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

by

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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.

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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.

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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 Incone! 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:

	<u>Temperature</u>		<u>Air Flow</u> (Measured at 150°F, 2 psi pressure)	
	<u>°F</u>	<u>°C</u>	<u>ft³/ft²/hr</u>	<u>m³/m²/hr</u>
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:

<u>Set</u>	<u>Time, min</u>	
	<u>Hot Bed</u>	<u>Intermediate Bed</u>
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 ASTM E-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 kv 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. Glenn(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 latter procedure is of particular value when the test section is of constant thickness and the crack length versus cycle number curves approximate straight lines. The wedge section specimen used in this investigation results in curved crack propagation curves and makes it difficult to accurately extrapolate the curves to zero crack length. The averaging method of Glenn 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 is 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:

<u>Rank</u>	<u>Alloy</u>	<u>Cycles to First Crack (3 min exposure)</u>
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.

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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 2858	0.038 0.020	-- --	-- --	21.39 19.72	Bal. Bal.	-- --	-- --	-- --	-- --	-- --	-- --	-- --	2.5ThO ₂ , .0005N, .006S 1.9ThO ₂ , .004N, .007S

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	3b	1	3a	1	2a
	7	3c			3	2a
	15	3c			4	2a
					12	2c
					20	2c
					22	2c

TABLE 4
TENSILE PROPERTIES AT 1400°F

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

(a) No specimens available.

(b) Rupture strength significantly lower than published data.

(c) Supplementary test.

TABLE 6

HEAT TREATMENTS FOR SPECIMENS

Alloy	Solution Treatment		Intermediate Aging		Final Aging	
	Temp. °C	Time, hr	Temp. °C	Time, hr	Temp. °C	Time, hr
B1900	--	-	--	-	1550	24
IN-100 & PWA 1401	2100	2	--	-	1700	16
X-40	--	-	--	-	1400	50
MAR-M 200 & PWA 664	--	-	--	-	1500	50
MAR-M 302	2250	8	--	-	1500	24
Udimet 700 (cast)	--	-	--	-	1400	16
Udimet 700 (wrought)	2050	4	1550	24	1400	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, 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	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
0	1725	1490	1480	1495	1730	1680	1400	1365	1430	1725	1670	1450	1345	1500	1715
1	1780	1580	1570	1585	1780	1750	1505	1480	1555	1790	1740	1560	1460	1590	1780
1	1810	1640	1635	1645	1810	1800	1600	1580	1635	1830	1790	1640	1560	1665	1820
1	1855	1705	1700	1710	1850	1840	1680	1655	1705	1865	1830	1710	1645	1740	1855
2	1890	1745	1740	1755	1895	1880	1740	1710	1760	1890	1870	1775	1705	1790	1880
2						1900	1790	1765	1805	1905	1890	1820	1765	1835	1895
2						1915	1830	1800	1840	1925	1905	1850	1815	1860	1920
2						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	
0	1665	1590	1560	1606	1715	1615	1395	1370	1500	1630	1580	1450	1350	1475	1600	
15	1745	1675	1670	1690	1775	1710	1530	1520	1590	1730	1670	1570	1500	1595	1690	
30	1800	1745	1740	1765	1825	1770	1620	1610	1675	1780	1740	1670	1620	1680	1765	
45	1840	1810	1805	1820	1855	1820	1700	1690	1740	1840	1800	1750	1700	1755	1815	
0	1875	1850	1845	1860	1880	1855	1760	1740	1790	1860	1840	1800	1770	1805	1850	
15						1880	1800	1780	1825	1885	1870	1835	1815	1845	1875	
30						1905	1820	1800	1855	1910	1895	1865	1845	1875	1900	
45						1920	1865	1855	1875	1925	1910	1890	1880	1900	1915	
0						1935	1885	1875	1900	1940	1920	1910	1900	1910	1925	
15											1930	1920	1915	1925	1935	
30											1940	1935	1930	1930	1940	
45											1945	1940	1935	1940	1950	
0											1950	1945	1940	1950	1955	

1 1 1 1 1 2 2 2 2 3 3 3 3 4

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
0	1680	1435	1415	1470	1710	1620	1390	1370	1415	1685	1530	1360	1340	1400	1640
15	1740	1515	1510	1565	1755	1670	1500	1475	1505	1740	1600	1490	1470	1500	1720
30	1760	1620	1600	1640	1790	1740	1590	1570	1595	1780	1665	1600	1580	1610	1775
45	1790	1680	1660	1690	1830	1780	1670	1665	1675	1830	1745	1680	1660	1690	1820
0	1820	1725	1710	1740	1860	1820	1725	1720	1740	1850	1795	1740	1725	1750	1850
15						1860	1775	1770	1790	1870	1835	1795	1785	1800	1875
30						1880	1815	1810	1835	1890	1860	1830	1820	1835	1895
45						1900	1845	1840	1865	1910	1880	1865	1855	1870	1910
0						1910	1875	1865	1880	1930	1895	1890	1880	1895	1920
15											1910	1910	1900	1915	1930
30											1925	1925	1915	1930	1940
45											1935	1935	1925	1935	1942
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
0	1640	1570	1560	1585	1675	1540	1340	1350	1430	1645	1535	1495	1305	1560	1635
15	1710	1655	1670	1670	1735	1630	1500	1470	1550	1715	1615	1605	1630	1660	1700
30	1770	1725	1745	1745	1785	1720	1605	1580	1640	1775	1690	1680	1710	1735	1755
45	1820	1790	1795	1800	1830	1775	1680	1650	1770	1870	1760	1750	1775	1795	1800
0	1855	1830	1825	1840	1865	1805	1750	1725	1775	1855	1825	1815	1830	1835	1840
15						1865	1790	1770	1820	1885	1860	1850	1865	1870	1875
30						1895	1840	1800	1860	1905	1880	1870	1890	1890	1900
45						1905	1860	1840	1885	1920	1900	1890	1905	1905	1915
0						1930	1890	1870	1910	1935	1910	1900	1920	1920	1930
15											1920	1915	1930	1930	1935
30											1930	1925	1933	1940	1945
45											1940	1935	1937	1945	1950
0											1950	1945	1940	1950	1955

1 1 1 1 1 2 2 2 2 2 3 3 3 3 4

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				5 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	
0	1690	1560	1540	1580	1715	1690	1520	1480	1560	1710	1620	1490	1390	1525	1700	
15	1755	1645	1640	1655	1760	1750	1620	1580	1660	1780	1700	1600	1530	1630	1770	
30	1795	1720	1710	1730	1790	1800	1700	1670	1730	1825	1750	1680	1630	1700	1820	
45	1825	1770	1765	1780	1830	1840	1750	1720	1780	1860	1800	1750	1710	1770	1850	
0	1850	1805	1800	1815	1860	1865	1795	1780	1830	1880	1840	1800	1770	1815	1875	
15						1885	1830	1820	1860	1900	1870	1825	1815	1835	1895	
30						1900	1860	1850	1890	1915	1895	1860	1845	1870	1910	
45						1910	1880	1870	1900	1930	1905	1890	1880	1900	1925	
0						1920	1895	1890	1910	1940	1915	1910	1900	1915	1935	
15											1930	1920	1915	1925	1938	
30											1940	1935	1930	1935	1942	
45											1945	1940	1935	1940	1947	
0											1950	1945	1940	1945	1950	

1 1 1 1 2 2 2 2 3 3 3 3 4

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
0	1000	1100	1130	1060	950	1025	1200	1235	1140	970	1055	1255	1290	1185	980
15	910	1010	1030	965	875	990	1070	1110	1050	880	960	1140	1155	1080	890
30	840	920	945	890	805	860	985	1005	955	820	880	1035	1060	980	830
45	790	860	885	830	750	800	910	925	885	770	820	960	970	910	775
0	750	805	815	800	730	760	845	855	830	730	790	900	910	860	750
15						720	800	810	780	690	740	840	855	820	715
30						685	760	770	750	670	700	805	810	770	690
45						665	730	740	720	650	685	775	775	740	675
0						650	705	710	690	640	675	745	745	725	665
15											655	720	720	695	655
30											645	705	700	680	645
45											635	685	780	670	635
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					5 min cycle				
	1	2	3	4	5	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					
0	1050	1200	1220	1170	985	1110	1260	1300	1200	1010	1145	1260	1300	1240	1050					
1	955	1090	1105	1070	900	1020	1150	1190	1100	910	1040	1140	1160	1120	970					
1	900	990	1005	965	840	940	1050	1080	1000	865	970	1040	1065	1010	900					
1	840	905	925	880	790	870	975	1000	950	810	875	965	960	940	830					
2	785	820	835	810	765	820	900	925	870	780	840	900	900	880	800					
2						790	830	840	810	730	795	835	850	865	765					
2						765	790	800	775	710	765	795	800	765	740					
2						720	750	760	730	685	740	755	770	725	710					
3						695	725	730	705	675	710	735	740	705	685					
3											685	710	725	695	665					
3											670	690	710	680	650					
3											655	680	690	670	645					
4											640	665	670	660	640					

TABLE 14

CALIBRATION DATA FOR INSTRUMENTED MAR-M 200 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	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	990	1170	1180	1135	945	1070	1210	1260	1205	995	1130	1290	1300	1210	1000
1	900	1065	1075	1045	870	980	1100	1140	1095	910	1010	1170	1170	1120	920
1	850	985	990	970	800	900	1020	1045	1005	845	935	1065	1075	1020	855
1	790	920	925	900	750	850	955	970	940	790	870	985	990	940	800
2	750	850	855	845	730	805	885	910	870	755	825	925	925	885	750
2						780	830	855	815	725	790	860	870	830	725
2						740	780	810	780	700	760	810	830	790	705
2						700	755	775	750	630	730	780	795	755	685
3						670	730	750	730	660	690	750	765	725	665
3											675	725	740	710	650
3											665	705	720	690	645
3											655	685	700	675	640
4											650	670	685	665	635

TABLE 15
CALIBRATION DATA FOR INSTRUMENTED MAR-M 302 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				5 min cycle			
	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	
0	1025	1180	1190	1175	1020	1050	1230	1250	1195	1040	1120	1230	1280	1170	1110	
1	950	1080	1090	1080	940	975	1115	1130	1040	960	1030	1120	1155	1055	1000	
1	890	1000	1005	995	860	910	1020	1020	1010	890	950	1025	1050	980	920	
1	835	935	935	930	800	845	950	960	945	835	875	940	975	910	850	
2	775	875	875	875	750	795	890	890	875	790	820	885	900	895	800	
2						765	825	840	830	760	780	830	845	790	770	
2						740	800	810	780	730	750	790	800	760	735	
2						715	760	770	755	710	720	765	755	725	710	
3						690	735	750	715	685	690	730	730	700	690	
3											675	705	700	680	675	
3											665	680	685	670	660	
3											655	670	675	660	650	
4											645	660	665	650	645	

TABLE 16

CALIBRATION DATA FOR INSTRUMENTED UDIMET 700 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	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
0	1010	1170	1205	1150	960	1000	1120	1150	1110	930	1030	1255	1325	1220	950
1	920	1065	1100	1050	880	920	1040	1060	1030	870	940	1125	1185	1100	870
1	850	980	1000	960	810	850	955	970	940	820	880	1030	1070	1000	830
1	800	920	950	890	760	800	890	900	880	780	800	955	980	930	780
2	760	840	850	820	740	765	850	860	840	750	770	890	905	870	745
2						730	800	815	790	720	740	825	860	815	720
2						700	770	790	760	685	720	790	805	770	700
2						680	750	765	735	660	700	750	770	735	680
3						655	725	740	710	640	680	730	740	710	660
3											660	710	720	690	650
3											650	690	705	675	640
3											645	680	685	665	635
4											640	665	670	650	630

INSPECTION POINTS AND TOTAL THERMAL CYCLES FOR EACH ALLOY

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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	Front	Back	Front	Back
A (2 min dwell)	0.025	Distance from bottom:	2.5 in.		1.95 in.		0.73 in.	
		1000	.117	.108				
		1400	.121	.165				
		2000	.204	.207	.194	.182	.073	.040
		3000	.220	.218	.210	.198	.095	.065
		4000	.370	.363	.373	.368	.176	.136
B (2 min dwell)	0.040	5000	.380	.365	.375	.377	.135	.149
		Distance from bottom:	3.00 in.		1.10 in.			
		4000	.240	.220	.140	.186		
		5000	.296	.240	.223	.265	.163	.167
		Distance from bottom:	1.50 in.		2.50 in.			
		800	--	.028				
C (2 1/2 min dwell)	0.025	1000	.211	.227	.138	.155	.1465	
		Distance from bottom:	2.55 in.		1.10 in.		3.20 in.	
		500	.123	.101				
		700	.214	.242				
		1000	.327	.357	.225	.204	.2145	
		1400	.335	.368	.262	.275	.269	.210
	0.040	2000	.469	.409	.330	.322	.326	.361
		Distance from bottom:	3.00 in.		2.30 in.			
		1400	.189	.220	.160	.172	.166	
		2000	.241	.214	.175	.173	.174	
		Distance from bottom:	2.05		.172		.166	

TABLE 18 (Continued)

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

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
B (2 min dwell)	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			
		Distance from bottom:	2.80 in.			1.00 in.			2.00 in.		
		4000	.286	.280	.283	.260	.268	.264	.228	.256	.242
C (2 1/2 min dwell)	0.040	5000	.295	.305	.300	.273	.297	.285	.305	.258	.282
		Distance from bottom:	2.20 in.								
		5000	.078	.074	.076						
		Distance from bottom:	3.10 in.			2.80 in.			1.00 in.		
		1400	.072	.048	.060	.066	.039	.053			
D (3 min dwell)	0.025	2000	.192	.158	.175	.116	.134	.125	.286	.310	.298
		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	First Crack		Second Crack		Third Crack	
			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			
0.025		4400	.413	.423	.418	.295	.315	.305
							.175	.155
								.165
		Distance from bottom:	2.00 in.					
		1000	.168	.224	.196			
F (4 min dwell)		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.			.295	.305	1.30 in.	.280	.288	0.97 in.			
		1000	.318	.298	.308							.300	.284	
B (2 min dwell)	0.025	Distance from bottom:	1.50 in.			.235	.229	1.00 in.	.154	.159	2.40 in.			
		625	.245	.238	.242							.232	.157	
		800	.279	.309	.294							.336	.298	.294
		1000	.321	.329	.325							.347	.310	.304
	0.040	Distance from bottom:	2.40 in.			.173	.146	1.80 in.	.298	.310				
		800	.167	.230	.199							.160		
		1000	.187	.223	.205							.207		
C (1/2 min dwell)	0.025	Distance from bottom:	2.75 in.			.180	.236	1.35 in.	.241	.130	2.00 in.			
		100	.268	.198	.233							.208	.186	
		200	.288	.294	.291							.279	.267	
		300	.344	.315	.330							.304	.292	
		500	.334	.330	.337							.320	.302	
		700	.345	.340	.343							.338	.330	
		1000	.355	.365	.360							.343	.347	
	0.040	Distance from bottom:	2.80 in.			.190	.223	1.10 in.	.185	.199	1.80 in.			
		500	.210	.217	.214							.206		
		700	.234	.232	.233							.223	.220	
		1000	.282	.320	.301							.240	.250	.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	.241	.231	.236	
		100	.330	.334	.337	.304	.306	.280	.340	.310	
		200	.340	.346	.343	.337	.341	.280	.346	.313	
		300	.352	.372	.362	.337	.341	.317	.347	.332	
		500	.352	.372	.362	.337	.342	.317	.348	.333	
		700	.363	.372	.368	.345	.342	.317	.348	.333	
E (3 1/2 min dwell)	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			
		Distance from bottom:	1.90 in.			2.60 in.					
		300	.049	.089	.069						
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
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			
		Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
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			
		Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
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			
		Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
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			
		Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
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			
		Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
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			
		Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
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			
		Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
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			
		Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
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			
		Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
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			
		Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
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			
		Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
F (4 min dwell)	0.040	Distance from bottom:	3.00 in.			1.10 in.			1.80 in.		
		100	.275	.275	.275	.236	.226	.175	.185	.180	
		200	.283	.285	.284	.265	.263	.204	.209	.207	
		300	.290	.292	.291	.272	.274	.239	.243	.241	
		500	.290	.315	.303	.276	.274	.242	.262	.252	
		700	.315	.325	.320	.276	.280	.242	.274	.258	
		Distance from bottom:	1.60 in.			2.00 in.			3.10 in.		
E (3 1/2 min dwell)	0.025	Distance from bottom:	1.90 in.			2.60 in.					

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

TABLE 21 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.					
			First Crack		Second Crack		Third Crack	
			Front	Back	Front	Back	Front	Back
E (3 1/2 min dwell)	0.025	Distance from bottom:	3.00 in.					
		300	.195	.199				
		500	.291	.293				
		700	.352	.308				
		1000	.348	.346				
F (4 min dwell)	0.025	1400	.408	.420				
		Distance from bottom:	2.80 in.					
		1500	.375	.365				
	0.040	Distance from bottom:	0.90 in.					
		500	.233	.219				
		700	.290	.286				
		1000	.360	.316				
		1500	.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	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
B (2 min dwell)	0.025	4000	.093	.089	.091	.065	.059	.062	.049	.031	.040
		5000	.093	.089	.091	.065	.059	.062	.108	.092	.100
		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
C (2 1/2 min dwell)	0.025	4000	.110	.140	.125	.090	.127	.099	.074	.114	.094
		5000	.119	.140	.130	.098	.130	.114	.110	.114	.112
		Distance from bottom:	0.80 in.								
D (3 min dwell)	0.025	1400	.062	.021	.043						
		2000	.077	.062	.070						
		Distance from bottom:	2.00 in.								
		2800	.030	.030	.030						
		3500	.130	.132	.131						
	0.040	4000	.130	.132	.131						
		Distance from bottom:	1.40 in.								
		2800	.050	.052	.051						
		3500	.055	.056	.056						
		4000	.057	.058	.058						

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						
	0.040	2000	.304	.285	.295						
		Distance from bottom:	2.62 in.								
		800	.054	--	.027						
B (2 min dwell)	0.025	1000	.079	.036	.058						
		2000	.162	.182	.172						
		Distance from bottom:	3.10 in.								
	0.040	800	.116	.114	.115						
		1000	.204	.204	.204	.110	.207	.159			
		2000	.320	.320	.320	.295	.314	.304	.108	.158	.133
C (2 1/2 min dwell)	0.040	Distance from bottom:	2.90 in.								
		1000	.062	--	.031						
		2000	.062	.089	.076	.116	.077	.097			
	0.025	Distance from bottom:	0.95 in.								
		700	.115	.140	.128						
		1000	.218	.222	.220	.088	.075	.082			
1400		.255	.280	.268	.198	.180	.189				
0.040	2000	.350	.366	.358	.257	.290	.274	.202	.235	.219	
	Distance from bottom:	2.40 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	Front	Back	Front	Back
			Avg		Avg		Avg	
D (3 min dwell)	0.025	Distance from bottom:	2.50 in.		1.20 in.		1.70 in.	
		700	.137	.135				
		980	.198	.208	.105	.120	.113	
		1400	.271	.298	.243	.247	.245	
	0.040	2000	.342	.322	.328	.340	.334	.154
								.162
								.158
E (3 1/2 min dwell)	0.025	Distance from bottom:	2.80 in.		.080 in.			
		700	.048	.052				
		980	.095	.113				
		1400	.222	.196	.145	.175	.160	
	0.040	2000	.222	.265	.207	.175	.191	
F (4 min dwell)	0.025	Distance from bottom:	2.25 in.		2.85 in.		1.65 in.	
		700	.103	.117				
		1000	.142	.156	.122	.264	.193	
		1400	.241	.249	.248	.268	.258	.188
	0.040	Distance from bottom:	1.40 in.				.278	
		1400	.094	.096				.233
	0.025	Distance from bottom:	2.90 in.		2.25 in.		1.00 in.	
		500	.083	.081				
		700	.176	.196	.165	.151	.158	.067
		1000	.285	.333	.274	.286	.280	.200
	0.040	1500	.362	.388	.341	.351	.346	.301
								.308
		Distance from bottom:	2.70 in.		1.25 in.			
		700	--	.066				
		1000	.110	.110	.104	.044	.074	
		1500	.147	.133	.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		Second Crack		Third Crack			
			Front	Back	Avg	Front	Back	Avg	Front	Back
A (2 min dwell)	0.025	Distance	from bottom:		0.95 in.			2.96 in.		
		1000	.140	.125	.133	.096	.113	.109	.058	--
		1400	.205	.191	.198	.206	.135	.170	.126	.099
		2000	.242	.254	.248	.218	.270	.244	.140	.162
		3000	.265	.271	.268	.225	.280	.252	.153	.168
	0.040	4000	.312	.310	.311	.337	.331	.334	.269	.267
		5000	.321	.313	.317	.337	.343	.340	.298	.280
		Distance	from bottom:		3.06 in.			1.20 in.		
		1000	.090	.059	.075	.051	.046	.049		
		1400	.144	.166	.155	.095	.125	.110	.128	.100
B (2 min dwell)	0.025	2000	.204	.210	.207	.156	.145	.150	.138	.178
		3000	.212	.215	.214	.162	.152	.157	.152	.185
		4000	.257	.248	.253	.162	.154	.158	.222	.206
		5000	.252	.261	.257	.162	.165	.164	.225	.213
		Distance	from bottom:		1.10 in.			0.95 in.		
	0.040	625	.070	.065	.068	.067	.064	.066		
		800	.124	.116	.120	.133	.123	.128	.105	.109
		1000	.148	.128	.138	.168	.166	.167	.141	.139
		Distance	from bottom:		3.05 in.					
		800	.051	.053	.052					
C (2 1/2 min dwell)	0.025	1000	.072	.076	.074					
		Distance	from bottom:		2.25 in.			1.50 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	Front	Back	Front	Back
			Avg		Avg		Avg	
C (2 1/2 min dwell)	0.040	Distance from bottom:	1.25 in.		2.10 in.			
		500	.097	.070				
		700	.122	.077				
		1000	.122	.105	.108	.108		
D (3 min dwell)	0.025	Distance from bottom:	3.00 in.		1.90 in.		2.30 in.	
		100	.053	.069				
		200	.136	.138				
		300	.178	.176	.115	.115	.087	.071
		500	.245	.243	.155	.160	.140	.142
		700	.267	.255	.171	.185	.162	.165
E (3 1/2 min dwell)	0.040	Distance from bottom:	1.40 in.		2.80 in.			
		500	.110	.108	.067	.073		
		700	.134	.122	.115	.123		
		Distance from bottom:	2.75 in.		1.70 in.		2.40 in.	
		300	.058	.064				
		500	.140	.130	.055	.045		
F (4 min dwell)	0.025	Distance from bottom:	1.10 in.		2.35 in.		1.90 in.	
		300	.039	.047				
		500	.128	.116	.135	.131	.092	.067
		700	.130	.142	.138	.185	.155	.155
		Distance from bottom:	1.00 in.		2.30 in.			
		500	.073	.093	.065	.053		

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	Front	Back	Front	Back
		Distance	Avg		Avg		Avg	
A (2 min dwell)	0.025	200	from bottom:	3.00 in.			1.68 in.	1.10 in.
		300	.300	.300	.041	.044	.043	
		450	.310	.310	.043	.046	.045	
		625	.310	.310	.068	.073	.072	
		800	.310	.310	.107	.109	.108	
		1000	.310	.310	.107	.125	.116	
B (2 min dwell)	0.040	200	.395	.349	.295	.298	.297	.386
		300						.365
		450						
		625						
		800						
		1000						
C (2 1/2 min dwell)	0.025	200	from bottom:	2.65 in.			1.84 in.	
		300	.249	.250	.236	.186	.211	
		450						
		625						
		800						
		1000						
D (2 min dwell)	0.040	200	from bottom:	1.50 in.			1.75 in.	2.30 in.
		300	.180	.190				
		450	.195	.203				
		625	.205	.209	.072	.065	.069	.092
		800	.227	.232	.076	.080	.078	.097
		1000	.283	.287	.163	.212	.188	.274
E (2 min dwell)	0.040	200	.283	.291	.175	.218	.197	.278
		300						
		450						
		625						
		800						
		1000						
F (2 min dwell)	0.040	200	from bottom:	1.40 in.			2.50 in.	1.90 in.
		300	.246	.234	.233	.250	.242	.209
		450	.246	.234	.257	.253	.255	.237
		625						
		800						
		1000						
G (2 min dwell)	0.025	200	from bottom:	3.00 in.				
		300	.230	.235				
		450	.350	.355	.308	.298	.303	
		625	.355	.358	.334	.325	.330	
		800	.355	.358	.345	.343	.344	.302
		1000	.355	.359	.345	.345	.345	.351
H (2 min dwell)	0.040	200	.362	.362	.362	.376	.369	.364
		300						
		450						
		625						
		800						
		1000						
I (2 min dwell)	0.040	200	from bottom:	1.50 in.				
		300	.230	.235				
		450	.350	.355	.308	.298	.303	
		625	.355	.358	.334	.325	.330	
		800	.355	.358	.345	.343	.344	.302
		1000	.355	.359	.345	.345	.345	.351
J (2 min dwell)	0.040	200	.362	.362	.362	.376	.369	.364
		300						
		450						
		625						
		800						
		1000						

TABLE 26 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.													
			First Crack		Second Crack		Third Crack		Avg	Front	Back	Avg				
			Front	Back	Front	Back	Front	Back								
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					
E (3 1/2 min dwell)	0.040	Distance	from bottom:		1.10 in.		2.80 in.		2.40 in.							
		50	.239	.223	.231		.190	.198			.194	.105	.109	.240 in.		
		100	.283	.273	.278		.235	.205			.220	.166	.206	.107		
		200	.286	.288	.287		.241	.239			.240	.227	.225	.186		
		300	.286	.288	.287		.248	.241			.245	.235	.237	.226		
		500	.295	.291	.293		.249	.245			.247	.237	.239	.236		
		700	.341	.315	.328		.254	.245			.250	.276	.265	.238	.271	.240 in.
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					
E (3 1/2 min dwell)	0.040	700	.346	.336	.341		.375	.371			.373	.318	.308	.313		

TABLE 26 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Distance	Crack Length, in.					
				First Crack		Second Crack		Third Crack	
				Front	Back	Front	Back	Front	Back
				Avg		Avg		Avg	
E (3 1/2 min dwell)	0.040	Distance from bottom:	50	.285	.265				
			100	.285	.267				
			200	.297	.268				
			300	.323	.331	.257	.270	.264	
			500	.323	.337	.257	.372	.315	
			700	.337	.340	.328	.328	.328	
				2.25 in.		1.80 in.		1.35 in.	
F (4 min dwell)	0.025	Distance from bottom:	25	.353	.333				
			50	.360	.368	.338	.326	.332	.270
			100	.374	.368	.348	.329	.339	.278
			200	.374	.370	.348	.338	.343	.298
			300	.376	.372	.348	.340	.344	.309
			500	.380	.376	.376	.394	.385	.330
				2.45 in.		3.10 in.		1.35 in.	
	0.040	Distance from bottom:	25	.273	.275				
			50	.292	.278				
			100	.370	.355	.240	.238	.239	
			200	.370	.356	.311	.276	.294	
			300	.370	.356	.311	.276	.294	
			500	.370	.356	.311	.280	.296	
				1.25 in.		2.10 in.		.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	Distance from bottom:	Crack Length, in.					
				First Crack		Second Crack		Third Crack	
				Front	Back	Front	Back	Front	Back
				Avg		Avg		Avg	
D (3 min dwell)	0.025	Distance from bottom: 5000	1.55 in. .010	.010					
F (4 min dwell)	0.025	Distance from bottom: 700 1000 1500	3.50 in. .036 .040 .060	.307 .048 .064					

TABLE 28

SUMMARY OF CRACK PROGACATION 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		Second Crack		Third Crack					
			Front	Back	Avg	Front	Back	Avg	Front	Back	Avg	
A (2 min dwell)	0.025	Distance	1.00 in.			1.25 in.			1.55 in.			
		1000	from bottom:	.054	.030	.042						
		1400		.164	.158	.161	.107	.094	.090	.101	.095	
		2000		.235	.253	.244	.120	.130	.170	.160	.165	
		3000		.246	.257	.252	.175	.152	.180	.185	.182	
		4000		.399	.379	.389	.176	.162	.320	.314	.317	
	0.040	5000		.410	.384	.394	.176	.162	.320	.318	.319	
		Distance	1.60 in.			1.30 in.			2.80 in.			
		3000	from bottom:	.168	.165	.167	.125	.127				
		4000		.260	.238	.249	.136	.160	.162	.174	.168	
		5000		.260	.254	.257	.139	.161	.187	.190	.189	
		B (2 min dwell)	0.025	Distance	2.25 in.			1.10 in.				
800	from bottom:			.225	.225	.225	.145	.150				
1000				.291	.288	.290	.224	.227				
0.040	Distance		1.80 in.			1.20 in.						
	1000		from bottom:	.155	.147	.151	.091	.035				
	C (2 1/2 min dwell)		0.025	Distance	1.80 in.			2.20 in.			1.00 in.	
300		from bottom:		.058	.068	.063	.018	.049				
500				.136	.136	.136	.105	.107				
700				.191	.196	.194	.157	.163				
1000				.257	.263	.260	.235	.243	.324	.324	.324	
0.040		Distance	1.90 in.			1.30 in.						
	300	from bottom:	.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
E (3 1/2 min dwell)	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
		Distance from bottom:	1.30 in.			3.10 in.					
		500	.049	.029	.039						
F (4 min dwell)	0.040	700	.101	.111	.106	.158	.160	.159			
		Distance from bottom:	1.1 in.			1.4 in.					
		700	.073	.110	.087	.044	.058	.051			
		Distance from bottom:	0.90 in.			2.90 in.					
		500	.070	.076	.073	.060	.084	.072			
		Distance from bottom:	2.55 in.								
500	.034	.076	.055								

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.										
		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.										
		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.										
		800	.048	.046	.047											
		1000	.055	.046	.056	.046	.060	.053								
C (2 1/2 min dwell)	0.025	Distance	from bottom:			3.00 in.										
		500	.207	.240	.224											
		700	.261	.265	.263	.198	.180	.189								
		1000	.330	.346	.338	.393	.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.										
		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			Second Crack			Third Crack		
			Front	Back	Avg	Front	Back	Avg	Front	Back	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						
E (3 1/2 min dwell)	0.025	3100	.240	.270	.255						
		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
F (4 min dwell)	0.040	1400	.285	.320	.303	.297	.295	.296	.261	.281	.271
		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	.059
		1400	.320	.361	.342	.110	.110	.110	.063	.075	.069
	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	.275	.281	.278
		1000	.337	.351	.344	.279	.315	.297	.370	.372	.371
		1500	.410	.410	.410	.350	.360	.355			

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	
B (2 min dwell)	0.040	5000	.330	.344	.337	.406	.385	.396	.294	.290	.292	
		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				
C (2 1/2 min dwell)	0.025	5000	.294	.370	.332	.222	.224	.223				
		Distance from bottom:	2.80 in.			1.70 in.			0.90 in.			
		1000	.278	.312	.295	.269	.259	.264	.242	.213	.223	
		Distance from bottom:	1.70 in.			1.10 in.			2.80 in.			
		500	.197	.160	.179							
		700	.264	.283	.276	.274	.300	.292	.193	.193	.196	
	0.040	1000	.292	.298	.295	.320	.324	.322	.328	.326	.327	
		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.		
		300	.174	.150	.162						1.20 in.
		500	.306	.308	.307						
		700	.375	.323	.359	.367	.375	.371	.318	.308	.313
E (3 1/2 min dwell)	0.040	Distance	from bottom:			2.10 in.					
		700	.075	.085	.080						
		Distance	from bottom:			2.25 in.			1.20 in.		
		700	.315	.335	.325	.319	.303	.311	.238	.194	2.70 in.
F (4 min dwell)	0.040	Distance	from bottom:			2.35 in.					
		700	.074	.098	.086						
		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	Front	Back	Front	Back
			Avg		Avg		Avg	
A (2 min dwell)	0.025	Distance from bottom:	3.25 in.		2.60 in.			
		1000	.048	.055	.051	.040	.046	
	0.040	Distance from bottom:	2.60 in.		1.55 in.			
		450	.210	.262				
		625	.228	.267				
B (2 min dwell)	0.025	Distance from bottom:	1.25 in.		2.35 in.			
		800	.307	.284	.075	.093	.084	
	0.040	Distance from bottom:	1.85 in.		2.65 in.			
		450	.040	.058				
		625	.156	.161				
C (2 1/2 min dwell)	0.025	Distance from bottom:	2.80 in.		3.20 in.		2.15 in.	
		25	.200	--	.100	--	.050	
	0.040	Distance from bottom:	1.15 in.		.085		.115	
		50	.230	--	.170	--	.035	
		100	.235	.175	.170	.180	.175	.055
		200	.235	.220	.170	.180	.175	.072
		300	.235	.265	.222	.220	.221	.160
		500	.283	.165	.223	.220	.221	.183
		700	.288	.302	.240	.220	.230	.185
		1000	.310	.312	.240	.220	.230	.265

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
E (3 1/2 min dwell)	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			
	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			
F (4 min dwell)	0.025	700	.247	.230	.239	.235	.173	.204			
		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	Front	Back	Front	Back
			Avg		Avg		Avg	
A (2 min dwell)	0.025	Distance from bottom:	2.80 in.		2.00 in.		1.15 in.	
		4000	.284	.266	.258	.260	.241	.265
		5000	.325	.323	.277	.286	.292	.270
			Avg		Avg		Avg	
B (2 min dwell)	0.040	Distance from bottom:	1.25 in.					
		5000	.034	.038				
		Distance from bottom:	2.60 in.		1.15 in.			
		3000	.242	.239				
C (2 1/2 min dwell)	0.025	4000	.345	.347	.330	.324	.327	.253
		5000	.358	.358	.330	.346	.338	.281
		Distance from bottom:	1.80 in.		2.65 in.			
		1000	.049	.003				
D (3 min dwell)	0.025	1400	.150	.180				
		2000	.293	.302	.215	.192	.204	
		Distance from bottom:	1.55 in.		2.60 in.		1.00 in.	
		700	.065	.077				
	0.040	980	.225	.243				
		1400	.280	.296	.234	.288	.261	
		2000	.340	.346	.343	.326	.335	
		2800	.408	.420	.411	.421	.416	
		3500	.443	.458	.442	.433	.437	.175
		4000	.445	.464	.445	.464	.455	.178
		4400	.470	.480	.490	.485	.488	.232
		5000	.470	.520	.509	.491	.500	.245
		Distance from bottom:	1.28 in.		1.80 in.		.285	
		5000	.070	.050	.040	.042	.295	.288
			Avg		Avg		Avg	

TABLE 32 (Continued)

Specimen Set	Edge Radius, in.	Cycles	Crack Length, in.					
			First Crack		Second Crack		Third Crack	
			Front	Back	Front	Back	Front	Back
			Avg		Avg		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				
		1500	.148	.156	.166	.154	.160	
			.152					
	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			
		Distance from bottom:	2.42 in.			1.45 in.			1.70 in.		
		200	.022	--	.011						
		300	.025	.005	.015						
B (2 min dwell)	0.025	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
		Distance from bottom:	1.60 in.			2.00 in.					
C (2 1/2 min dwell)	0.040	800	.182	.090	.136						
		1000	.190	.132	.161	.132	.073	.103			
		Distance from bottom:	2.15 in.			1.60 in.			2.60 in.		
		200	.129	.120	.125						
		300	.193	.193	.193	.135	--	.068			
	0.025	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
		Distance from bottom:	1.40 in.			1.30 in.					
		500	.190	.183	.184	.164	.196	.180			
	0.040	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		Avg	Front	Back	Avg
			Front	Back	Front	Back	Front	Back				
D (3 min dwell)	0.025	Distance from bottom:	2.70 in.		1.40 in.		1.40 in.					1.70 in.
		100	.174	.090	.086	.086						
		200	.240	.258	.204	.226						
		300	.295	.291	.235	.233				.221	.242	.232
		500	.295	.292	.235	.233				.222	.242	.232
		700	.346	.320	.239	.270				.222	.278	.250
E (3 1/2 min dwell)	0.040	Distance from bottom:	2.40 in.		1.40 in.		1.40 in.					
		200	.098	.092		.086						
		300	.158	.136	.173	.149						
		500	.315	.310	.330	.332				.161	.331	
		700	.315	.310	.330	.332				.331	.331	
		Distance from bottom:	2.60 in.		1.40 in.		1.40 in.					1.70 in.
F (4 min dwell)	0.025	300	.089	.093	.074	.070						
		500	.122	.127	.150	.131						
		700	.250	.149	.290	.220				.160	.120	.140
	0.040	Distance from bottom:	1.40 in.		1.80 in.		1.80 in.					2.30 in
		700	.219	.195	.080	.140				.106	.080	.093
		Distance from bottom:	1.30 in.		2.30 in.		2.30 in.					1.75 in.
F (4 min dwell)	0.025	200	.085	.065								
		300	.242	.240	.235	.227						
		500	.289	.303	.278	.280				.255	.241	.248
	0.040	Distance from bottom:	1.70 in.		2.50 in.		2.50 in.					
		300	.176	.161								
		500	.228	.215	.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								
B (2 min dwell)	0.040	Distance from bottom:	1.65 in.			.300			.320	.310	.290	.286	.288
		1000	.050	.056	.053								
		Distance from bottom:	2.30 in.			1.20 in.			2.00 in.				
		200	.017	--	.009								
		300	.020	.008	.014								
		450	.020	.009	.015								
C (2 1/2 min dwell)	0.040	Distance from bottom:	1.90 in.			.307			.297	.302	.196	.214	.205
		800	.163	.139	.151	.352	.342	.352	.277	.255	.266		
		1000	.196	.213	.205	.118	.128	.123					
		Distance from bottom:	1.90 in.			2.45 in.			3.00 in.				
		100	.194	.203	.199	.020	.020	.020					
		200	.260	.269	.265	.165	.205	.185	.307	.293	.300		
C (2 1/2 min dwell)	0.025	Distance from bottom:	1.20 in.			.228			.218	.223	.318	.332	.325
		300	.273	.290	.282	.228	.218	.223	.307	.293	.300		
		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		
		Distance from bottom:	1.20 in.			0.80 in.			3.00 in.				

