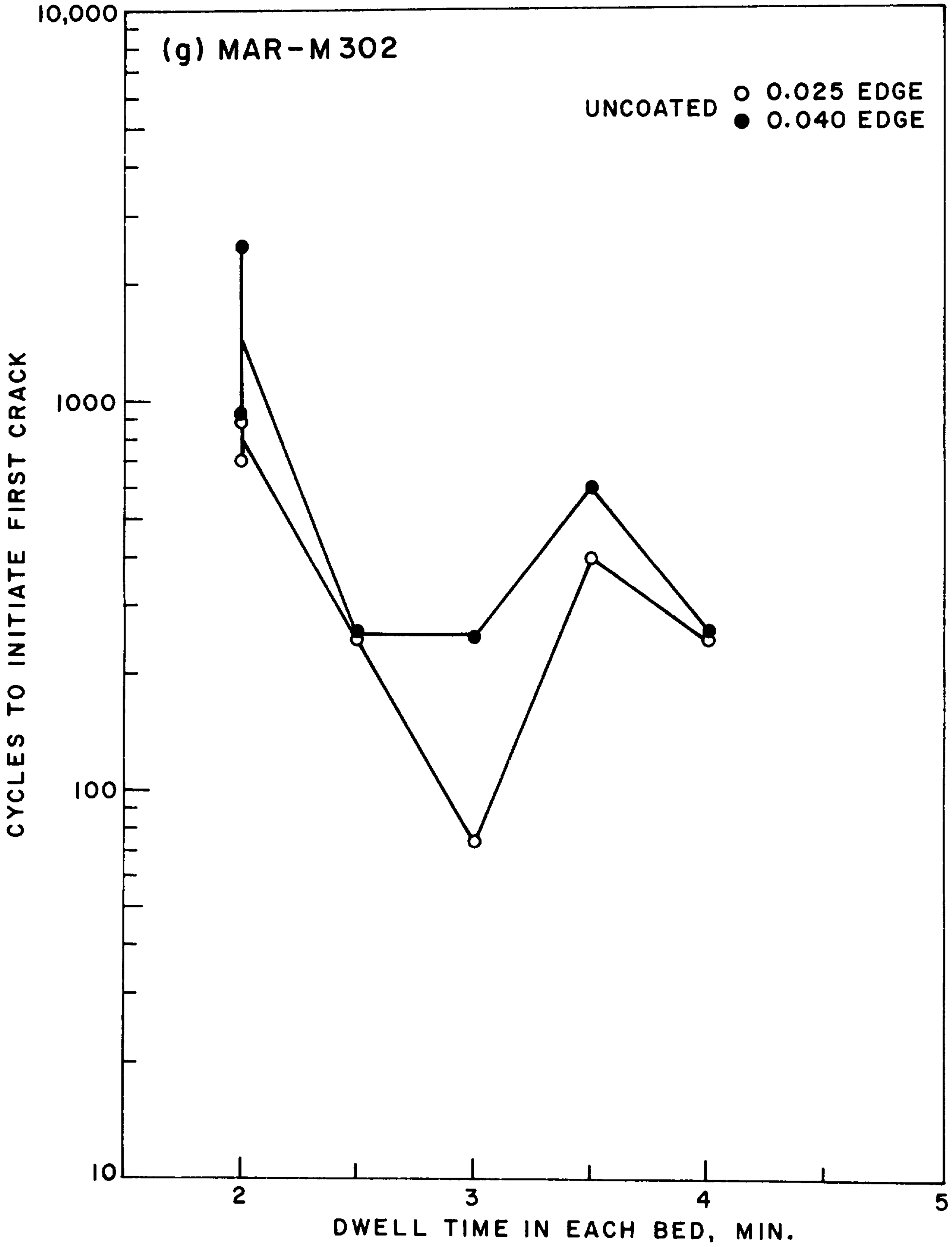


Fig. 17(g) - Thermal Cycles to Initiate the First Crack in MAR-M 302 Test Specimens in Either Test Edge under Test Conditions A to F.

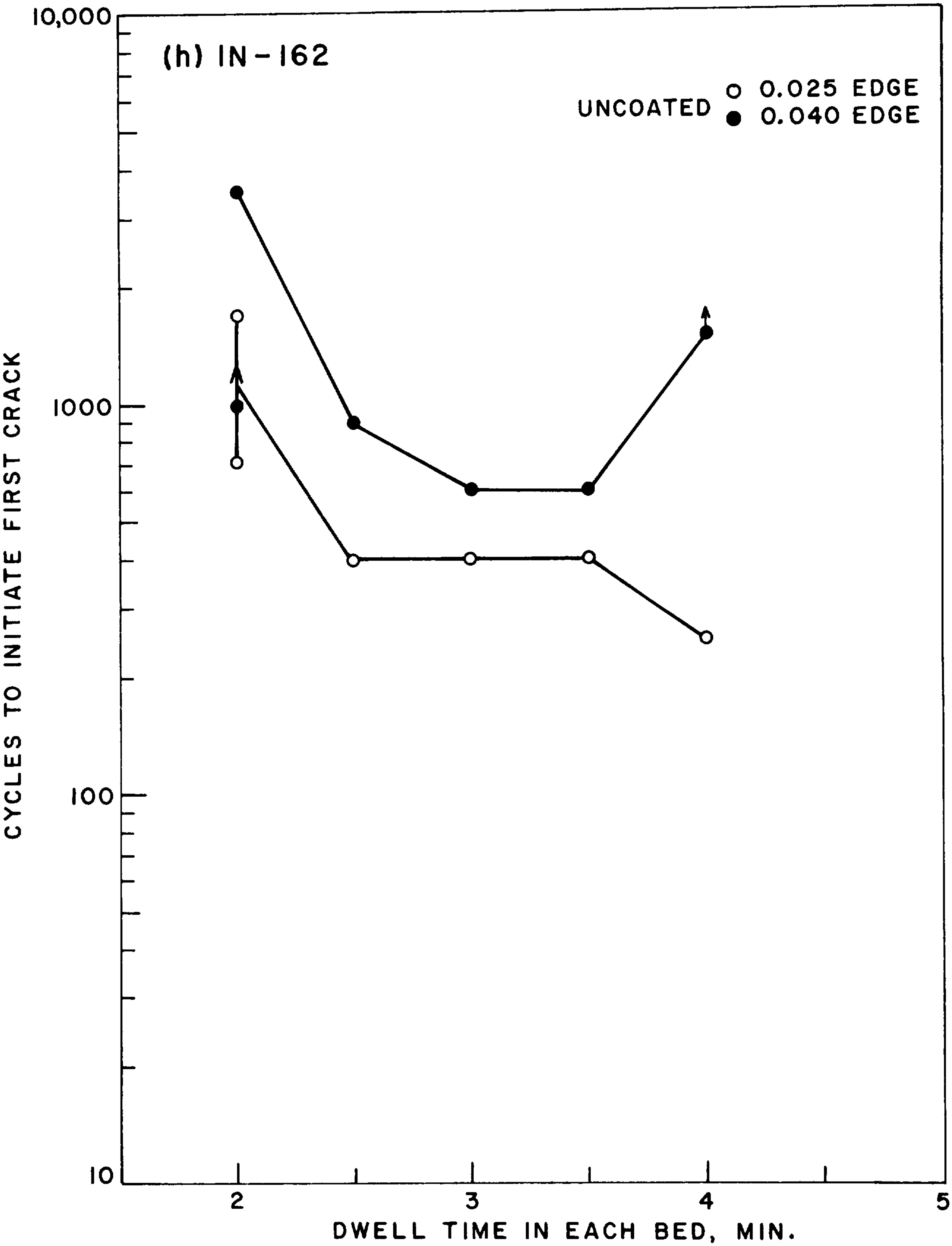


Fig. 17(h) - Thermal Cycles to Initiate the First Crack in IN-162 Test Specimens in Either Test Edge under Test Conditions A to F.

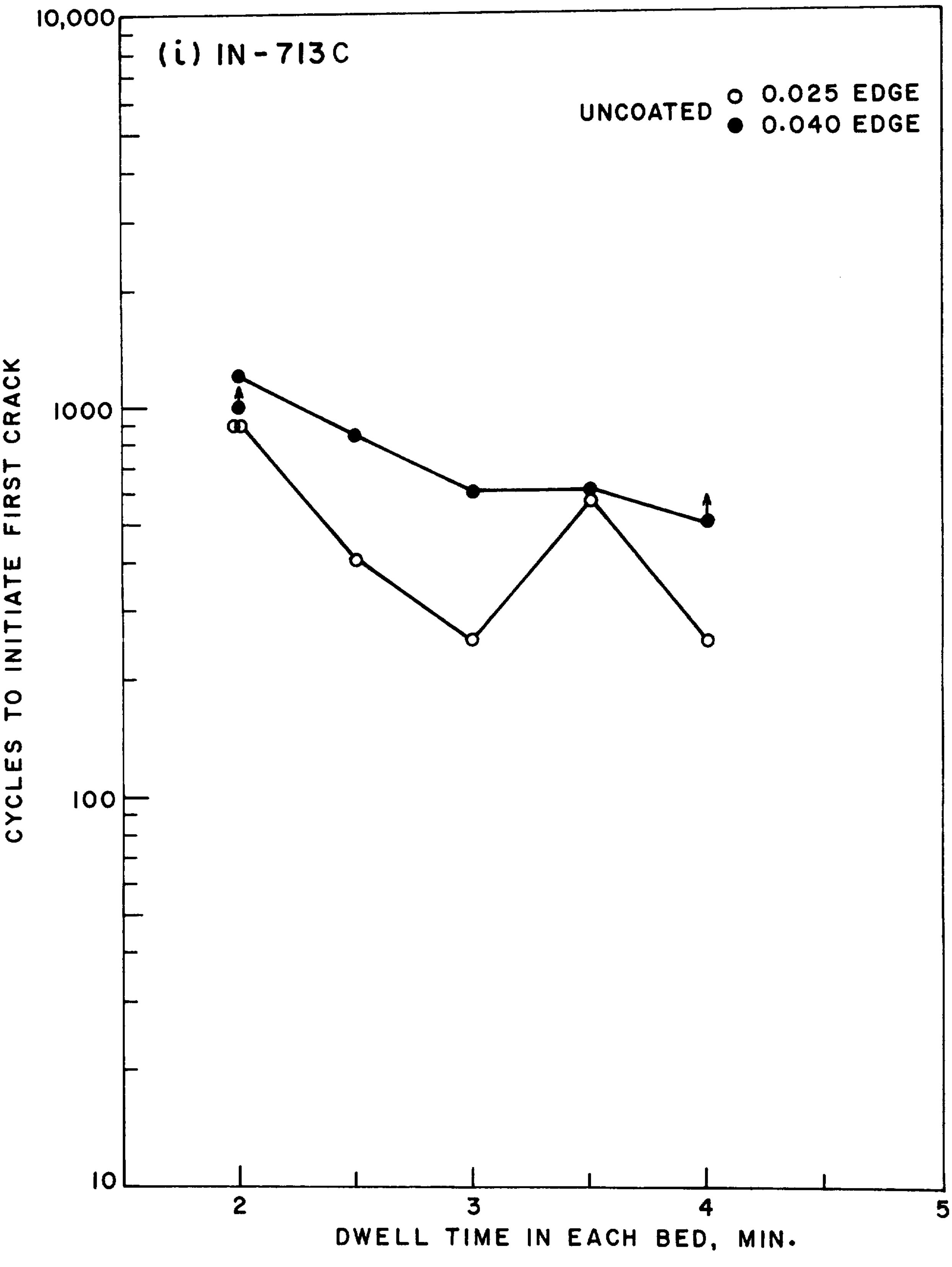


Fig. 17(i) - Thermal Cycles to Initiate the First Crack in IN-713C Test Specimens in Either Test Edge under Test Conditions A to F.

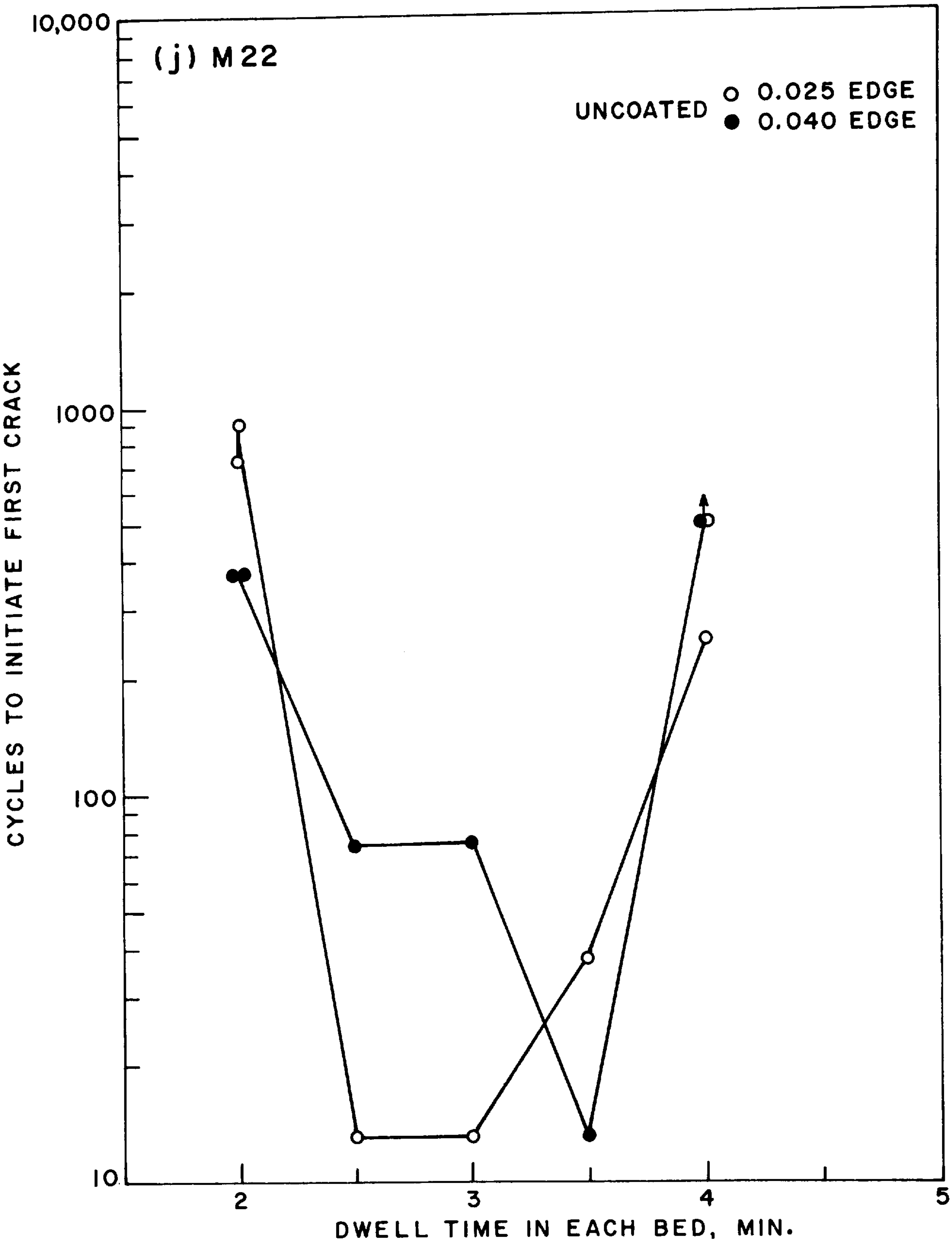


Fig. 17(j) - Thermal Cycles to Initiate the First Crack in M22 Test Specimens in Either Test Edge under Test Conditions A to F.

