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DURABILITY TESTING OF COMMERCIAL CERAMIC MATERIALS FINAL REPORT

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A Unit of AlliedSignal Aerospace Company

January 1996

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTD.)

LIST OF FIGURES

LIST OF FIGURES (CONTD.)

LIST OF FIGURES (CONTD.)

LIST OF FIGURES (CONTD.)

LIST OF FIGURES (CONTD.)

LIST OF FIGURES (CONTD.)

LIST OF FIGURES (CONTD.)

LIST OF FIGURES (CONTD.)

LIST OF FIGURES (CONTD.)

LIST OF FIGURES (CONTD.)

LIST OF FIGURES (CONTD.)

LIST OF FIGURES (CONTD.)

LIST OF TABLES

LIST OF TABLES (CONTD.)

LIST OF TABLES (CONTD.)

LIST OF ABBREVIATIONS AND ACRONYMS

Acronym	Definition
ACC	AiResearch Casting Company, AlliedSignal Ceramic Components
AE	AlliedSignal Engines
AGT	Advanced Gas Turbine
AS	Aluminosilicate
AZ	Arizona
C	Celsius
cm	Centimeter
cm^3	Cubic Centimeters
Co.	Company
Corp.	Corporation
DF-2	Diesel Fuel No. 2
DoD	Dept. of Defense
DoE	Dept. of Energy
EDX	Energy Dispersive X-Ray
F	Fahrenheit
GE	General Electric Company
g	Grams
GTE	General Telephone and Electronics Sylvania Laboratories, Inc.
HA188	Haynes Alloy 188
HIP	Hot Isostatic Press
hrs	Hours
Jet A	Jet Petroleum Fuel Grade "A"
ksi	Thousands of Pounds Per Square Inch
LAS	Lithium Aluminosilicate
MA	Massachusetts
MI	Michigan
mm	Millimeter
N	Nitrogen
NAC	Norton Advanced Ceramics Company
NASA	National Aeronautics and Space Administration
No.	Number
NY	New York
O	Oxygen
OH	Ohio
PA	Pennsylvania
pp.	Pages
PSC	Pressure Slip Cast
Pt	Platinum

LIST OF ABBREVIATIONS AND ACRONYMS (CONTD.)

Acronym	Definition
qty.	Quantity
RBSN	Reaction-Bonded Silicon Nitride
Rh	Rhodium
rms	Root Mean Square
rpm	Revolutions Per Minute
SEM	Scanning Electron Microscope
Si	Silicon
SiC	Silicon Carbide
Si-SiC	Siliconized Silicon Carbide
Si_3N_4	Silicon Nitride
SRBSN	Sintered Reaction Bonded Silicon Nitride
TBC	Thermal Barrier Coating
TiB_2	Titanium DiBoride
U.S.	United States
Vol.	Volume
WDX	Wavelength Dispersive X-Ray
X	Times Magnification
Y	Yttrium
Y_2O_3	Yttrium Oxide
α-SiC	Alpha Phase Silicon Carbide
β-SiC	Beta Phase Silicon Carbide
μ inch	Micro Inches (One-Millionth of an Inch)
μm	Microns (One-Thousandth of a Millimeter)

FOREWORD

This document, prepared by AlliedSignal Engines, Phoenix, AZ, a division of AlliedSignal Aerospace Company, is the Final Report for the Durability Testing of Commercial Ceramic Materials Program. The program was conducted for the U.S. Department of Energy (DoE) and administered by the National Aeronautics and Space Administration (NASA) under Contract No. DEN3-27. This report covers the period from February 1978 through September 1995.

ACKNOWLEDGMENTS

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FINAL REPORT

DURABILITY TESTING OF COMMERCIAL CERAMIC MATERIALS (Contract No. DEN3-27)

1.0 SUMMARY

This document is the Final Report for the Durability Testing of Commercial Ceramic Materials Program. This program was conducted by AlliedSignal Engines (AE), Phoenix, AZ, a division of AlliedSignal Aerospace Company, and its predecessors,[(1,2)*] for the U.S. Department of Energy (DoE) with administration by the National Aeronautics and Space Administration (NASA) Lewis Research Center, Cleveland, OH under Contract No. DEN3-27. The objective of the program, initiated in 1978, was to evaluate commercially-available ceramic structural materials for suitability in gas turbine engines. Cyclic thermal tests were conducted in a hot combustion environment at temperatures up to 1371C (2500F) for periods up to 3500 hours. These conditions were selected to simulate the severe environment that would typically be encountered by the hot flowpath components in an automotive gas turbine engine.