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	.203	.211	.039	.060	.075	.053	.033	.043		
		300	.231	.267	.121	.114	.118	.102	.102	.102		
		500	.293	.291	.239	.233	.236	.238	.238	.238		
		700	.310	.309	.242	.245	.244	.255	.258	.257		
		1000	.329	.219	.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								
		50	.293	.281	.290	.278	.284	.289	.278	.284		
		100	.314	.302	.313	.303	.308	.320	.320	.320		
		200	.349	.341	.342	.346	.344	.344	.342	.343		
		300	.371	.373	.347	.349	.348	.366	.364	.365		
E (3 1/2 min dwell)	0.040	Distance from bottom:	2.90 in.			1.00 in.			2.05 in.			
		100	.269	.265	.234	.242	.246	.235	.233	.234		
		200	.297	.299	.275	.277	.276	.276	.275	.276		
		300	.311	.309	.295	.291	.293	.290	.292	.291		
		500	.317	.315	.309	.307	.308	.308	.305	.307		
		700	.359	.323	.353	.328	.341	.342	.340	.347		
	0.025	Distance from bottom:	2.90 in.			2.15 in.			1.80 in.			
		50	.291	.291								
		100	.292	.291	.180	.210	.195					
		200	.292	.291	.185	.210	.198					
		300	.312	.317	.269	.281	.275					
		500	.328	.317	.279	.281	.280					
			.360	.350	.318	.320	.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
	0.040	500	.387	.415	.401	.374	.378	.376	.358	.368	.363
		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

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SUMMARY OF CRACK PROPAGATION FOR TD-NiCr

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

[illegible]

TABLE 36

THERMAL CYCLES REQUIRED TO INITIATE THE FIRST CRACK IN EACH EDGE

Material and Condition	Set A (2 min dwell) .025 .040 edge edge		Set B (2 min dwell) .025 .040 edge edge		Set C (2½ min dwell) .025 .040 edge edge		Set D (3 min dwell) .025 .040 edge edge		Set E (3½ min dwell) .025 .040 edge edge		Set F (4 min dwell) .025 .040 edge 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

Alloy	As Received: Met.	Set C (2½ min dwell):		Set D (3 min dwell):		Set F (4 min dwell):	
		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	Set B	Set C	Set D	Set E	Set F
		(2 min dwell) Cycles R_C	(2 min dwell) Cycles R_C	(2½ min dwell) Cycles R_C	(3 min dwell) Cycles R_C	(3½ min dwell) Cycles R_C	(4 min dwell) Cycles R_C
B1900	38	1000	1000	1000	700	700	500
		37	38	38	37	38	38
		1400		1400	980		
		35		36	36		
		2000		2000	1400		
IN-100	38	3000			2000		
		34			36		
		33					
		4000					
		33					
PWA 1401	39	5000					
		36					
		1000	1000	1000	700	700	500
		36	36	36	36	37	36
		1000					
X-40	38	1400					
		33					
		1400	1000	1000	700	700	500
		32	35	35	34	39	36
		2000	1400	1400	980	1000	700
WI-52	36	3000	2000	2000	1400	1400	1000
		32	30	33	35	33	35
		4000	3000	2000	2000	1400	1500
		33	30	33	35	33	35
		5000	5000	5000	2800	1000	700
X-40	38	32	30	33	35	33	36
		36	35	35	36	37	36
		1000	1000	1000	700	700	500
		36	35	35	36	37	36
		1400	1400	1400	980	1000	700
WI-52	36	2000	2000	2000	1400	1400	1000
		32	35	31	34	34	33
		4000	34	34	2000	1400	1500
		30	34	34	33	35	34
		5000	1000	1000	700	700	500

TABLE 38 (Continued)

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

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			1000	45
		4000	43	4000	43			2800	43			1500	45
		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								

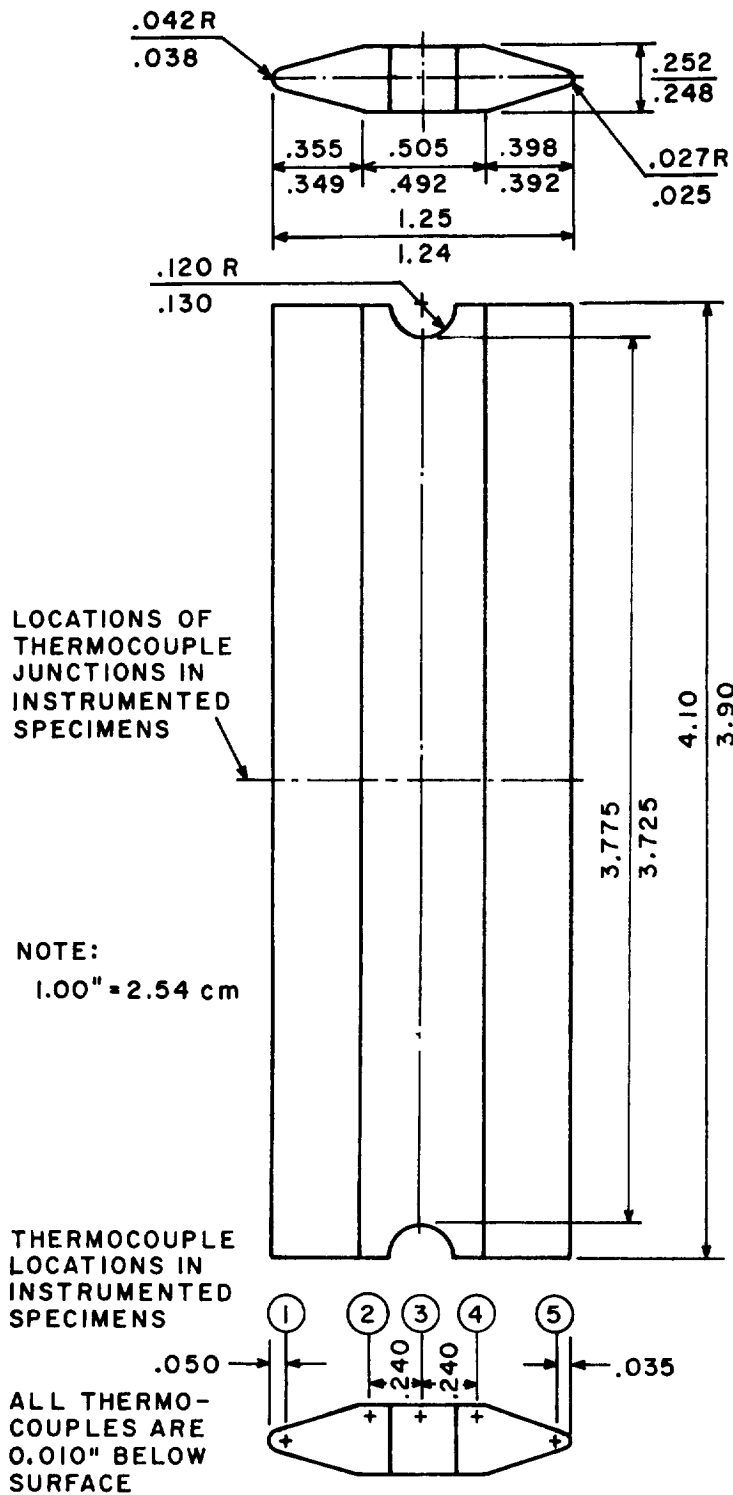
TABLE 39

MICROHARDNESS MEASUREMENTS IN THERMAL FATIGUE SAMPLE SECTIONS

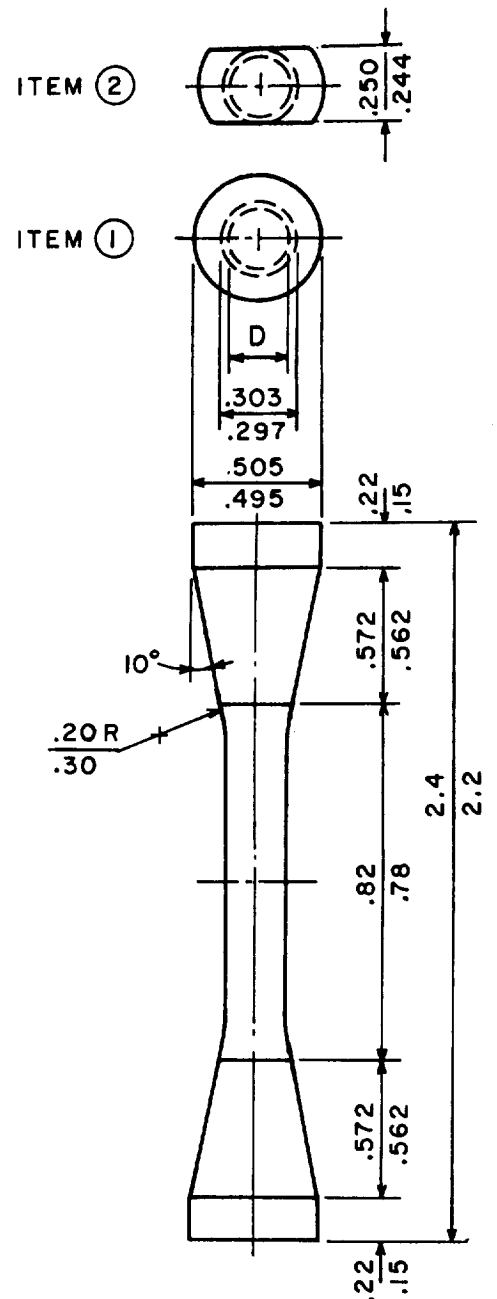
Material	Set	Cycles	Microhardness, DPH (500 g)				
			Near Surface		Below Surface		
			Removed from Crack	Near Crack (.003 in.)	.100-.150 in. Below Surface	Near Crack Tip (.003 in.)	White Layer Adjacent* to Crack
B1900	F	500	340	345	371	375	430
B1900, coated	D	4400	371	380	371	375	450
IN-100	F	500	340	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.



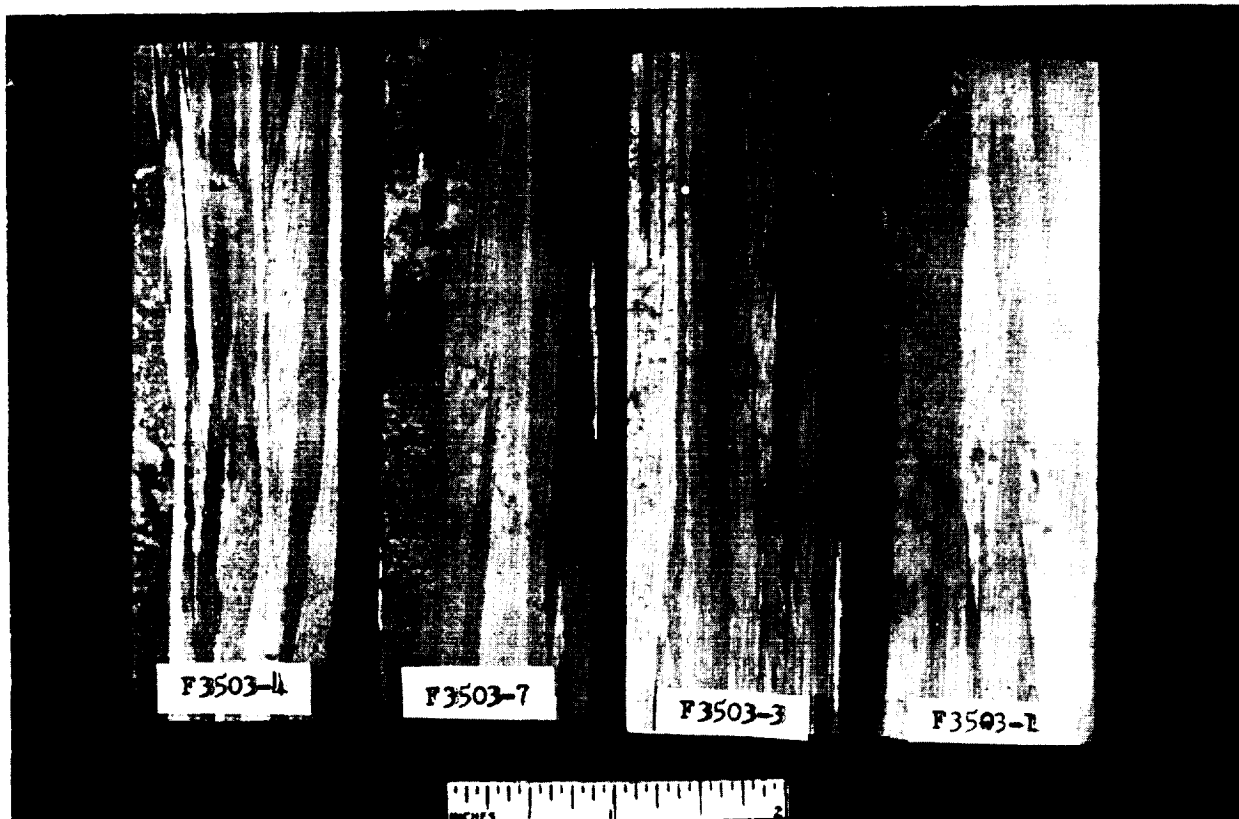
THERMAL FATIGUE TEST PIECE



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

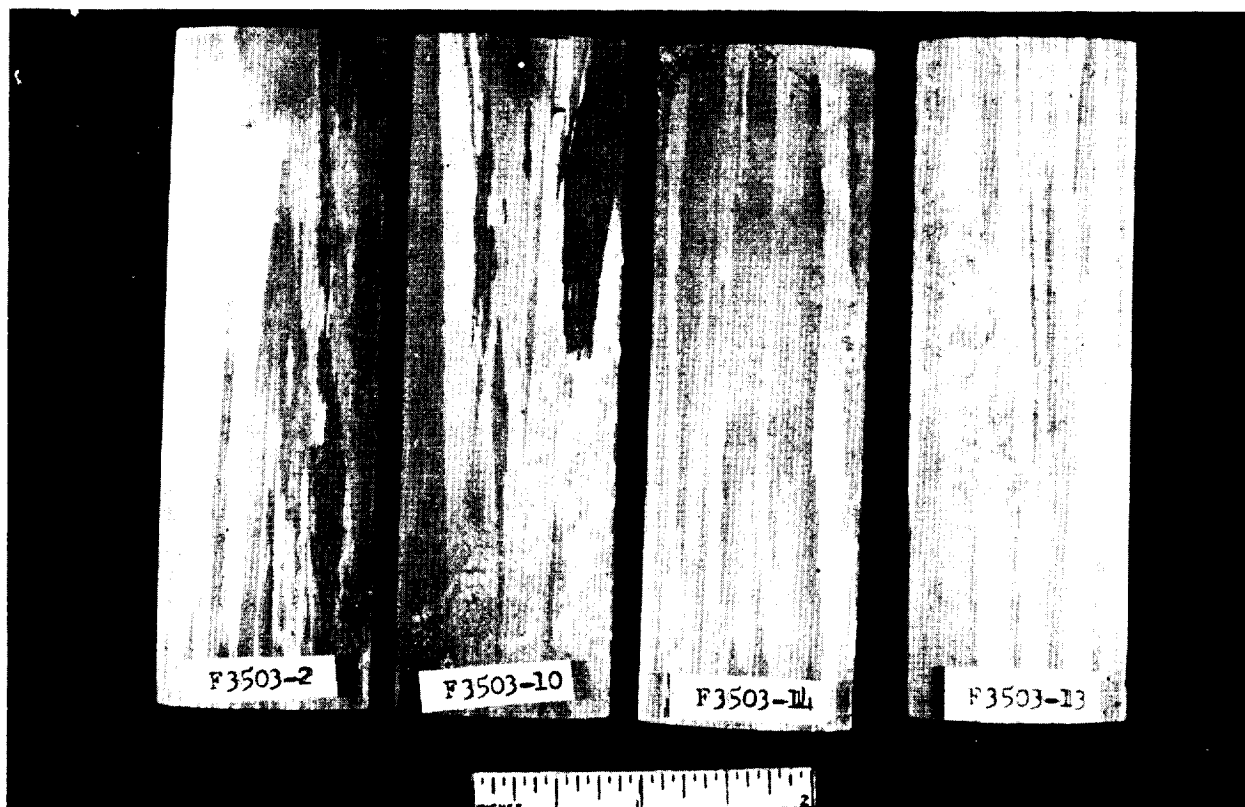
UNIAXIAL TEST PIECE

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



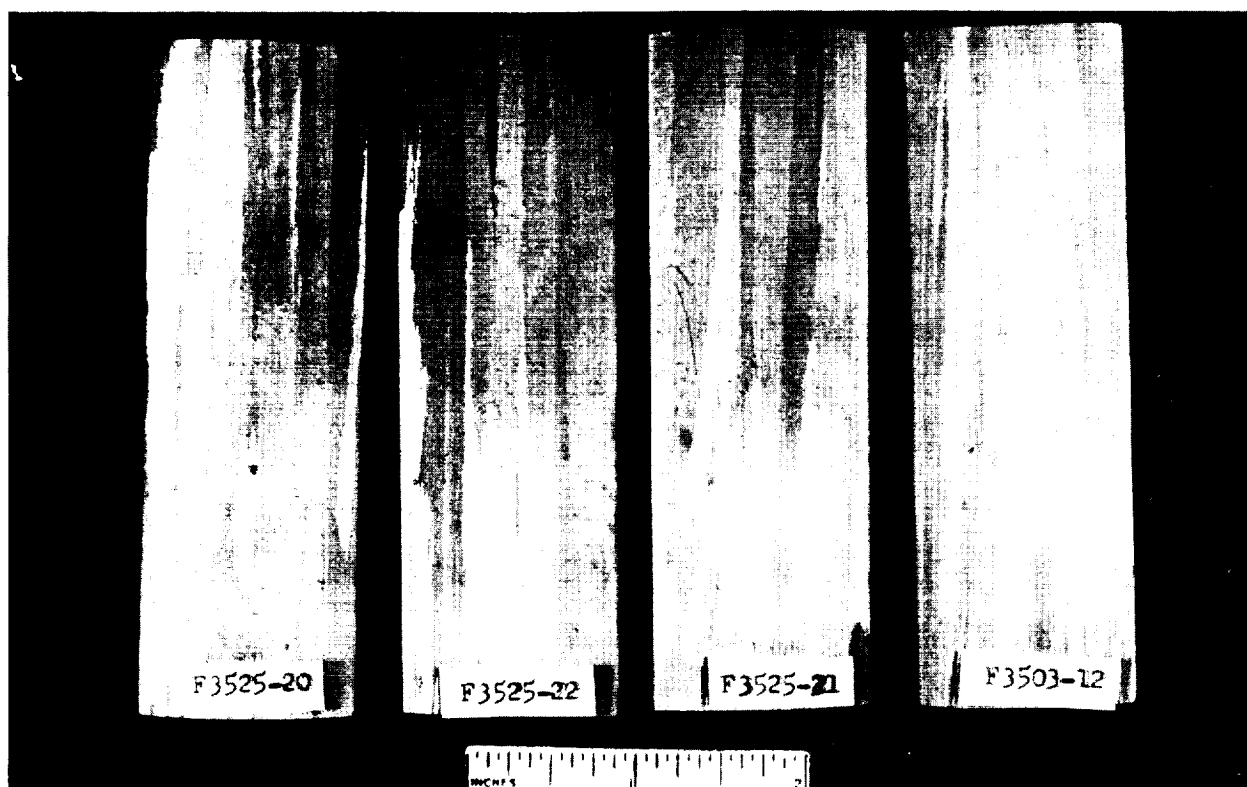
(a)

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



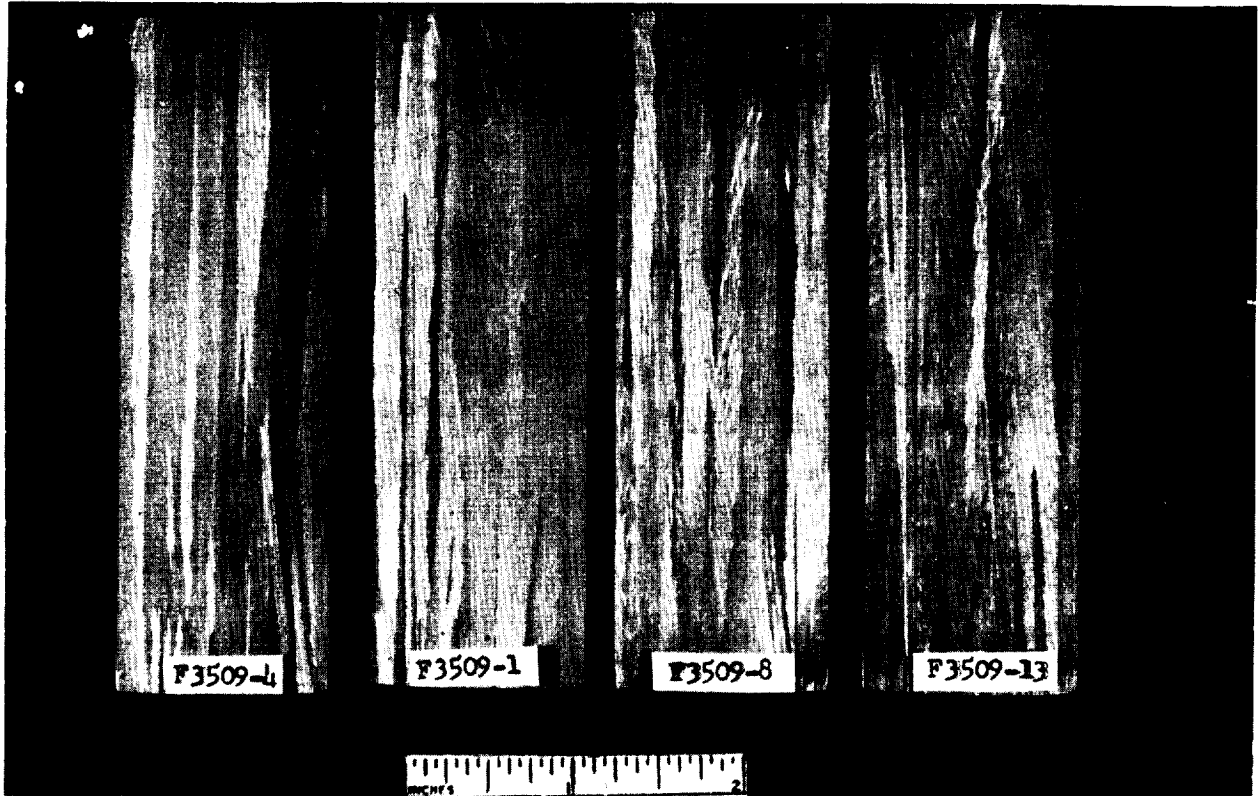
(b)

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



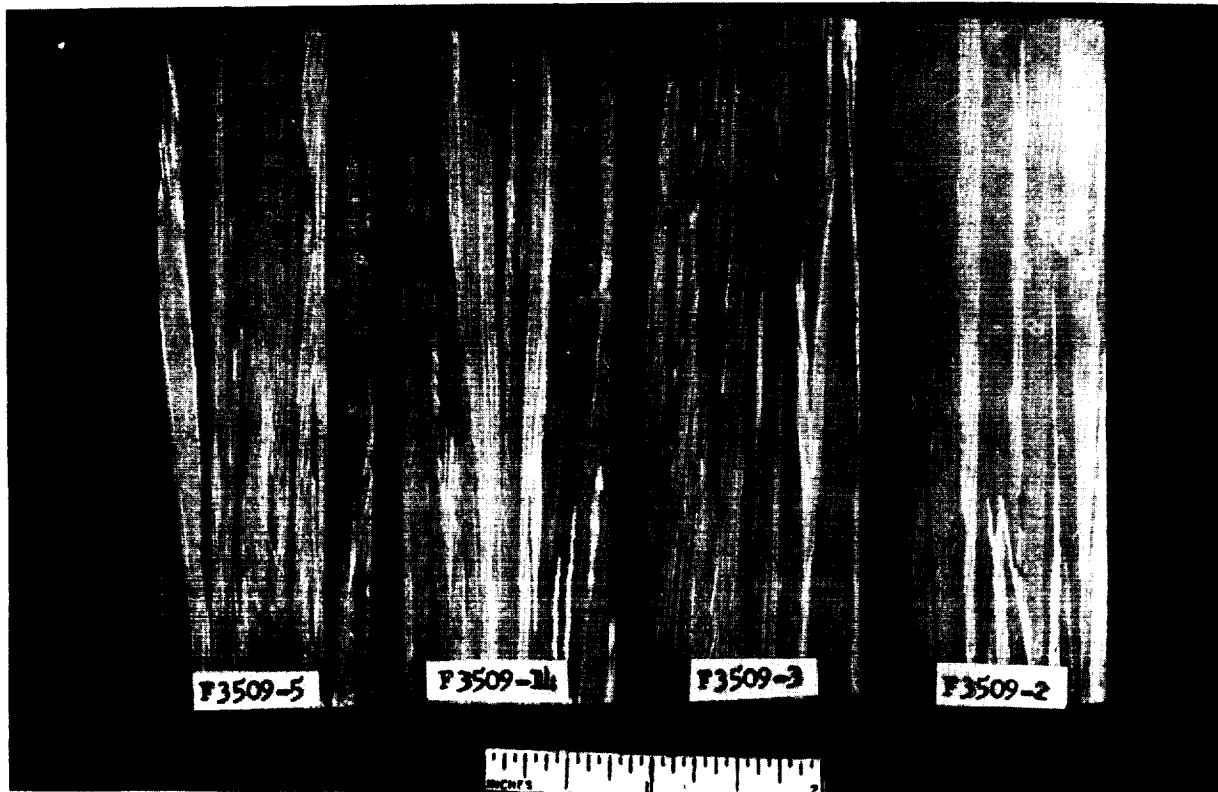
(c)

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



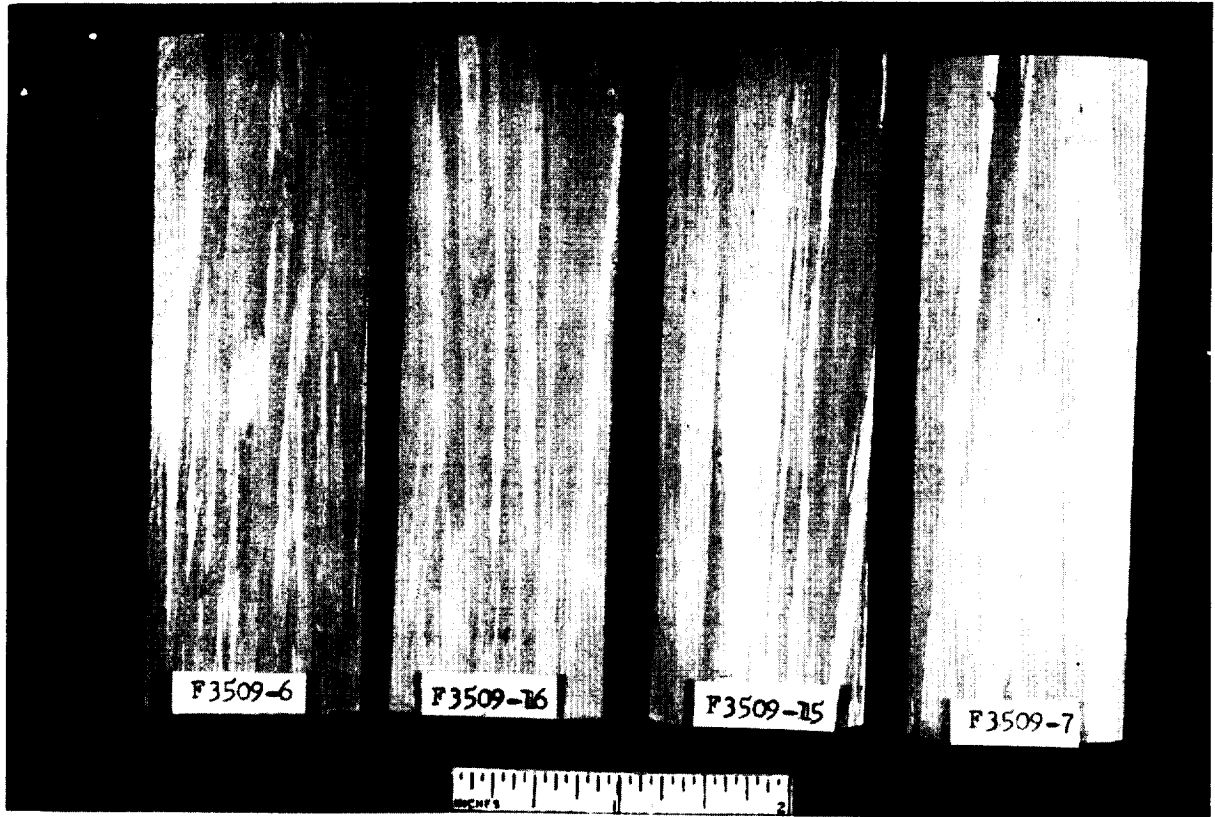
(a)

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



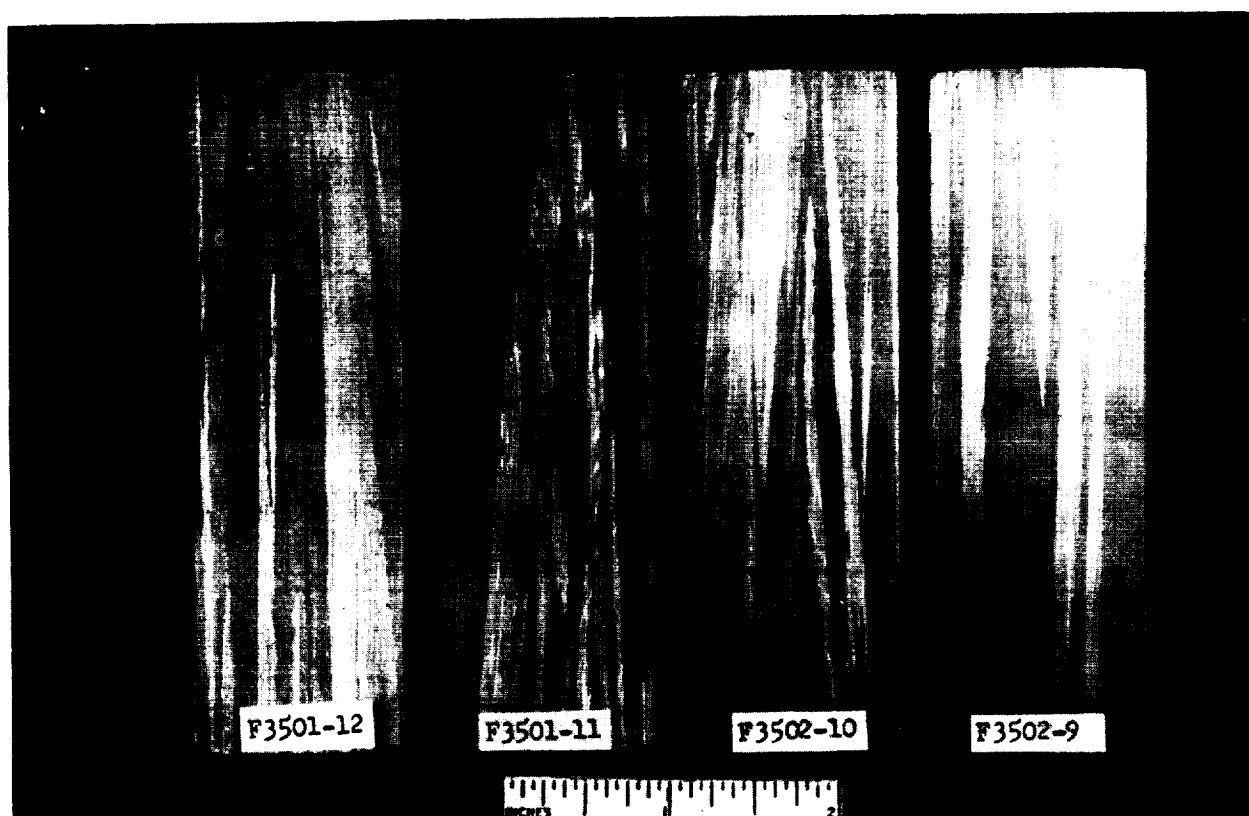
(b)

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

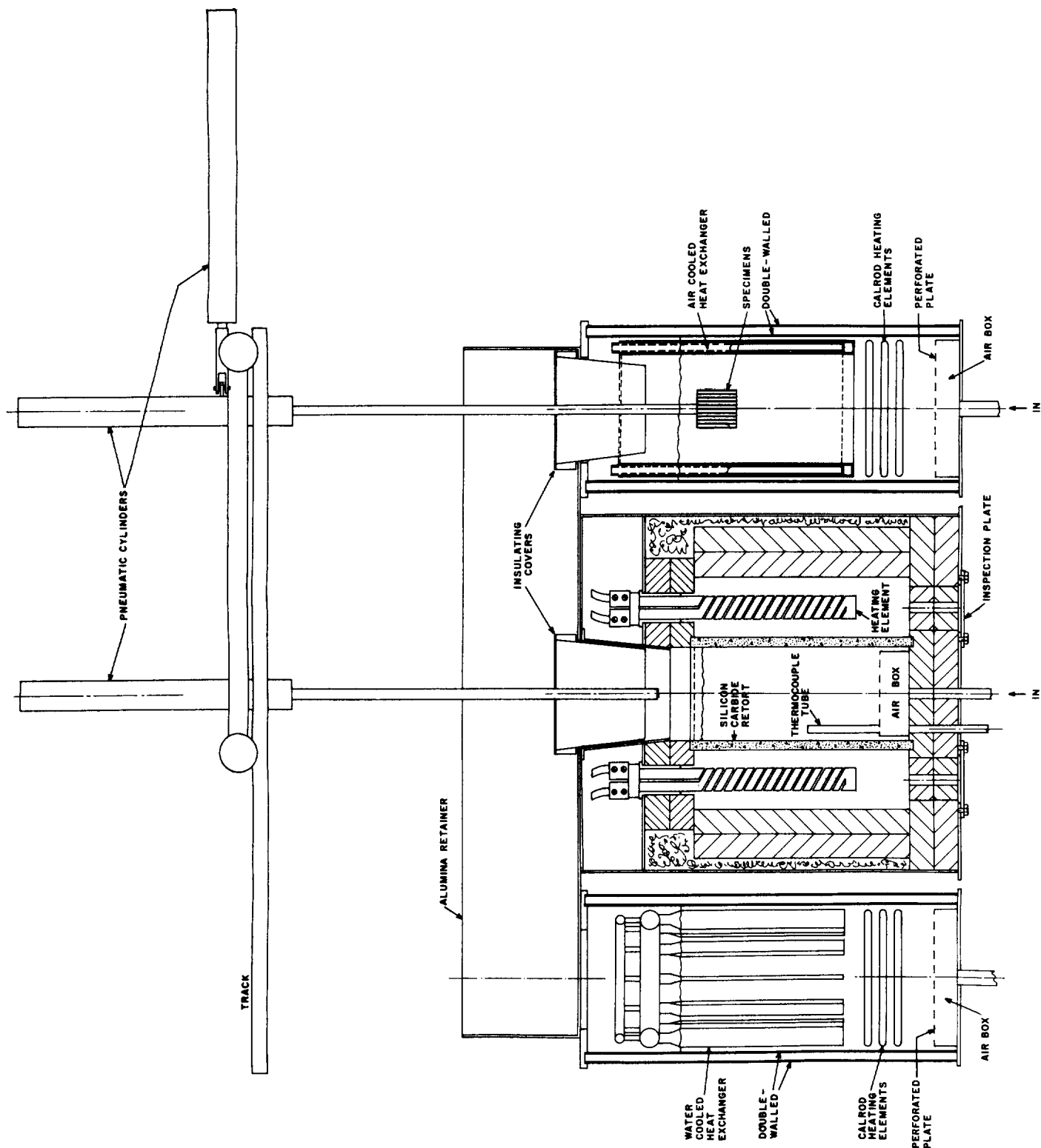


Fig. 4 - Schematic View of Thermal Fatigue Facility.