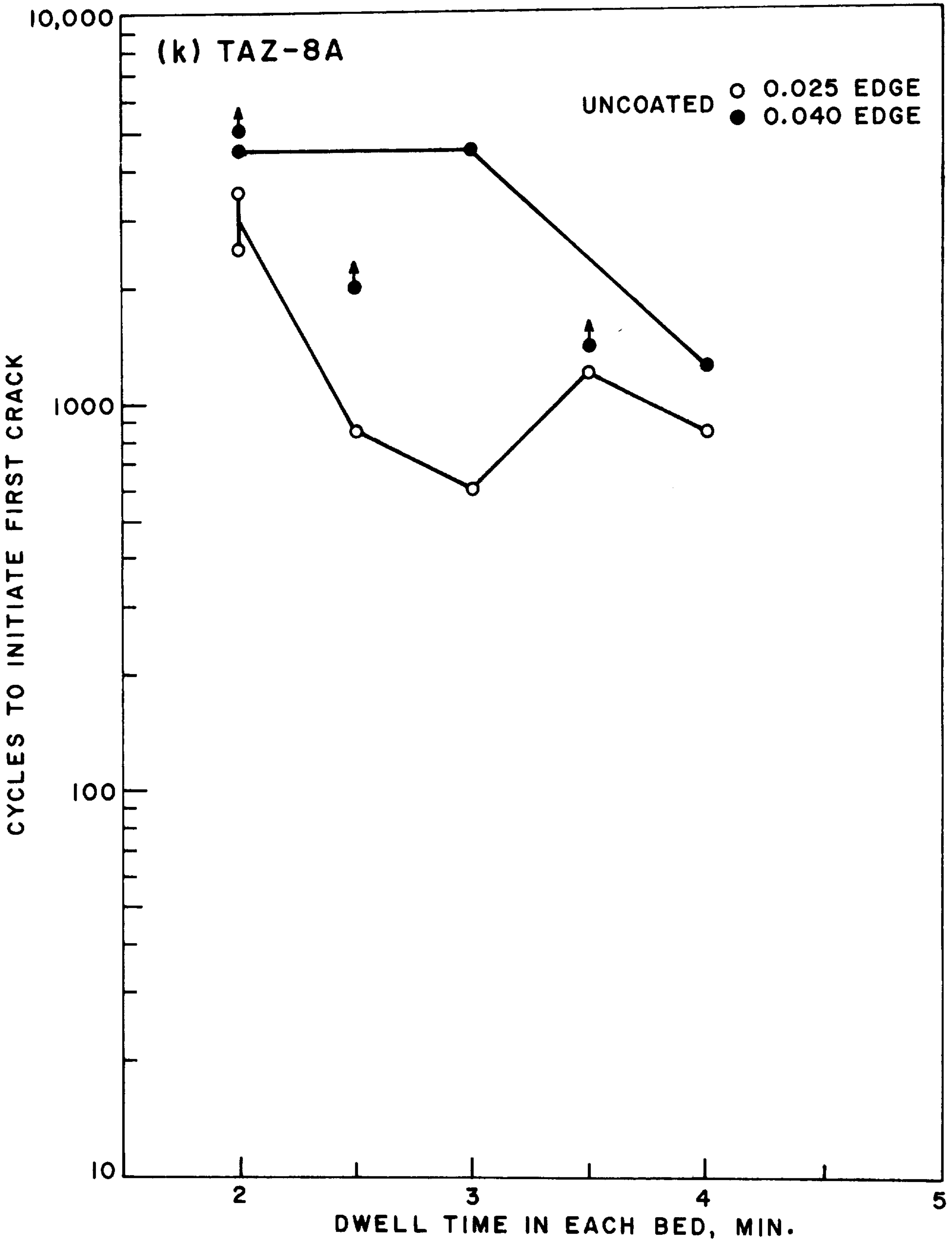


Fig. 17(k) - Thermal Cycles to Initiate the First Crack in TAZ-8A Test Specimens in Either Test Edge under Test Conditions A to F.

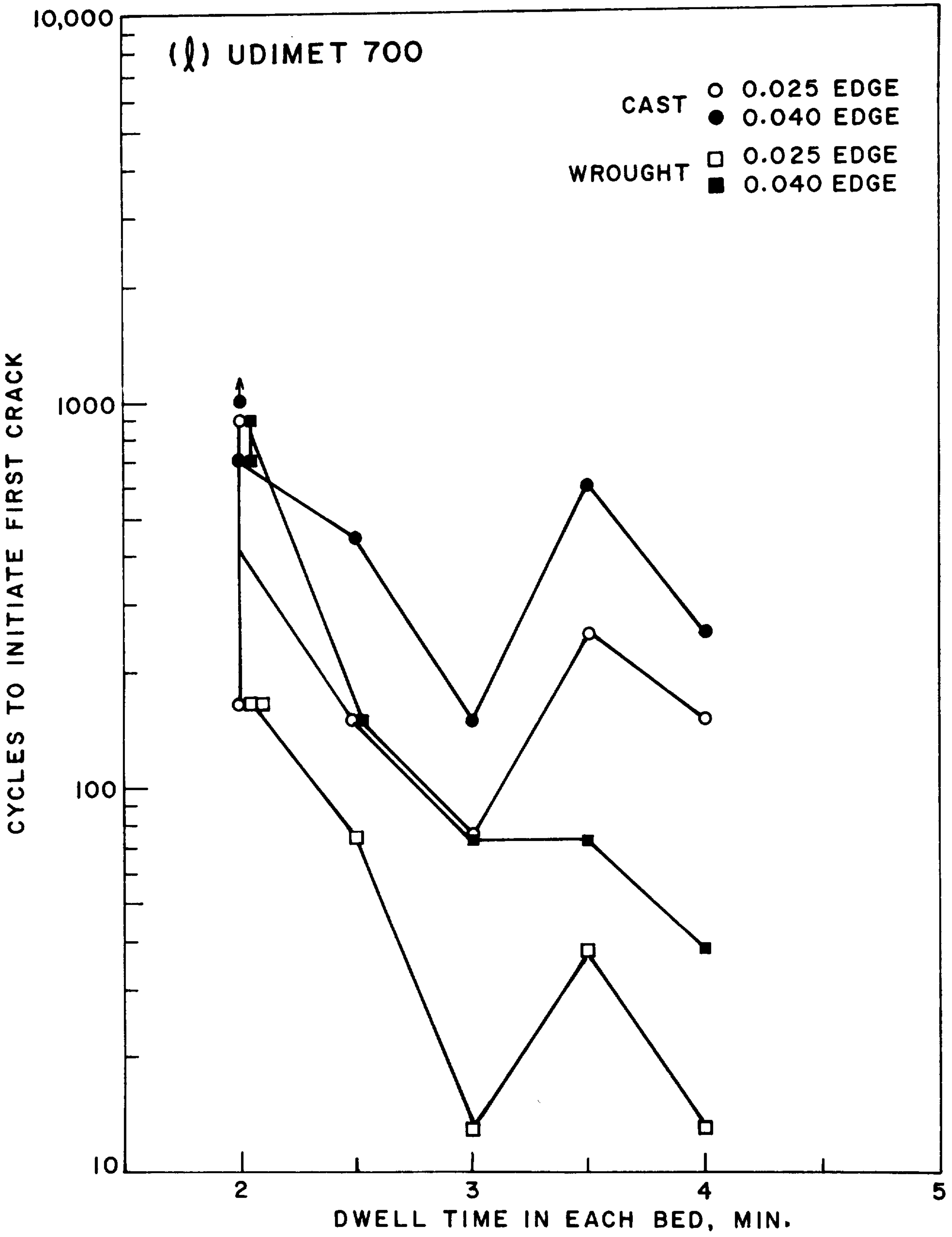


Fig. 17(l) - Thermal Cycles to Initiate the First Crack in Udimet 700 Test Specimens in Either Test Edge under Test Conditions A to F.

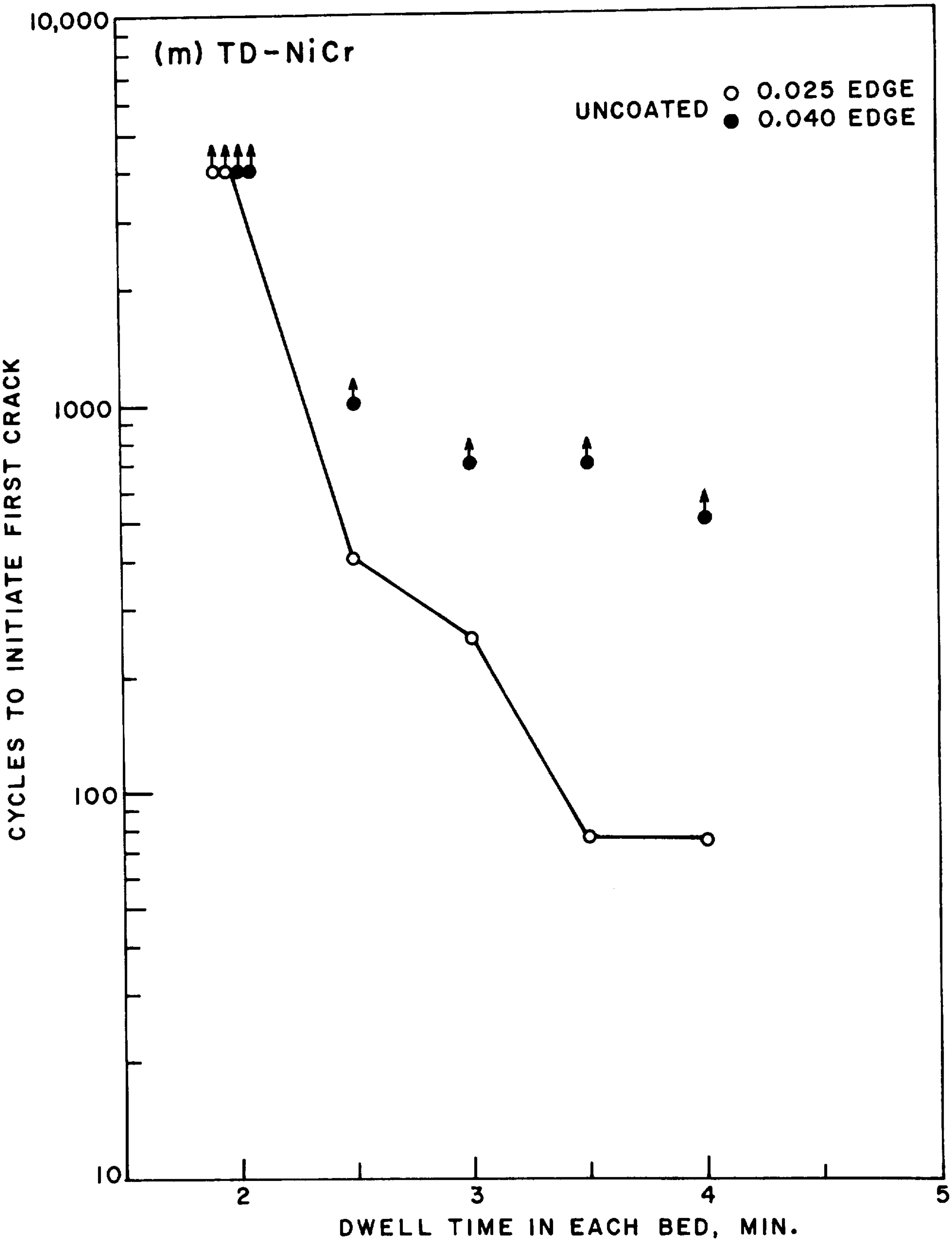


Fig. 17(m) - Thermal Cycles to Initiate the First Crack in TD-NiCr Test Specimens in Either Test Edge under Test Conditions A to F.

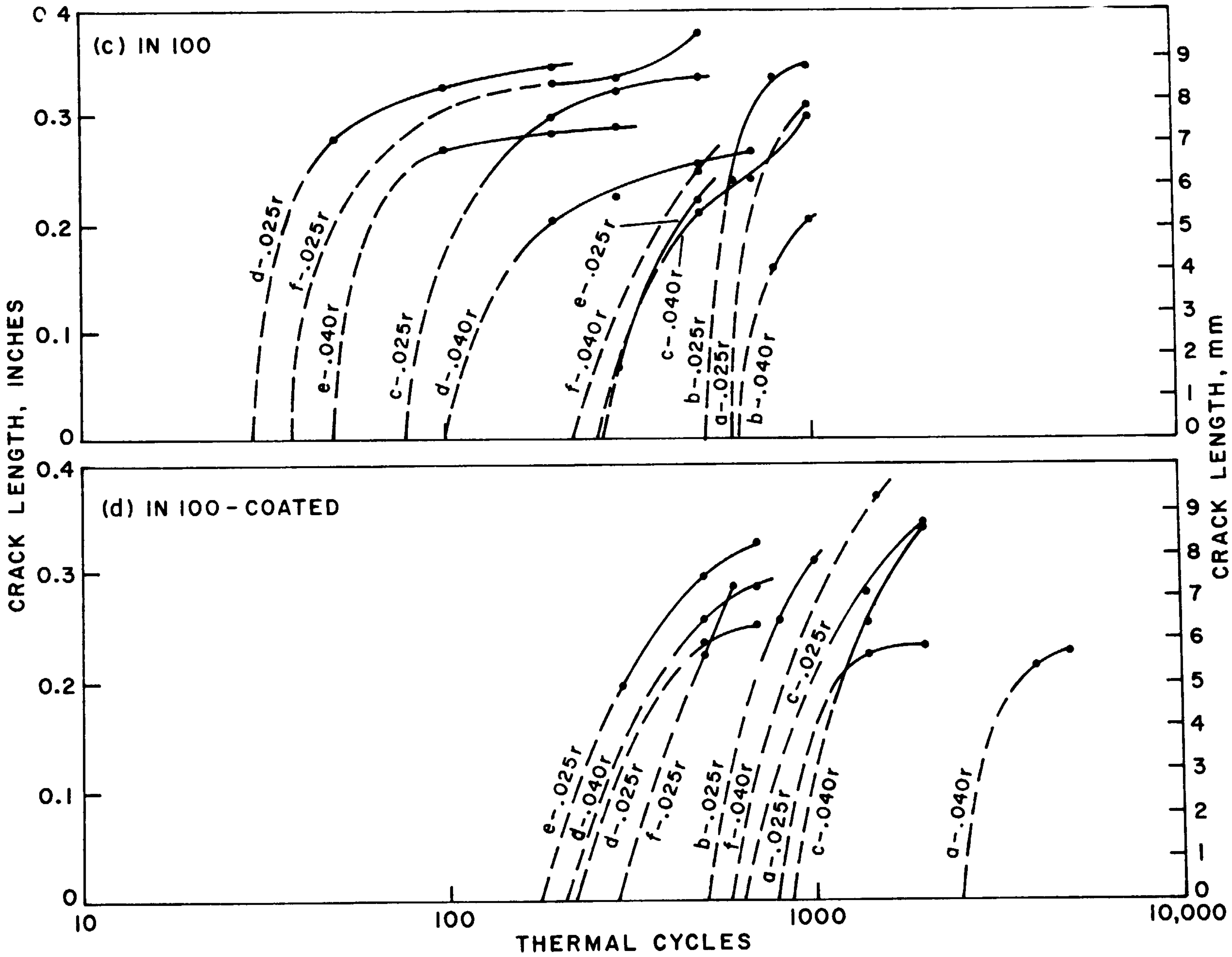


Fig. 18 - Crack Propagation Data for the First Crack Formed in Uncoated and Coated IN-100.