To accomplish the test objectives of this program, four hot burner cyclic test rigs and associated control systems were designed, fabricated, and installed at the AlliedSignal Engines Engineering Test Laboratory in Phoenix, AZ. Each of these test rigs can simultaneously expose up to 24 ceramic test specimens to a high-velocity, high-temperature burner discharge, followed by cool air quenching, for controlled, repetitive cycles. The configuration of the ceramic test specimen bars was designed to accommodate destructive flexure strength test measurements after completion of the cyclic exposures, as well as measurements of any weight or dimensional changes. Photographs of the test specimens were taken to document their condition, and detailed fractographic examinations were conducted following the destructive strength tests.

During the 18-year span of the test program (from February 1978 through September 1995), a total of 29 advanced structural ceramic materials were evaluated in the AE burner rig test facility, and 40 cyclic oxidation exposure durability test series were conducted. The materials evaluated under this program are listed in Table 1. The first column in the table lists the section number of this document in which test results on the particular material may be found.

The cyclic oxidation durability tests performed under this program have been beneficial in identifying ceramic structural materials capable of long-term use in a gas turbine engine environment, and have provided information for direct comparisons of newly-developed materials with those tested earlier in the program. Additionally, this testing has been successful in screening out materials with catastrophic stability problems that otherwise could have gone undetected through the component development process until engine testing was performed.

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* References are listed in Section 8.0

For these reasons, completion of a cyclic oxidation burner rig test before consideration of any ceramic material candidate for use in development or production engine applications is recommended.

TABLE 1. CERAMIC MATERIALS EVALUATED.

Sect	Manufacturer	Designation	Material
6.1	AiResearch Casting Company	RBN101	Reaction Bonded Silicon Nitride (RBSN)
6.2	AiResearch Casting Company	RBN104	Reaction Bonded Silicon Nitride (RBSN)
6.3	AiResearch Casting Company	Code 2	Sintered Silicon Nitride
6.4	AlliedSignal Ceramic Components	GN-10	Hot Isostatically Pressed (HIPped) Silicon Nitride
6.5	Carborundum Co.	Hexoloy KX01	Siliconized Silicon Carbide (Si-SiC)
6.6	Carborundum Co.	Hexoloy SA	Sintered Alpha Silicon Carbide (α-SiC)
6.7	Carborundum Co.	Hexoloy ST	Titanium Diboride Toughened Sintered Silicon Carbide
6.8	Corning Glass Works	Code 9458	Lithium Aluminosilicate (LAS)
6.9	Ford Motor Co.	Ford RBSN	Reaction Bonded Silicon Nitride (RBSN)
6.10	General Electric Co.	GE β-SiC	Beta (β)-Sintered Silicon Carbide
6.11	GTE Laboratories	AY6	Sintered Silicon Nitride
6.12	GTE Laboratories	PY6	Sintered Silicon Nitride
6.13	Kyocera Ceramics Corp. (Japan)	SC-201	Silicon Carbide (SiC)
6.14	Kyocera Ceramics Corp. (Japan)	SN-250M	Sintered Silicon Nitride
6.15	Kyocera Ceramics Corp. (Japan)	SN-251	Sintered Silicon Nitride
6.16	Kyocera Ceramics Corp. (Japan)	SN-252	Sintered Reaction Bonded Silicon Nitride
6.17	Kyocera Industrial Ceramics Corp.	SN-253	Sintered Silicon Nitride
6.18	Kyocera Ceramics Corp. (Japan)	SN-260	Sintered Silicon Nitride
6.19	Kyocera Ceramics Corp. (Japan)	SN-281	Sintered Silicon Nitride
6.20	NGK Insulators (Japan)	SN-50	Sintered Silicon Nitride
6.21	NGK Insulators (Japan)	SN-82	Sintered Silicon Nitride
6.22	NGK Insulators (Japan)	SN-84	Sintered Silicon Nitride
6.23	NGK Insulators (Japan)	SN-88	Sintered Silicon Nitride
6.24	Norton Co.	NCX-34	Hot Pressed Silicon Nitride
6.25	Norton Advanced Ceramics	NT-154	HIPped Silicon Nitride
6.26	Norton Advanced Ceramics	NT-164	HIPped Silicon Nitride
6.27	Norton Advanced Ceramics	NT-230	Siliconized Silicon Carbide (Si-SiC)
6.28	Pure Carbon Co.	Refel	Siliconized Silicon Carbide (Si-SiC)
6.29	Toshiba Corp. (Japan)	Toshiba Si_3N_4	Sintered Silicon Nitride