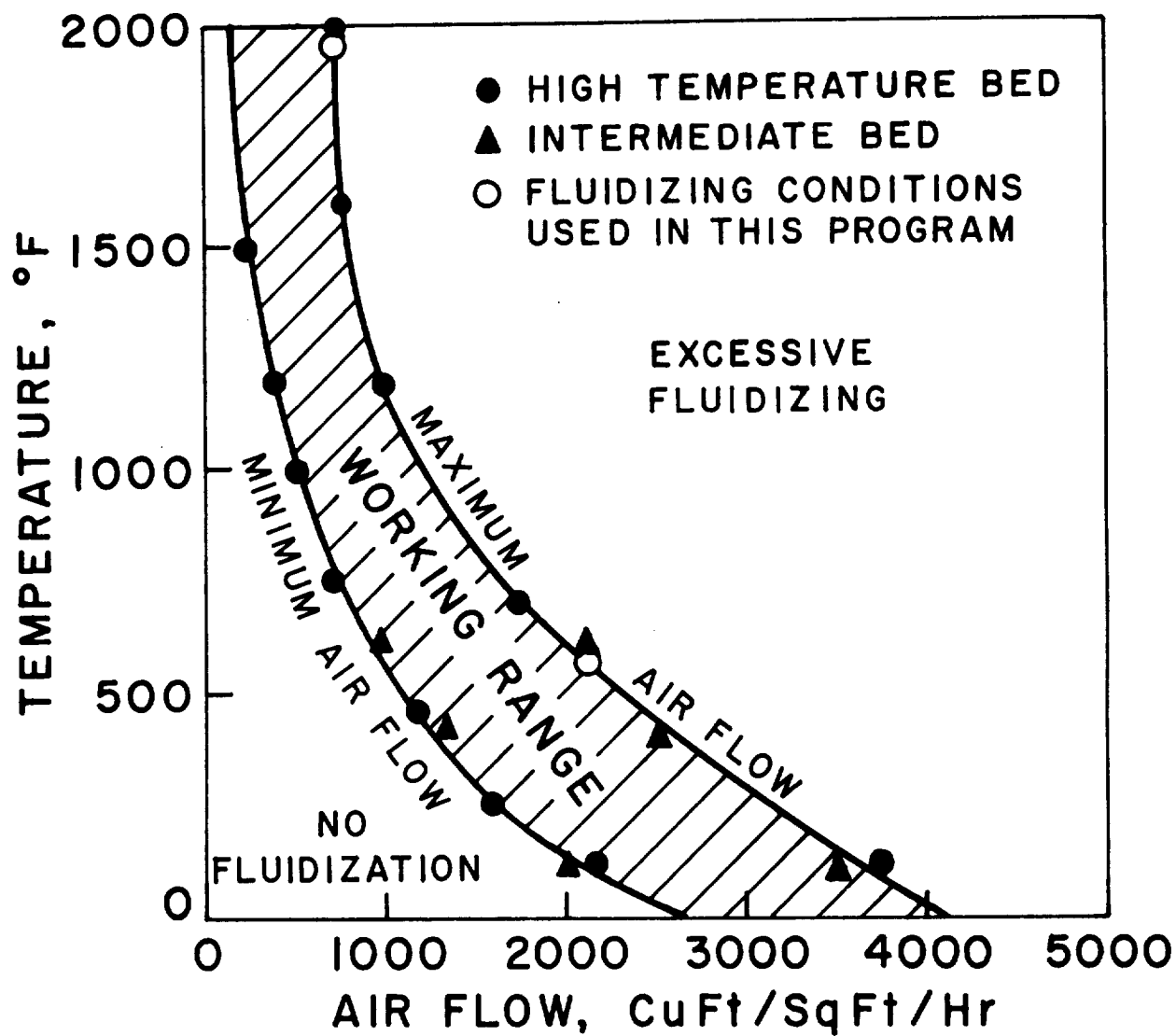


Fig. 5 - Fluidized Bed Air Requirements (28-48 mesh tabular alumina particles).

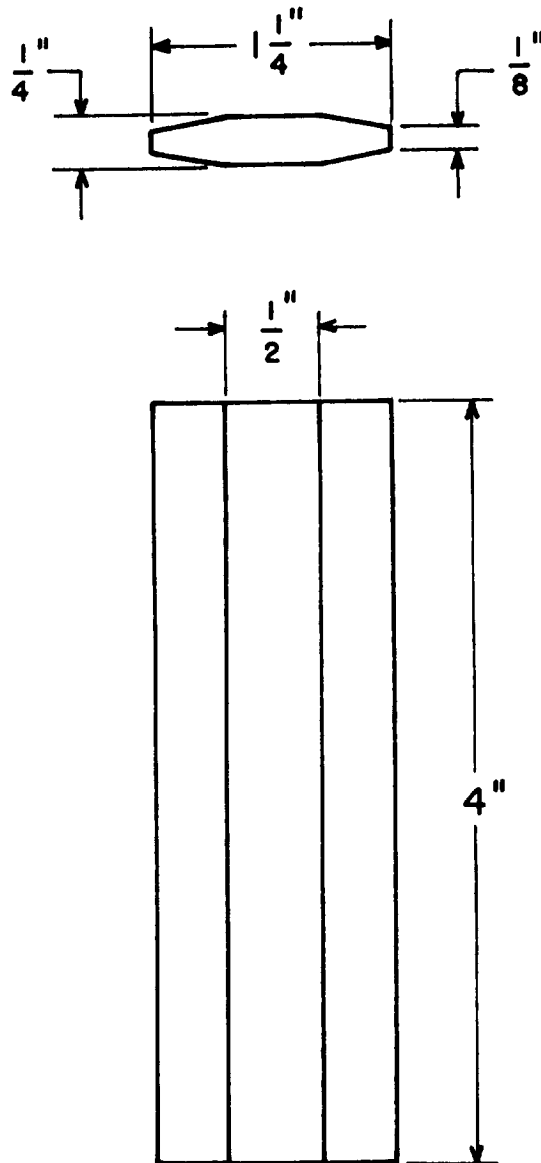
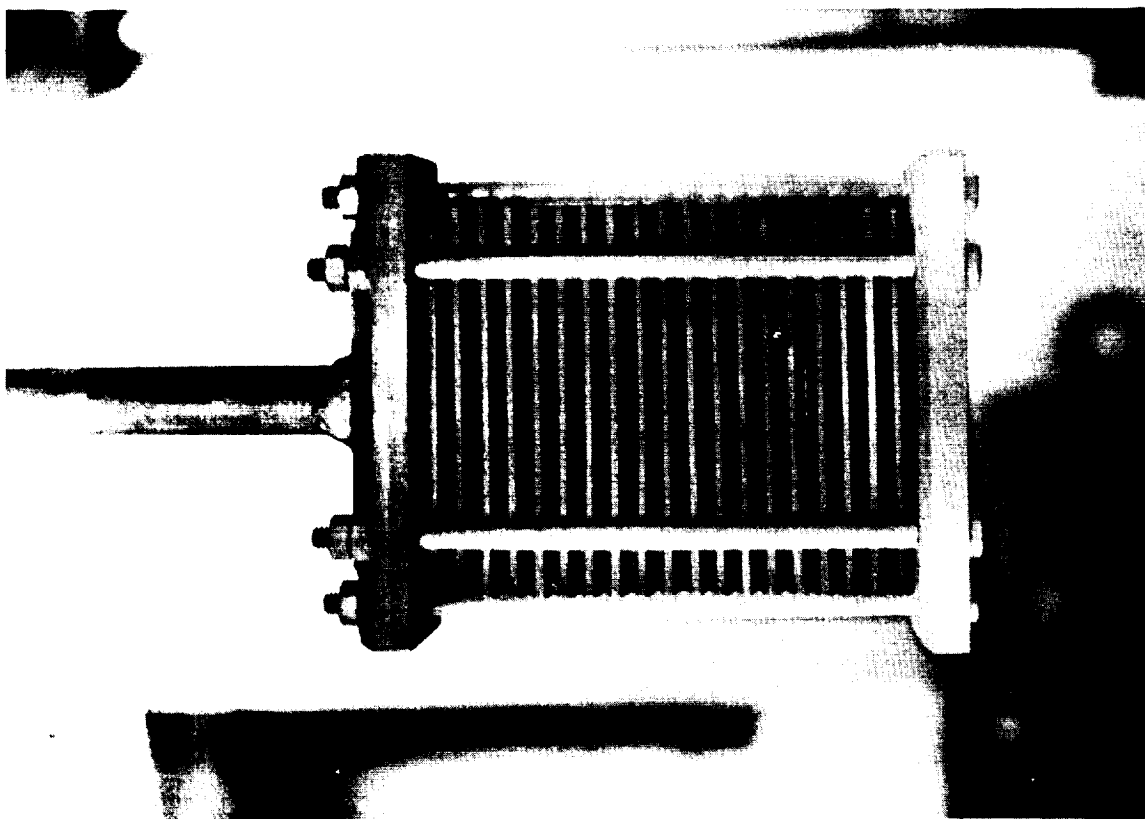
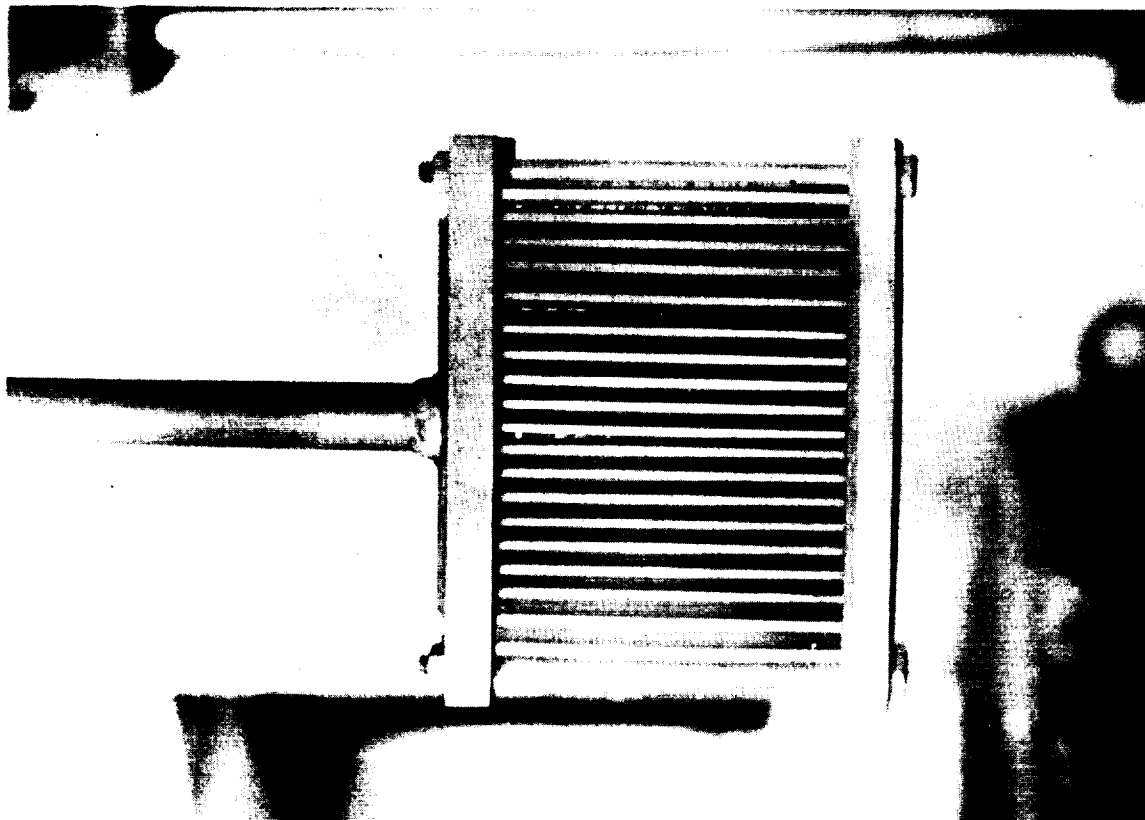


Fig. 6 - Simulated Thermal Fatigue Specimen
Utilized During Fixture Development.



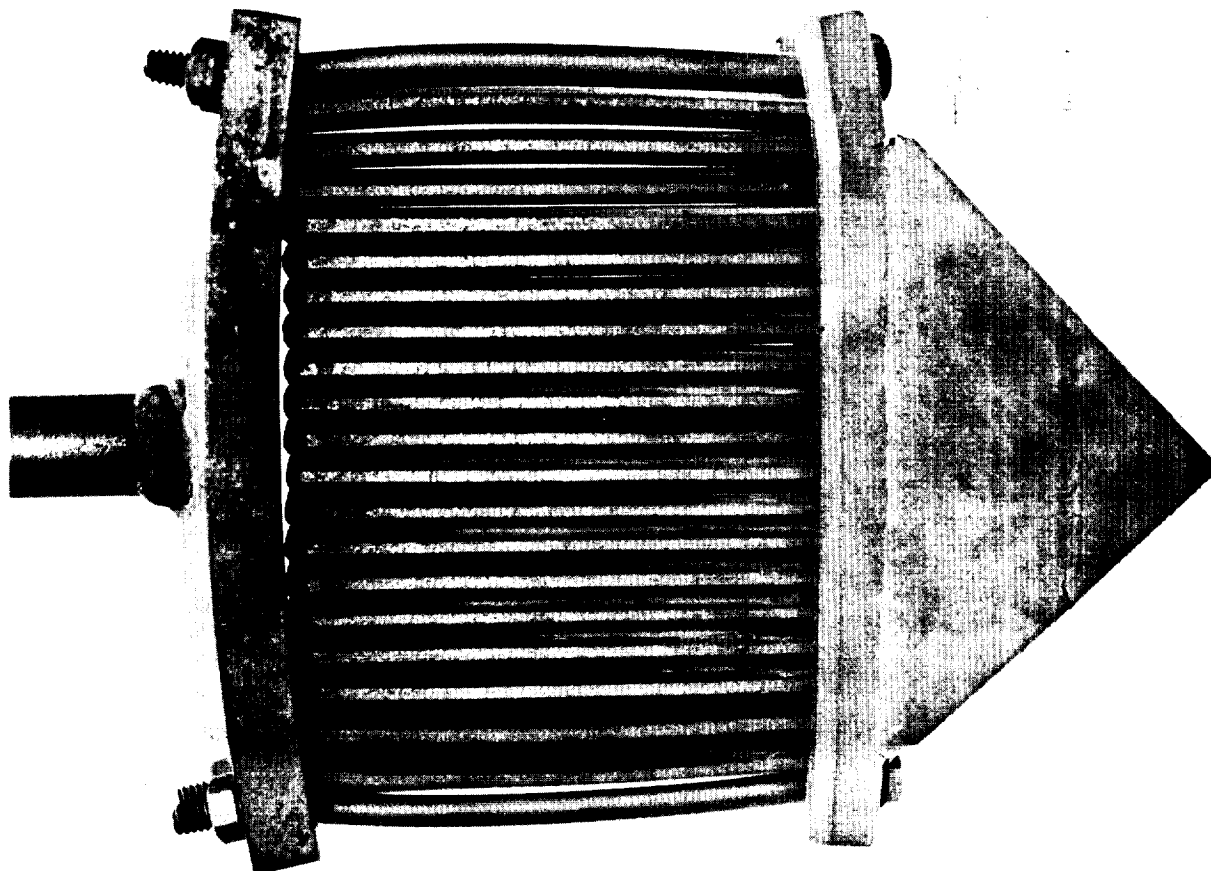
Neg. No. 37854

Fig. 7 - Temperature Gradient in Horizontally Held Specimens.



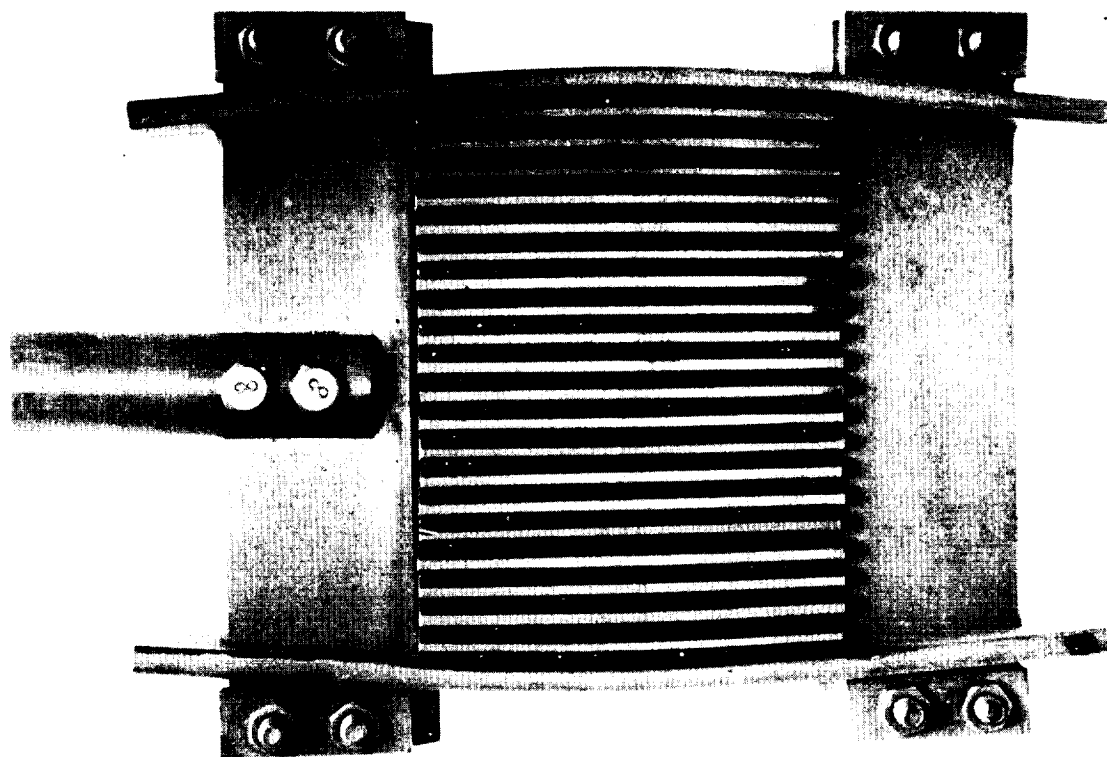
Neg. No. 37853

Fig. 8 - Temperature Gradient in Vertically Held Specimens.



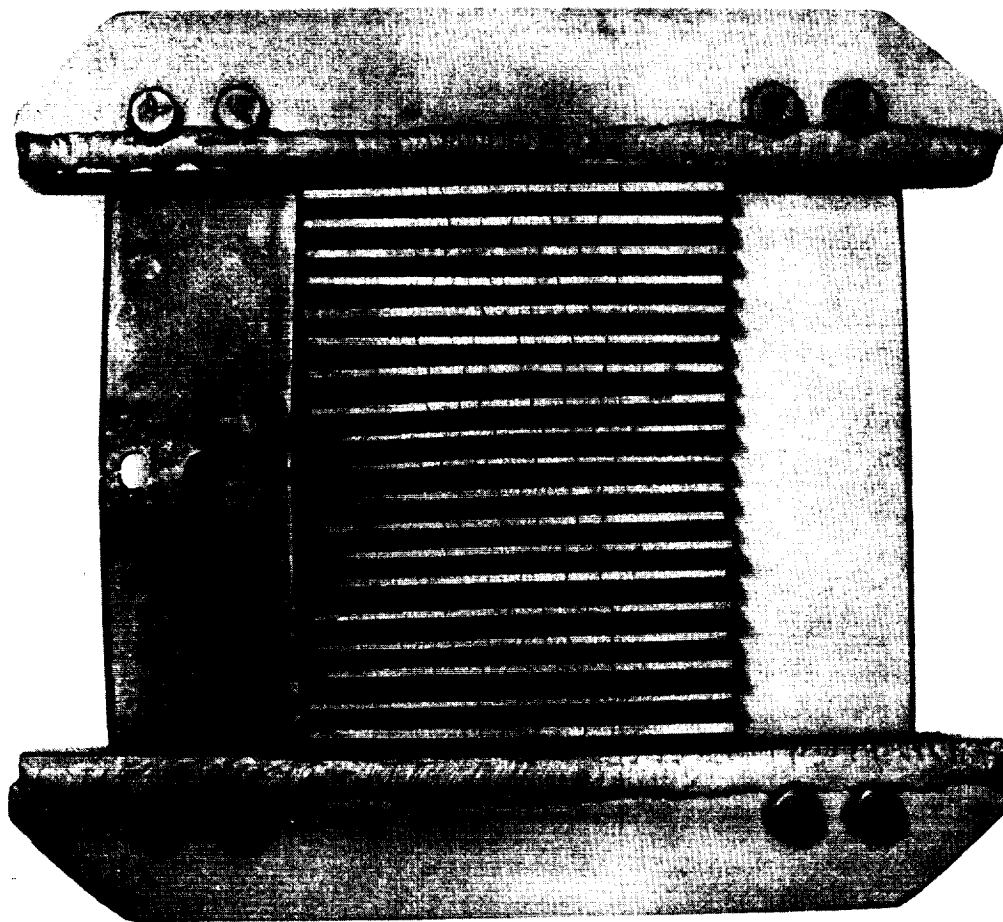
Neg. No. 33484

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.



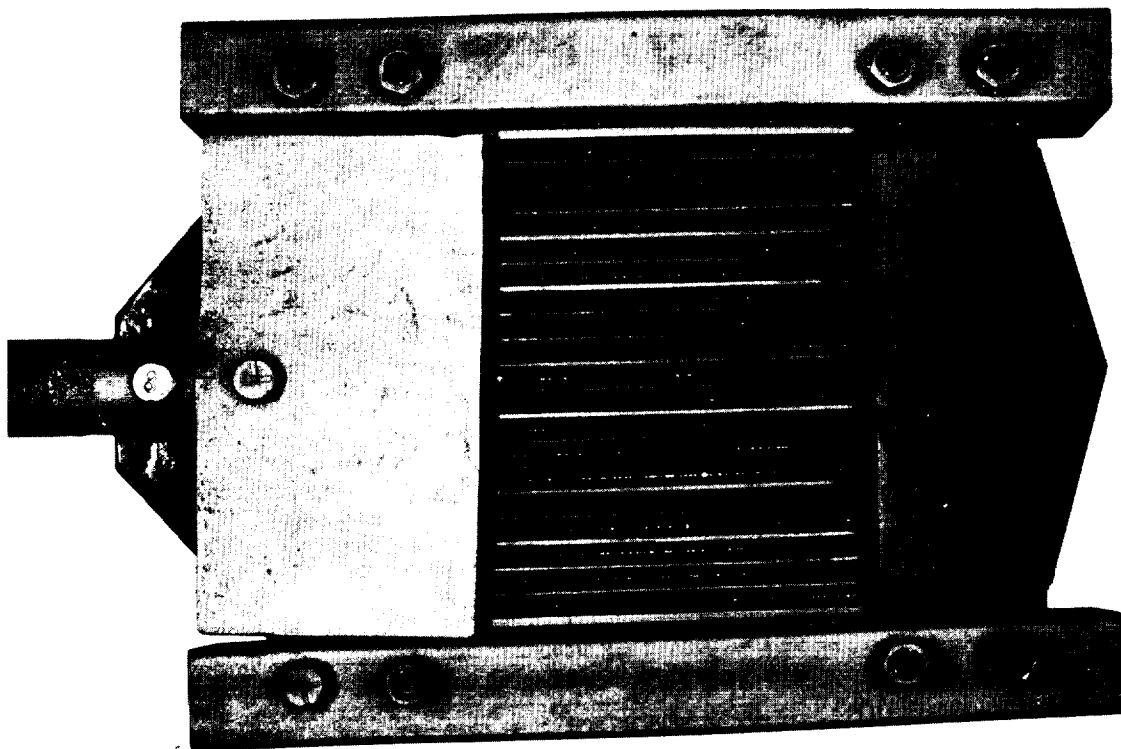
Neg. No. 33949

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



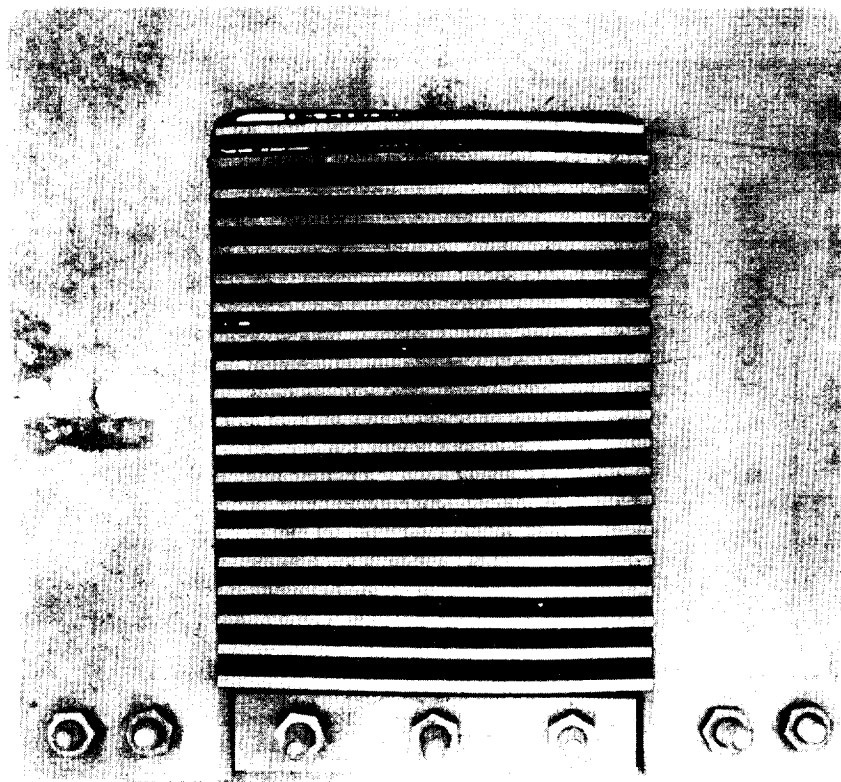
Neg. No. 34825

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.

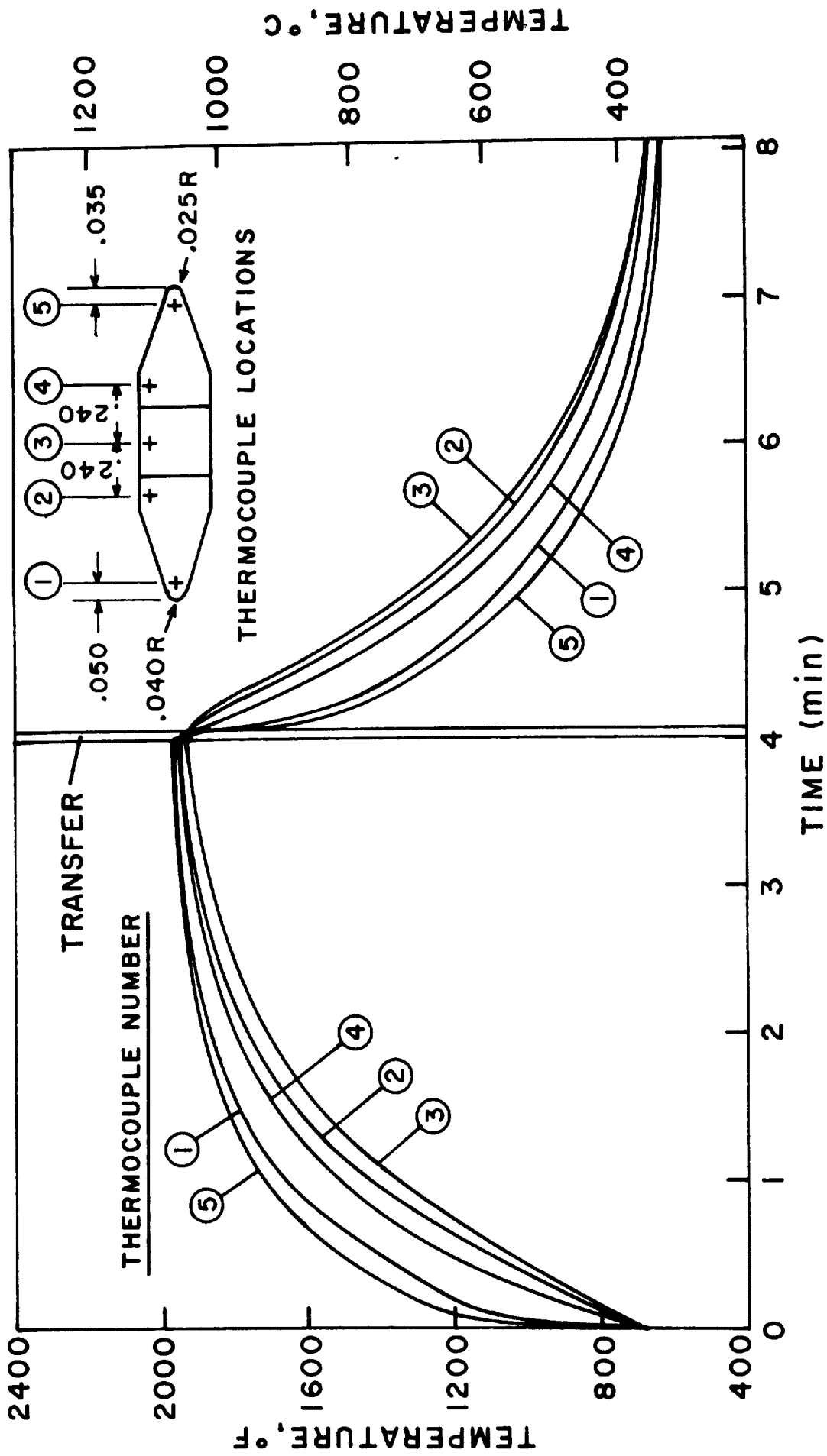
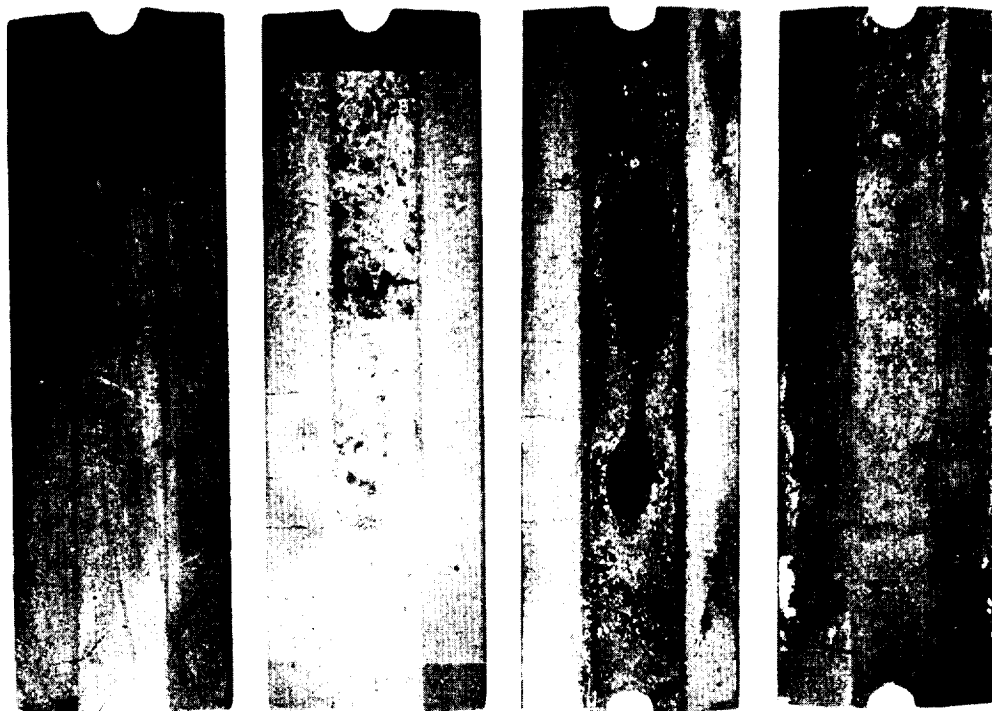


Fig. 15 - Temperature Calibration Curves for IN-100 Cycled under Set F Conditions