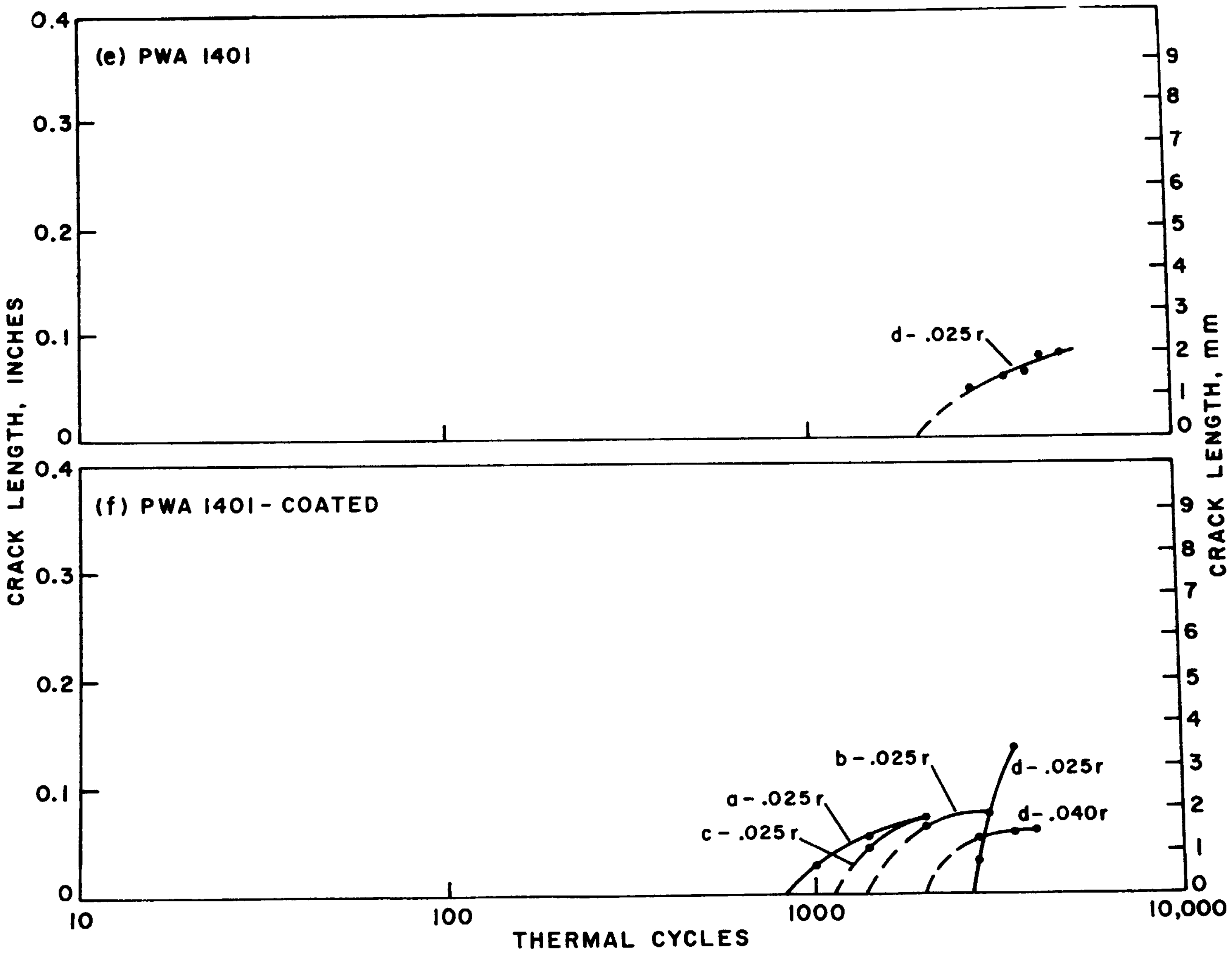


Fig. 19 - Crack Propagation Data for the First Crack Formed in Uncoated and Coated PWA 1401.

Neg. No. 37868 Neg. No. 37869 Neg. No. 37870

(a) B1900 (2000 cycles) (b) B1900, Coated (4400 cycles) (c) IN-100 (700 cycles)

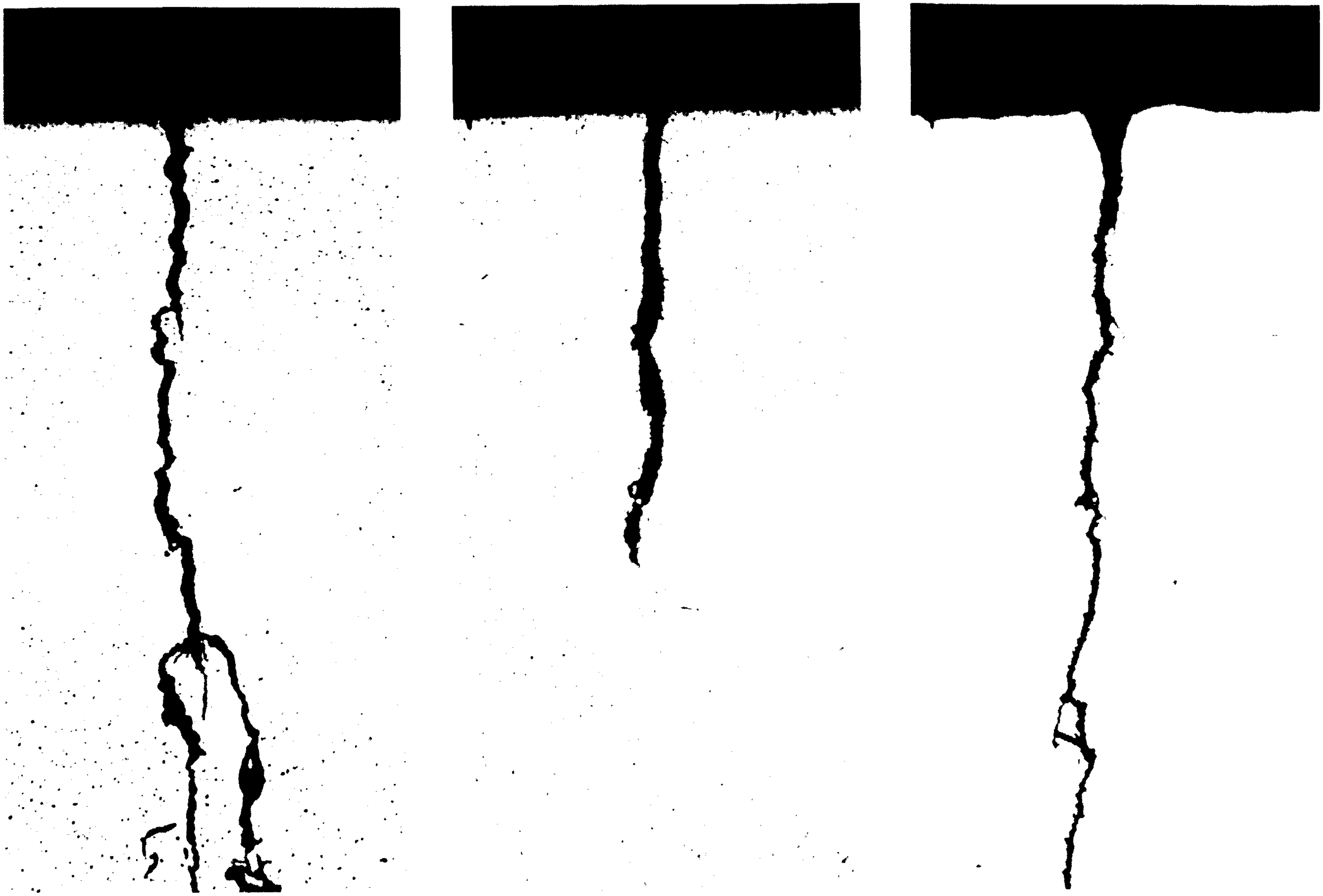
Fig. 20 - Appearance of Crack Propagation Path in Thermal Fatigue Specimen (X20, unetched

Neg. No. 37871 (d) IN-100, Coated (2000 cycles)

Neg. No. 37872 (e) X-40 (2000 cycles)

Neg. No. 37873 (f) WI-52 (700 cycles)

Fig. 20 (Continued) - Appearance of Crack Propagation Path in Thermal Fatigue Specimen (X20, unetched)

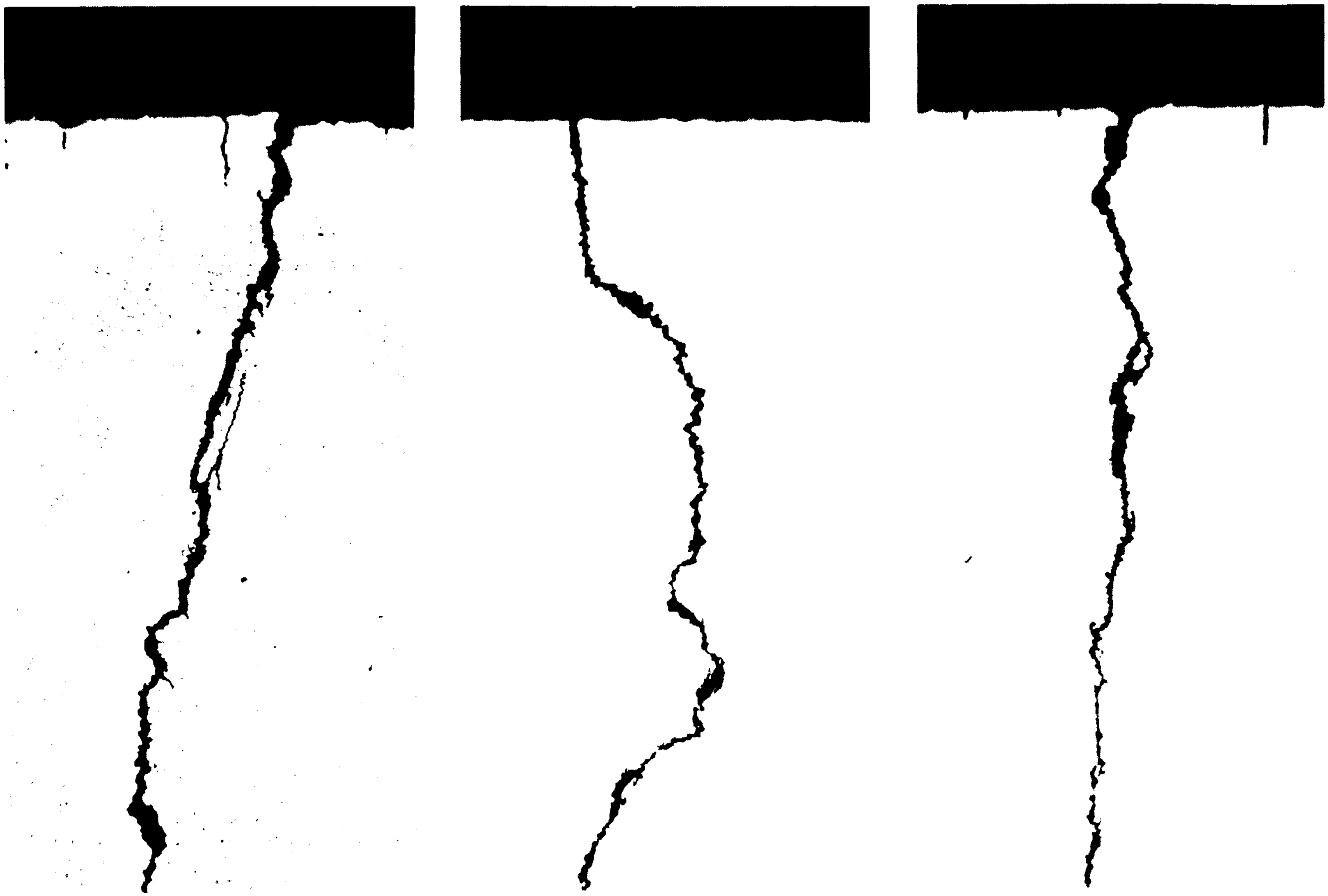


Neg. No. 37874 (g) MAR-M 200 (700 cycles)

Neg. No. 37875 (h) MAR-M 302 (700 cycles)

Neg. No. 37876 (i) IN-162 (3100 cycles)

Fig. 20 (Continued) - Appearance of Crack Propagation Path in Thermal Fatigue Specimen (X20, unetched)

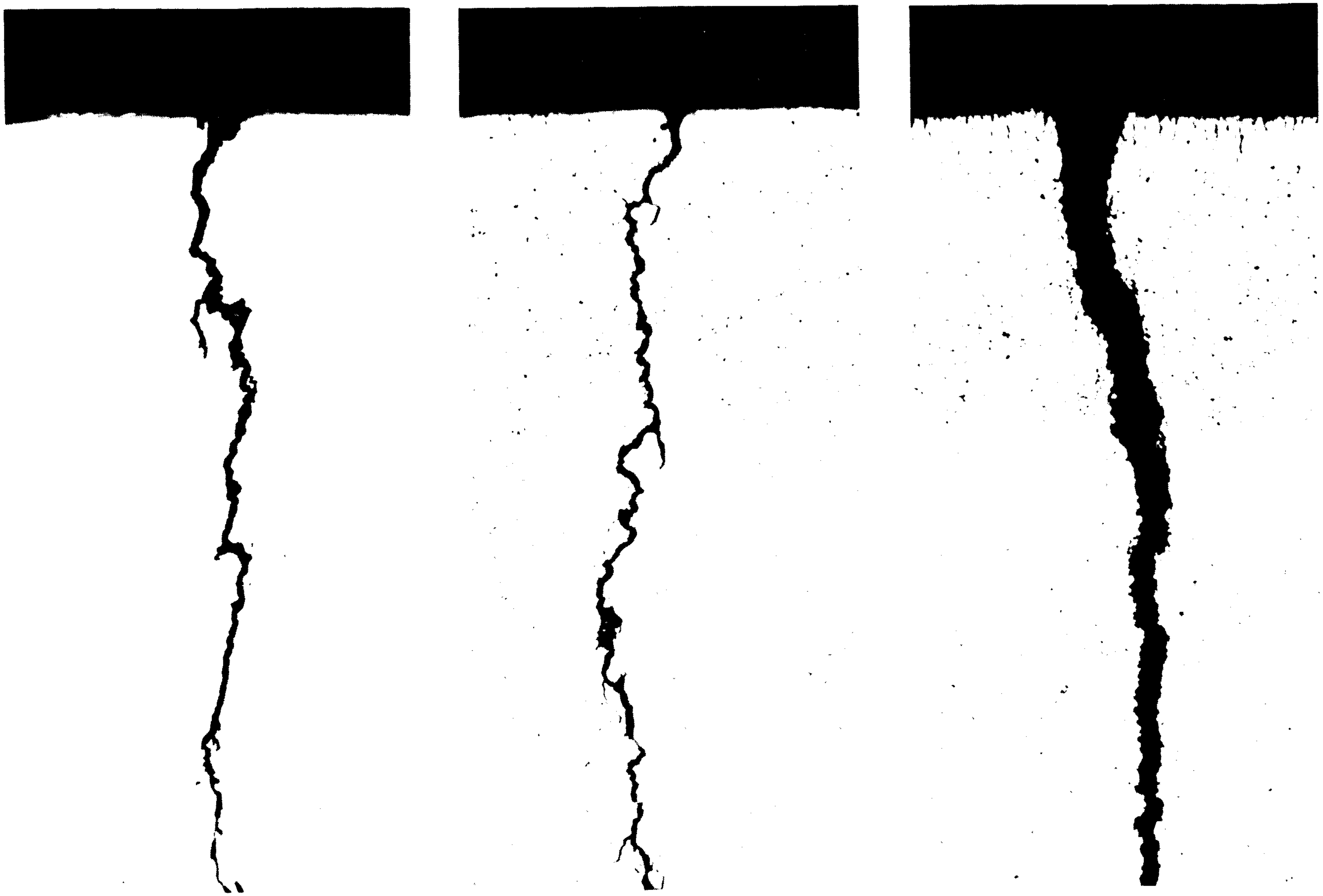


Neg. No. 37877
(j) IN-713C (700 cycles)

Neg. No. 37879
(k) M22 (700 cycles)

Neg. No. 37878
(l) TAZ-8A (5000 cycles)

Fig. 20 (Continued) - Appearance of Crack Propagation Path in Thermal Fatigue Specimen (X20, unetched)