2.0 INTRODUCTION

Operational testing has confirmed that significant improvement in gas turbine engine operating efficiencies can be obtained through the use of uncooled ceramic components operating at material temperatures above those typically attainable with present high-temperature metallic alloys. Both the U.S. Department Of Energy (DoE) and Department Of Defense (DoD) advanced turbine engine development programs have provided evidence that improved performance can be realized with the use of ceramic turbine components.[3,4,5] However, these programs have also demonstrated that an expanded technology base is required to achieve reliable, cost-effective ceramic components.

During the past two decades, a number of programs have focused on introducing ceramic materials, such as silicon nitrides (Si_3N_4), silicon carbides (SiC), and alumino silicates (AS) into gas turbine engines. Much of the materials characterization testing performed at high temperature on these materials has been conducted in relatively clean environments, such as inert gas or static air. However, the kinetics of oxidation may differ greatly in the cyclic combustion environment seen by hot flowpath surfaces inside gas turbine engines. For ceramics, this is analogous to the corresponding situation for metallic technology, where the mechanisms and rates of oxidation can vary markedly, depending upon the temperature, the quality of the environment, and the composition and structure of the materials.[6] However, the mode of deterioration in ceramics is different than for metals. Metals are life-limited in oxidation and corrosion by material removal and the resulting losses suffered in engine performance. Ceramic materials have much slower material removal rates, but are life-limited by the formation of surface flaws that reduce the effective material strength. If strength loss is excessive, catastrophic failure of the ceramic component can result.

A necessary prerequisite to the accurate prediction of ceramic component life and achievement of system reliability is an understanding of ceramic material behavior in environments truly representative of actual engine operating conditions. The objective of the present program was to evaluate the long-term oxidation durability of selected structural ceramic materials in cyclic exposures to a gas burner environment at temperatures up to 1371C (2500F), with cumulative exposures up to 3500 hours. These conditions were selected to simulate the severe environment that would typically be encountered by hot flow path components in an automotive gas turbine engine. The ceramic materials chosen for evaluation were selected as representing existing and developing silicon nitride (Si_3N_4), silicon carbide (SiC), and alumino-silicate (AS) materials technology, suitable for gas turbine applications.

3.0 MATERIALS TESTED

3.1 Material Selection

The ceramic materials selected for testing in this program comprised a representative sampling of new and developing silicon nitride (Si_3N_4), silicon carbide (SiC), and alumino-silicate (AS) ceramic materials technology. All materials considered for this oxidation/durability testing were established candidates for use under the U.S. DoE "Turbine Engine Propulsion Systems For Highway Vehicles" programs. Test specimens of 29 advanced structural ceramic materials were procured for evaluation in 40 cyclic oxidation durability exposure tests. Several materials were used in multiple durability tests, to evaluate multiple exposure temperatures, with different surface conditions (machined and as-processed), and/or later vintages of materials offering potential improvements over previously-tested versions. The different material and test combinations comprising the 40 cyclic oxidation durability tests performed under this program are summarized in Table 2.