Neg. No. 37994

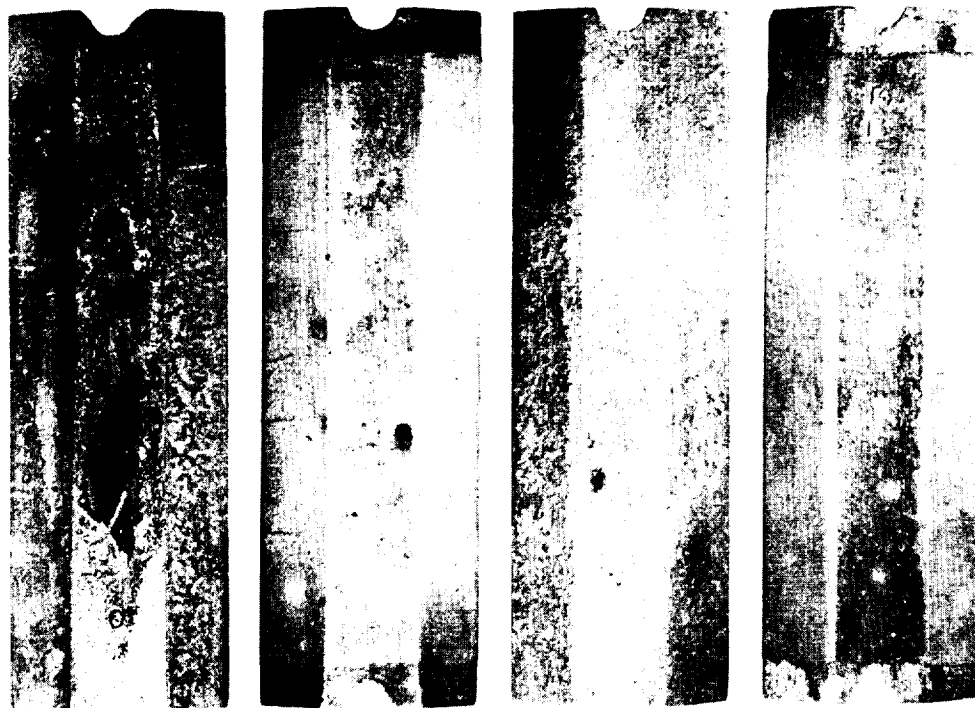
B1900
(5000 Cycles)

B1900 Coated
(5000 Cycles)
(a) Set A Specimens

MAR-M 200
(1000 Cycles)

PWA 664
(5000 Cycles)

(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)



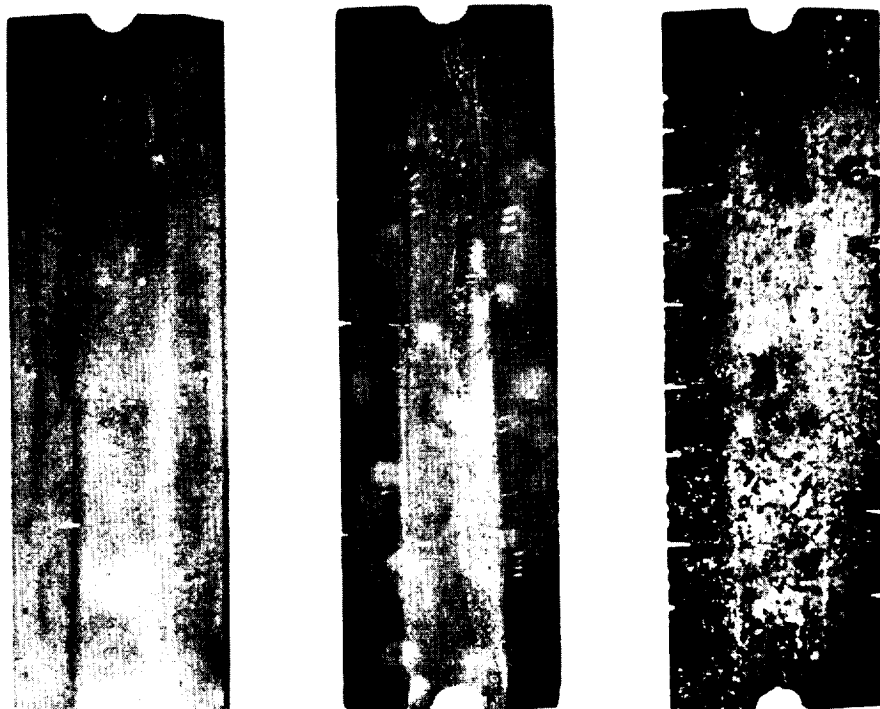
Neg. No. 37993

IN-162
(5000 Cycles)

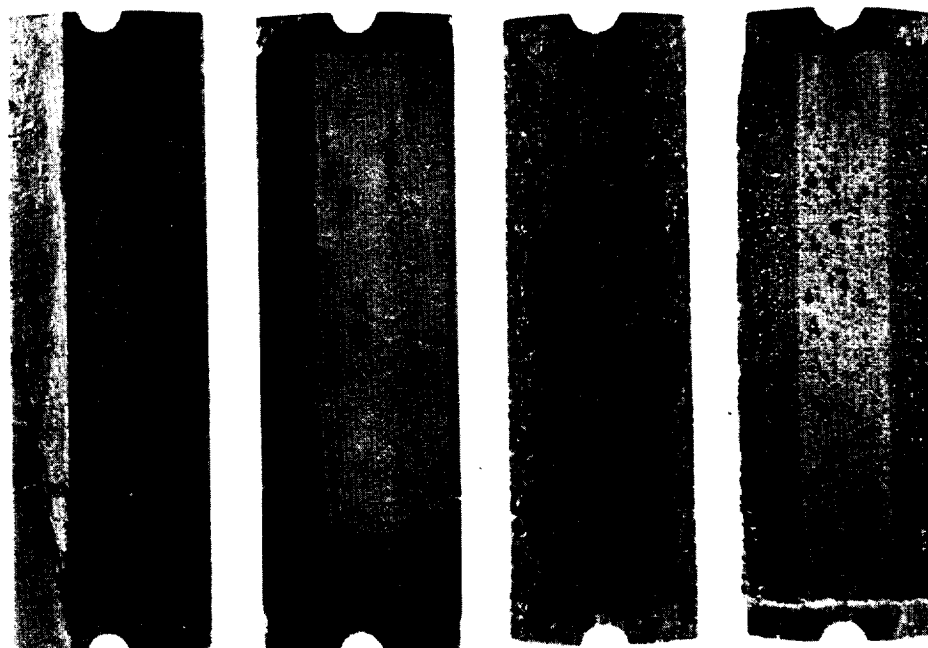
TAZ-8A
(5000 Cycles)
(d) Set A Specimens

M22
(1000 Cycles)
(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)



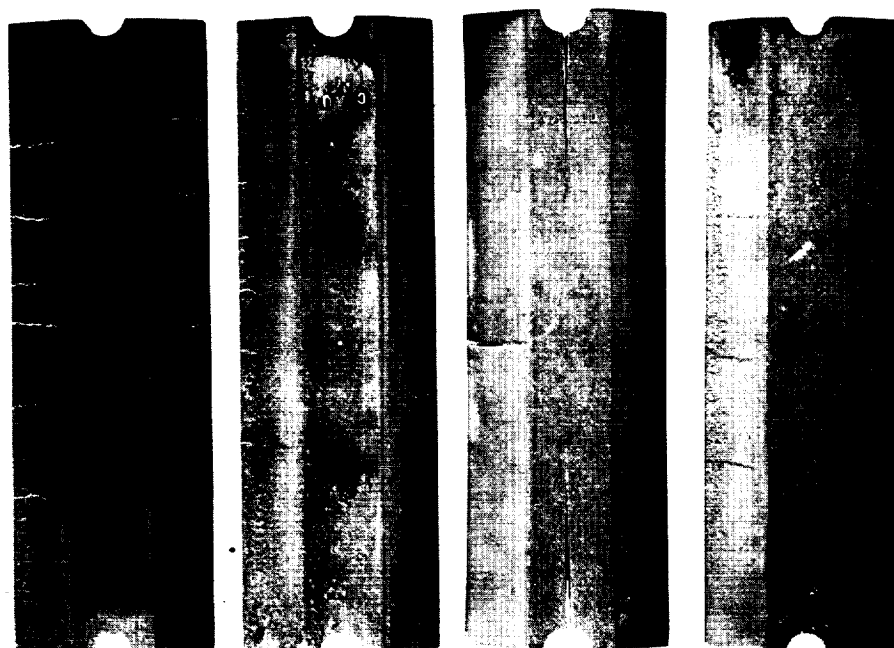
Neg. No. 37776
 B1900 B1900 Coated MAR-M 200 PWA 664
 (2000 Cycles) (4400 Cycles) (700 Cycles) (5000 Cycles)
 (f) Set D Specimens (3 min exposure)

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



Neg. No. 37778

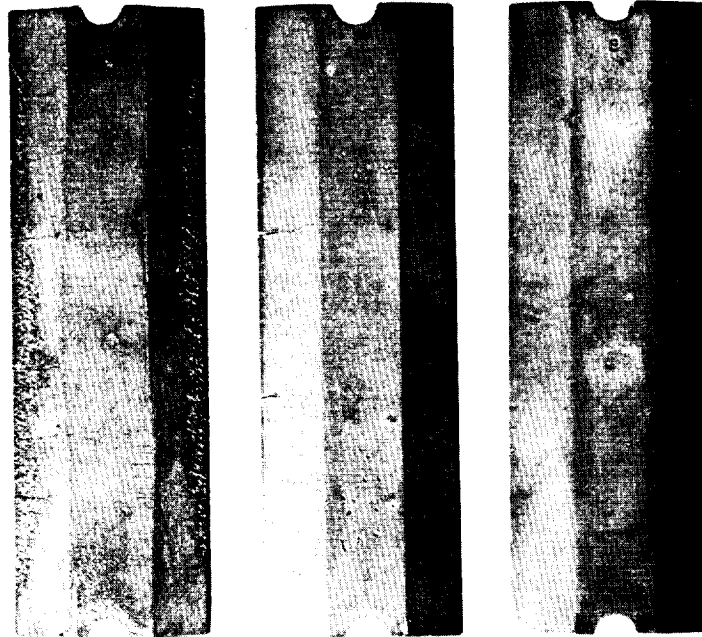
IN-100	IN-100 Coated	PWA 1401	PWA 1401 Coated
(700 Cycles)	(2000 Cycles)	(5000 Cycles)	(5000 Cycles)
(g) Set D Specimens		(3 min exposure)	



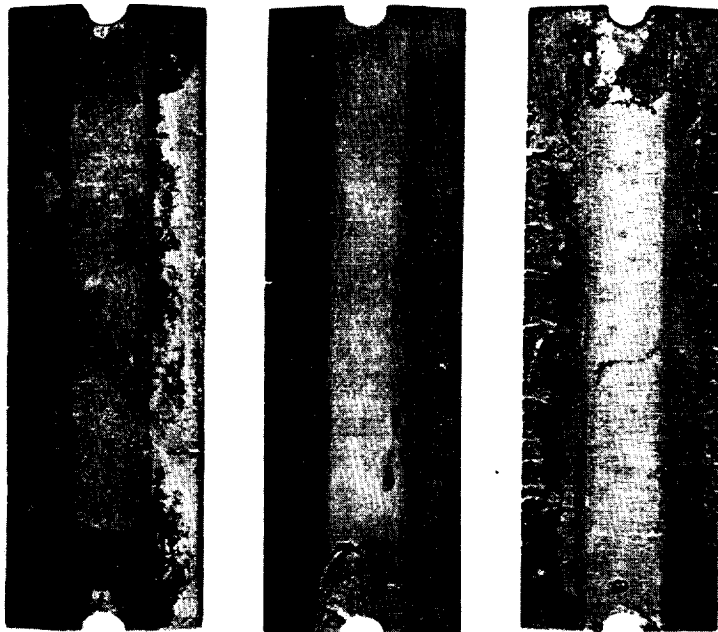
Neg. No. 37775

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 TAZ-8A M22
 (3100 Cycles) (5000 Cycles) (700 Cycles)
 (i) Set D Specimens (3 min exposure)



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

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

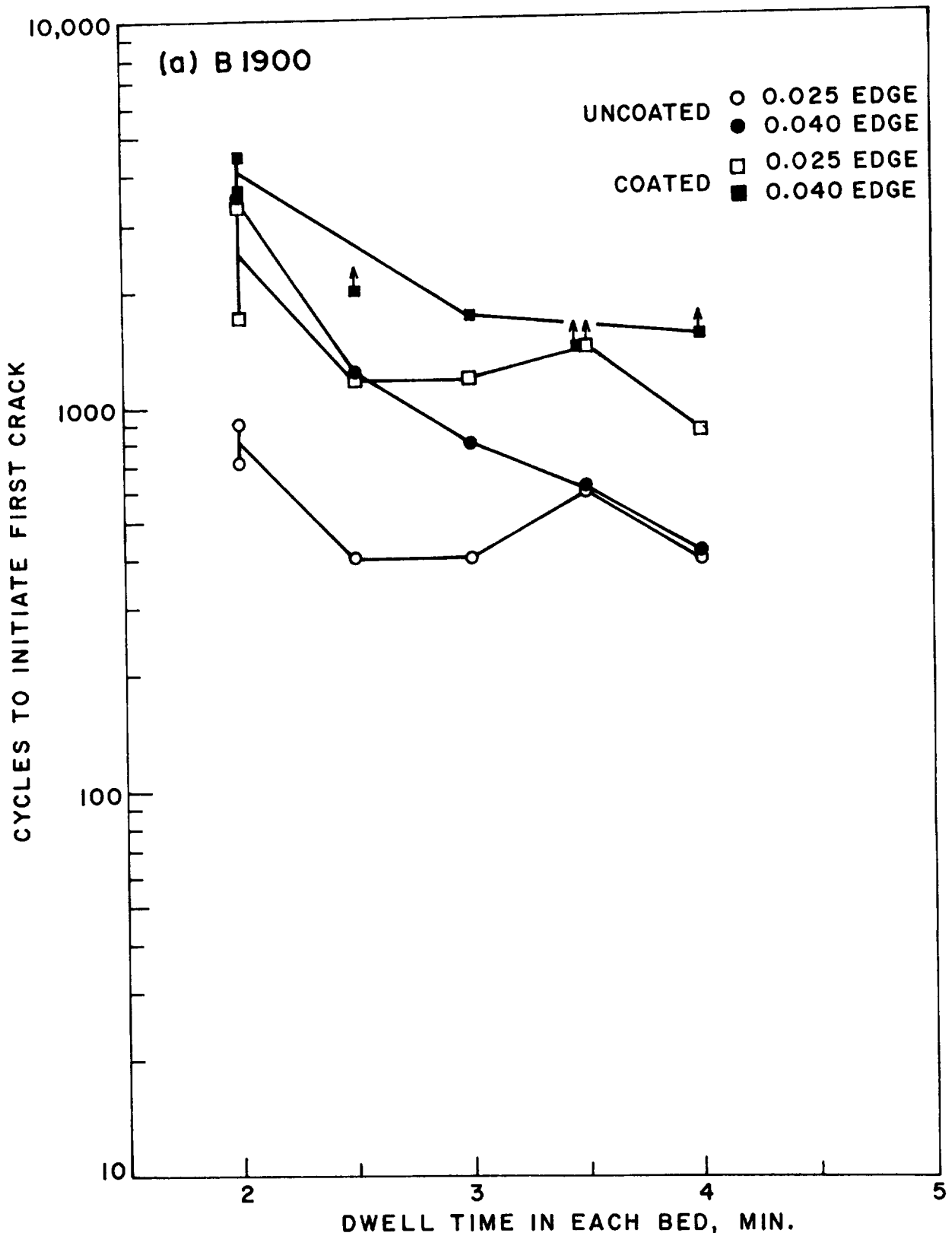


Fig. 17(a) - Thermal Cycles to Initiate the First Crack in B1900 Test Specimens in Either Test Edge under Test Conditions A to F.

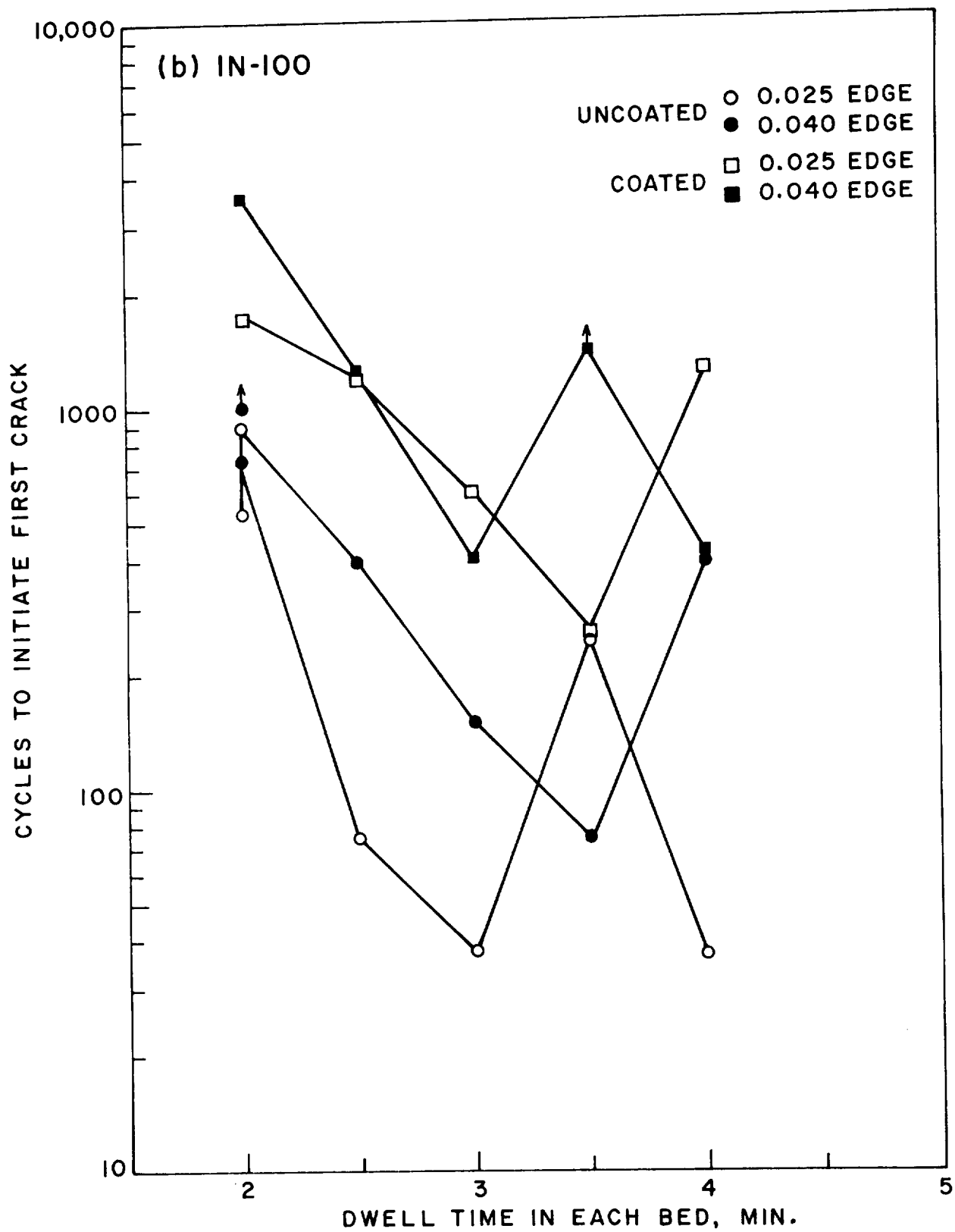


Fig. 17(b) - Thermal Cycles to Initiate the First Crack in IN-100 Test Specimens in Either Test Edge under Test Conditions A to F.

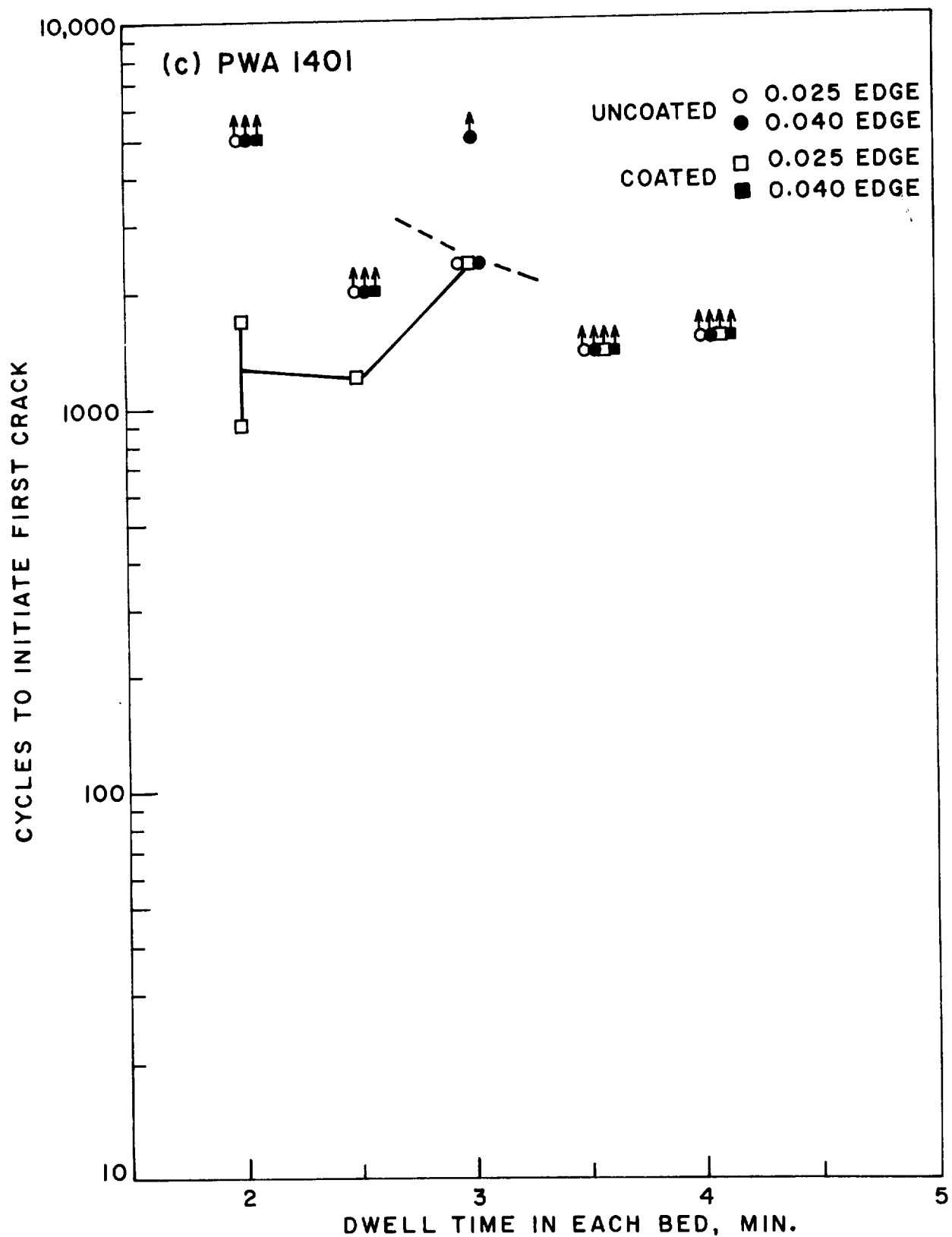


Fig. 17(c) - Thermal Cycles to Initiate the First Crack in PWA 1401 Test Specimens in Either Test Edge under Test Conditions A to F.

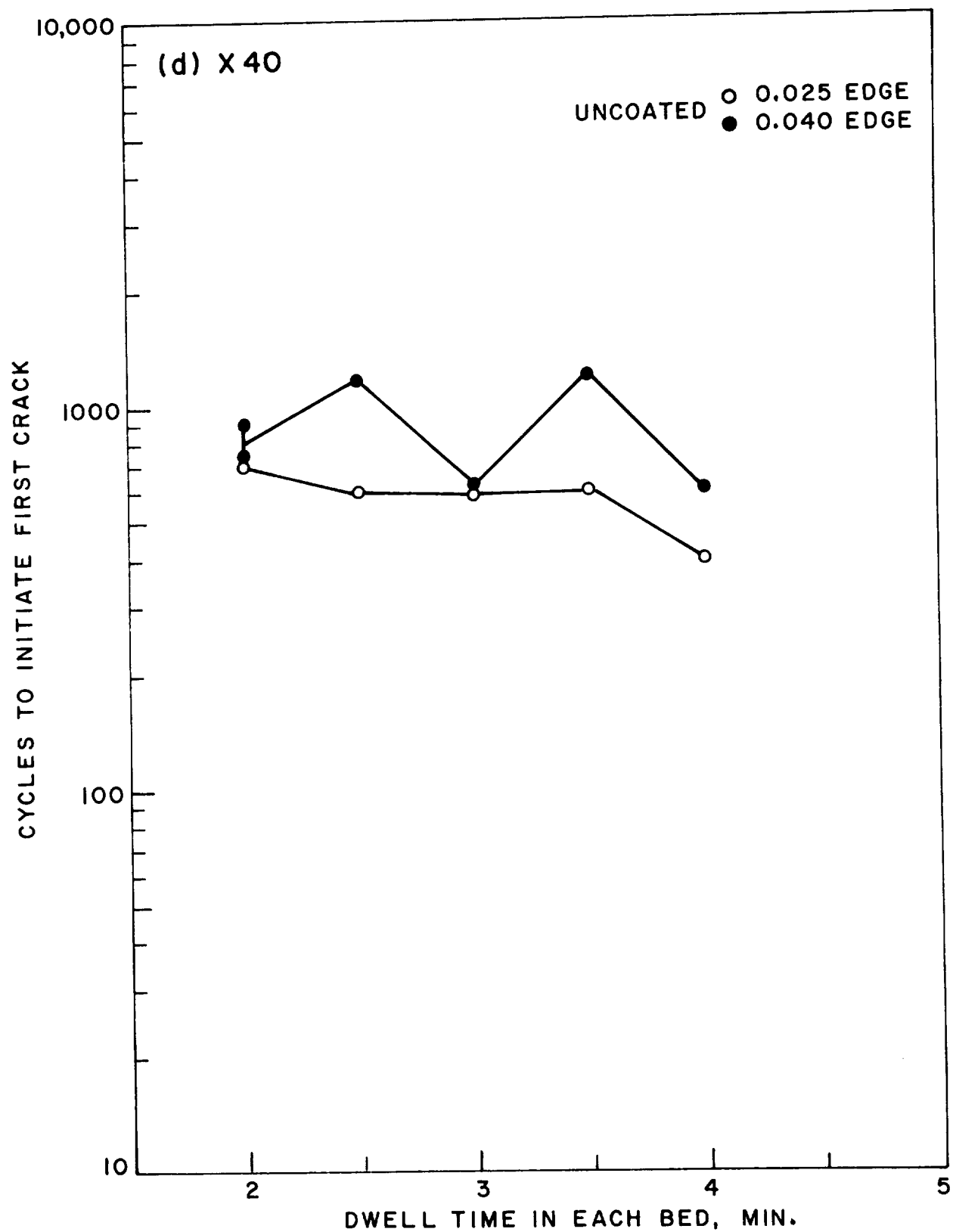


Fig. 17(d) - Thermal Cycles to Initiate the First Crack in X-40 Test Specimens in Either Test Edge under Test Conditions A to F.

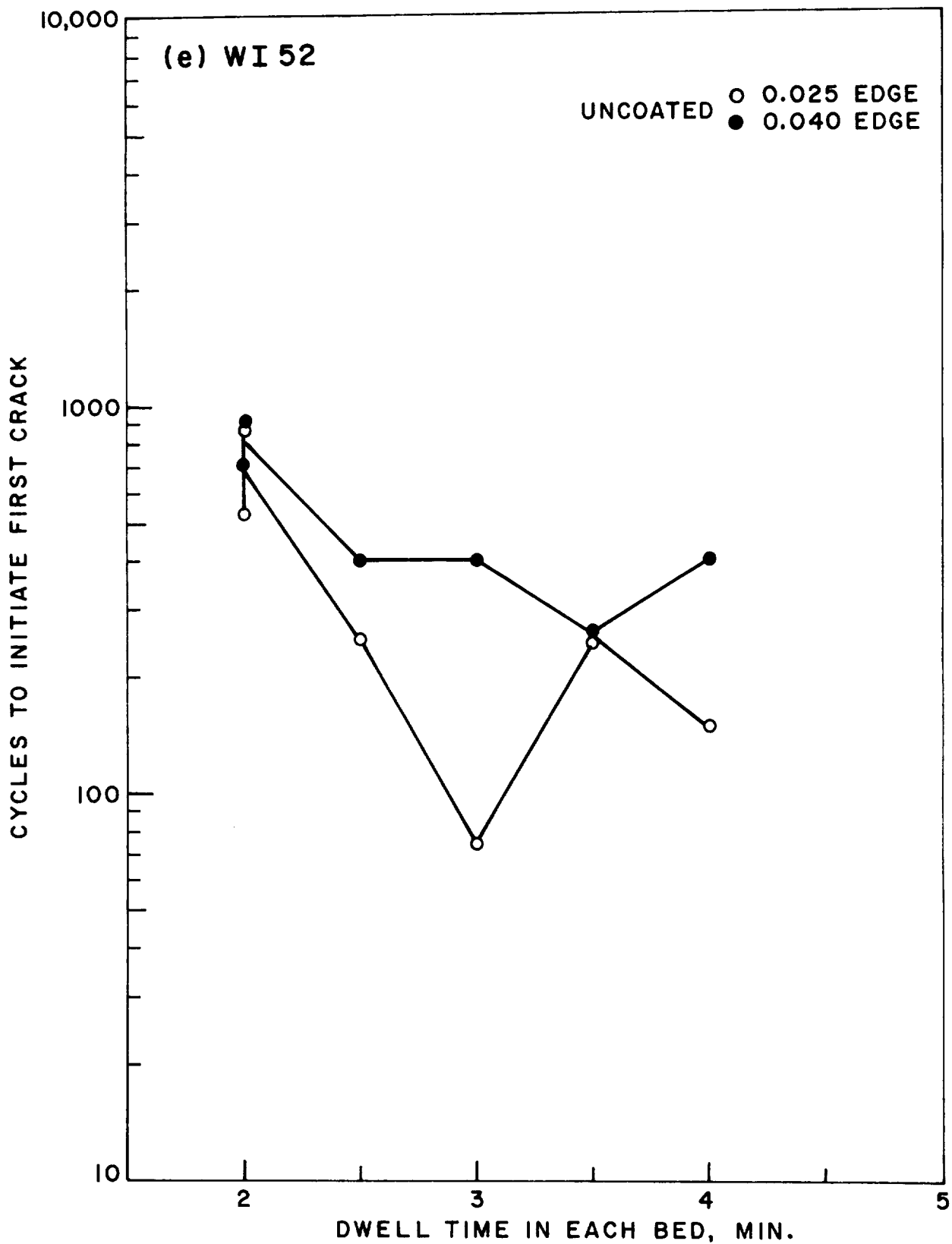


Fig. 17(e) - Thermal Cycles to Initiate the First Crack in WI-52 Test Specimens in Either Test Edge under Test Conditions A to F.

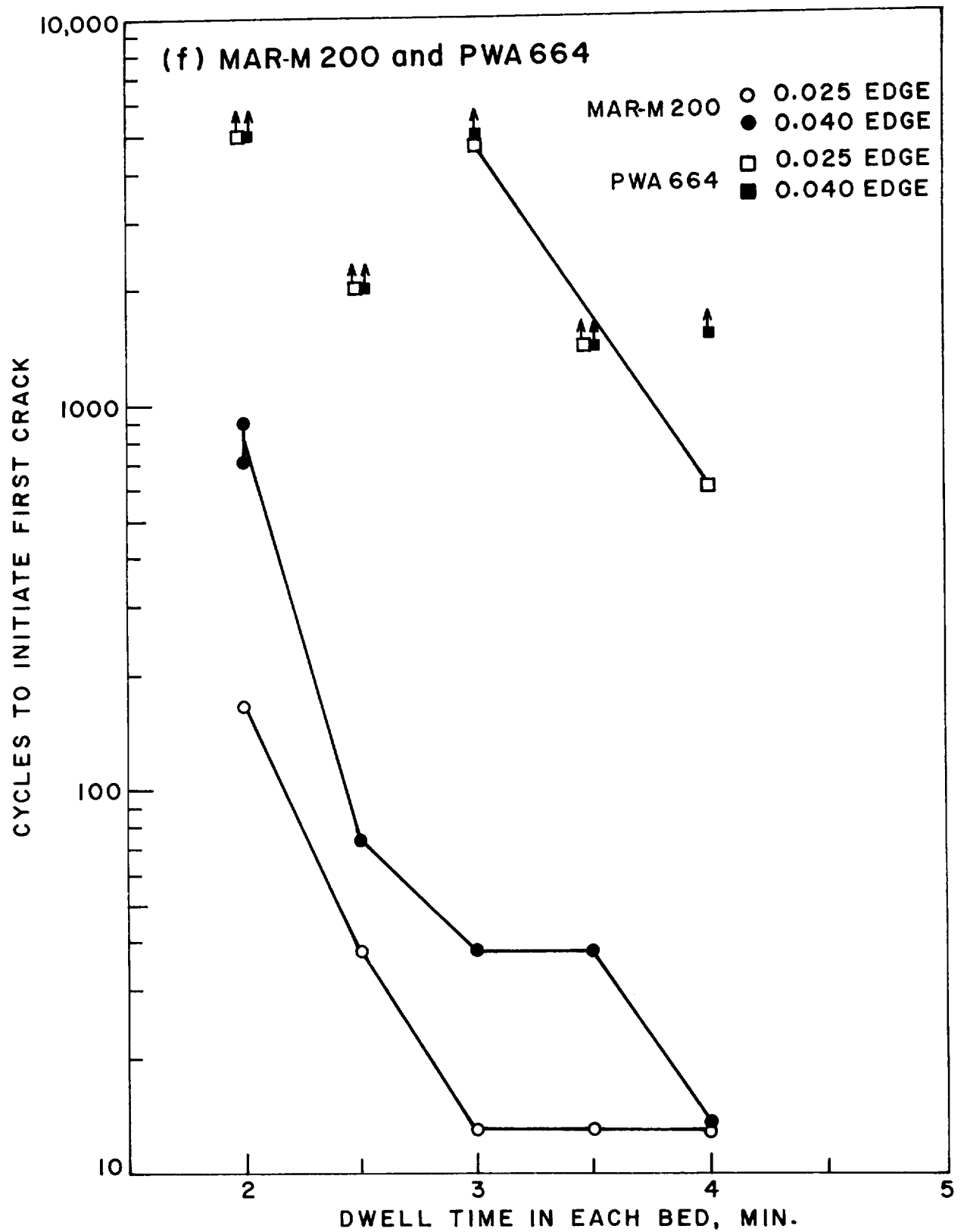


Fig. 17(f) - Thermal Cycles to Initiate the First Crack in MAR-M 200 and PWA 664 Test Specimens in Either Test Edge under Test Conditions A to F.