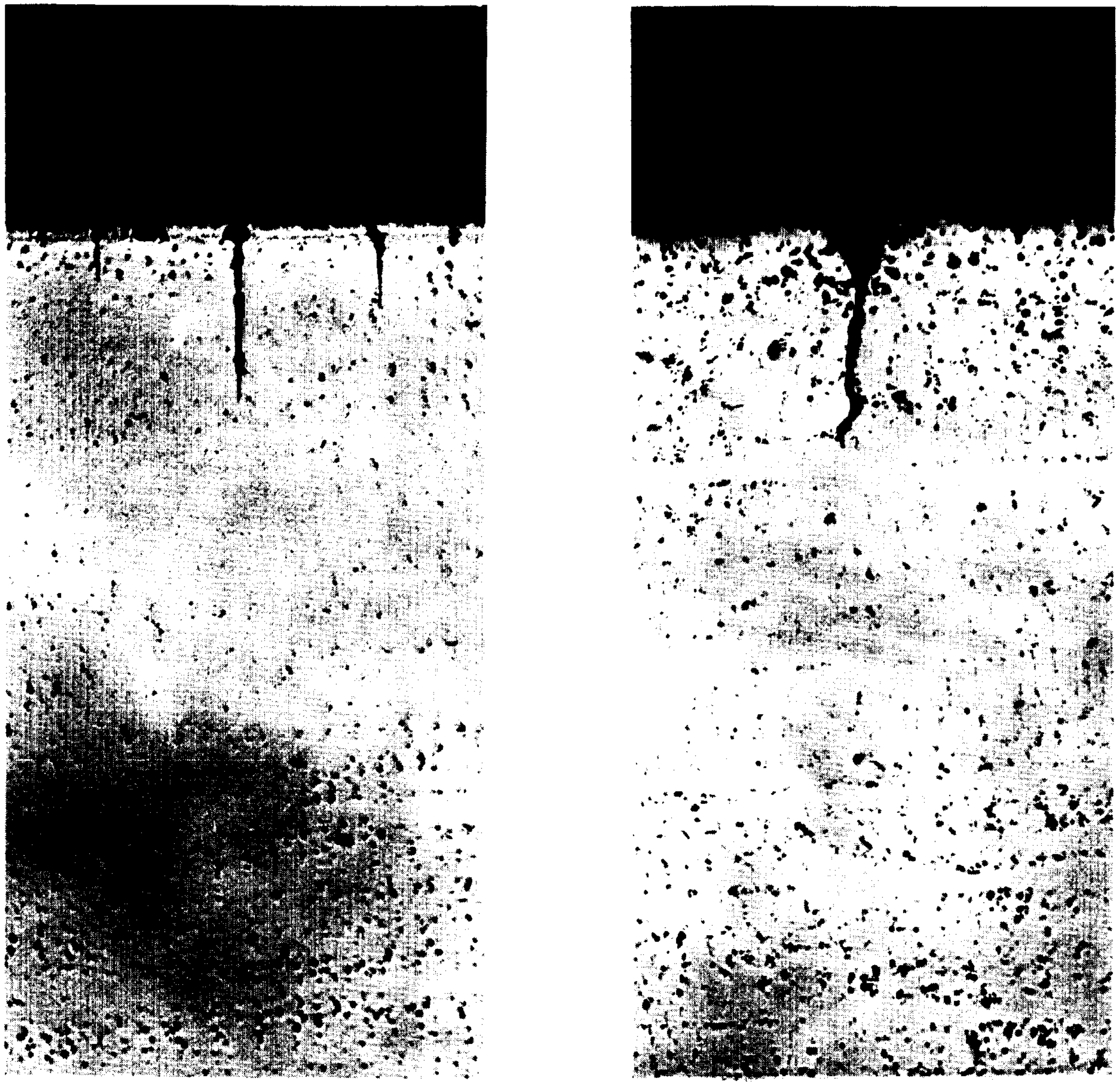


Neg. No. 37880
(m) Udimet 700(Cast)(700 cycles)

Neg. No. 37882
(n) Udimet 700 (Wrought)
(700 cycles)

Neg. No. 37881
(o) TD-NiCr (700 cycles)

Fig. 20 (Continued) - Appearance of Crack Propagation Path in Thermal Fatigue Specimen
(X20, unetched)



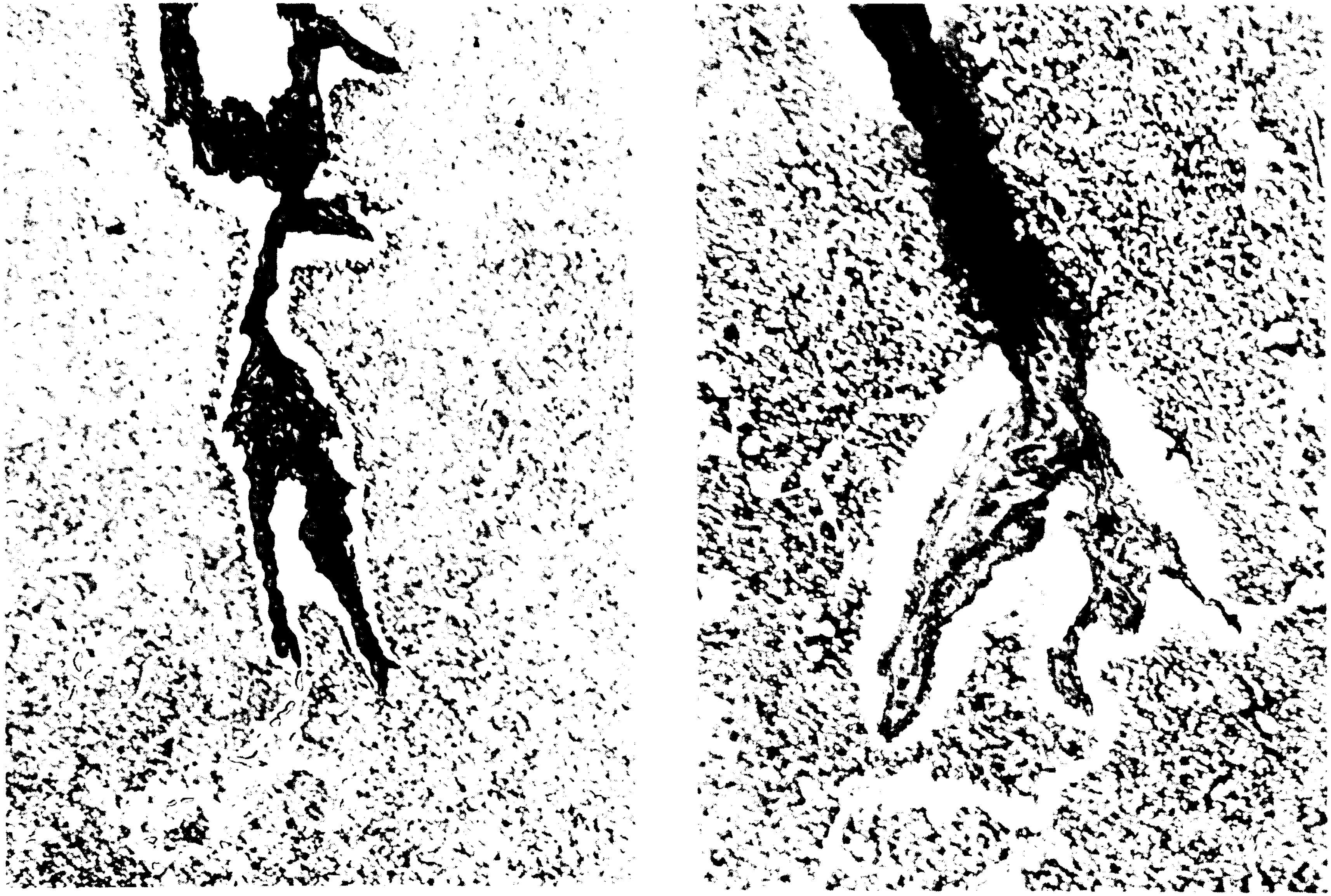
Neg. No. 38031

(p) PWA 1401-Coated
(1500 cycles) Set F

Neg. No. 38030

(q) PWA 664
(2600 cycles) Set C

Fig. 20 (Continued) - Appearance of Crack Propagation Path in Thermal Fatigue Specimen (X20, unetched).



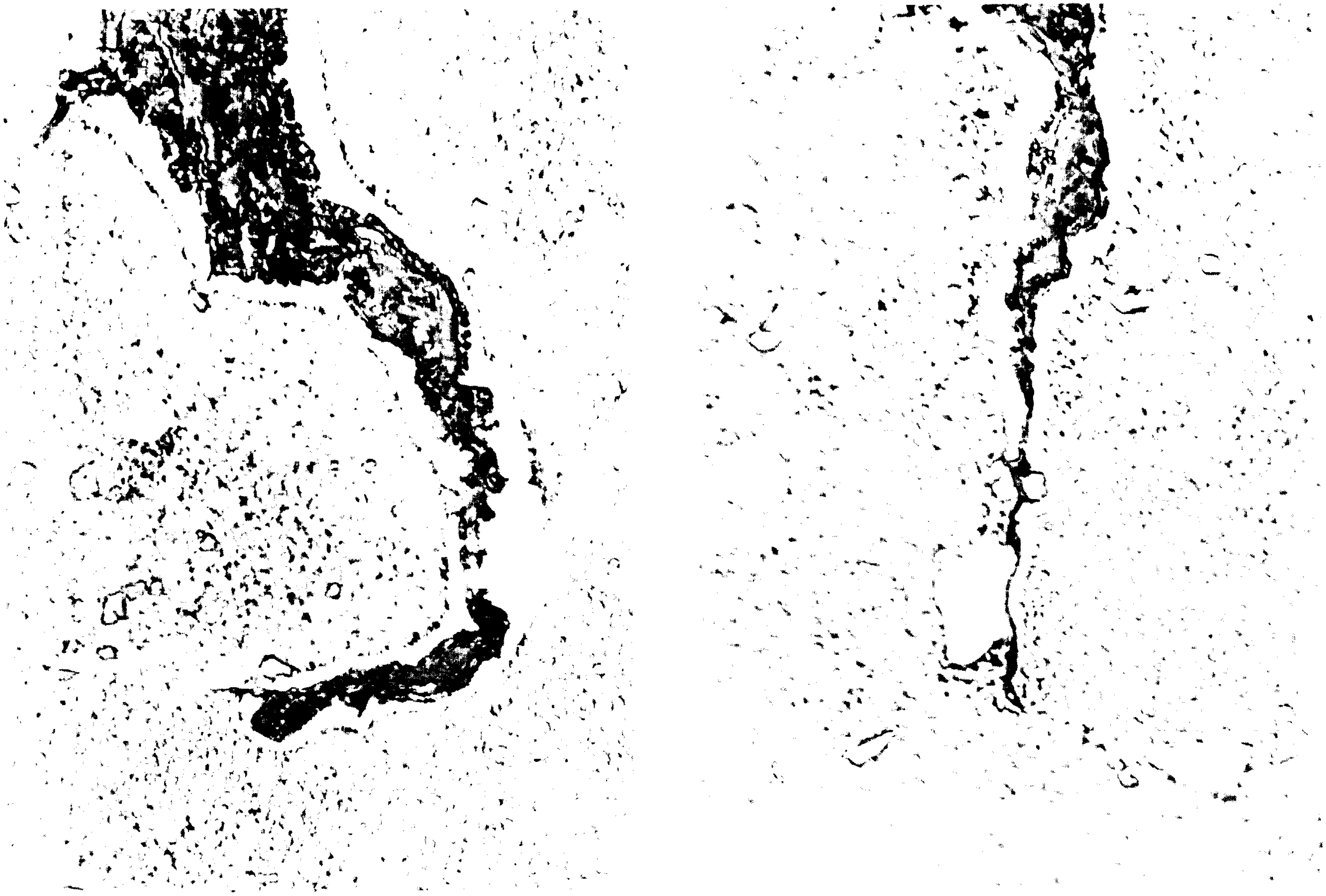
Neg. No. 37903

(a) B1900 (2000 cycles)

Neg. No. 37904

(b) B1900, Coated (4400 cycles)

Fig. 21 - Root of Crack in Thermal Fatigue Specimens, Longitudinal Section (etched, X500)



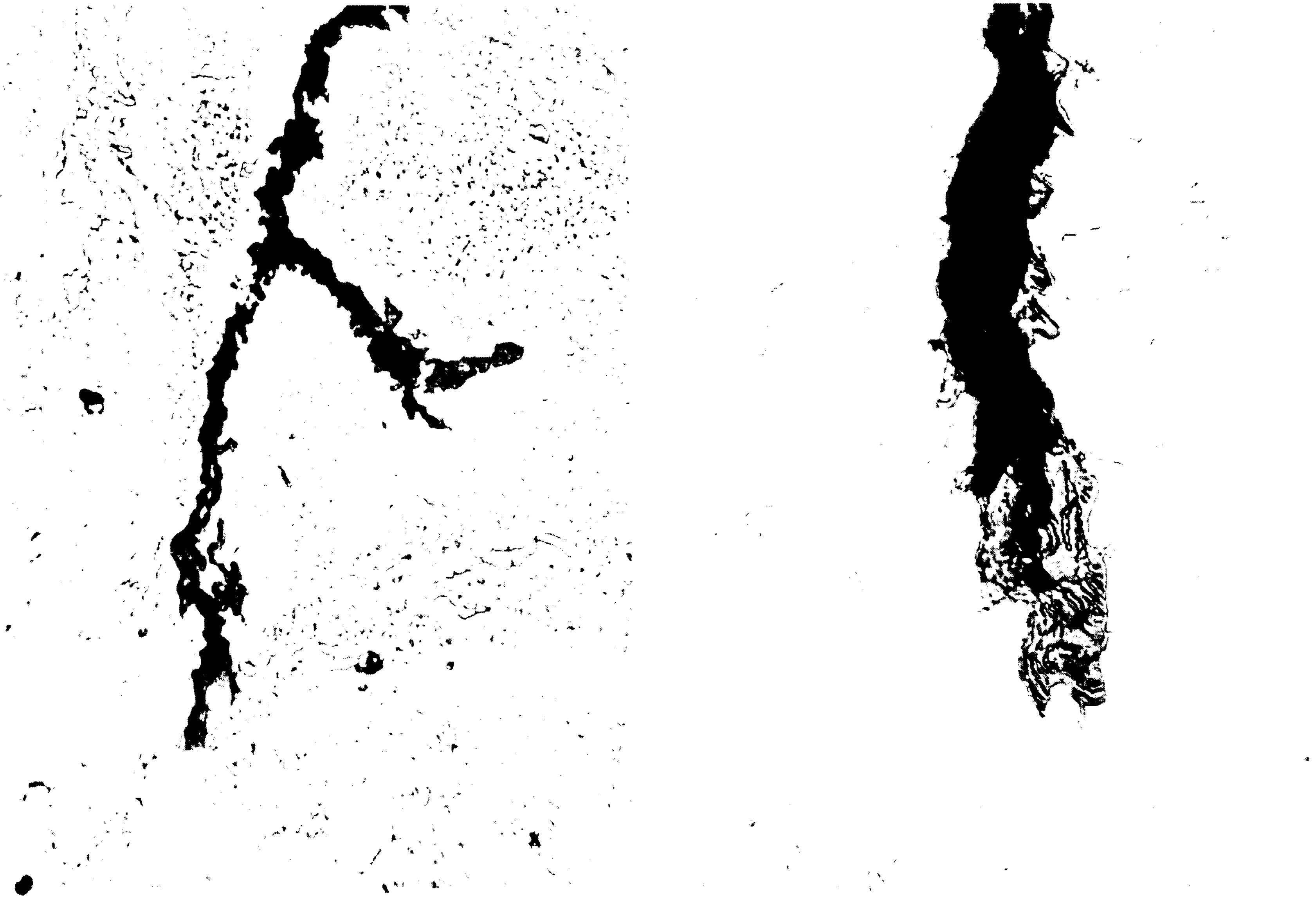
Neg. No. 37905

(c) IN-100 (700 cycles)

Neg. No. 37906

(d) IN-100, Coated (2000 cycles)

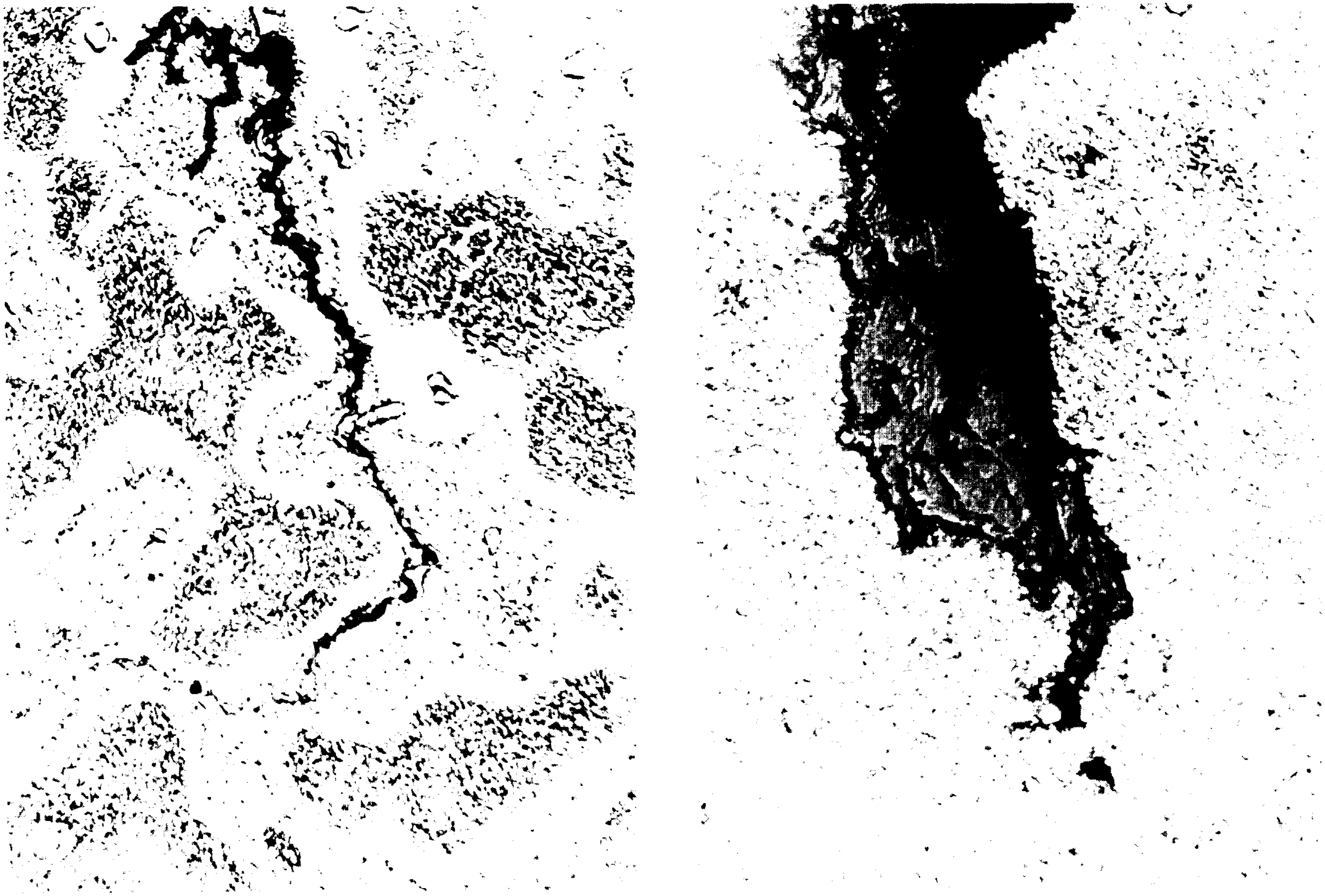
Fig. 21 (Continued) - Root of Crack in Thermal Fatigue Specimens, Longitudinal Section (etched, X500)



Neg. No. 37914 Neg. No. 37916

(e) X-40 (2000 cycles) (f) WI-52 (700 cycles)

Fig. 21 (Continued) - Root of Crack in Thermal Fatigue Specimens, Longitudinal Section (etched, X500)



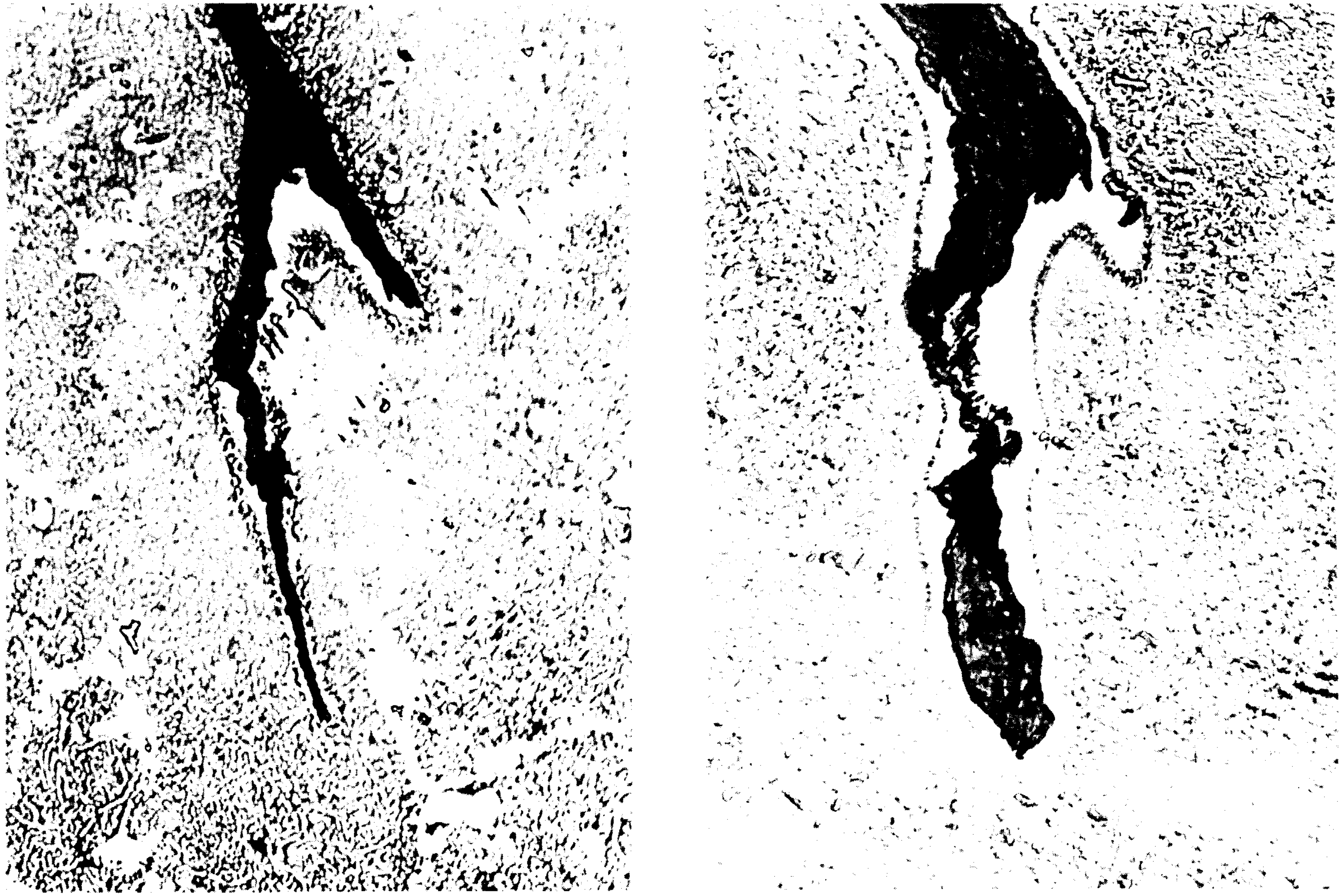
Neg. No. 37918

(g) MAR-M 200 (700 cycles)

Neg. No. 37923

(h) MAR-M 302 (700 cycles)

Fig. 21 (Continued) - Root of Crack in Thermal Fatigue Specimens, Longitudinal Section (etched, X500)



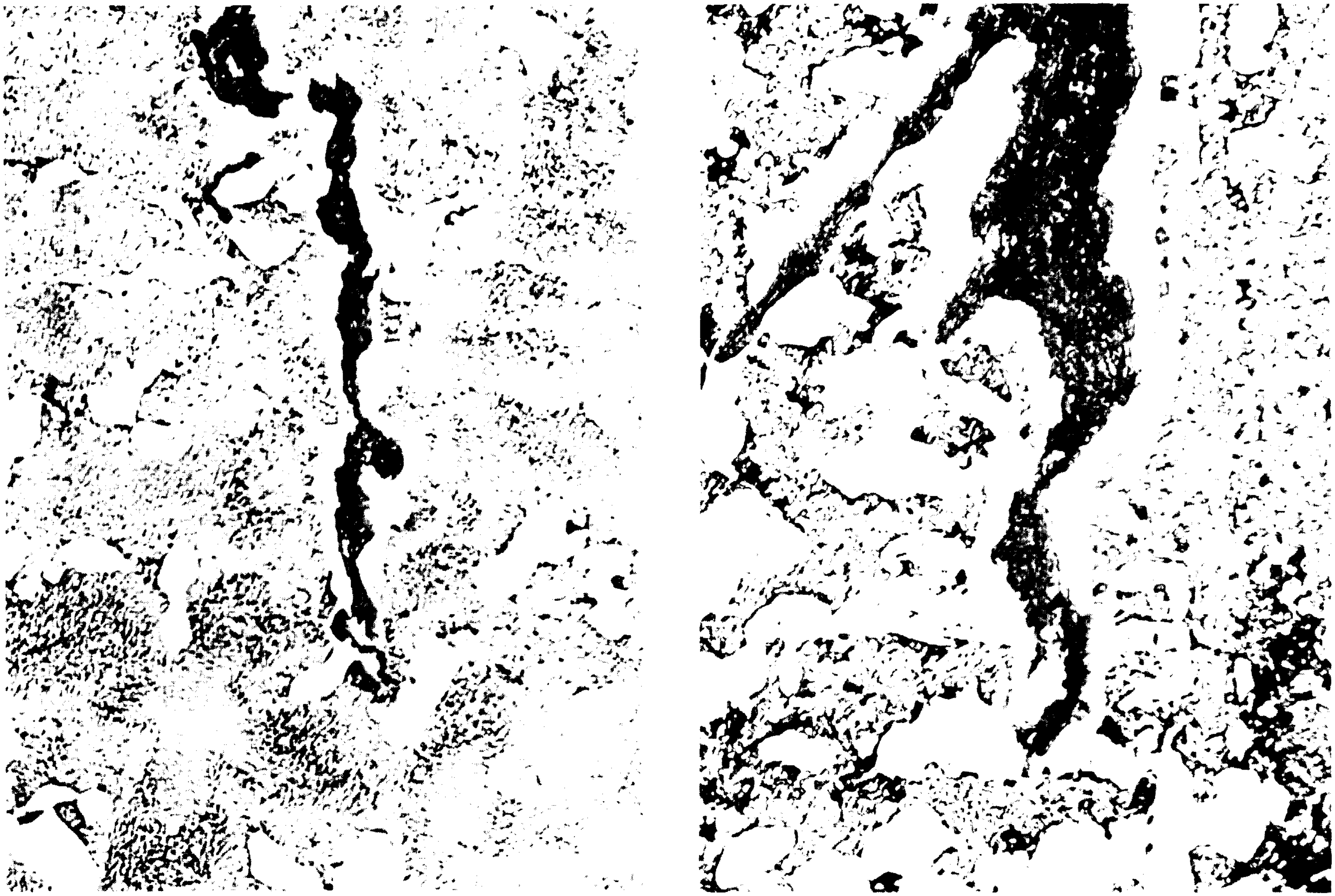
Neg. No. 37922

(i) IN-162 (3100 cycles)

Neg. No. 37925

(j) IN-713C (700 cycles)

Fig. 21 (Continued) - Root of Crack in Thermal Fatigue Specimens, Longitudinal Section (etched, X500)



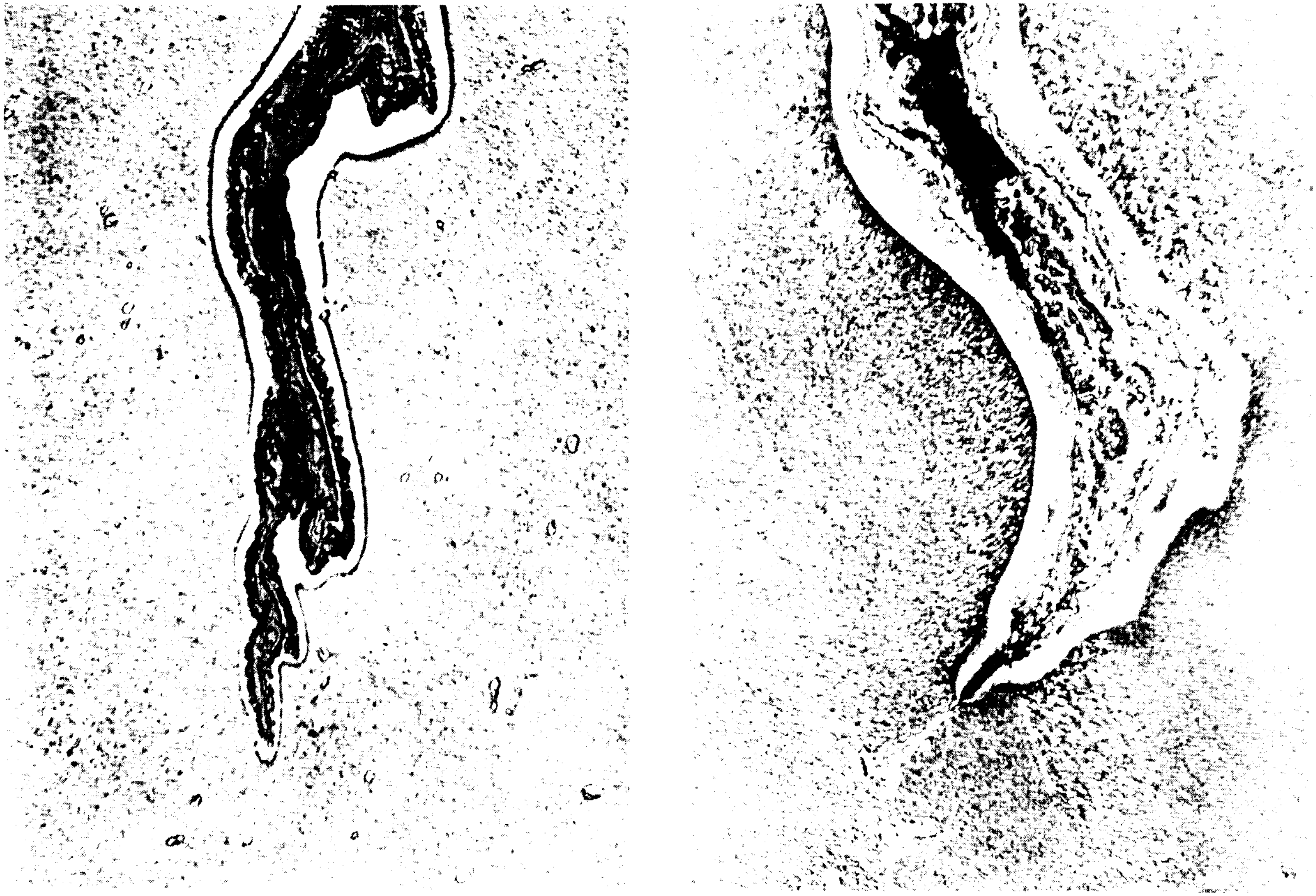
Neg. No. 37928

(k) M22 (700 cycles)

Neg. No. 37930

(1) TAZ-8A (5000 cycles)

Fig. 21 (Continued) - Root of Crack in Thermal Fatigue Specimens, Longitudinal Section (etched, X500)



Neg. No. 37934
(m) Udimet 700 (Cast) (700 cycles)

Neg. No. 37932
(n) Udimet 700 (Wrought) (700 cycles)

Fig. 21 (Continued) - Root of Crack in Thermal Fatigue Specimens, Longitudinal Section (etched, X500)

Neg. No. 38032

(o) PWA 1401-Coated (2000 cycles, Set C)

Neg. No. 38033

(p) PWA 664 (1500 cycles, Set F)