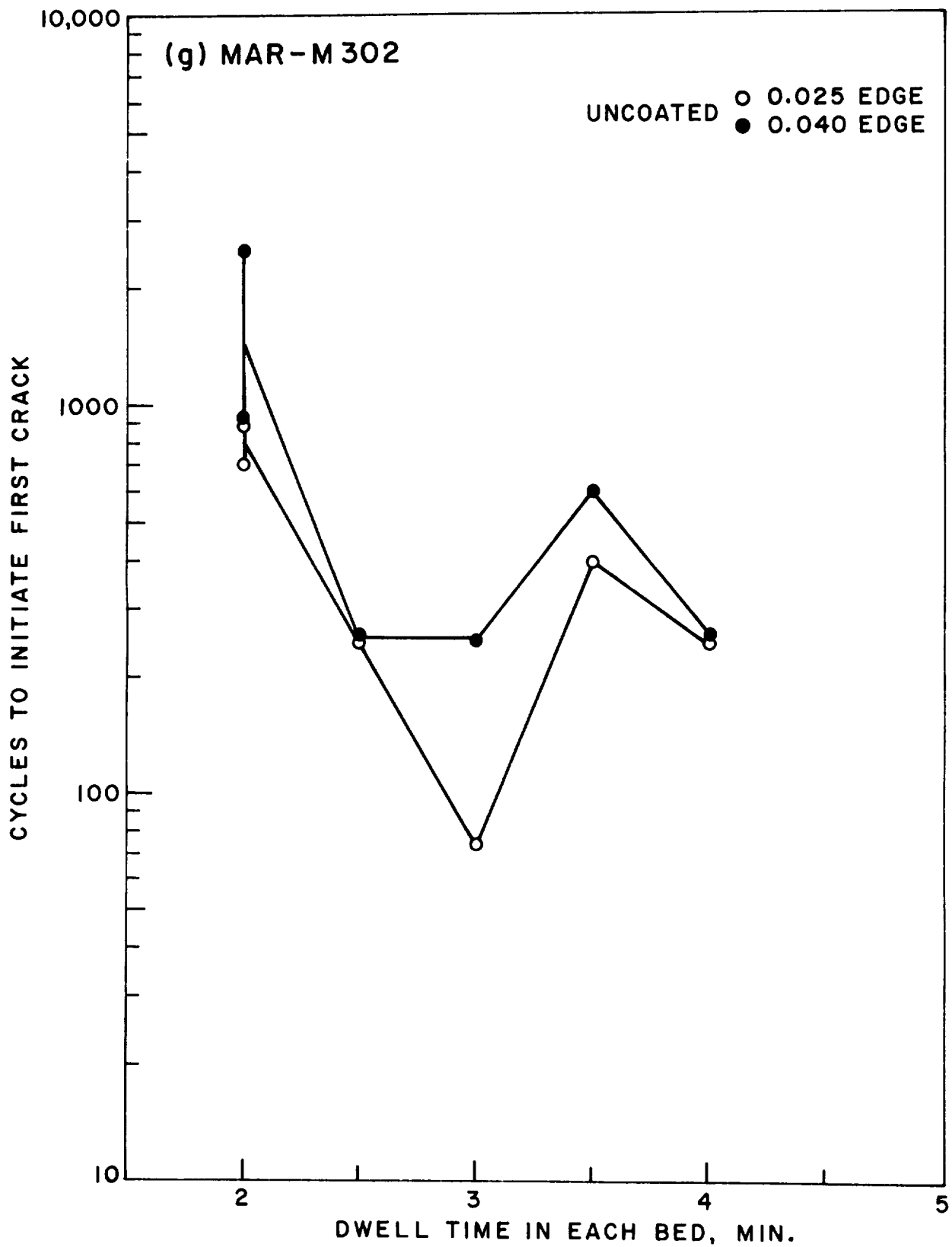


Fig. 17(g) - Thermal Cycles to Initiate the First Crack in MAR-M 302 Test Specimens in Either Test Edge under Test Conditions A to F.

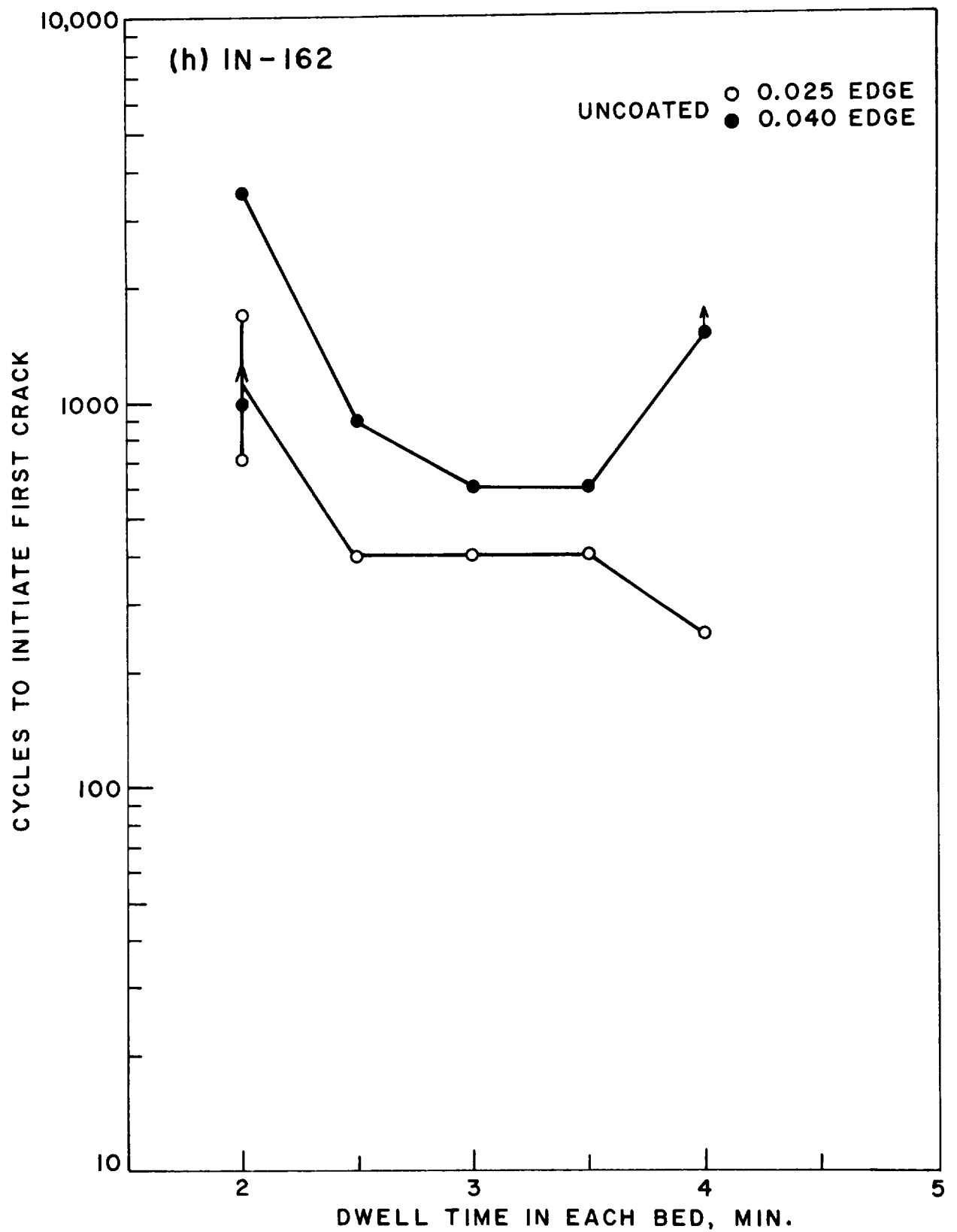


Fig. 17(h) - Thermal Cycles to Initiate the First Crack in IN-162 Test Specimens in Either Test Edge under Test Conditions A to F.

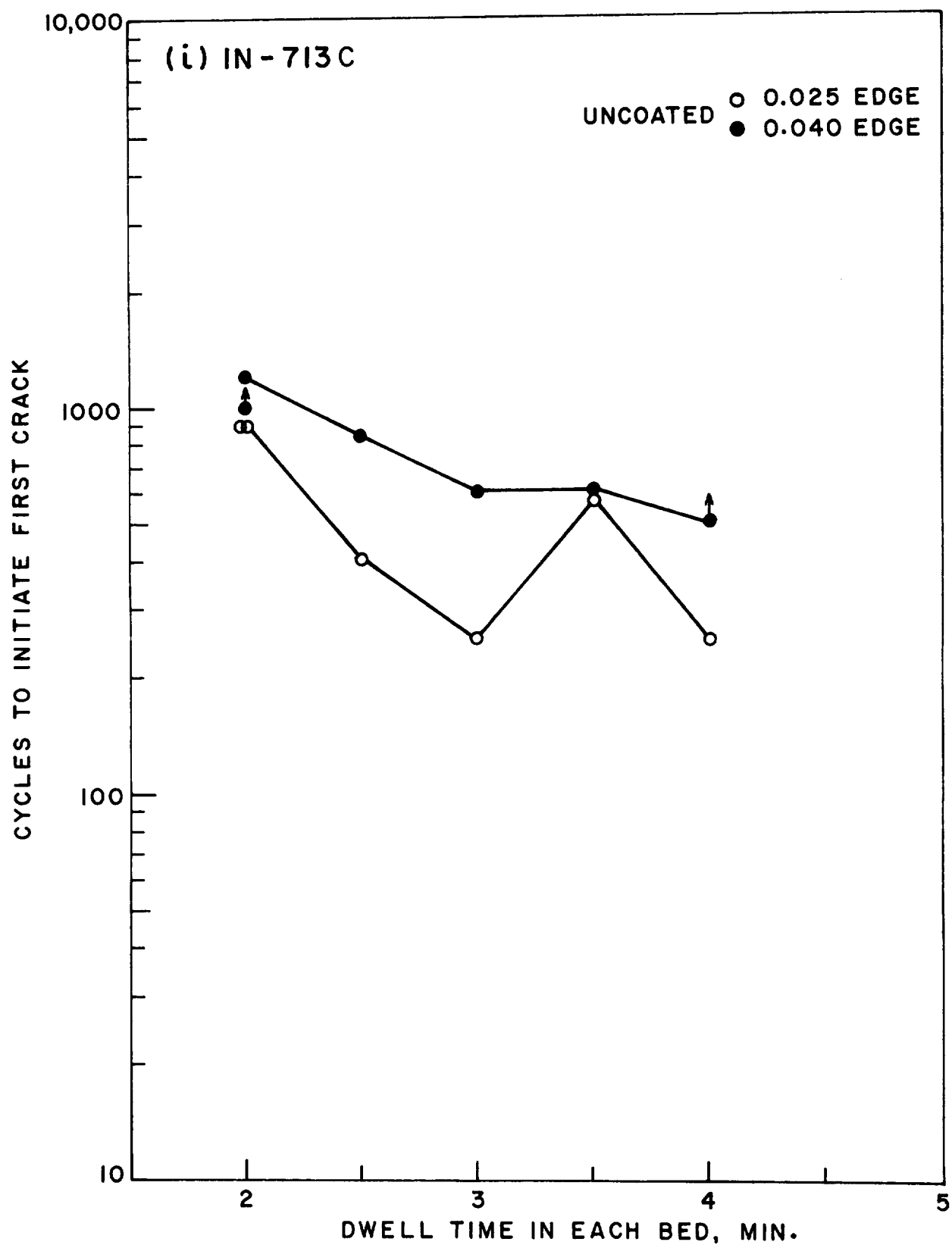


Fig. 17(i) - Thermal Cycles to Initiate the First Crack in IN-713C Test Specimens in Either Test Edge under Test Conditions A to F.

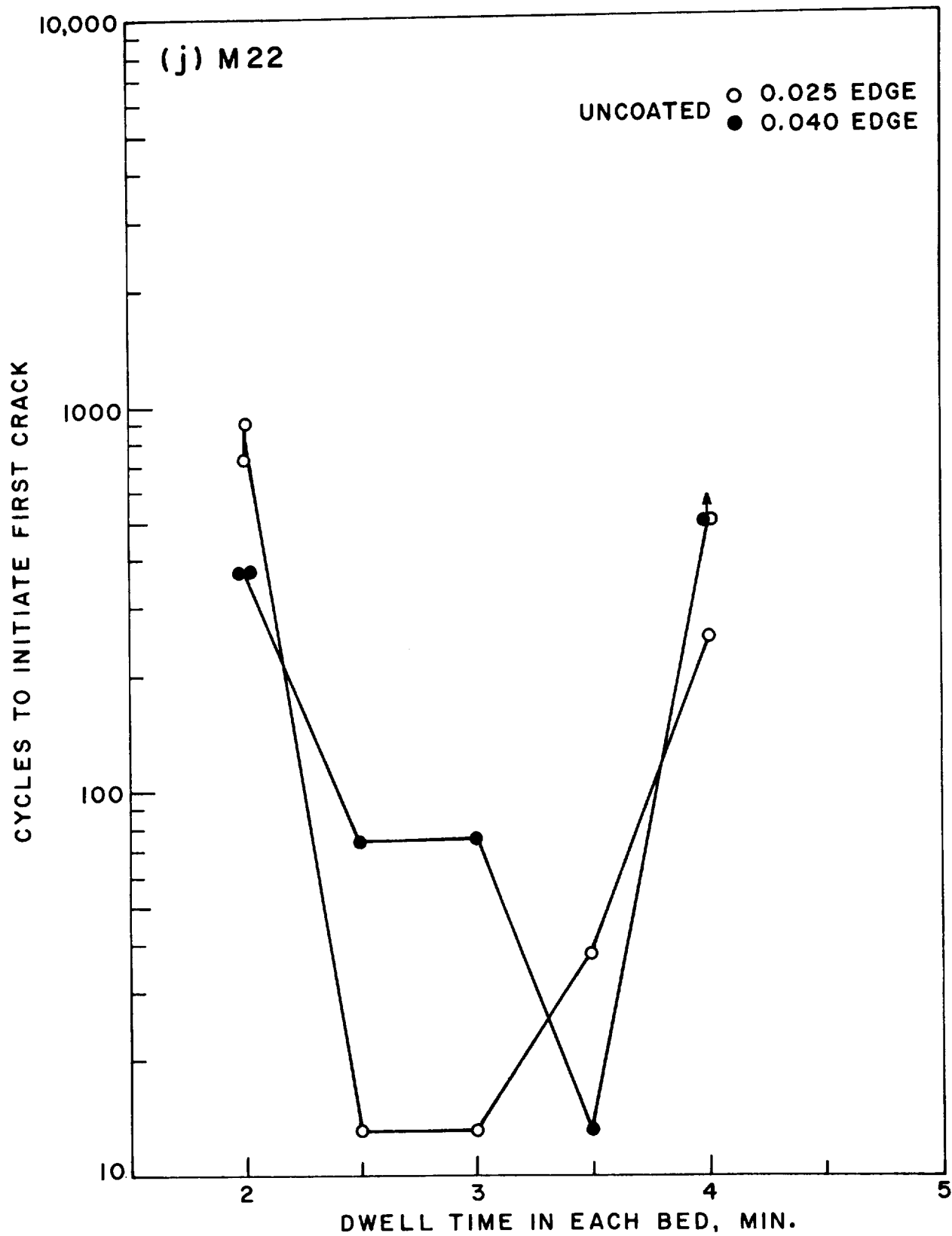


Fig. 17(j) - Thermal Cycles to Initiate the First Crack in M22 Test Specimens in Either Test Edge under Test Conditions A to F.

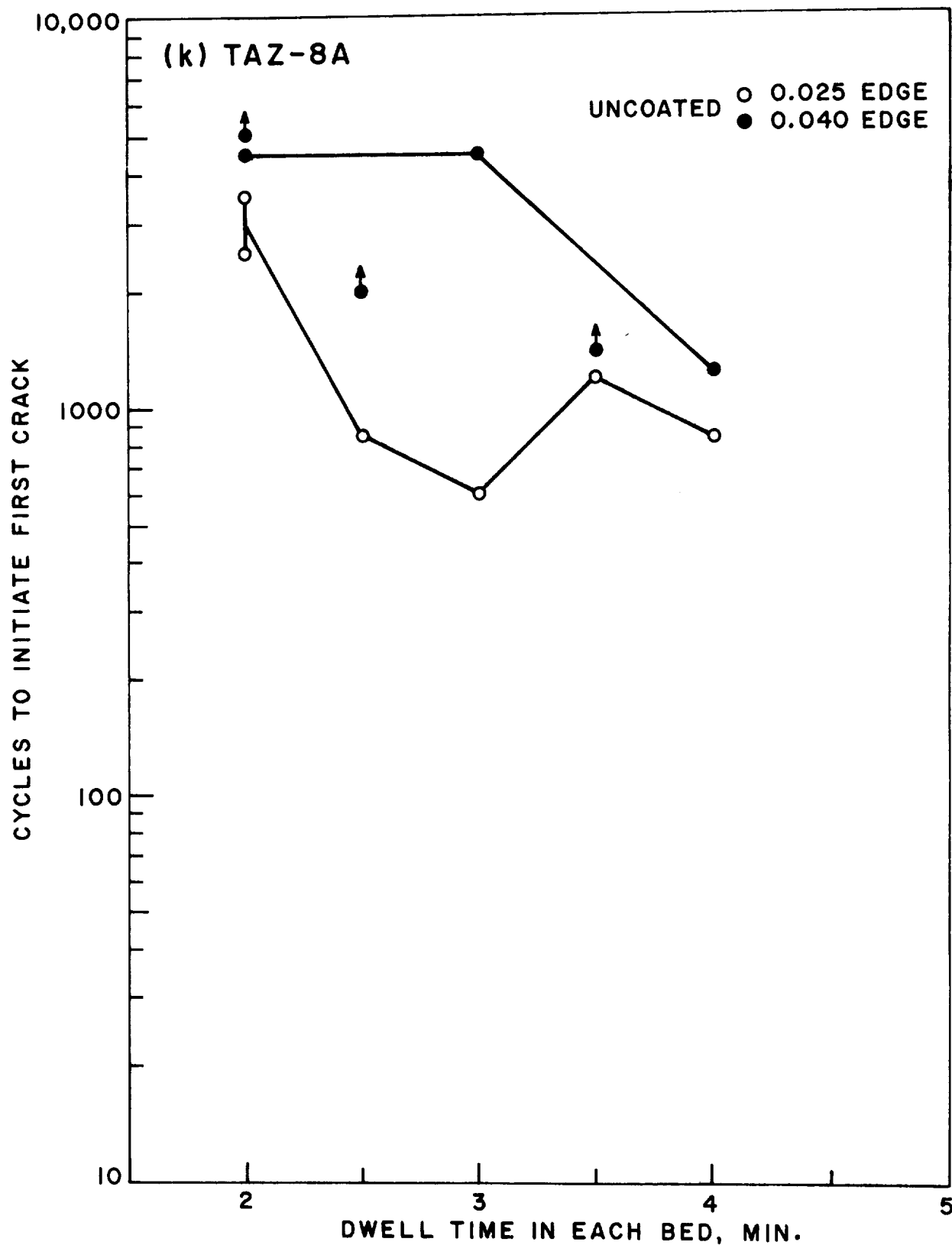


Fig. 17(k) - Thermal Cycles to Initiate the First Crack in TAZ-8A Test Specimens in Either Test Edge under Test Conditions A to F.

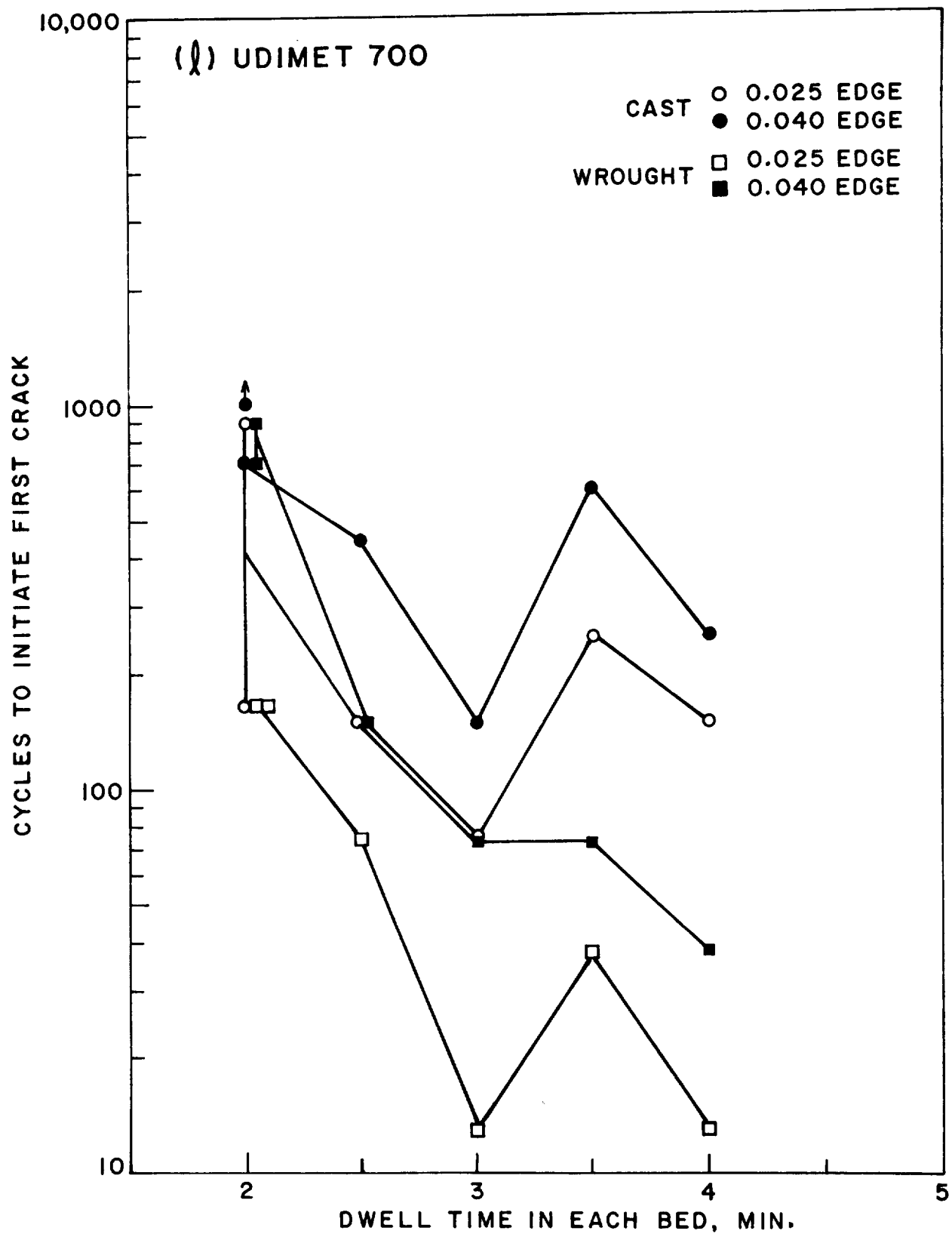


Fig. 17(1) - Thermal Cycles to Initiate the First Crack in Udimet 700 Test Specimens in Either Test Edge under Test Conditions A to F.

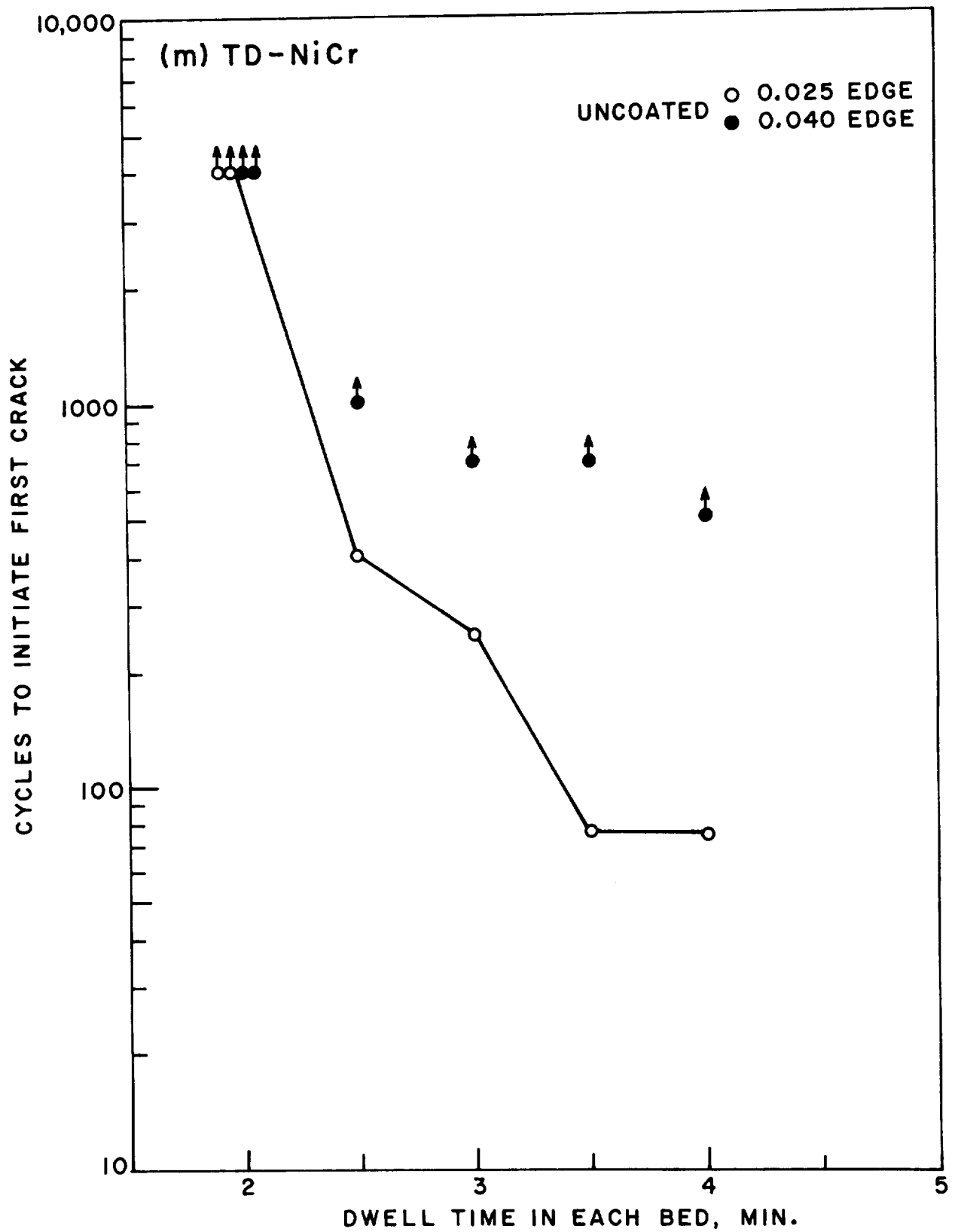


Fig. 17(m) - Thermal Cycles to Initiate the First Crack in TD-NiCr Test Specimens in Either Test Edge under Test Conditions A to F.

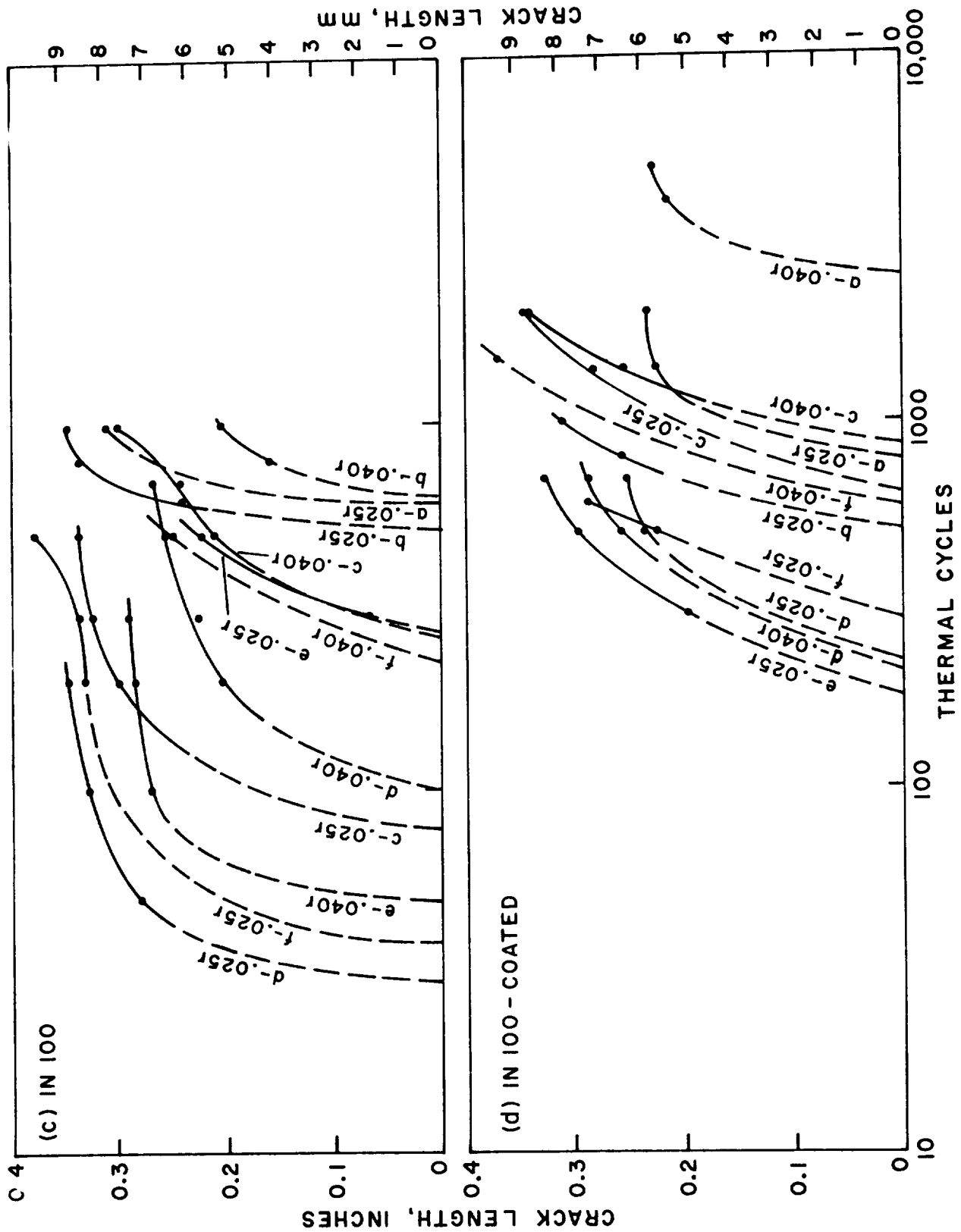


Fig. 18 - Crack Propagation Data for the First Crack Formed in Uncoated and Coated IN-100.

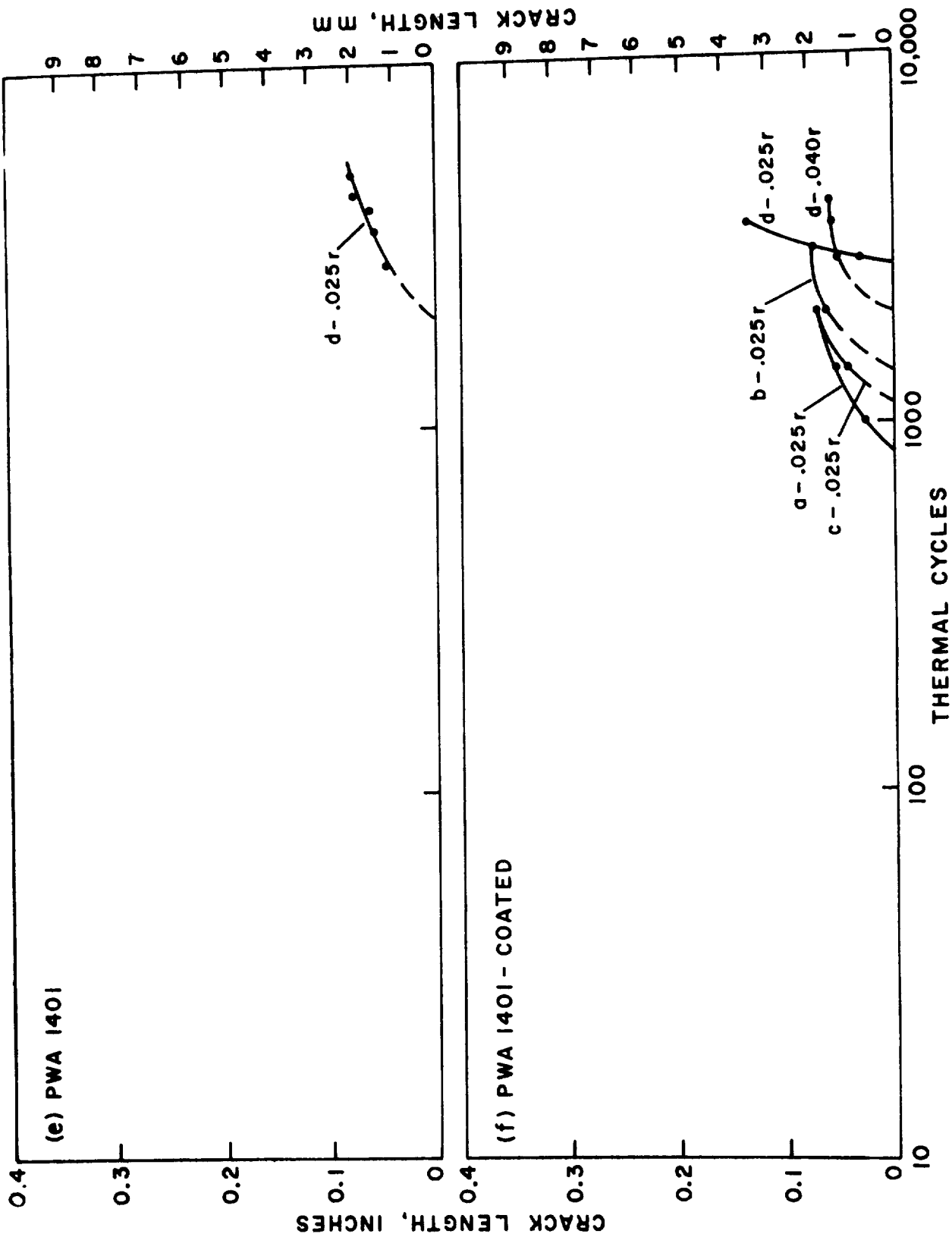
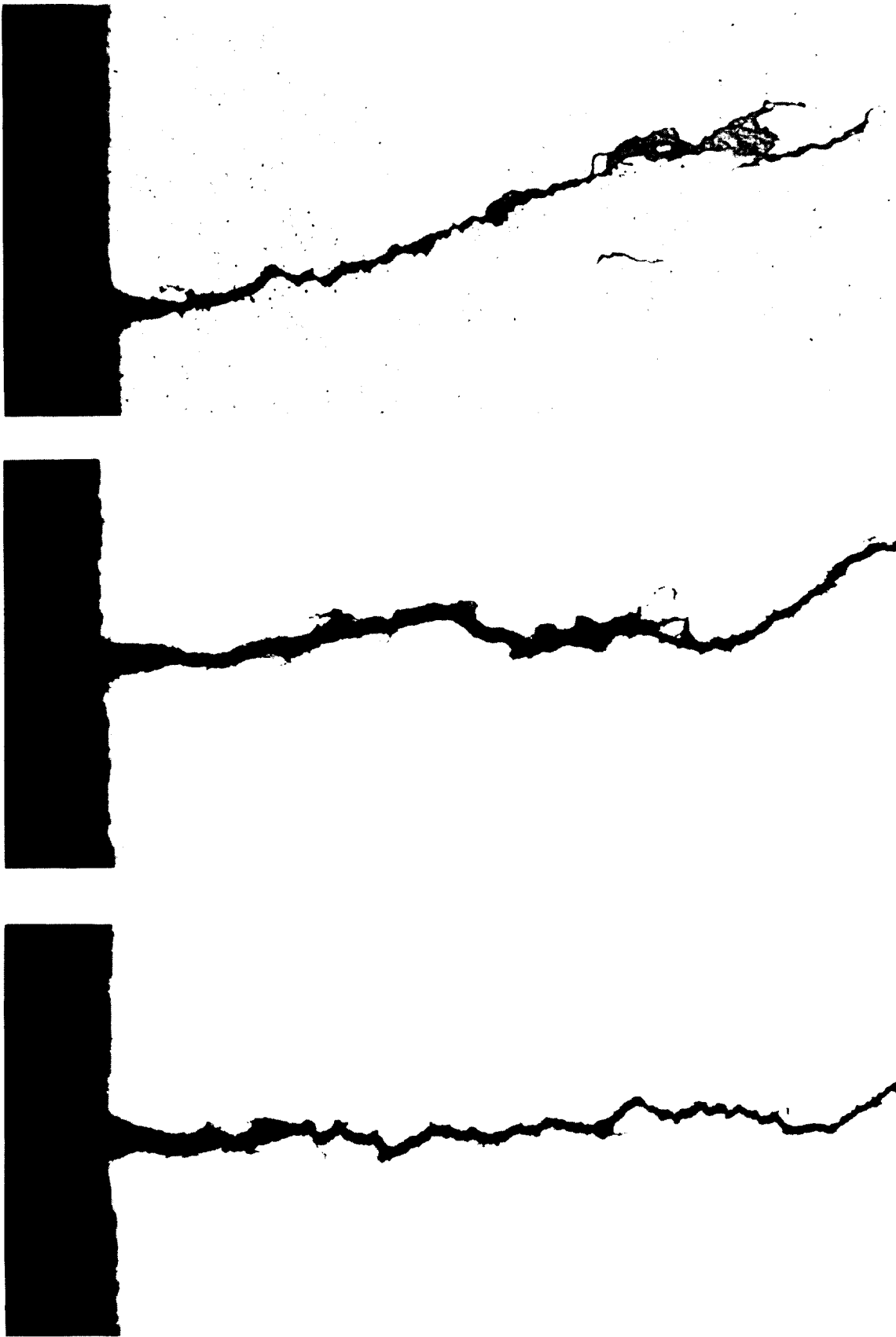


Fig. 19 - Crack Propagation Data for the First Crack Formed in Uncoated and Coated PWA 1401.