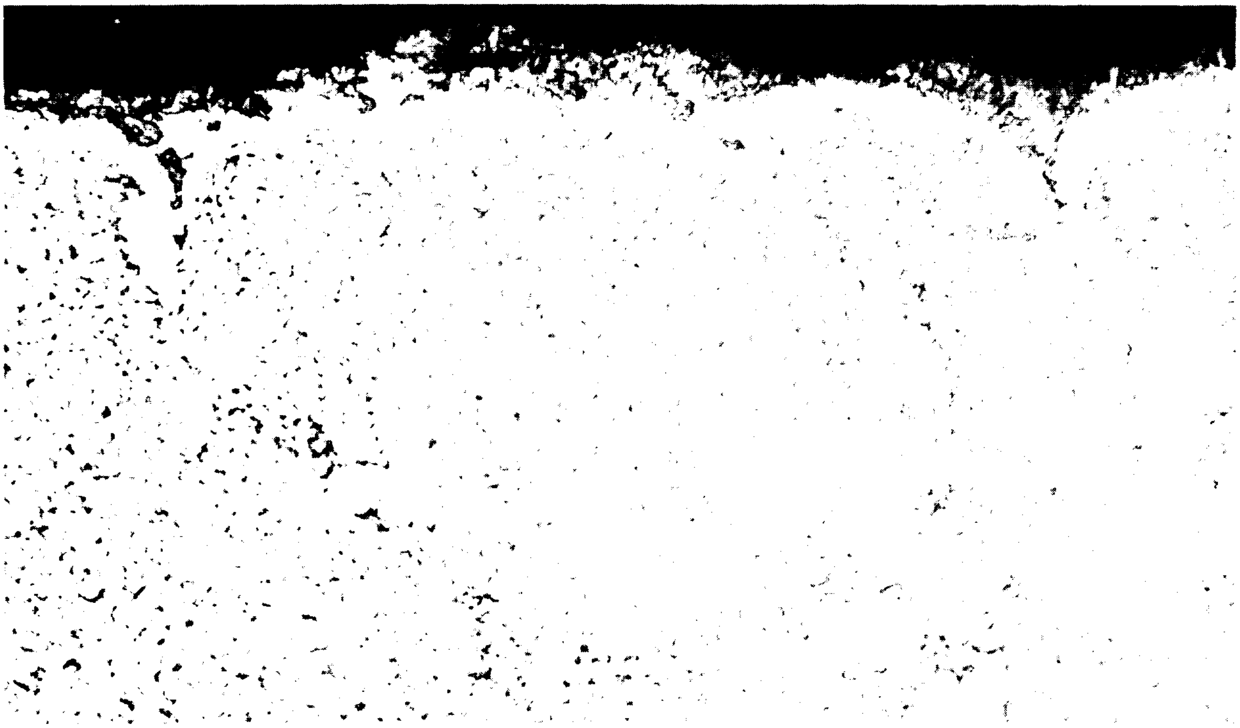
Fig. 21 (Continued) - Root of Crack in Thermal Fatigue Specimens, Longitudinal Section (etched, X500)

Neg. No. 37910 Etched X500

Fig. 22 - B1900, Coated Sample. Transverse section showing crack through coating.

Neg. No. 37911 Etched X500

Fig. 23 - IN-100, Coated Sample. Transverse section showing crack through coating.



Neg. No. 37913 Etched X500

Fig. 24 - IN-100, Transverse Section Showing Possible Crack Nucleation Points.

Neg. No. 37929 Etched X500

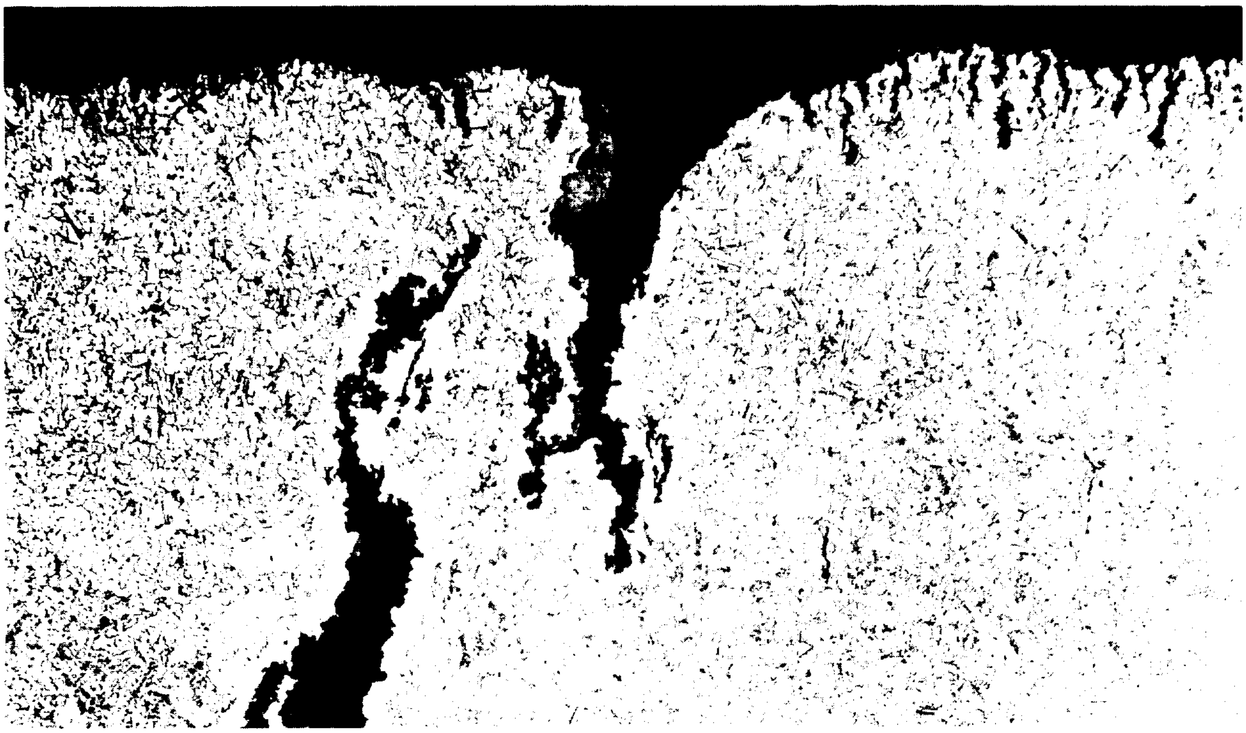
Fig. 25 - PWA 1401, Transverse Section Showing a Possible Crack Nucleation Point.

Neg. No. 37908 Etched X500

Fig. 26 - PWA 1401, Coated Sample, Showing Thermal Fatigue Crack Through Coating.

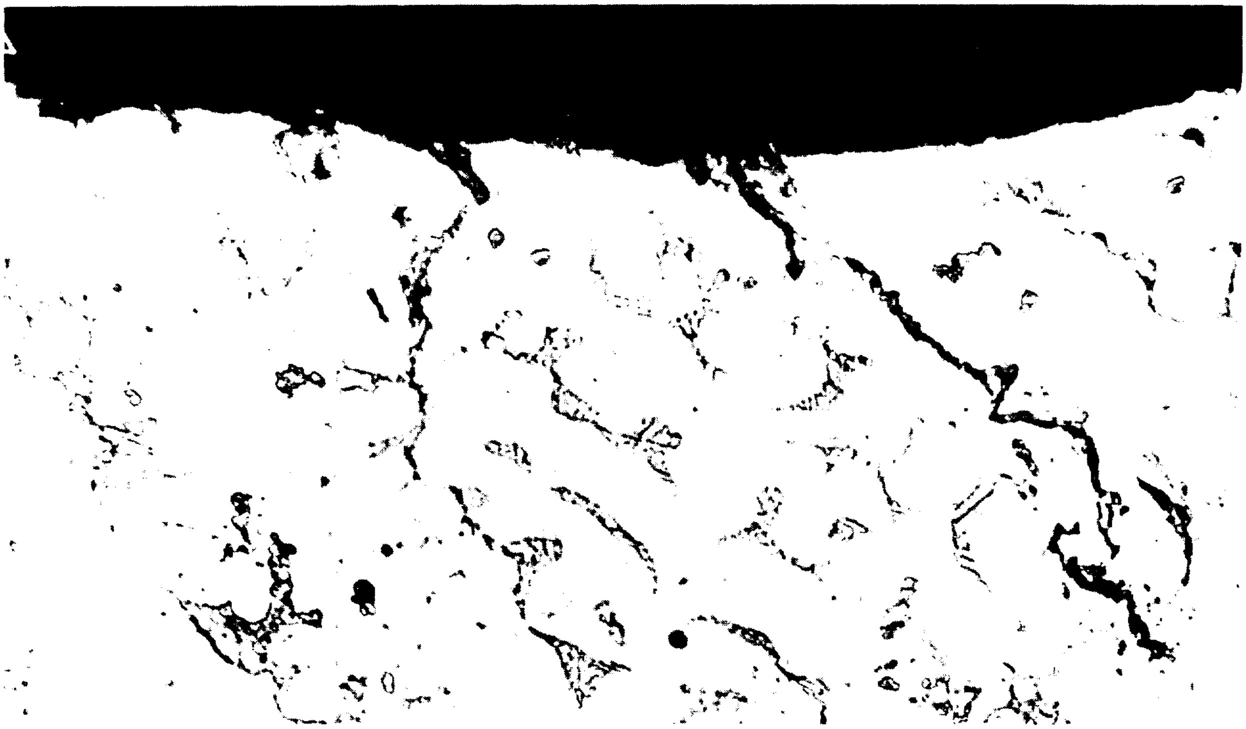
Neg. No. 37926 Etched X500

Fig. 27 - IN-713C Sample Showing Possible Crack Nucleation Sites.



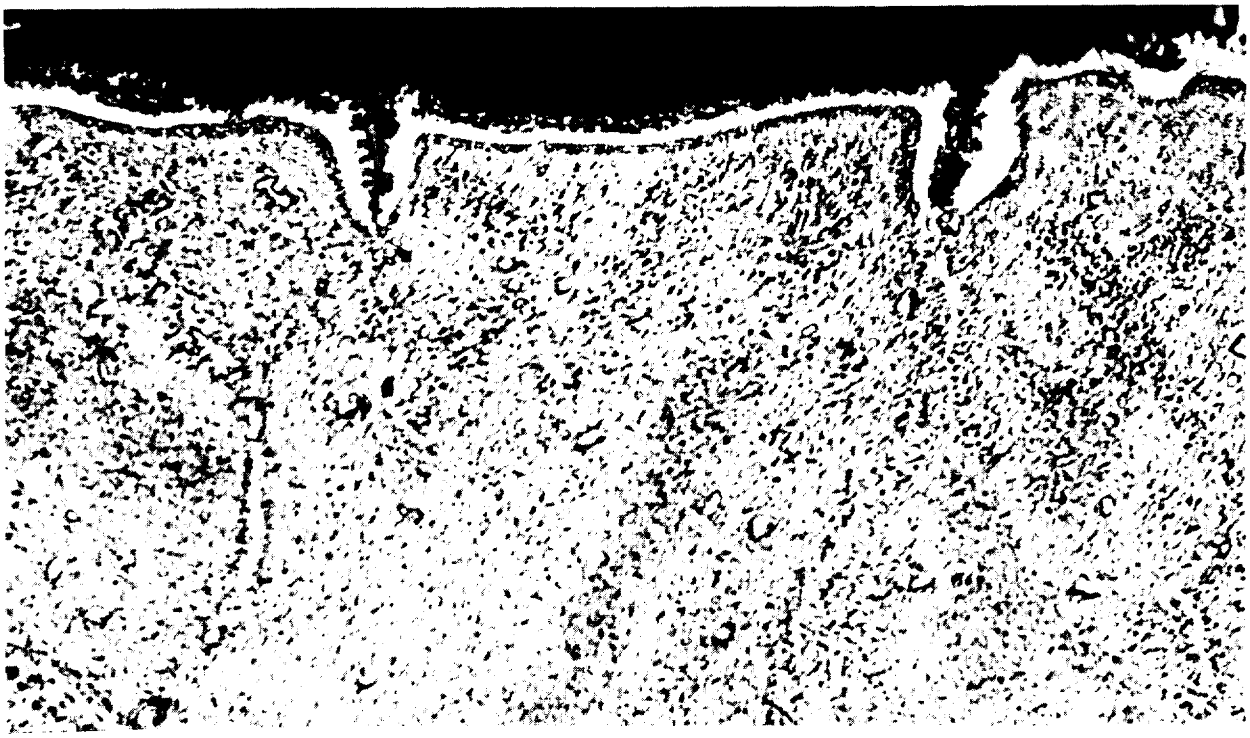
Neg. No. 37915 Etched X125

Fig. 28 - X-40 Sample Showing Early Stages of Crack Propagation.



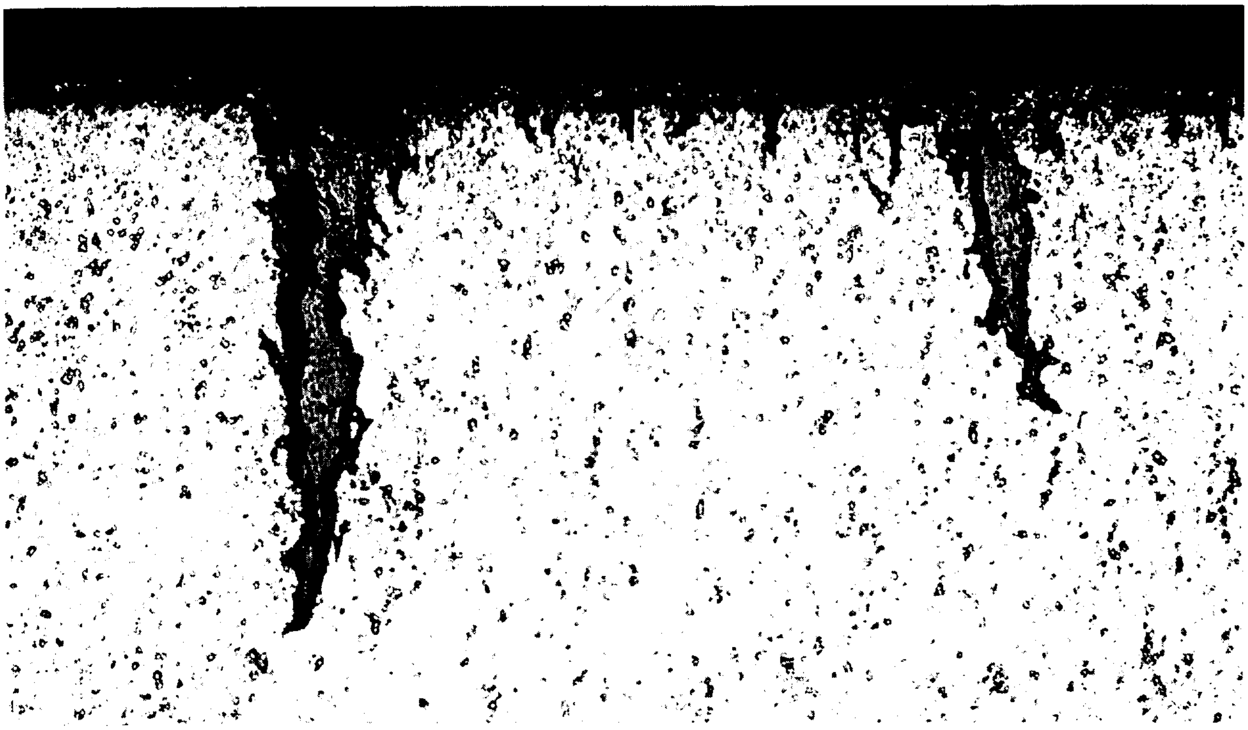
Neg. No. 37917 Etched X500

Fig. 29 - WI-52 Longitudinal Section Showing Possible Crack Nucleation Sites.



Neg. No. 37919 Etched X500

Fig. 30 - MAR-M 200 Longitudinal Section Showing Possible Crack Nucleation Sites.



Neg. No. 37921 Etched X125

Fig. 31 - MAR-M 302 Longitudinal Section Showing Early Stages of Crack Propagation.