Neg. No. 37868

Neg. No. 37869

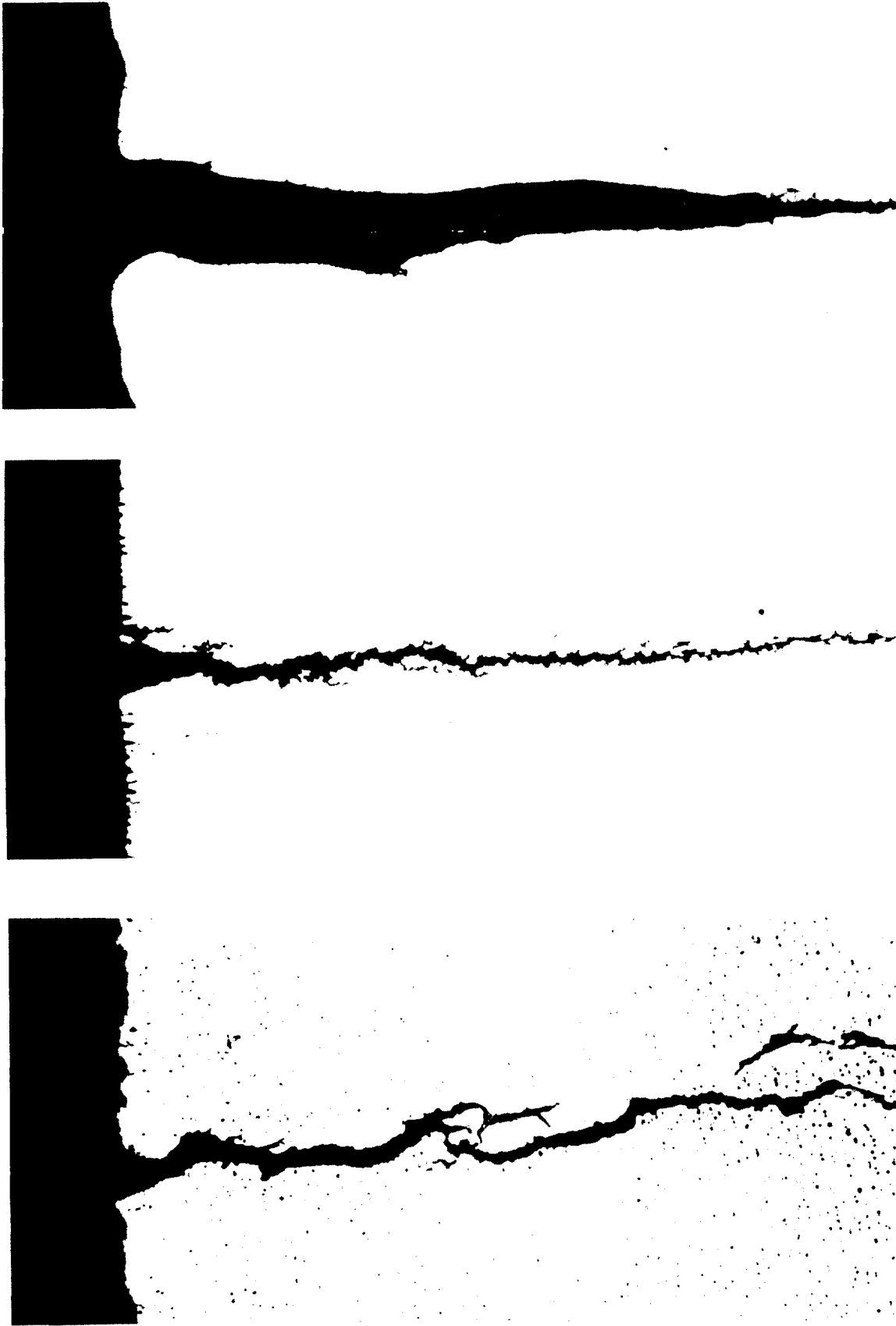
Neg. No. 37870

(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)

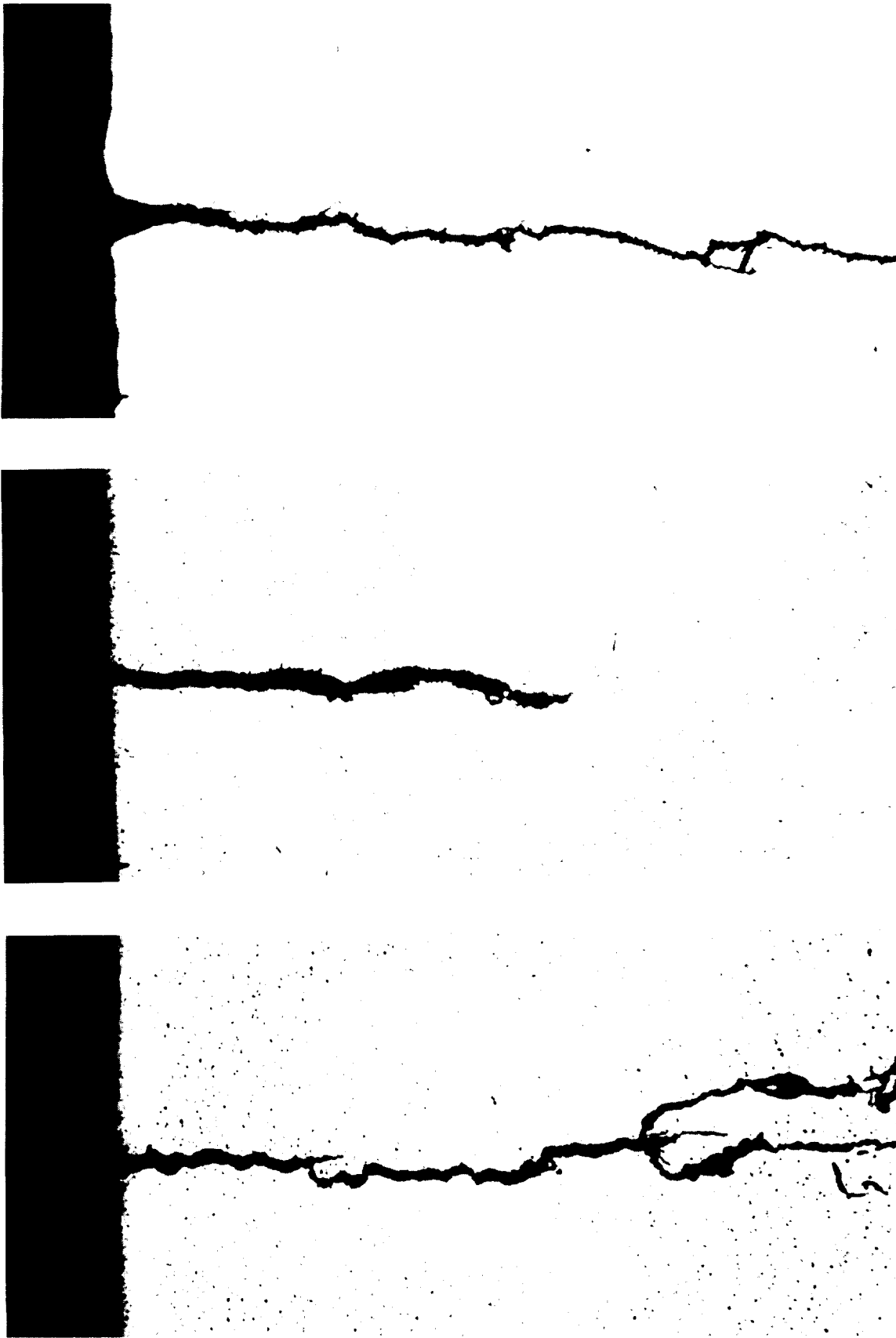
Neg. No. 37872

(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)

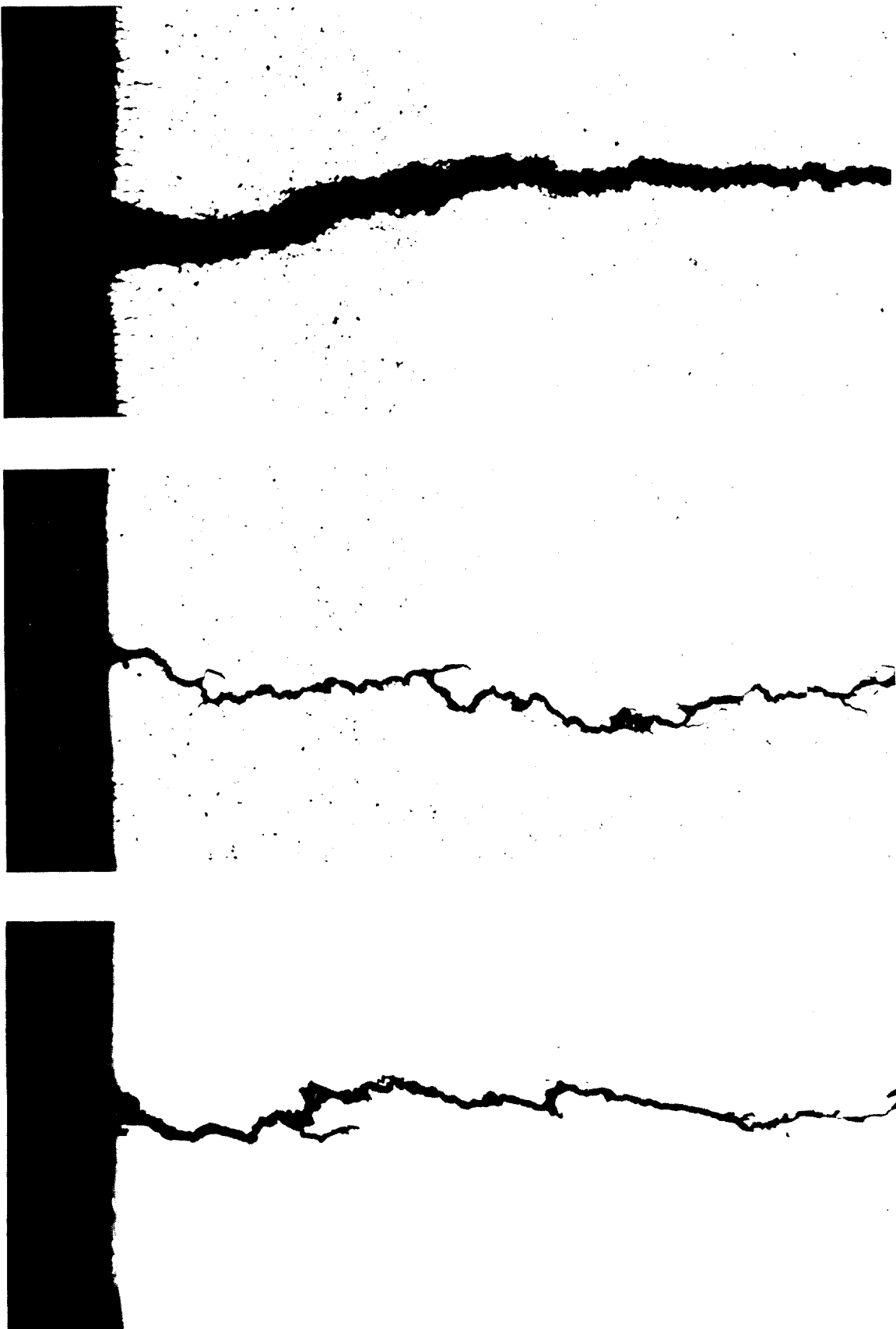
Neg. No. 37879

(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

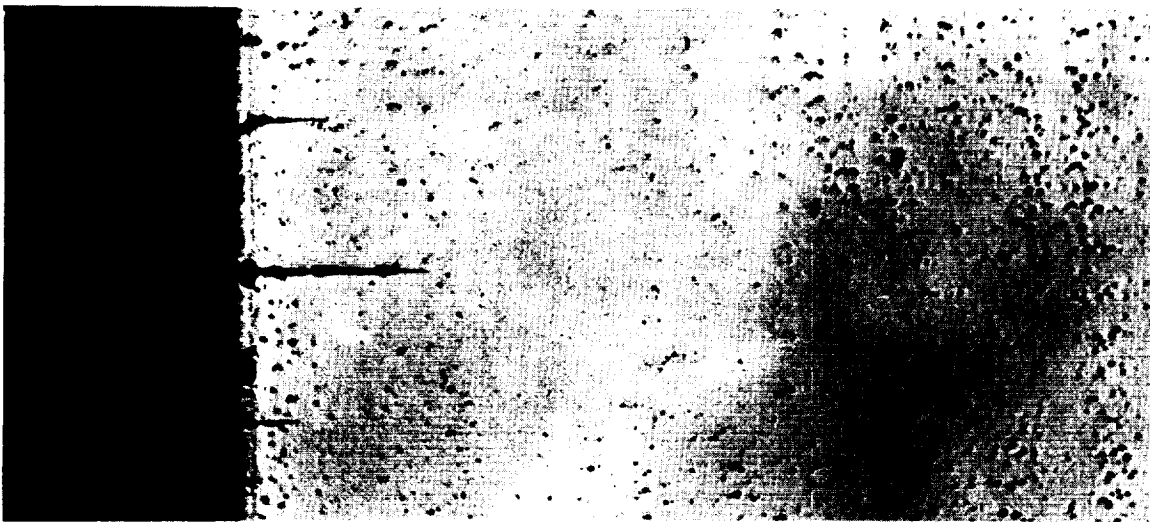
(m) Udimet 700 (Cast) (700 cycles)

Neg. No. 37882

(n) Udimet 700 (Wrought)
(700 cycles)

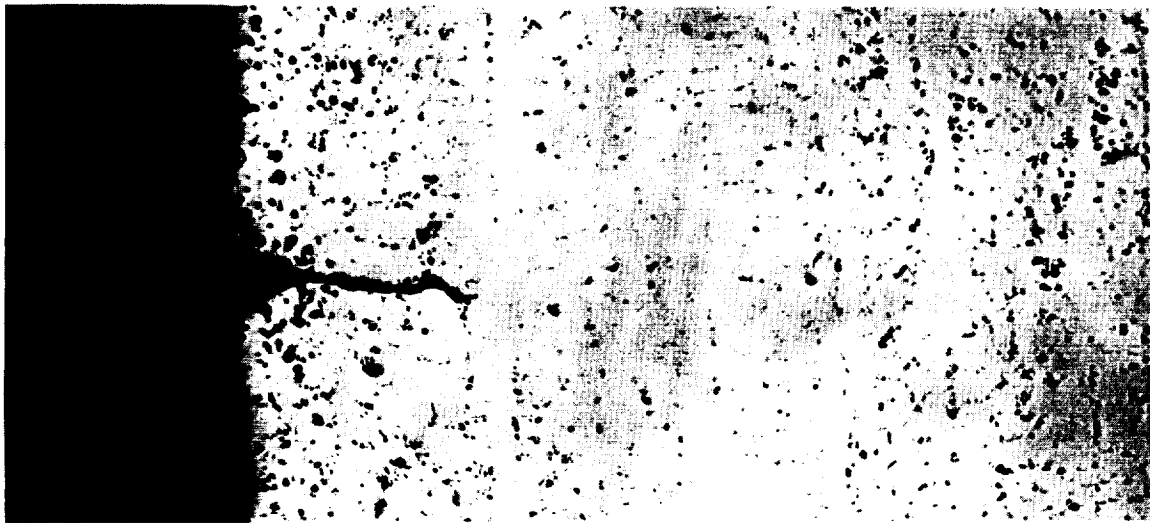
Neg. No. 37881

(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

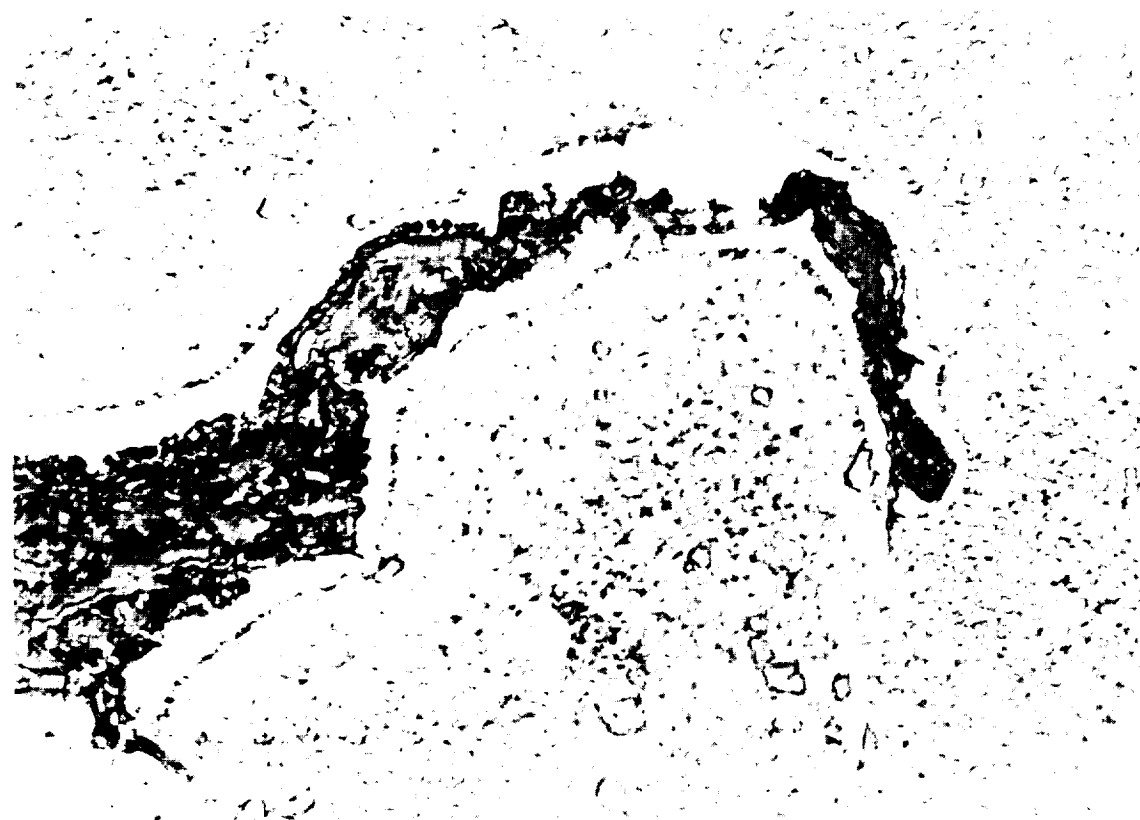
(a) B1900 (2000 cycles)



Neg. No. 37904

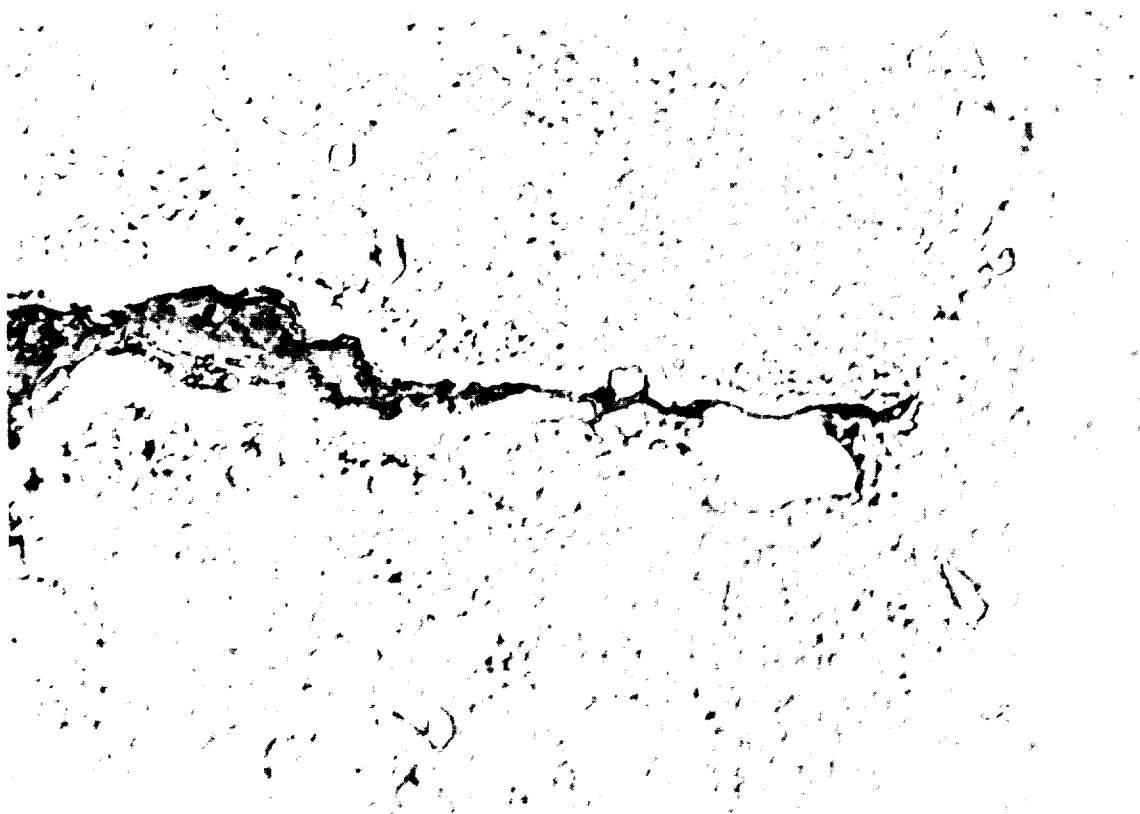
(b) B1900, Coated (4400 cycles)

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



Neg. No. 37905

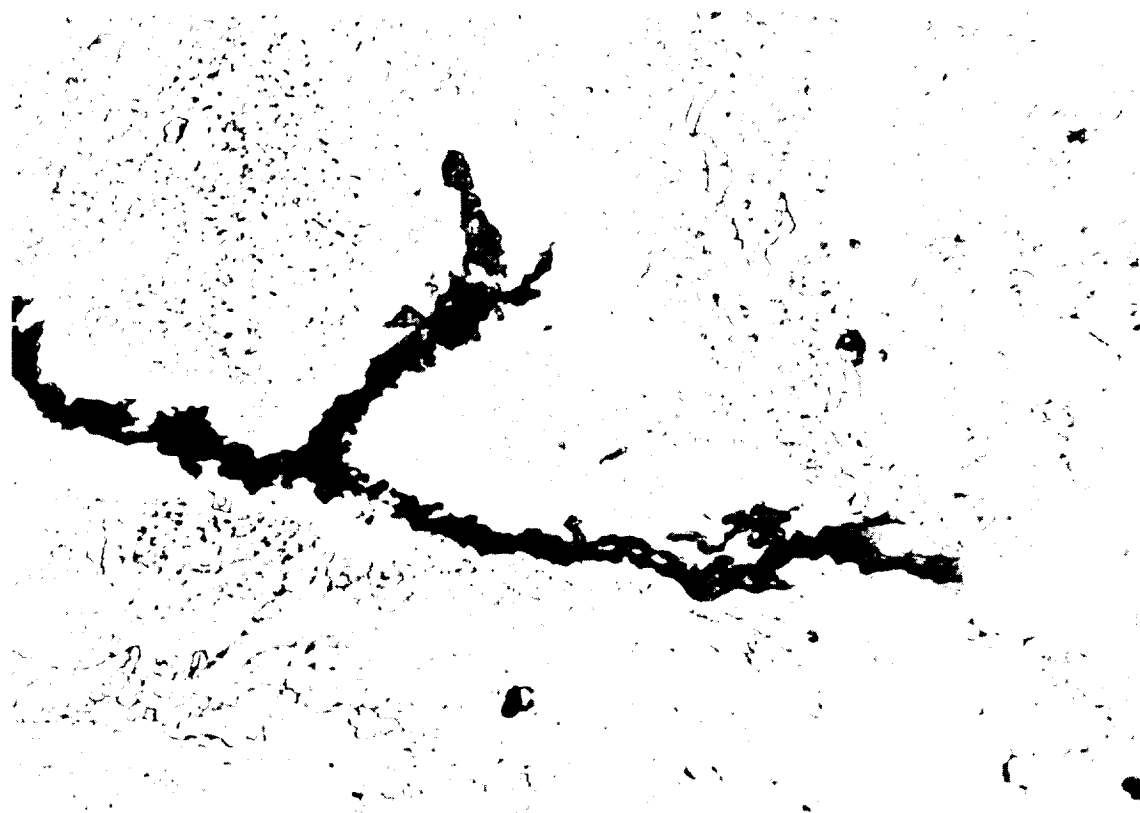
(c) IN-100 (700 cycles)



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

(e) X-40 (2000 cycles)

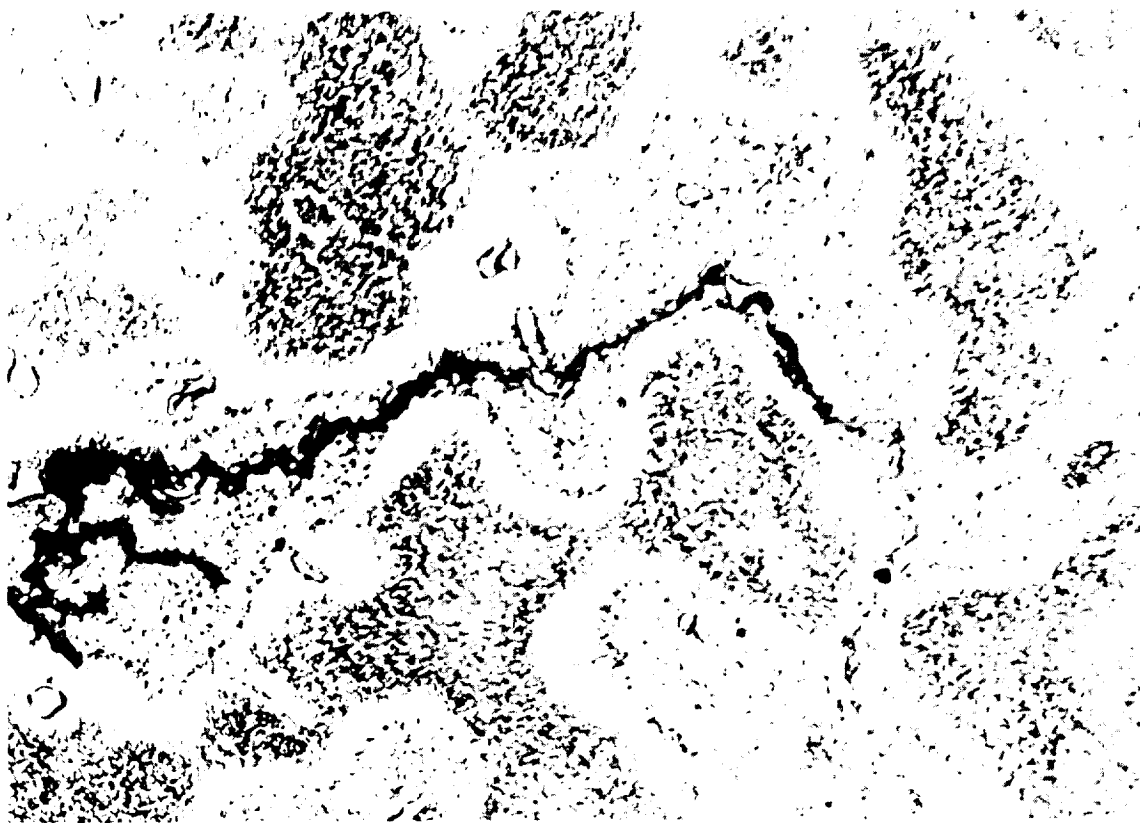
Fig. 21 (Continued) - Root of Crack in Thermal Fatigue Specimens, Longitudinal Section
(etched, X500)



Neg. No. 37916

(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

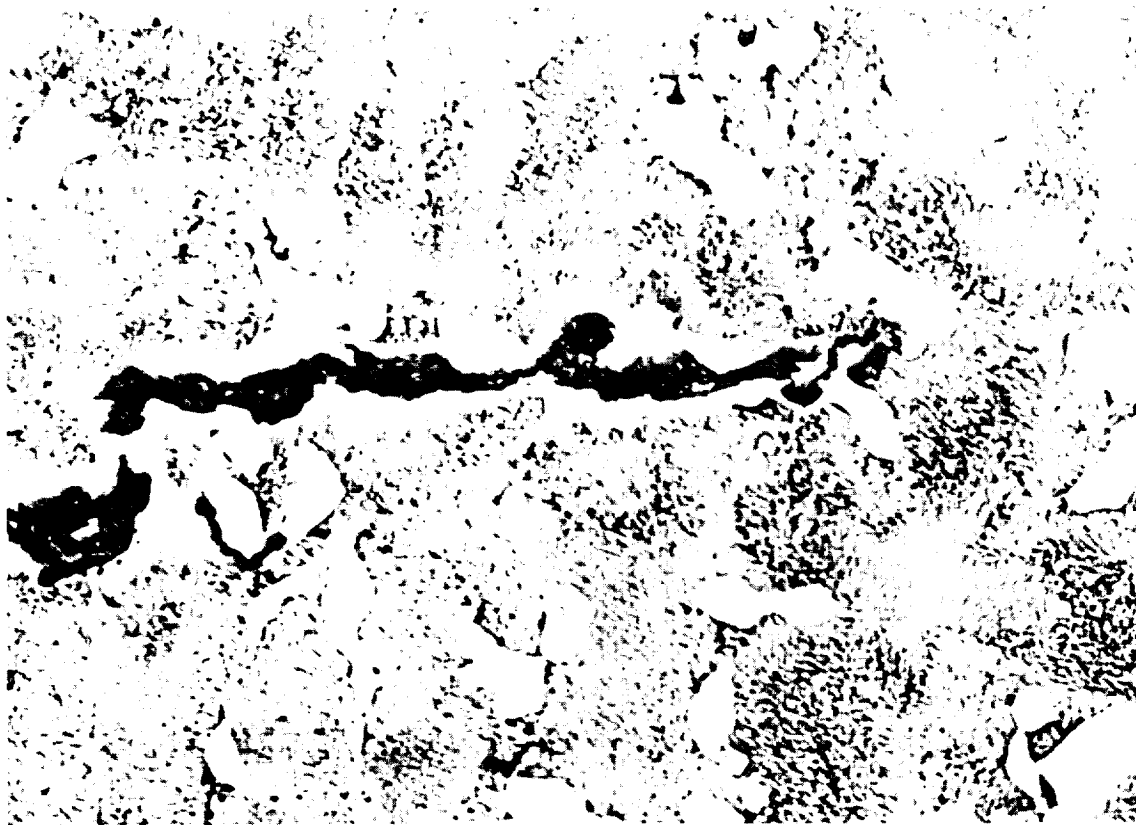
(i) IN-162 (3100 cycles)



Neg. No. 37925

(j) IN-713C (700 cycles)

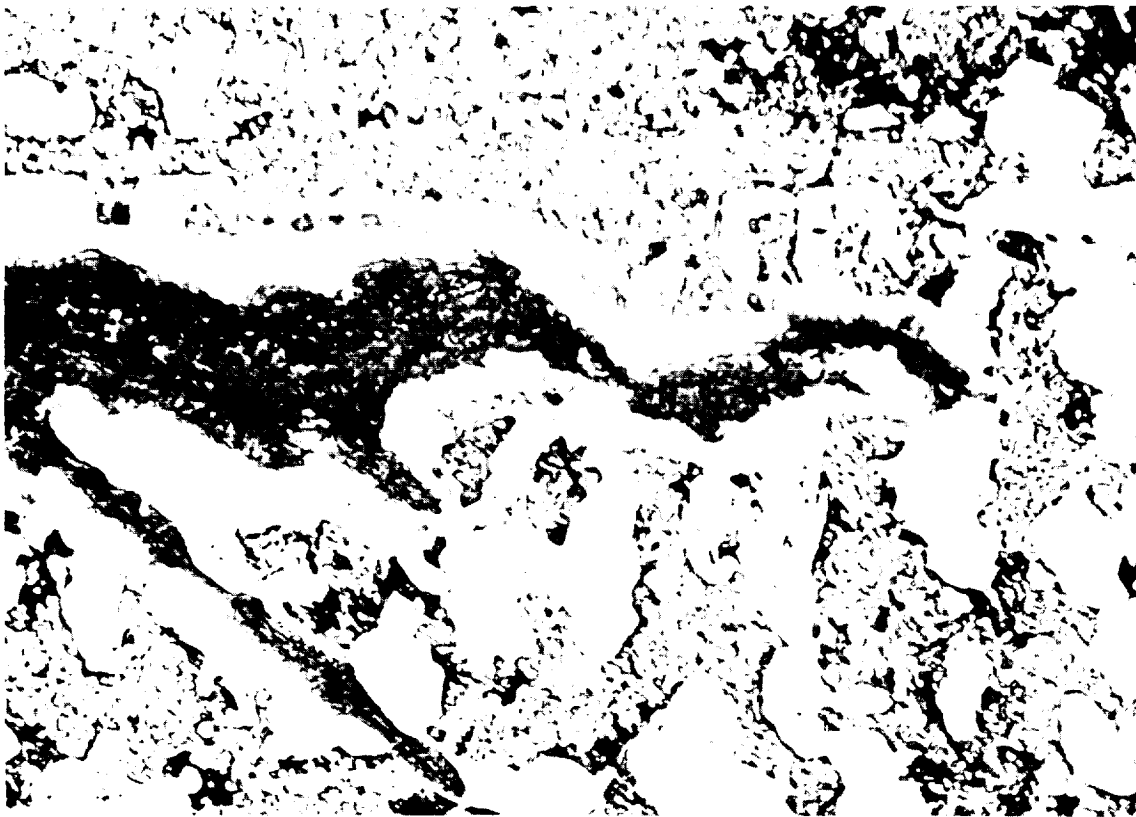
Fig. 21 (Continued) - Root of Crack in Thermal Fatigue Specimens, Longitudinal Section
(etched, X500)