Neg. No. 37929 Etched X500

Fig. 32 - M22 Longitudinal Section Showing a Possible Crack Nucleation Site.

Neg. No. 37931 Etched X500

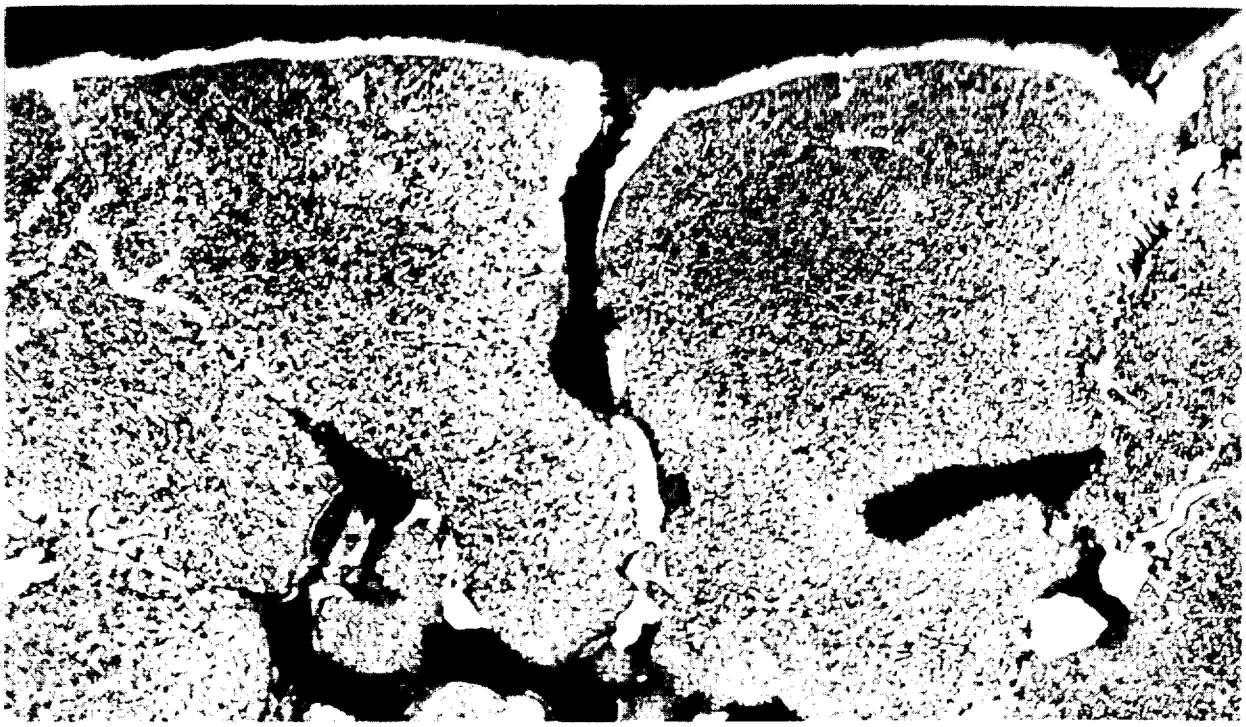
Fig. 33 - TAZ-8A Longitudinal Section Showing the Early Stage of a Crack.

Neg. No. 37935 Etched X500

Fig. 34 - Cast Udimet 700 Longitudinal Section Showing Possible Crack Nucleation Sites.

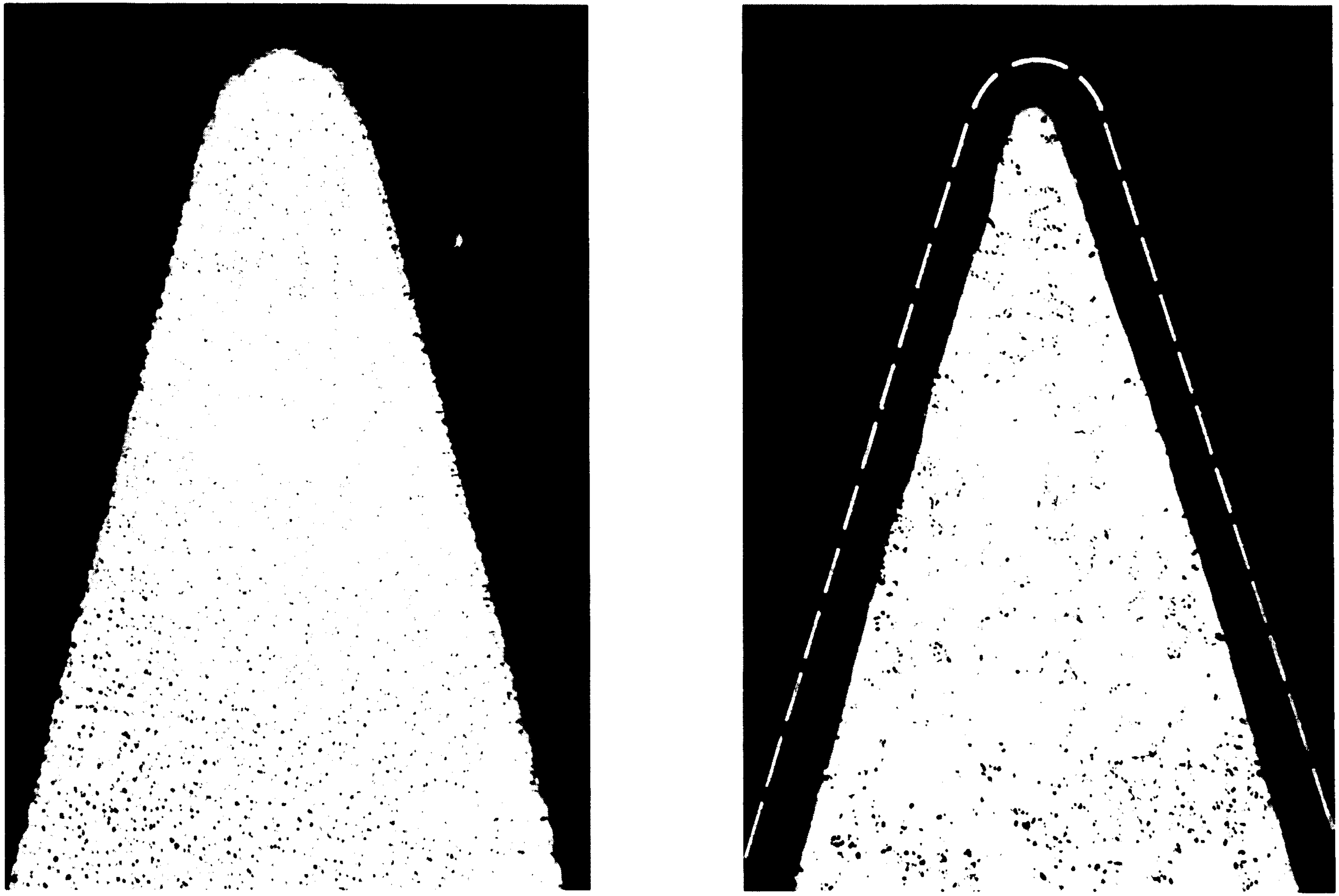
Neg. No. 37933 Etched X500

Fig. 35 - Wrought Udimet 700 Longitudinal Section Showing Possible Crack Nucleation Site.



Neg. No. 38034 Etched X250

Fig. 36 - PWA 664 Longitudinal Section Showing Subsurface Porosity as Possible Crack Nucleation Site.



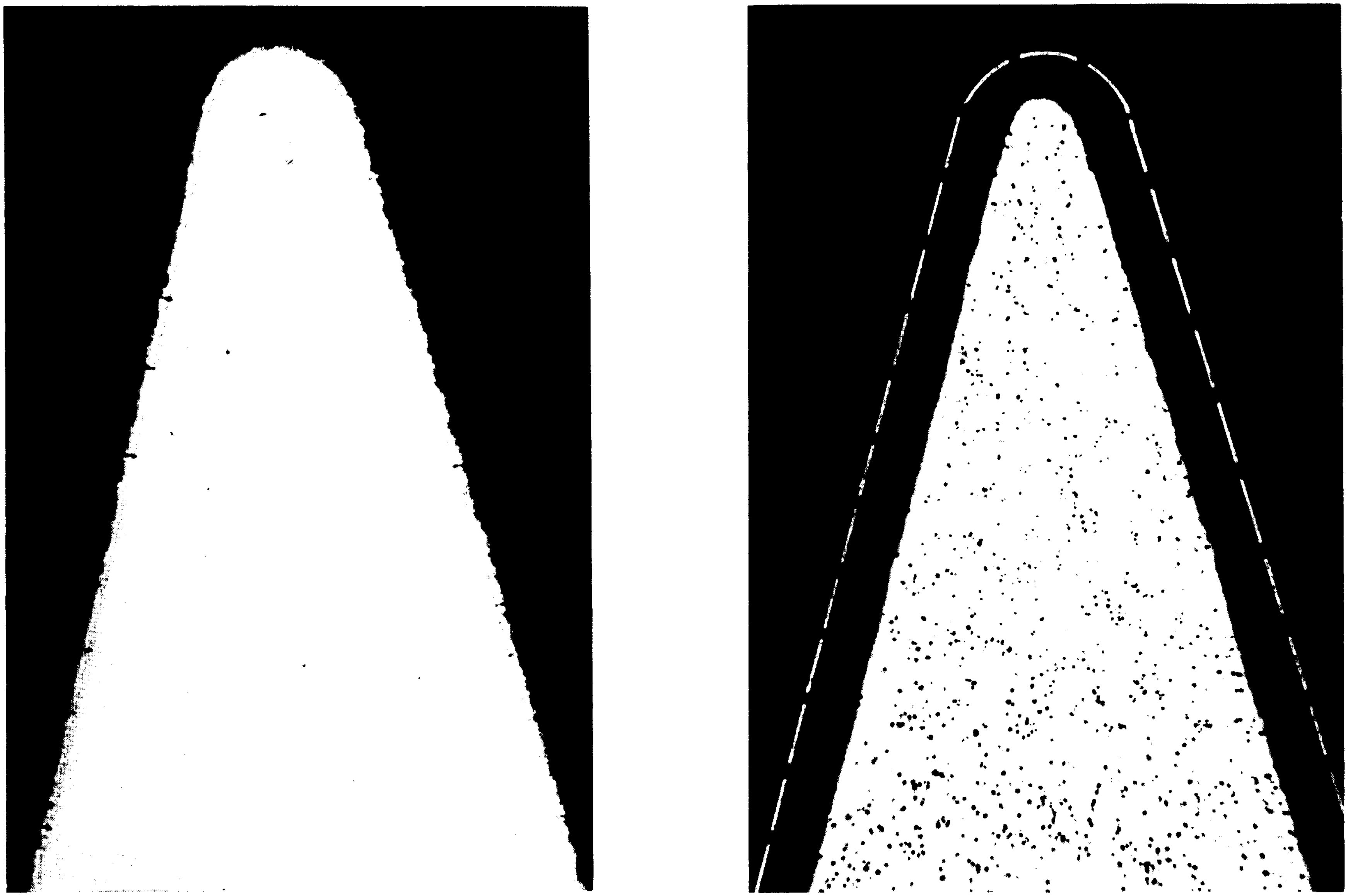
Neg. No. 37884

(a) IN-100, Coated (2000 Cycles)

Neg. No. 37885

(b) PWA 1401 (5000 Cycles)

Fig. 37 - Transverse Section through the Original 0.025 in. Radius after Thermal Fatigue Testing for the Cycles Indicated. Original Profile of PWA 1401 shown by the dashed line. (unetched, X20)



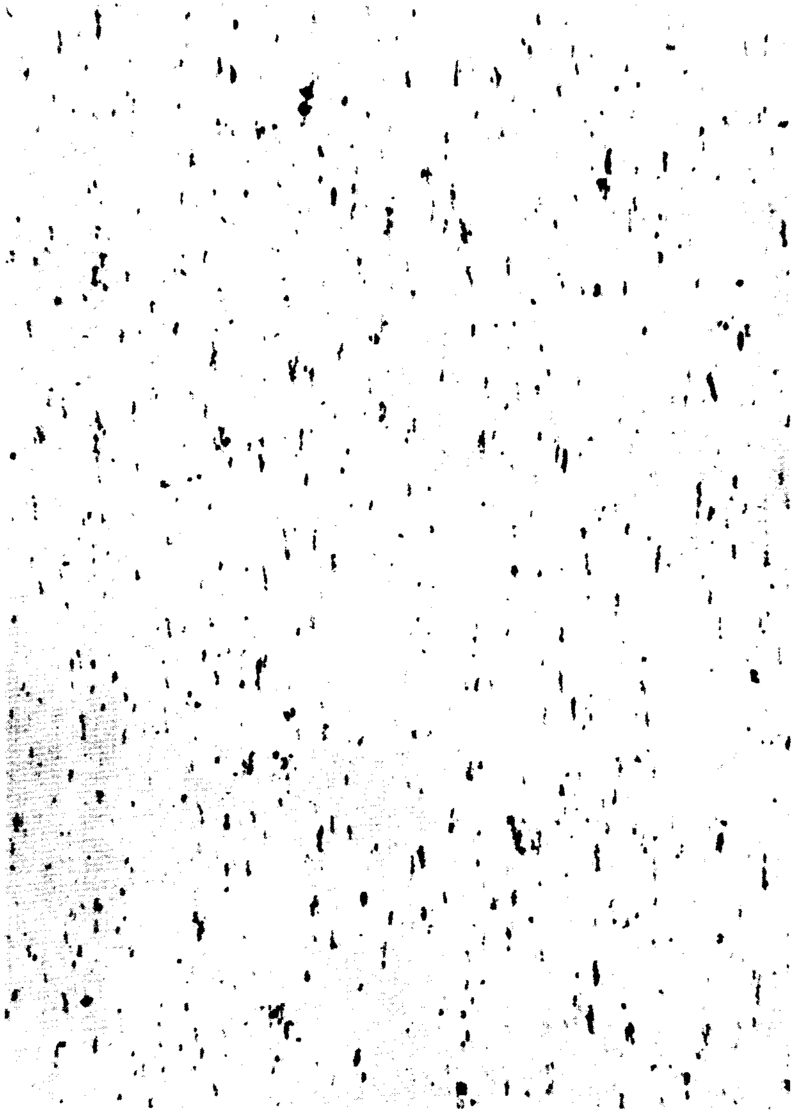
Neg. No. 37883

(c) B1900, Coated (4400 Cycles)

Neg. No. 37886

(d) PWA 664 (5000 Cycles)

Fig. 37 (Continued) - Transverse Section through the Original 0.025 in. Radius after Thermal Fatigue Testing for the Cycles Indicated. Original Profile of the PWA 664 shown by the dashed line. (unetched, X20)

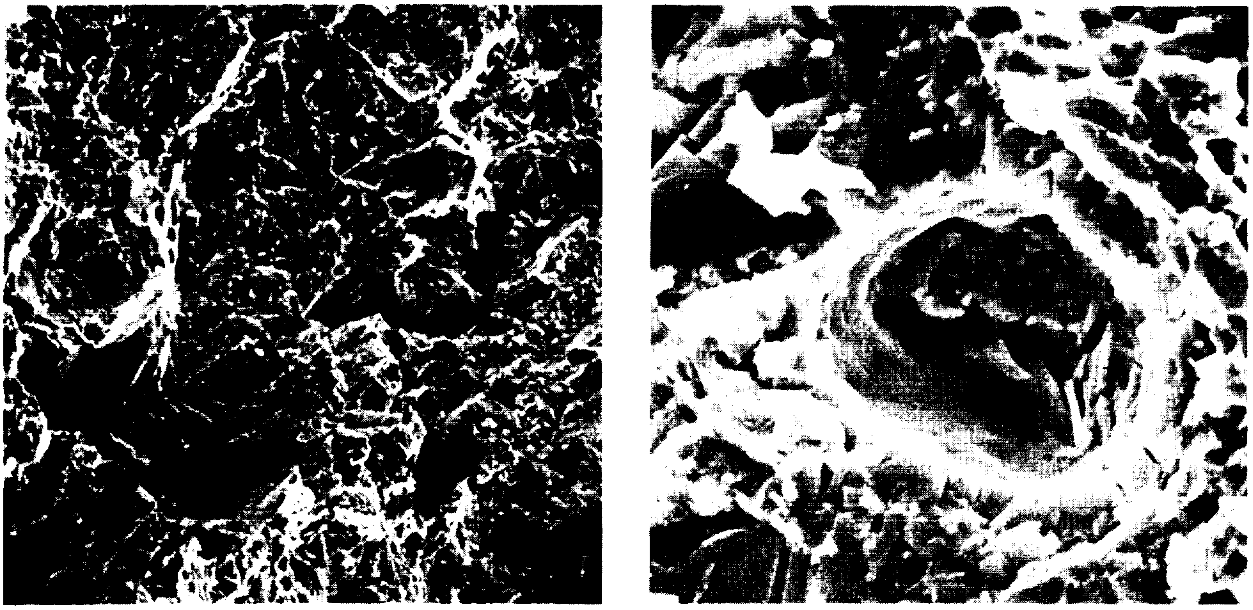


Neg. No. 37572 Unetched, X100

Fig. 38 - ThO_2 Dispersion in TD-NiCr Material Used in This Program.