Neg. No. 37928

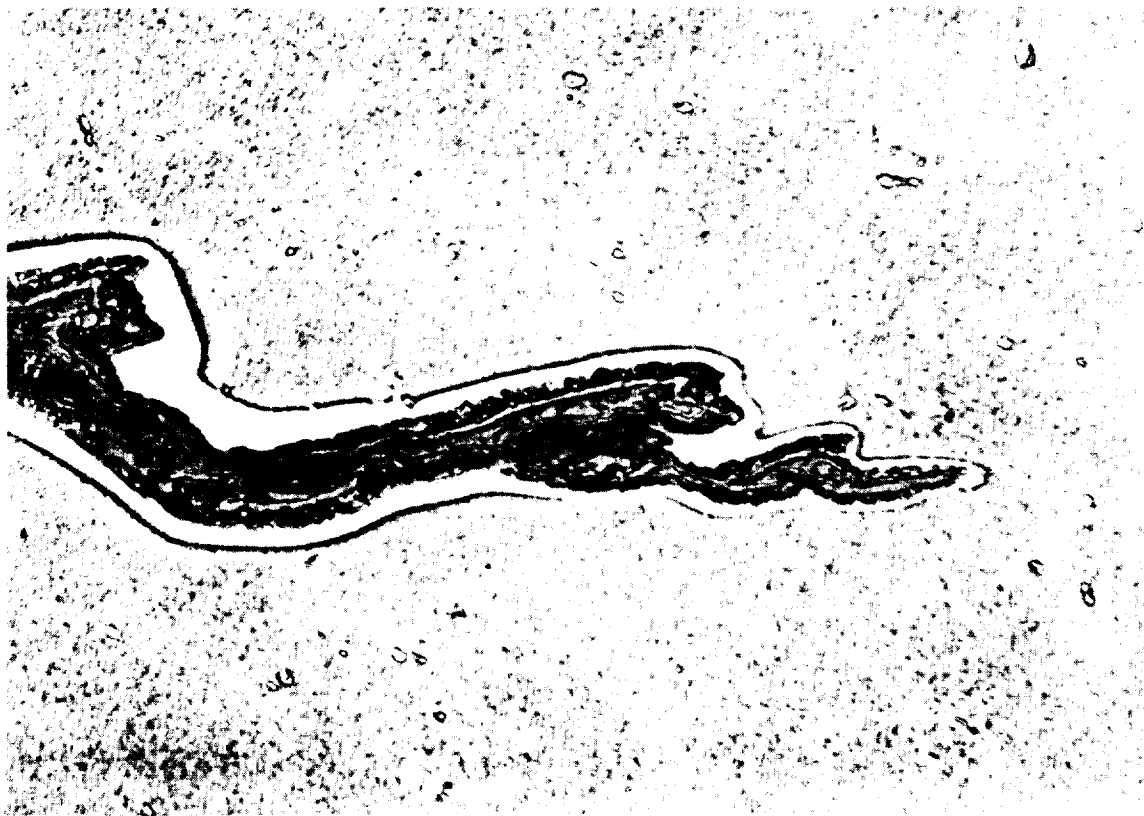
(k) M22 (700 cycles)

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



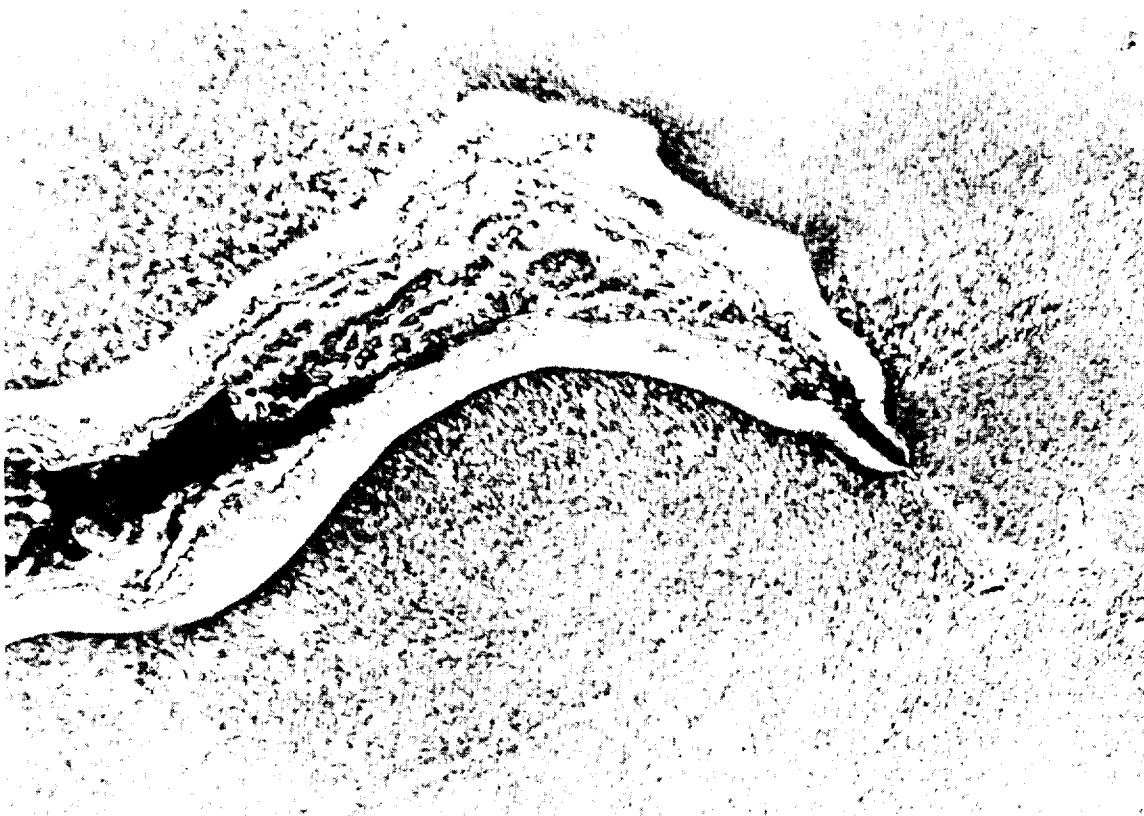
Neg. No. 37930

(1) TAZ-8A (5000 cycles)



Neg. No. 37934

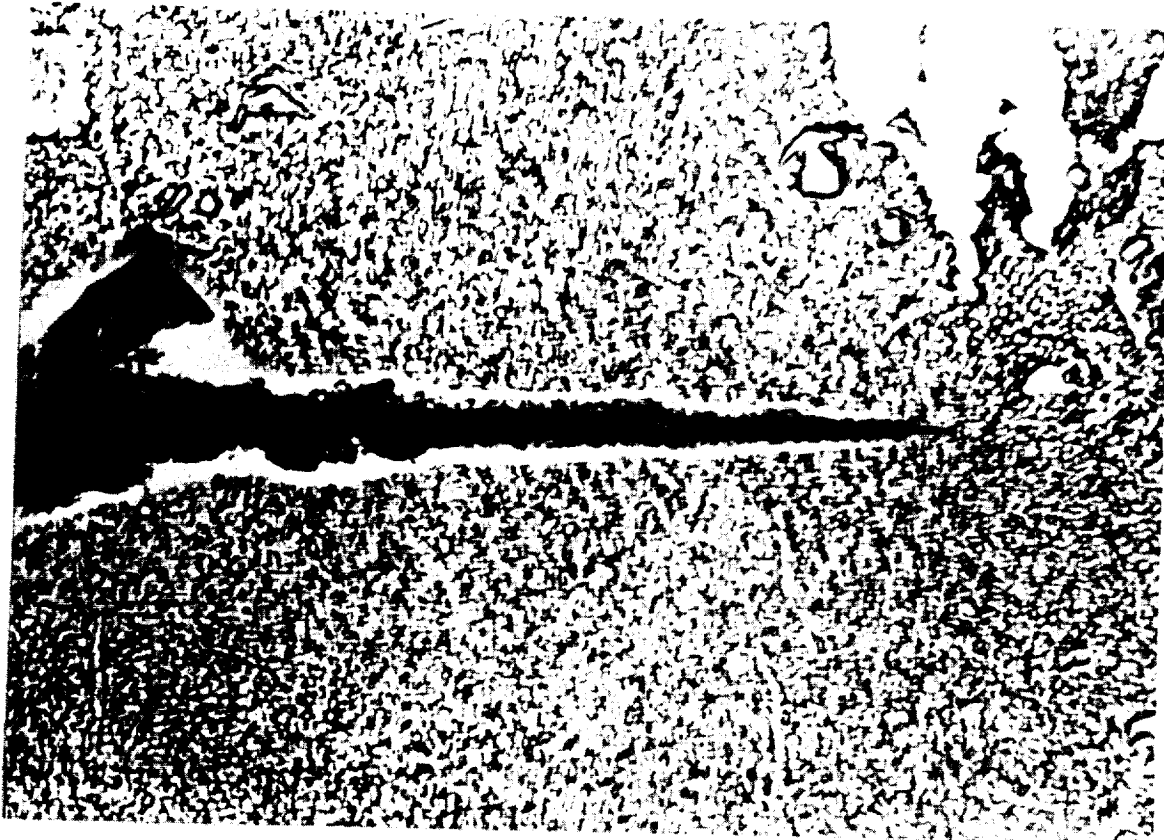
(m) Udimet 700 (Cast) (700 cycles)



Neg. No. 37932

(n) Udimet 700 (Wrought) (700 cycles)

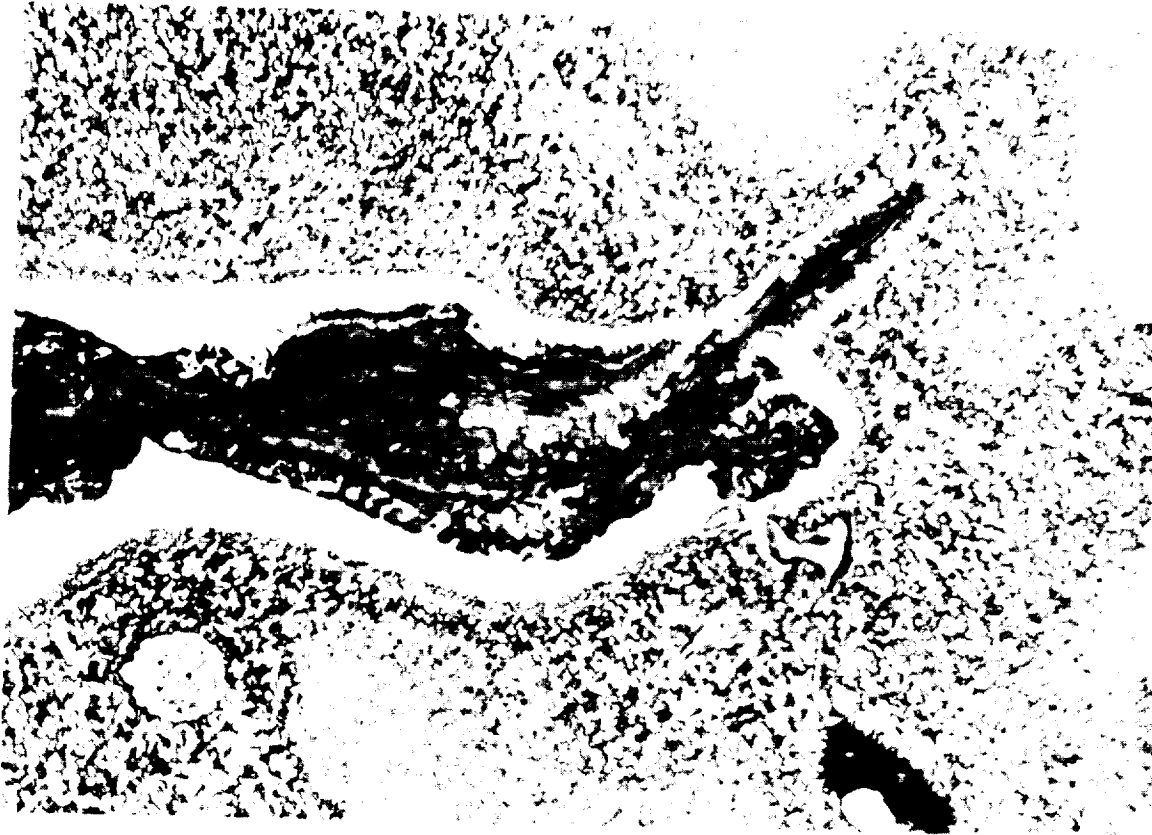
Fig. 21 (Continued) - Root of Crack in Thermal Fatigue Specimens, Longitudinal Section (etched, X500)



Neg. No. 38032

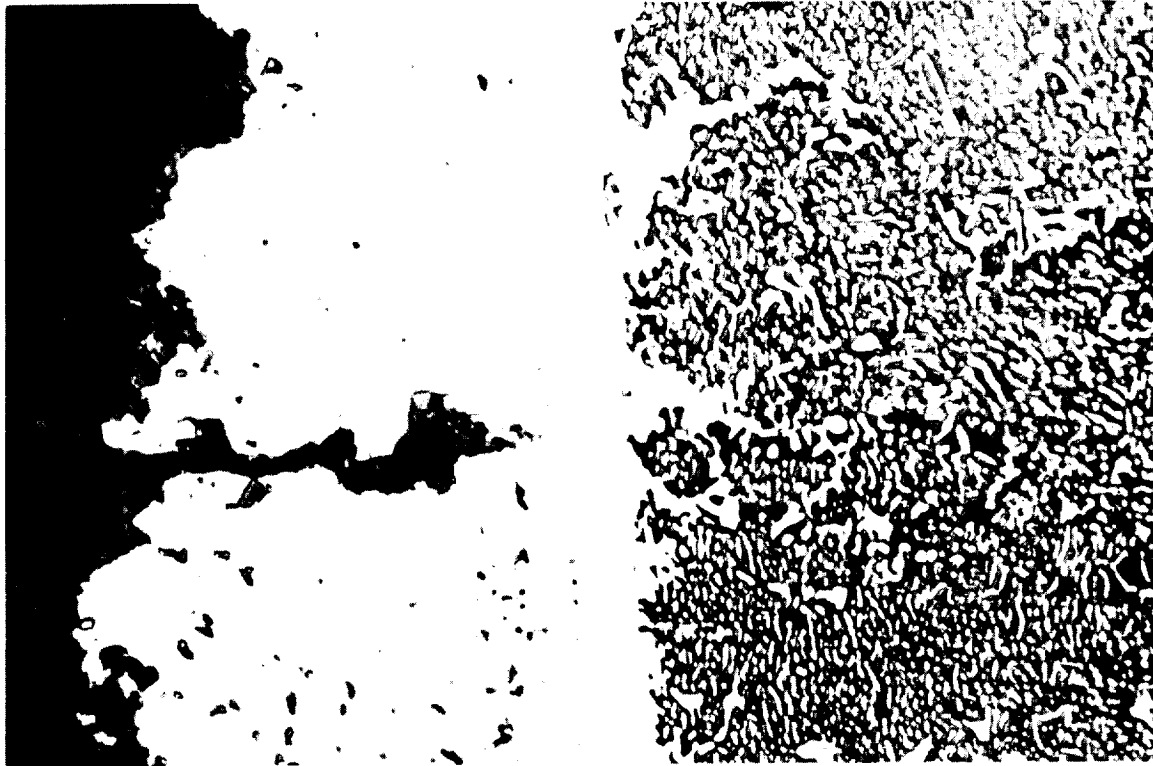
(o) PWA 1401-Coated (2000 cycles, Set C)

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



Neg. No. 38033

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



Neg. No. 37910

Etched X500

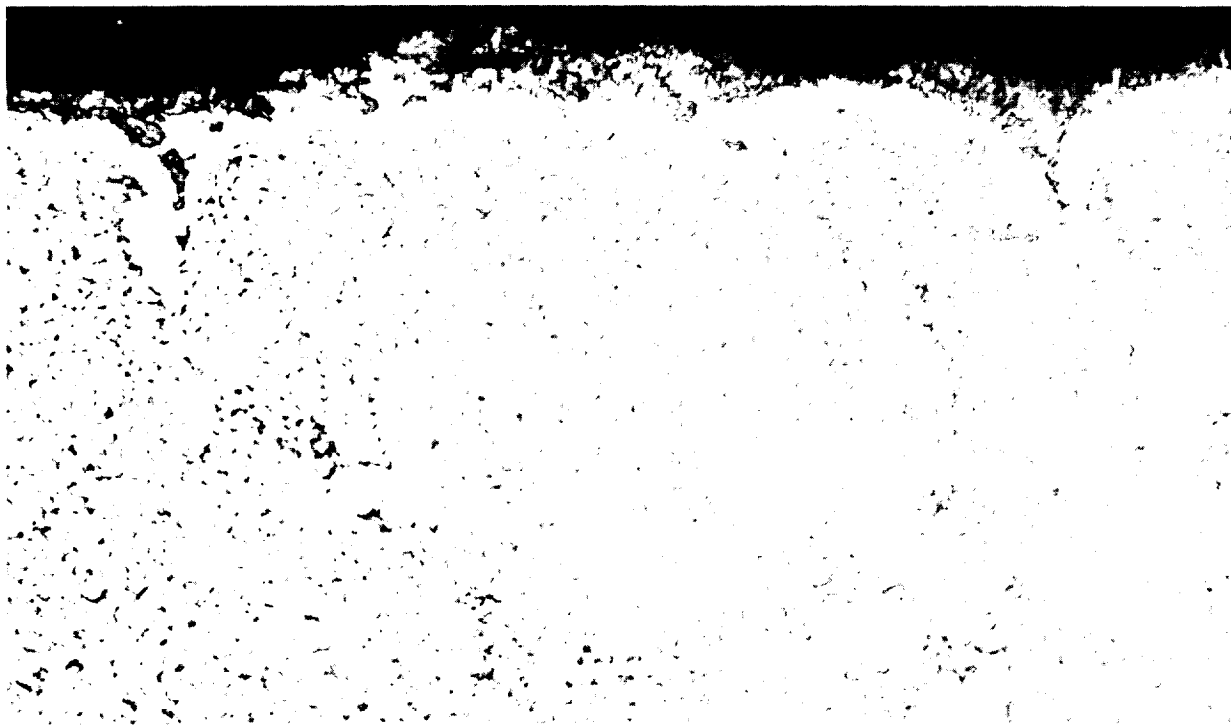
Fig. 22 - B1900, Coated Sample. Transverse section showing crack through coating.



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.



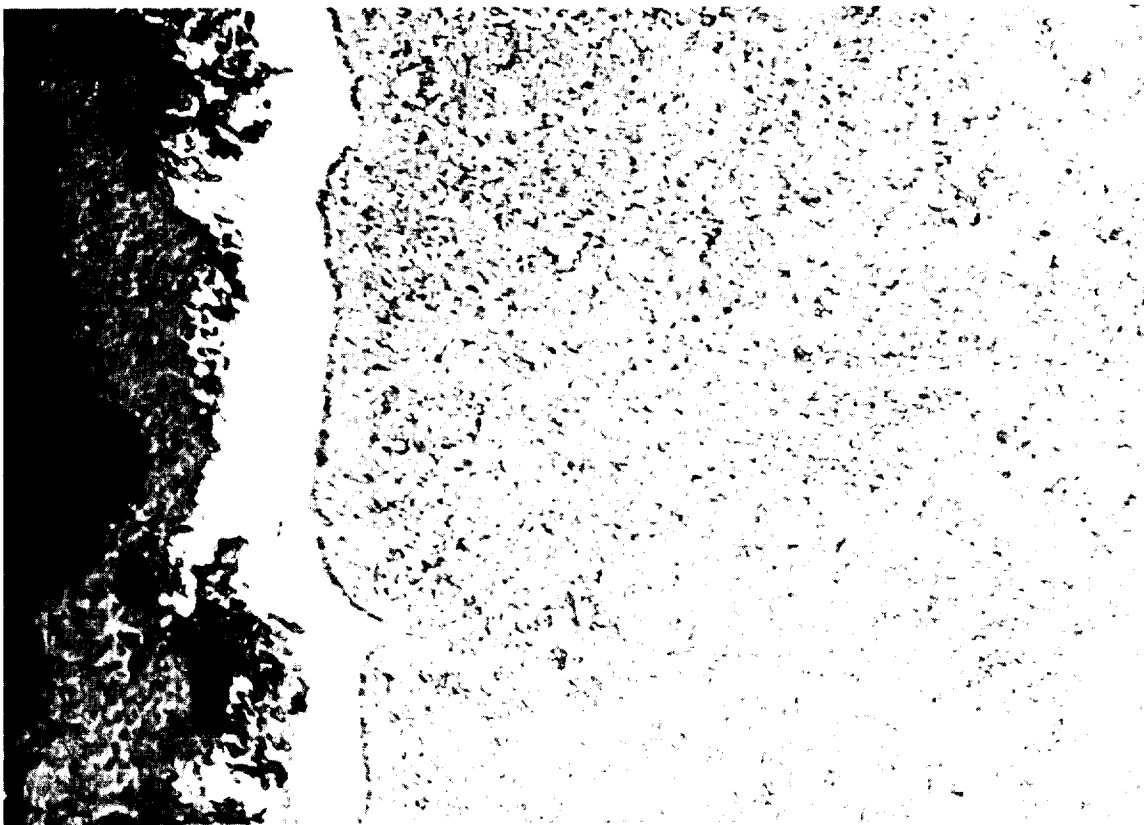
Neg. No. 37929

Etched X500

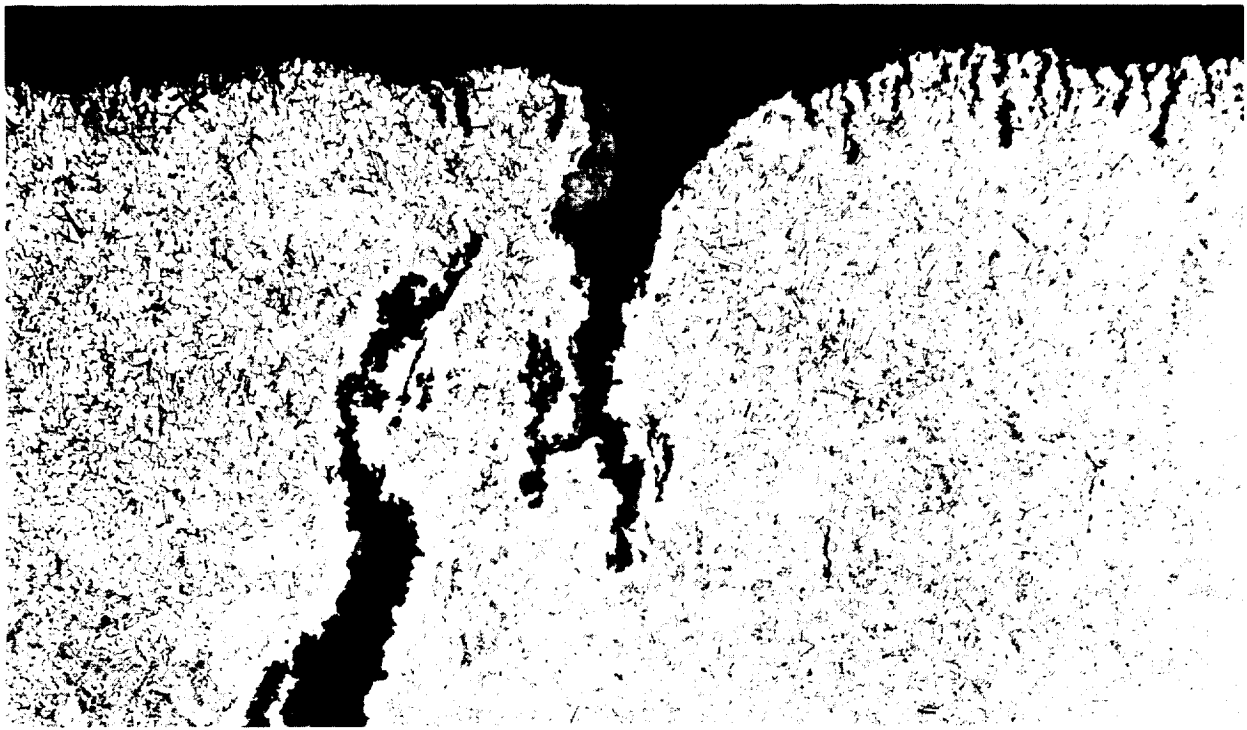
Fig. 25 - PWA 1401, Transverse Section Showing a Possible Crack
Nucleation Point.



Neg. No. 37908 Etched X500
 Fig. 26 - FWA 1401, Coated Sample, Showing
 Thermal Fatigue Crack Through
 Coating.



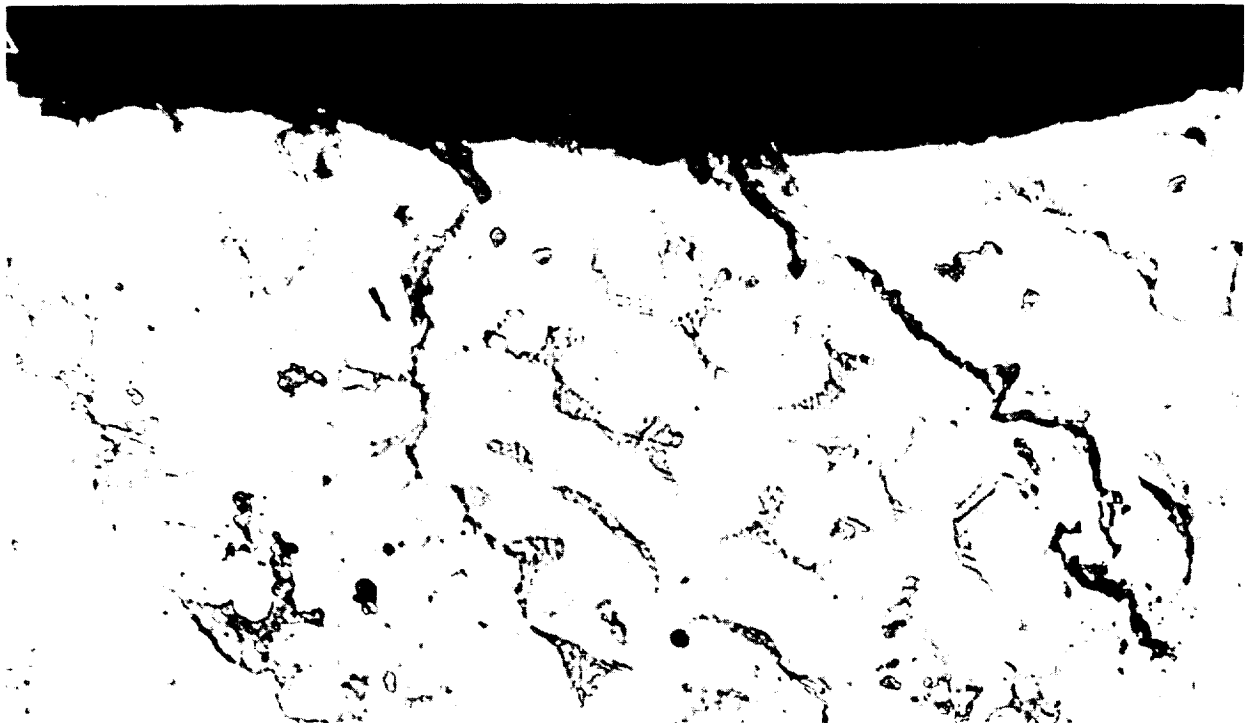
Neg. No. 37926 Etched X500
 Fig. 27 - IN-713C Sample Showing Possible
 Crack Nucleation Sites.



Neg. No. 37915

Etched X125

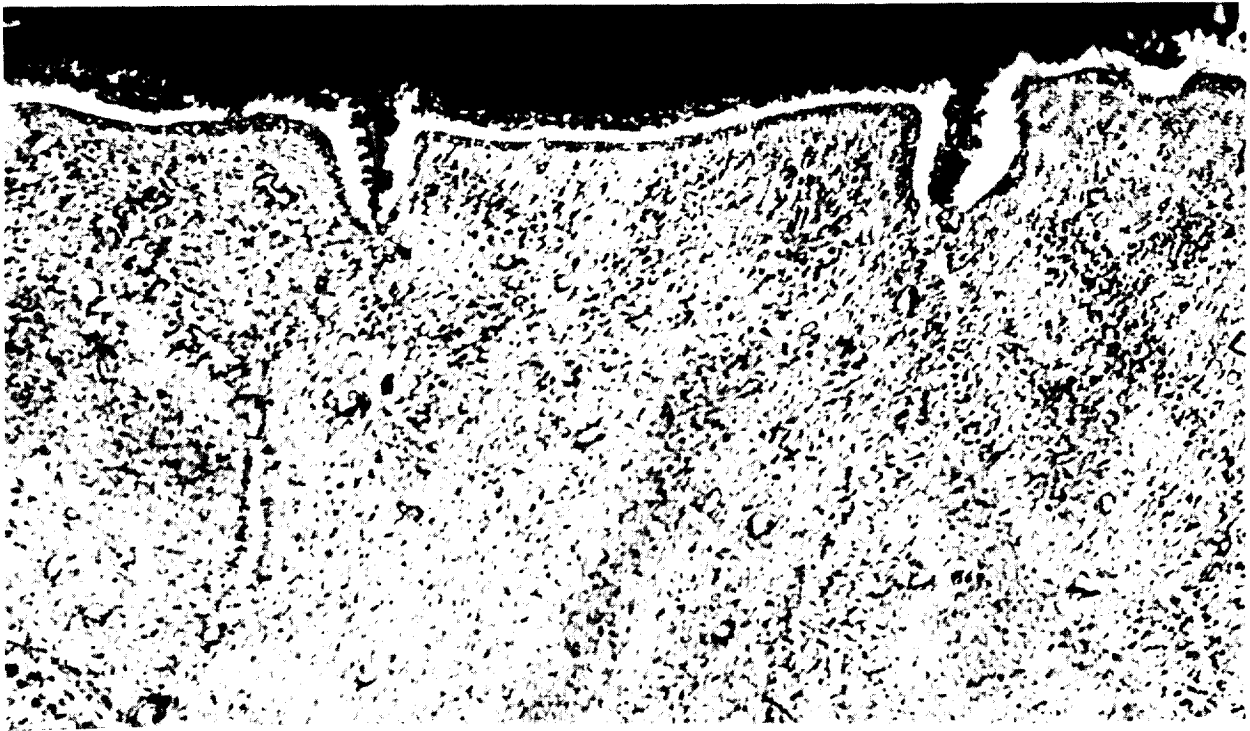
Fig. 28 - X-40 Sample Showing Early Stages of Crack Propagation.



Neg. No. 37917

Etched X500

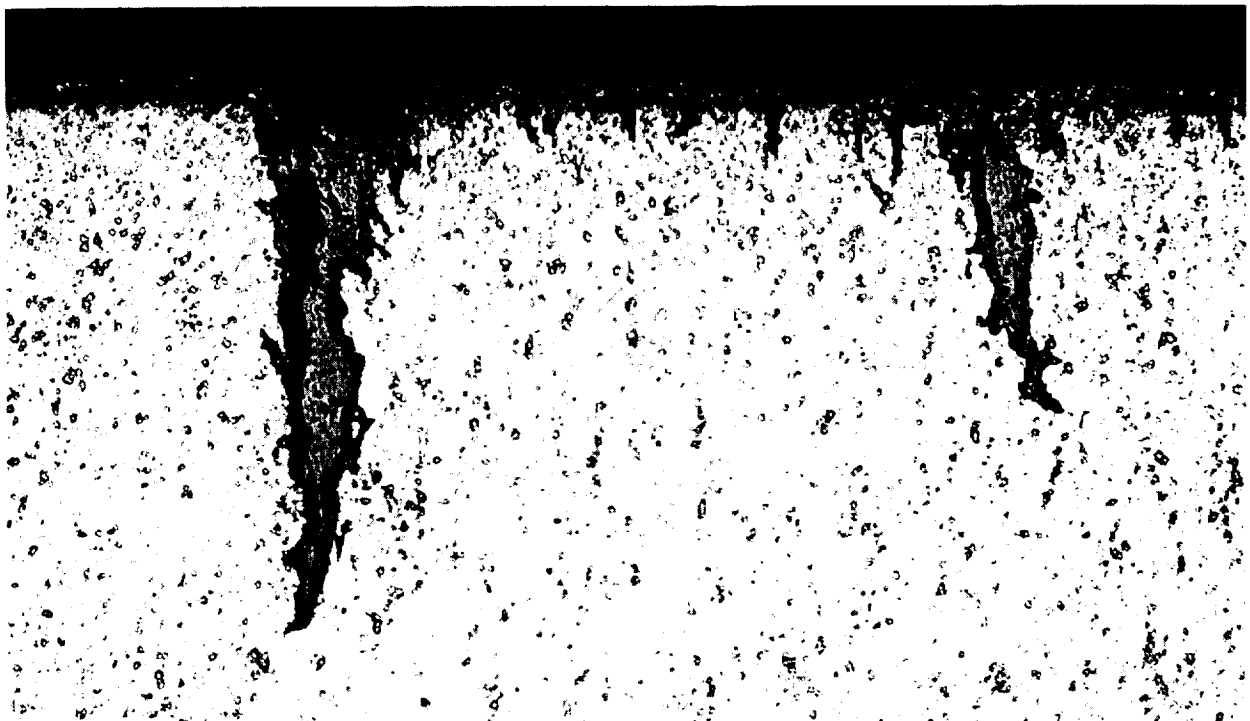
Fig. 29 - WI-52 Longitudinal Section Showing Possible Crack Nucleation Sites.



Neg. No. 37919

Etched X500

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



Neg. No. 37921

Etched X125

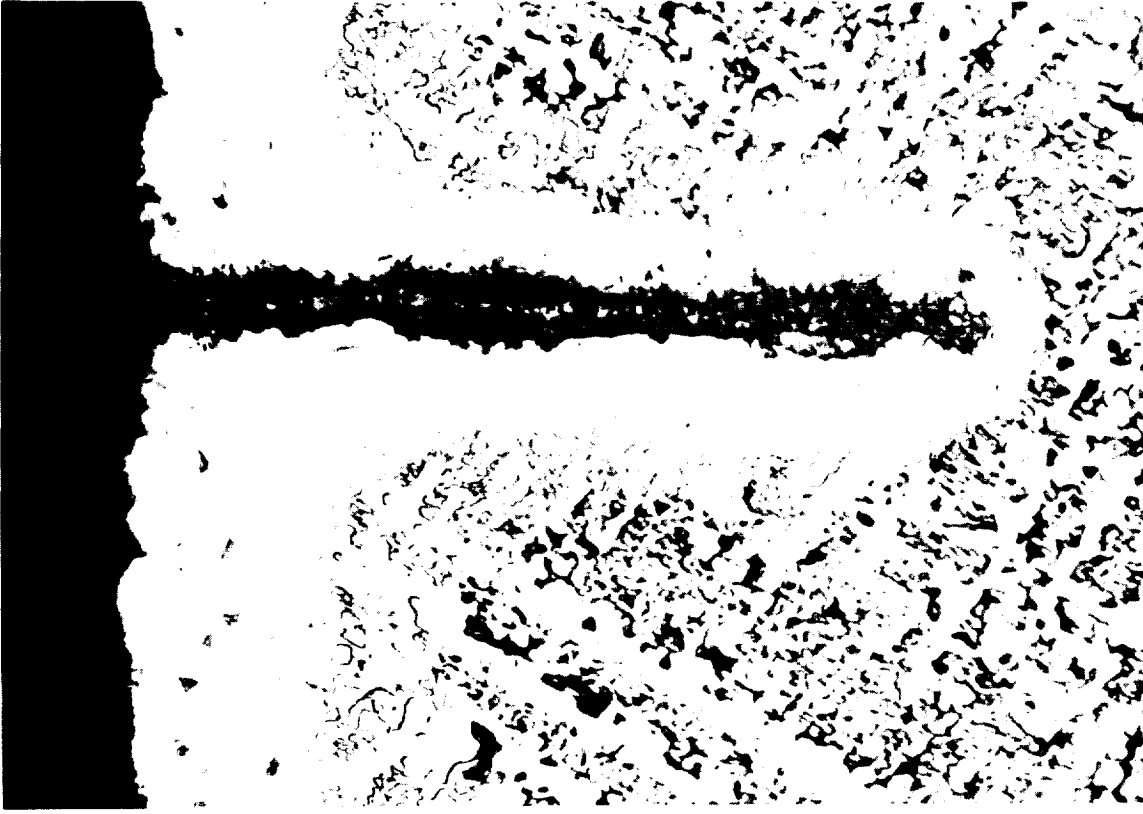
Fig. 31 - MAR-M 302 Longitudinal Section Showing Early Stages of Crack Propagation.