Neg. No. 37573 Unetched, X100

Fig. 39 - ThO_2 Dispersion in TD-NiCr Material Known to Have Satisfactory Properties.



SEM 8372 X300 SEM 8373 X3000

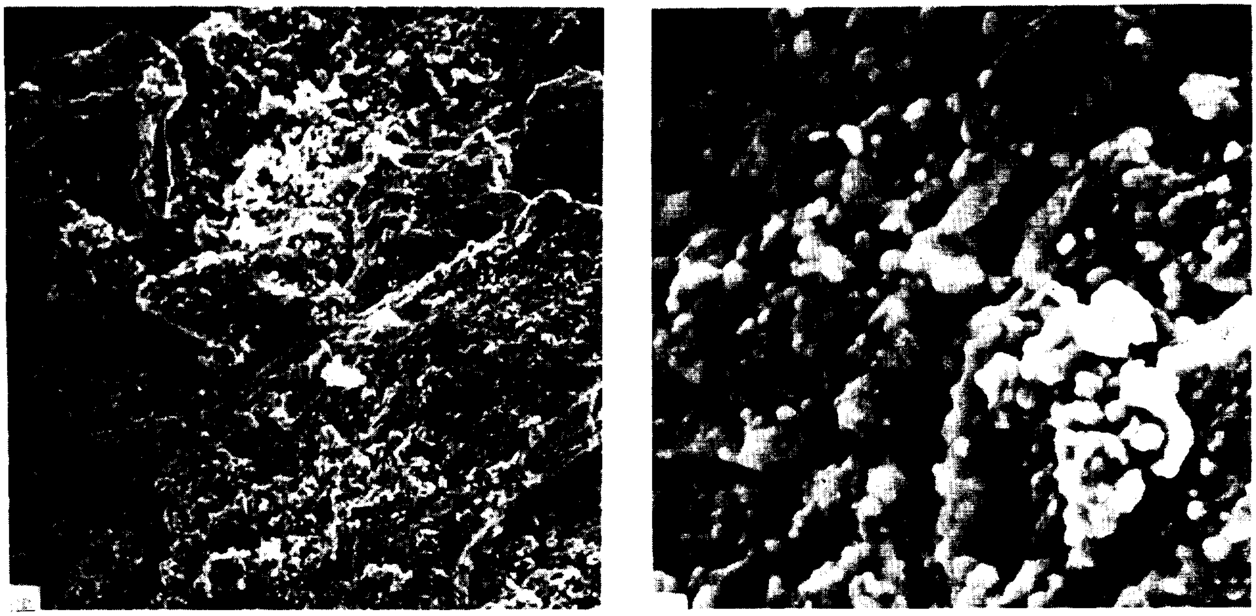
(a) (b)

Fig. 40 - Appearance of Thermal Fatigue Fracture of IN-100 in the SEM.

SEM 8375 X300 SEM 8310 X3000

(a) (b)

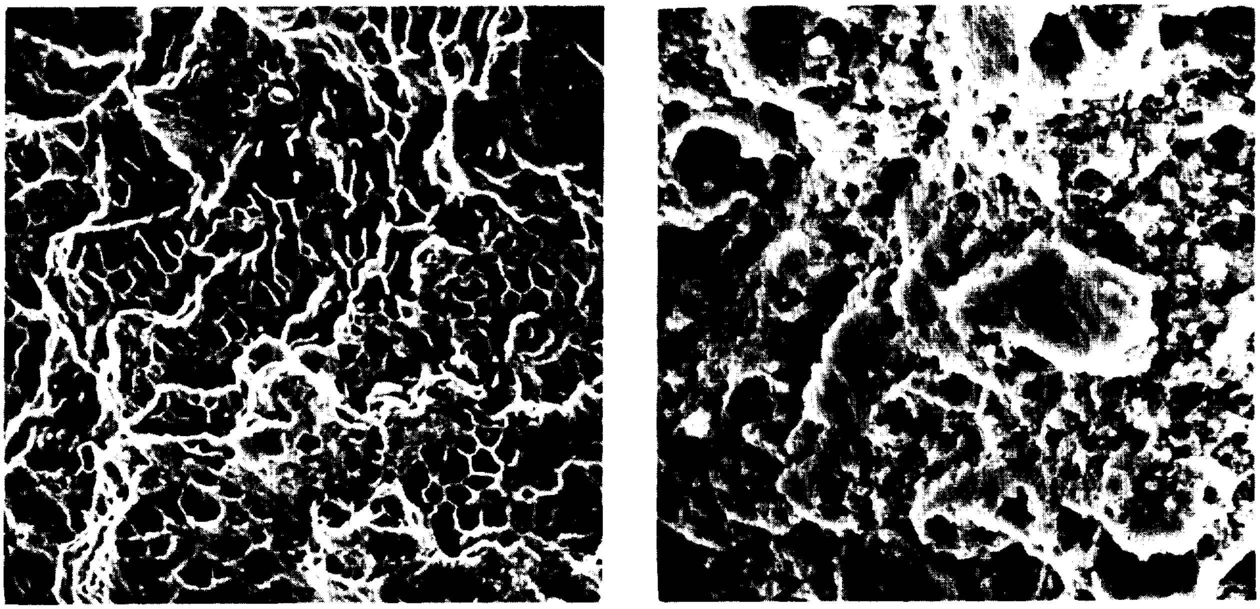
Fig. 41 - Appearance of Thermal Fatigue Fracture of MAR-M 200 in the SEM.



SEM 8317 X300 (a)

SEM 8316 X3000 (b)

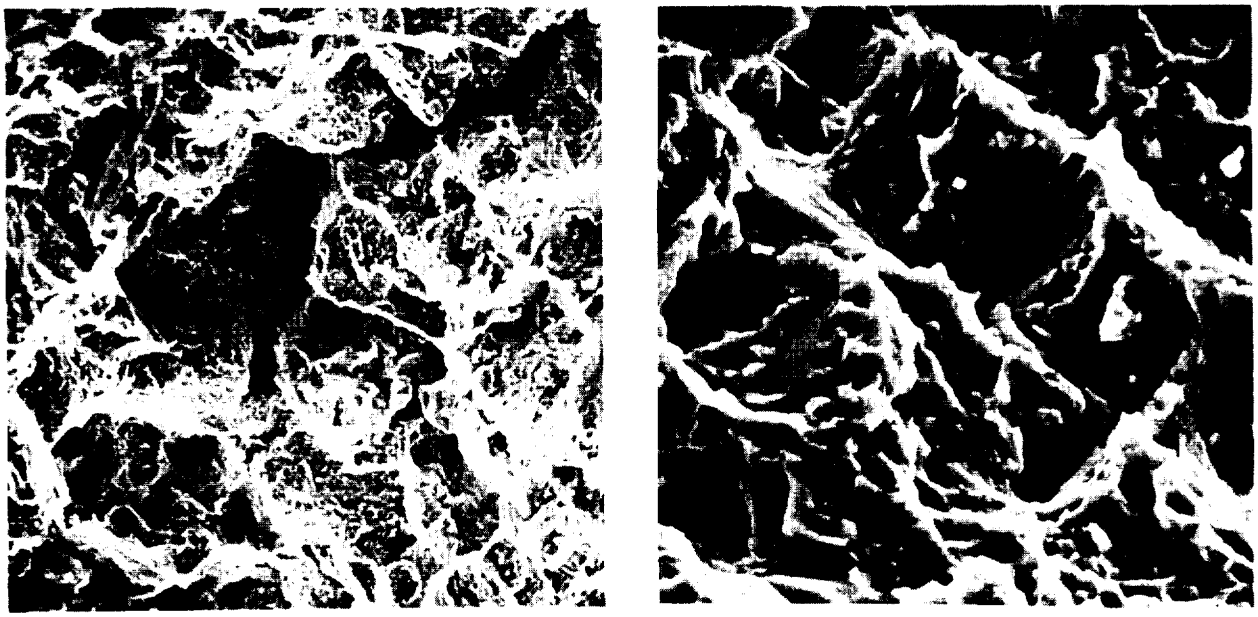
Fig. 42 - Appearance of Thermal Fatigue Fracture of MAR-M 302 in the SEM.



SEM 8371 X1000 (a)

SEM 8370 X3000 (b)

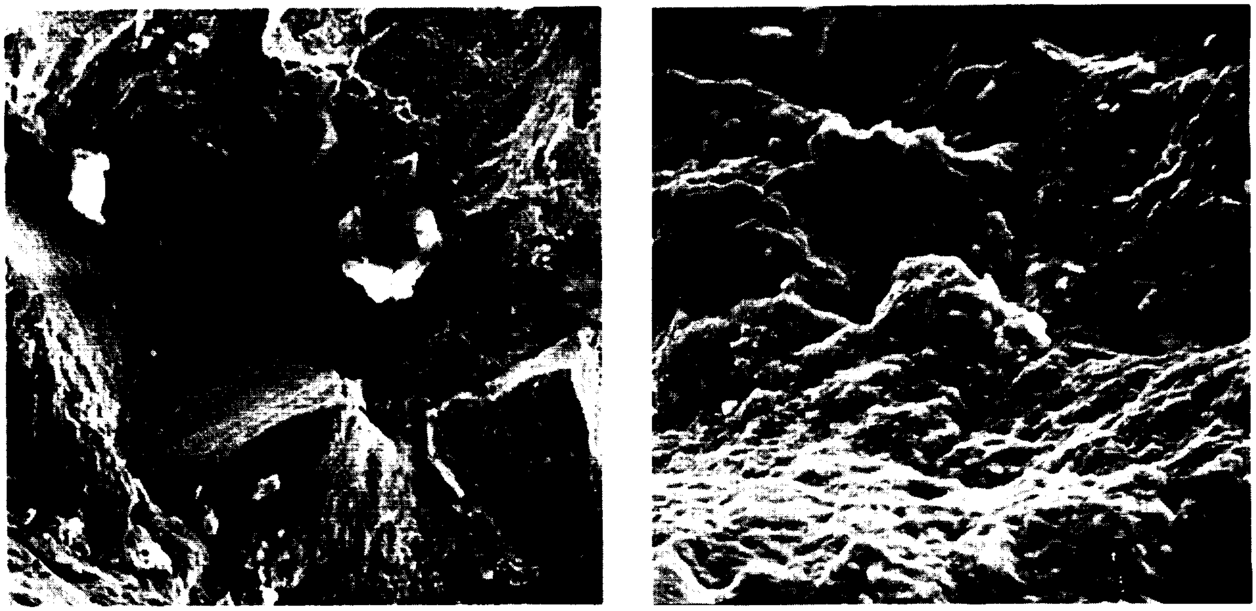
Fig. 43 - Appearance of Thermal Fatigue Fracture of TD-NiCr in the SEM.



SEM 8308 X300 SEM 8306 X3000

(a) (b)

Fig. 44 - Appearance of Thermal Fatigue Fracture of Cast Udimet 700 in the SEM.



SEM 8365 X300 SEM 8303 X1000

(a) (b)

Fig. 45 - Appearance of Thermal Fatigue Fracture of Wrought Udimet 700 in the SEM.

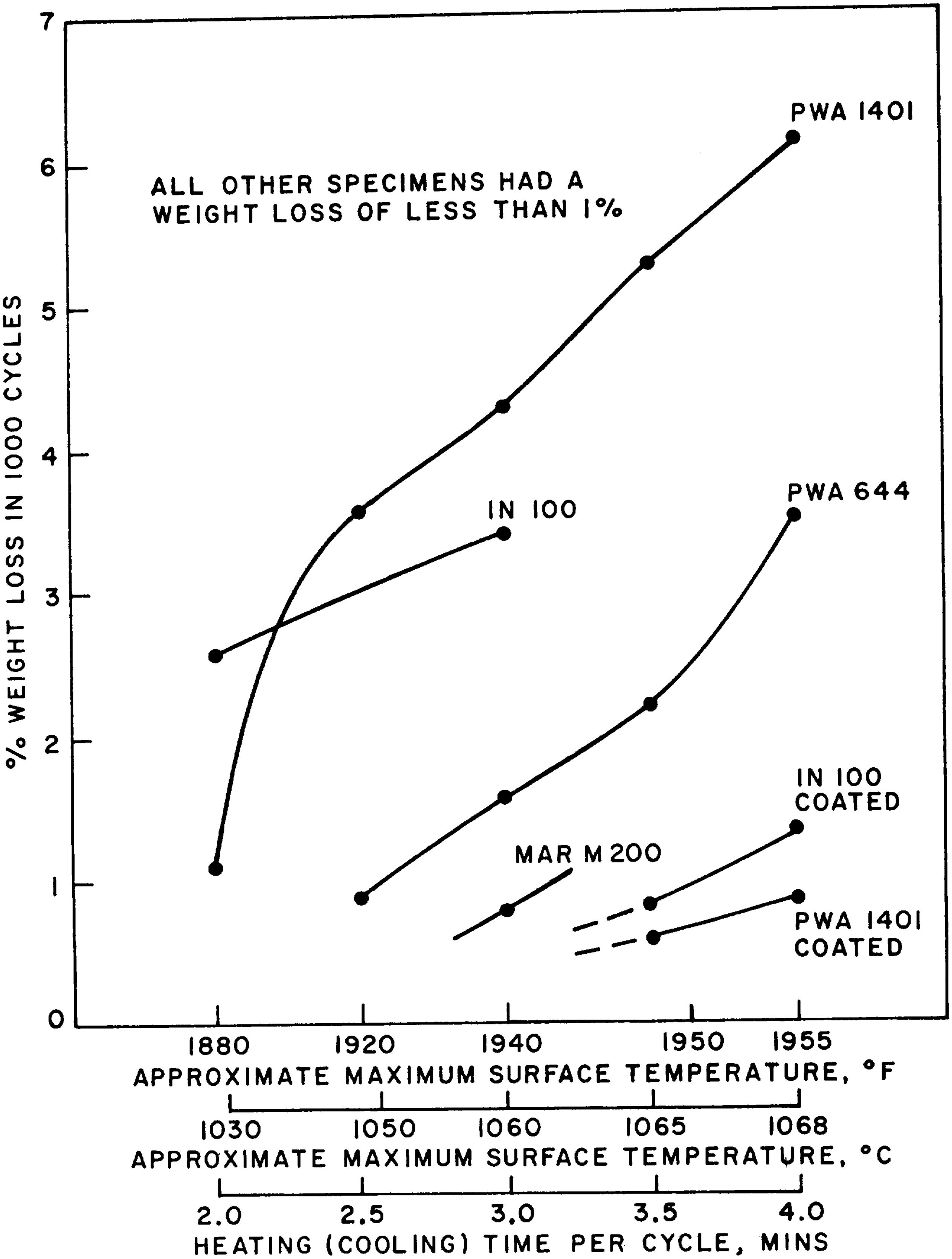


Fig. 46 - Weight Loss for 1000-Cycle Exposure.
Bed temperatures, 1990°F and 600°F.