Neg. No. 37929

Etched X500

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



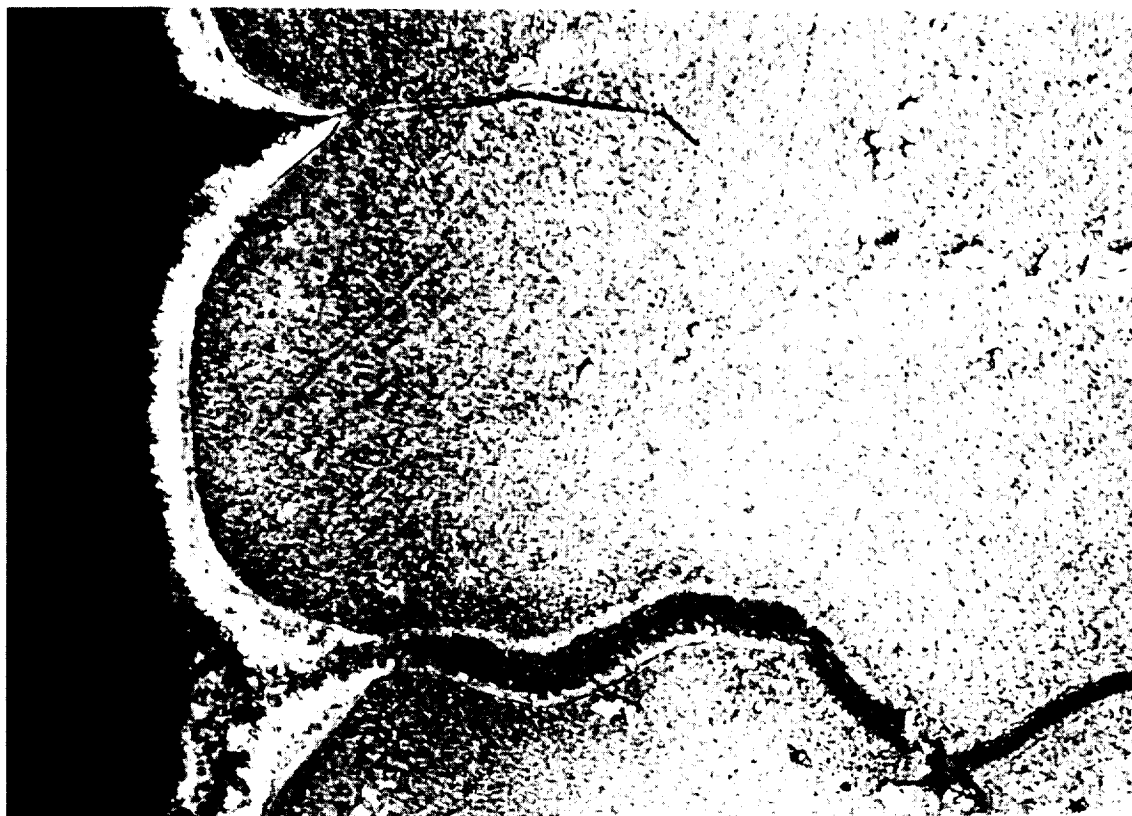
Neg. No. 37931

Etched X500

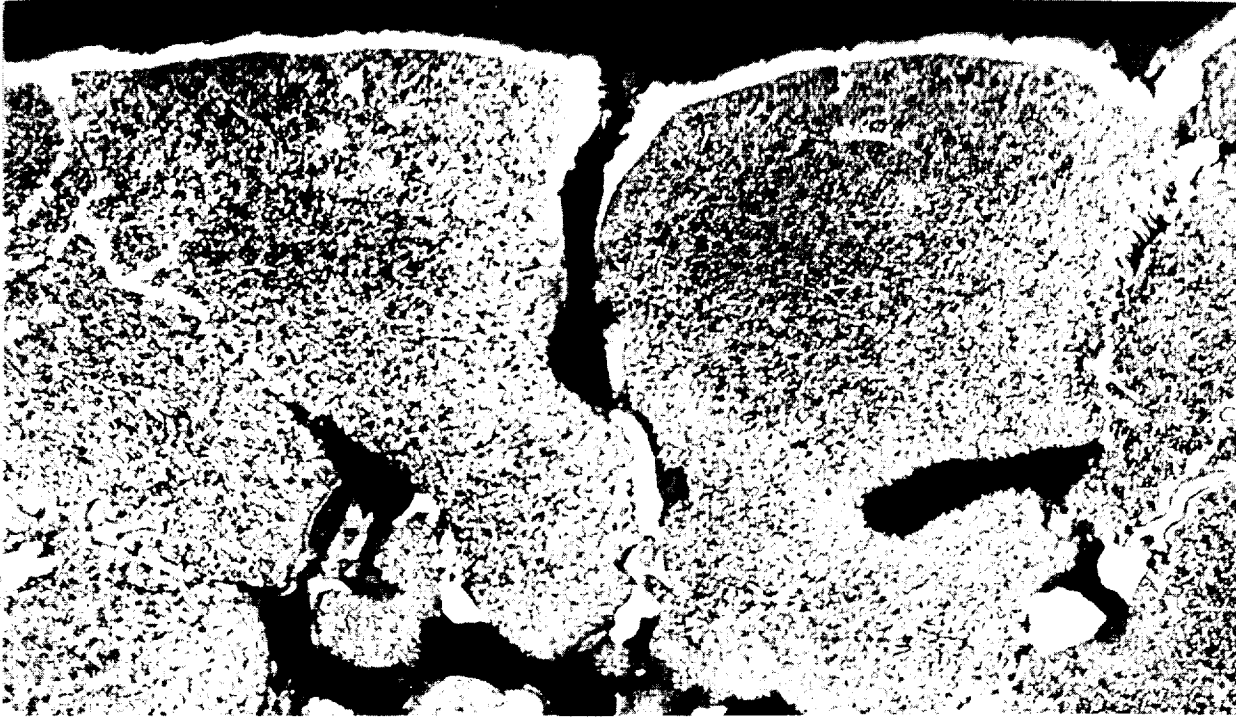
Fig. 33 - TAZ-8A Longitudinal Section Showing
the Early Stage of a Crack.



Neg. No. 37935 Etched X500
 Fig. 34 - Cast Udimet 700 Longitudinal
 Section Showing Possible Crack
 Nucleation Sites.



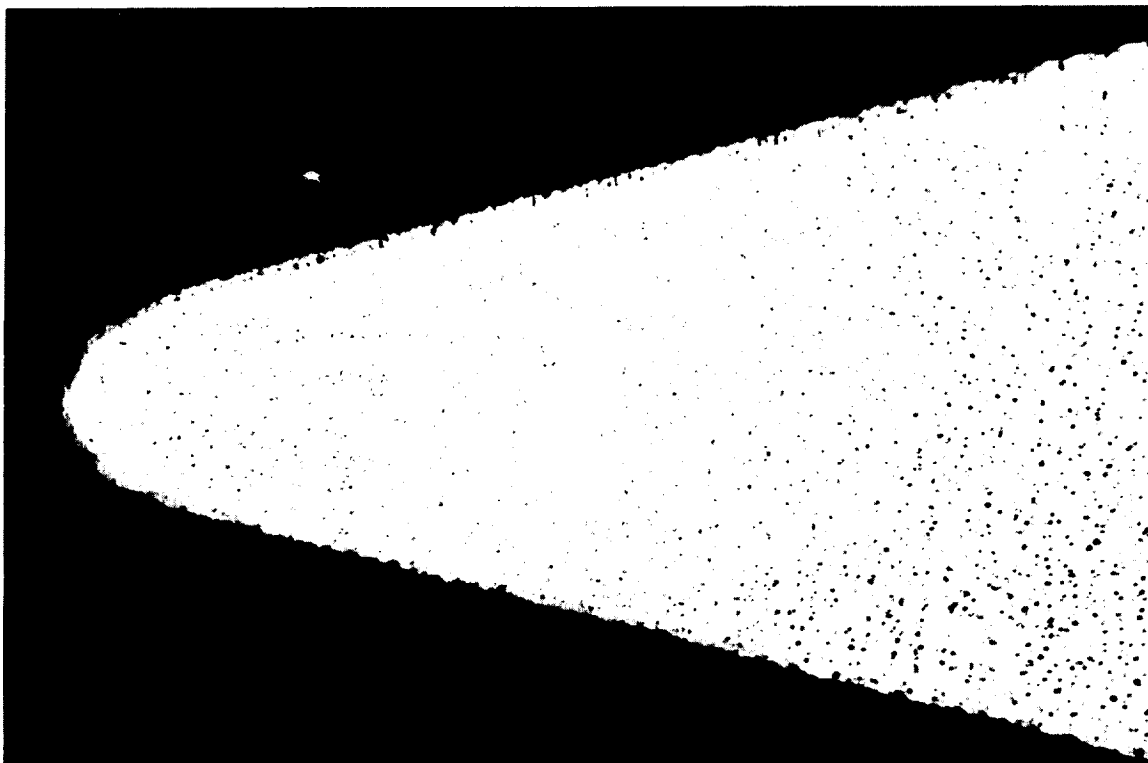
Neg. No. 37933 Etched X500
 Fig. 35 - Wrought Udimet 700 Longitudinal
 Section Showing Possible Crack
 Nucleation Site.



Neg. No. 38034

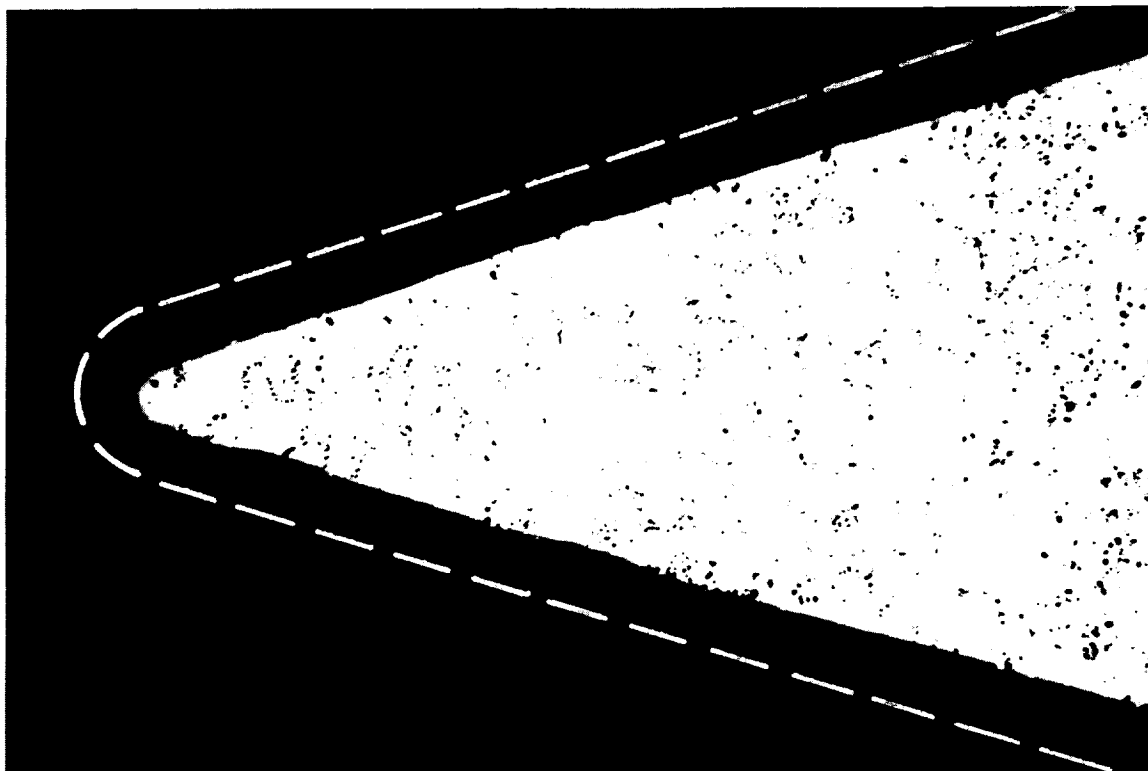
Etched X250

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



Neg. No. 37884

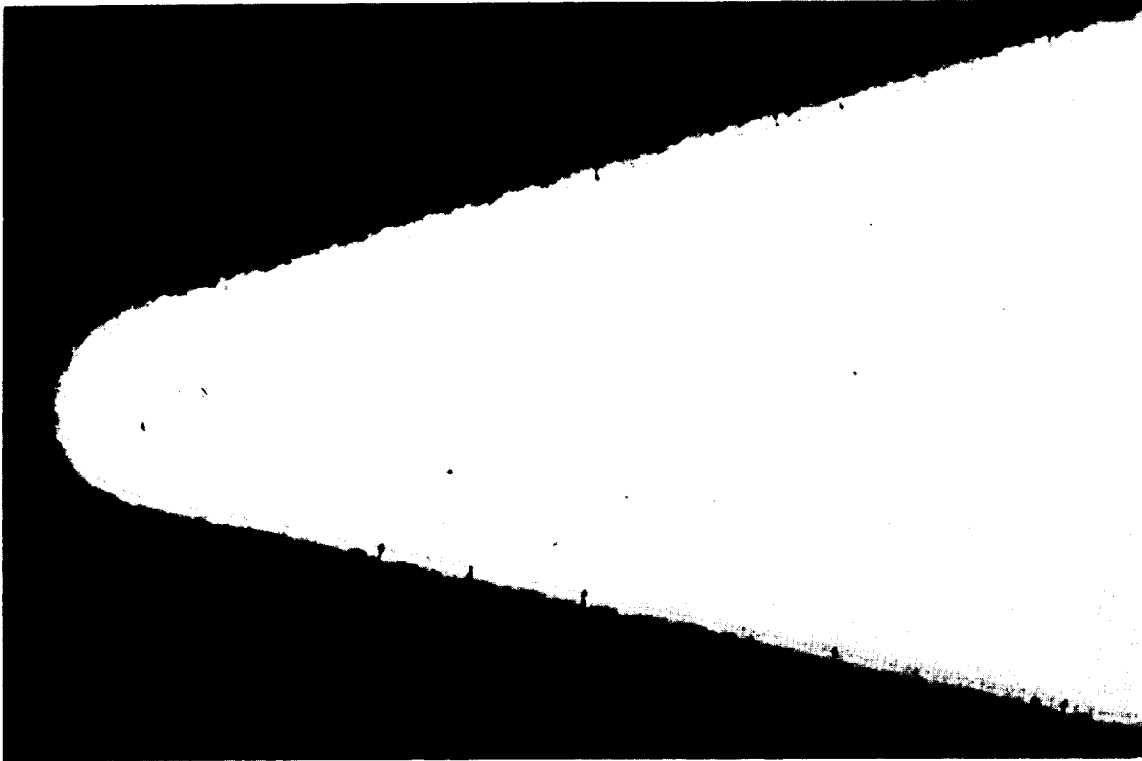
(a) IN-100, Coated (2000 Cycles)



Neg. No. 37885

(b) PWA 1401 (5000 Cycles)

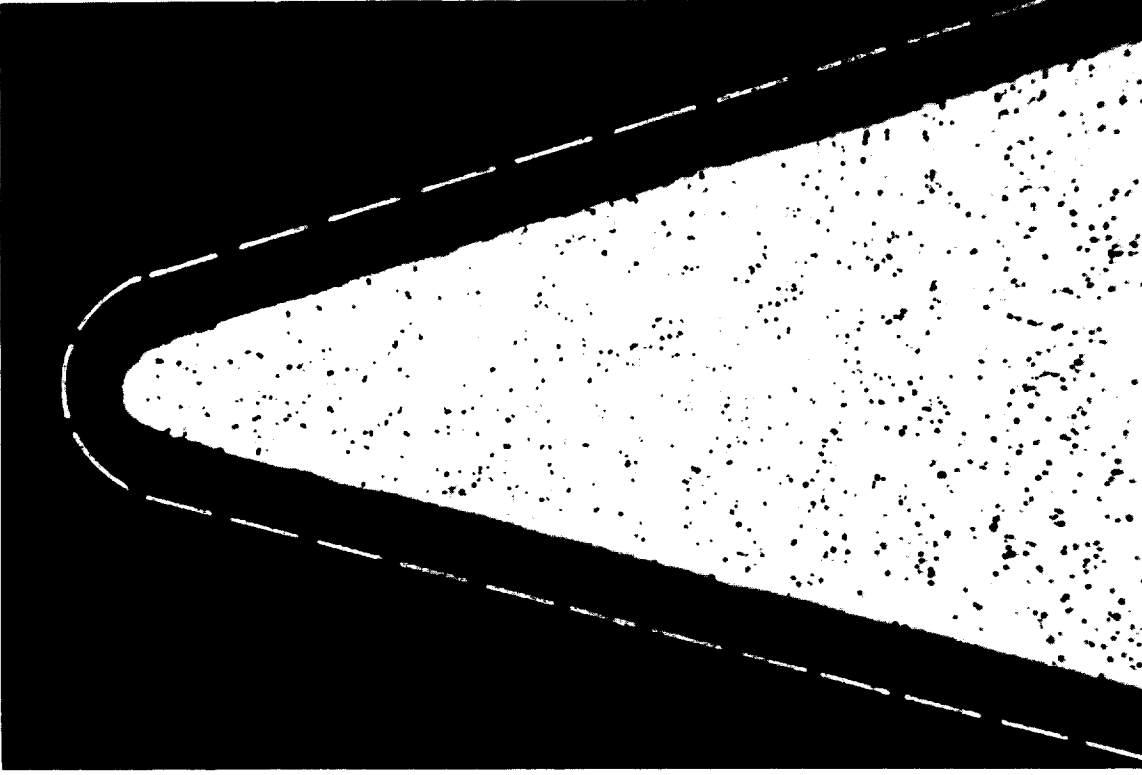
Fig. 37 - Transverse Section through the Original 0.025 in. Radius after Thermal Fatigue Testing for the Cycles Indicated. Original Profile of PWA 1401 shown by the dashed line. (unetched, X20)



Neg. No. 37883

(c) B1900, Coated (4400 Cycles)

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. 37886

(d) PWA 664 (5000 Cycles)



Neg. No. 37572

Unetched, X100

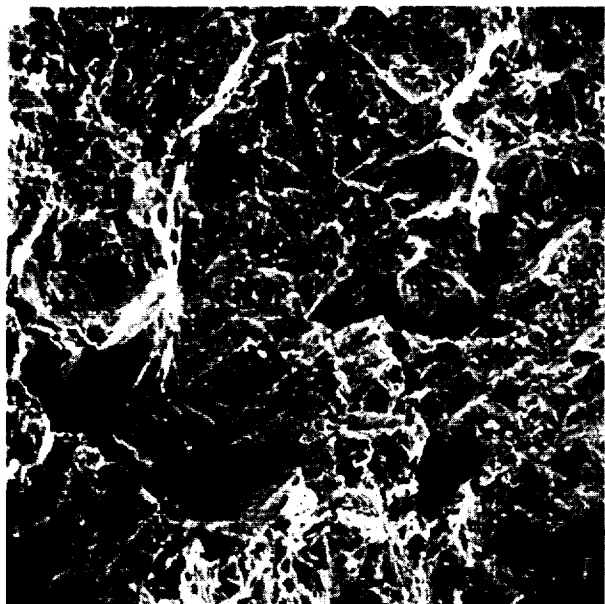
Fig. 38 - ThO₂ Dispersion in TD-NiCr
Material Used in This Program.



Neg. No. 37573

Unetched, X100

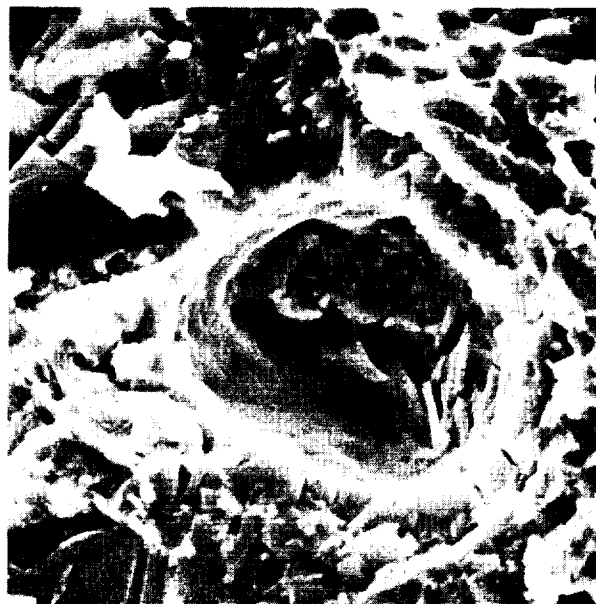
Fig. 39 - ThO₂ Dispersion in TD-NiCr Material
Known to Have Satisfactory Properties.



SEM 8372

X300

(a)



SEM 8373

X3000

(b)

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



SEM 8375

X300

(a)

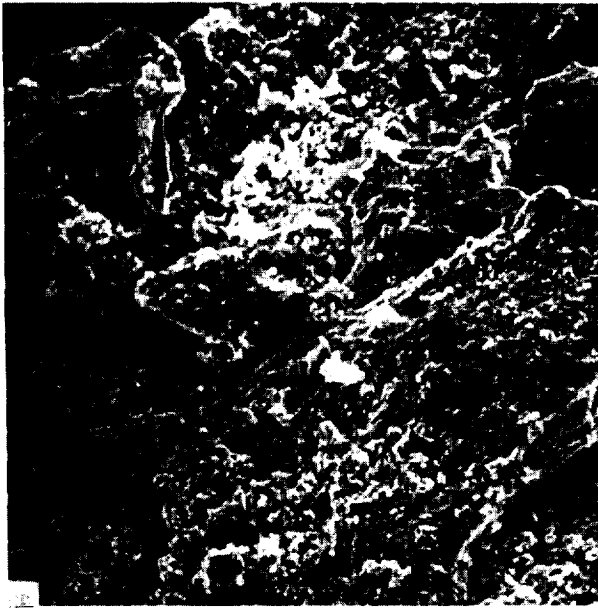


SEM 8310

X3000

(b)

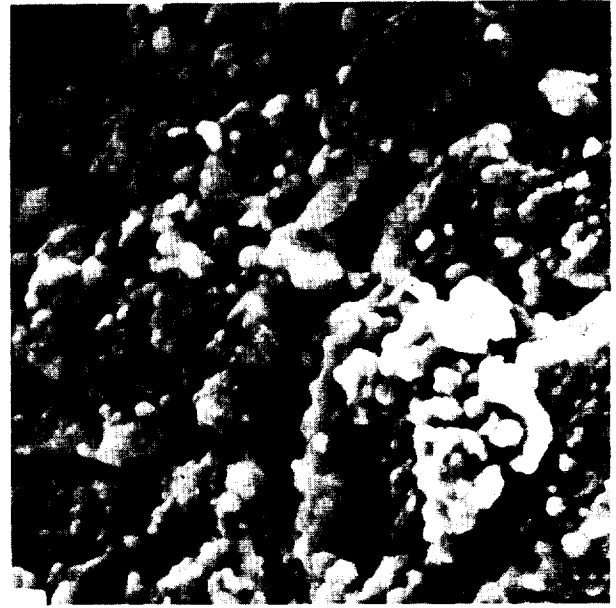
Fig. 41 - Appearance of Thermal Fatigue Fracture of MAR-M 200 in the SEM.



SEM 8317

X300

(a)

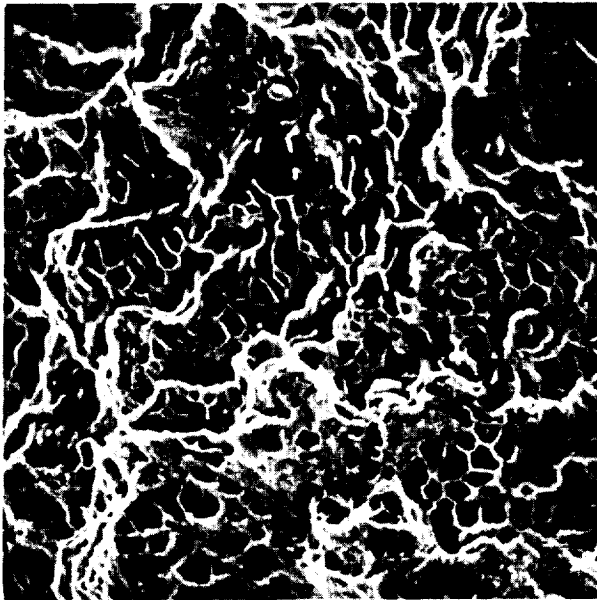


SEM 8316

X3000

(b)

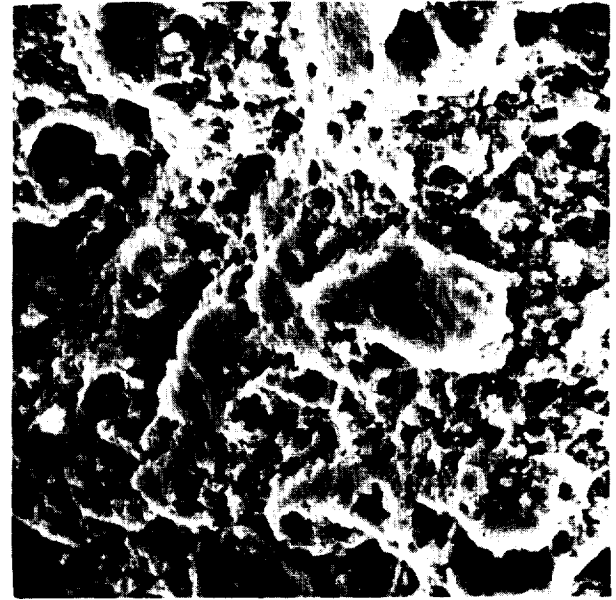
Fig. 42 - Appearance of Thermal Fatigue Fracture of MAR-M 302 in the SEM.



SEM 8371

X1000

(a)

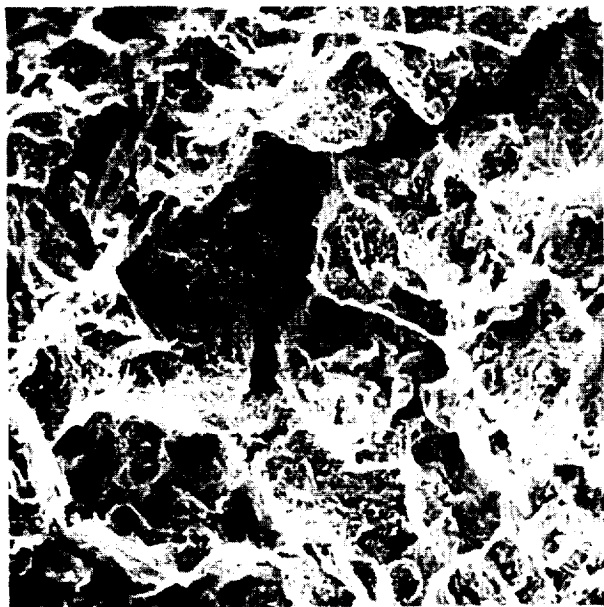


SEM 8370

X3000

(b)

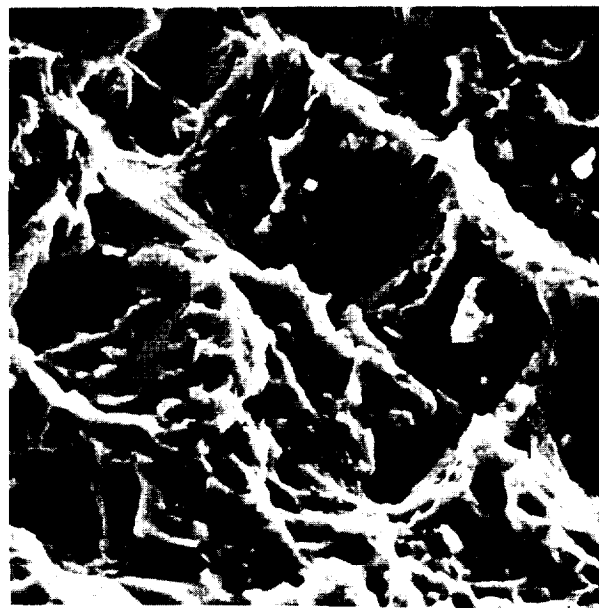
Fig. 43 - Appearance of Thermal Fatigue Fracture of TD-NiCr in the SEM.



SEM 8308

X300

(a)

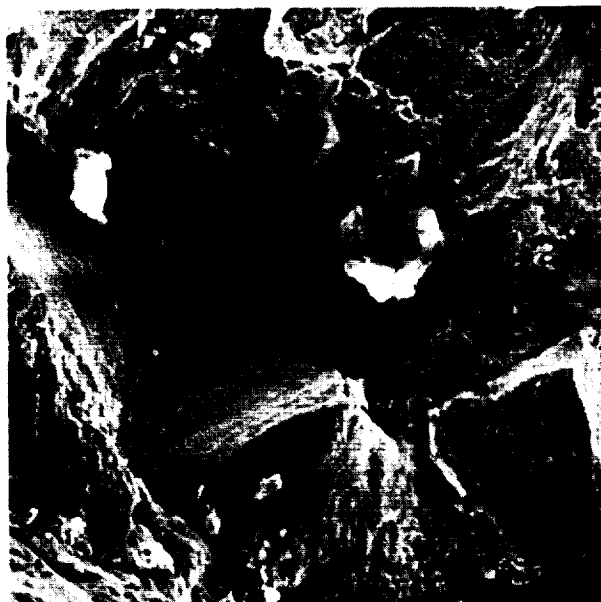


SEM 8306

X3000

(b)

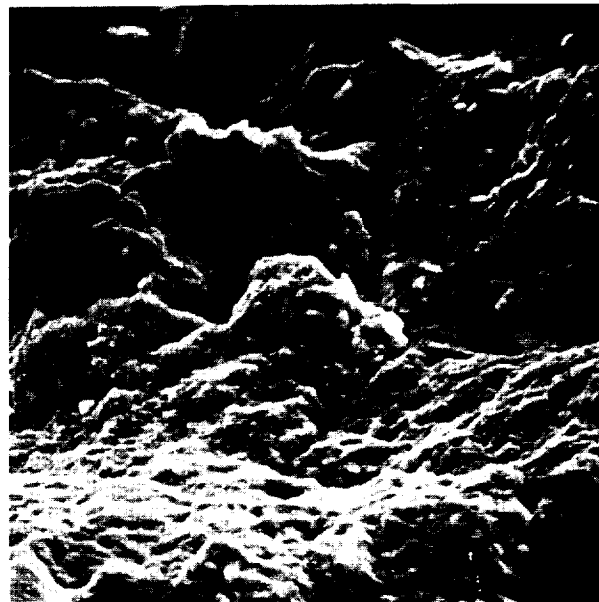
Fig. 44 - Appearance of Thermal Fatigue Fracture of Cast Udimet 700 in the SEM.



SEM 8365

X300

(a)



SEM 8303

X1000

(b)

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

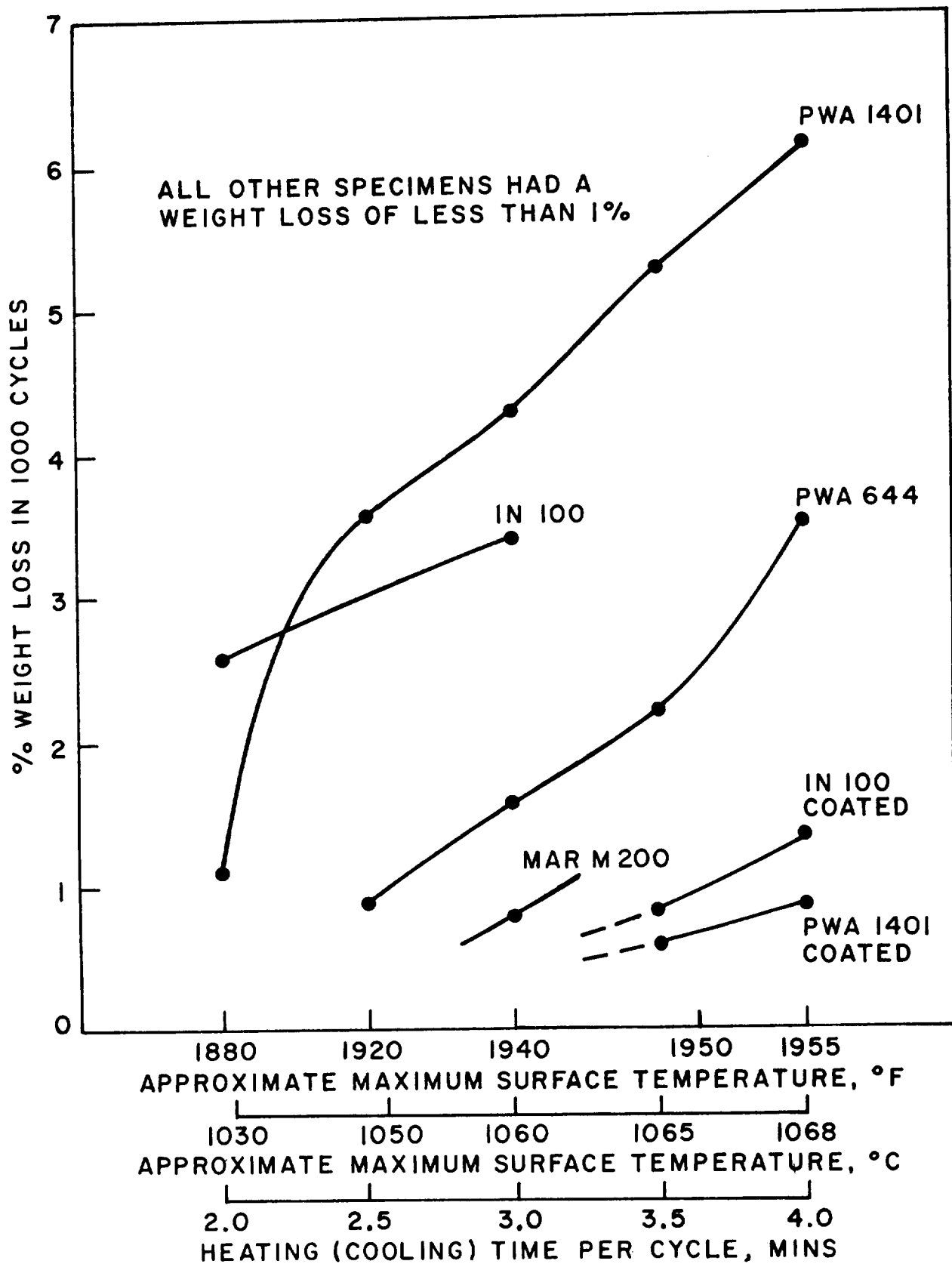


Fig. 46 - Weight Loss for 1000-Cycle Exposure.
Bed temperatures, 1990°F and 600°F.