3.2 Specimen Fabrication

Specimen schematics for the ceramic baseline and durability tests are shown in Figures 1 and 2, respectively. Both specimen types have a nominal cross-section of 6.35 x 3.175 mm (0.250 x 0.125 inch). The baseline test specimens measured 50.8 mm (2.0 inches) in length; the durability test specimens were 101.6 mm (4.0 inches) in length and contained a rounded notch for fixturing in a position approximately 12.7 mm (0.5 inch) from one end of the specimen. All final machining was performed parallel to the longitudinal axis of the specimen with 320-grit diamond or finer grinding wheels. The long edges of the test bars were chamfered 0.127 to 0.254 mm (0.005 to 0.010 inch) at a 45-degree angle. Preferably, one side of each test specimen was left in the as-processed (unmachined) condition. In some instances, the fabrication capability could not accommodate manufacture of as-processed surface test specimens, so fabrication of fully-machined test specimens was permitted.

TABLE 2. SUMMARY OF CERAMIC MATERIALS AND DURABILITY TESTS.

Manufacturer	Material Designation	Material	Vintage, Mo/Yr	Surface	Exposure Temperature	Comments
AiResearch Casting Co.	RBN101	Reaction Bonded Silicon Nitride (RBSN)	6/78	Machined	1204C (2200F)	---
			6/78	Machined	1371C (2500F)	---
			6/78	Machined	1371C (2500F)	Repeat Test
AiResearch Casting Co.	RBN104	RBSN	12/80	As-Processed	1371C (2500F)	---
AiResearch Casting Co.	Code 2	Sintered Silicon Nitride	3/85	As-Processed	1204C (2200F)	---
AlliedSignal Ceramic Components	GN-10	Hot Isostatically Pressed (HIPped) Silicon Nitride	5/89	Machined	1204C (2200F)	---
Carborundum Co.	Hexoloy KX01	Siliconized Silicon Carbide (Si-SiC)	4/83	As-Processed	1204C (2200F)	---
Carborundum Co.	Hexoloy SA	Sintered Alpha Silicon Carbide (α-SiC)	6/78	Machined	1204C (2200F)	---
			6/78	Machined	1371C (2500F)	---
			6/78	Machined	1371C (2500F)	Repeat Test
			7/83	As-Processed	1371C (2500F)	---
Carborundum Co.	Hexoloy ST	Titanium Diboride (TiB2) Toughened Silicon Carbide	10/87	As-Processed	1204C (2200F)	---
			10/88	As-Processed	1260C (2300F)	---
Corning Glass Works	Code 9458	Lithium Aluminosilicate (LAS)	8/81	Machined	1093C (2000F)	---
Ford Motor Co.	Ford RBSN	RBSN	11/82	As-Processed	1204C (2200F)	---
General Electric Co.	GE β–SiC	Sintered Beta Silicon Carbide (β–SiC)	12/84	As-Processed	1371C (2500F)	---
GTE Laboratories	AY6	Sintered Silicon Nitride	7/83	Machined	1204C (2200F)	---
GTE Laboratories	PY6	Sintered Silicon Nitride	4/81	Machined	1204C (2200F)	---
			1/90	As-Processed	1204C (2200F)	HIPped Version Of PY6
Kyocera Ceramics Corp.	SC-201	Sintered Silicon Carbide	5/84	As-Processed	1371C (2500F)	---
Kyocera Ceramics Corp.	SN-250M	Sintered Silicon Nitride	10/86	Machined	1204C (2200F)	---
Kyocera Ceramics Corp.	SN-251	Sintered Silicon Nitride	2/90	Machined	1204C (2200F)	---
Kyocera Ceramics Corp.	SN-252	Sintered RBSN (SRBSN)	5/90	Machined	1204C (2200F)	---
Kyocera Industrial Ceramics Corp.	SN-253	Sintered Silicon Nitride	5/95	As-Processed	1316C (2400F)	---
Kyocera Ceramics Corp.	SN-260	Sintered Silicon Nitride	2/91	As-Processed	1260C (2300F)	---
Kyocera Ceramics Corp.	SN-281	Sintered Silicon Nitride	5/95	As-Processed	1316C (2400F)	---
NGK Insulators	SN-50	Sintered Silicon Nitride	9/84	As-Processed	1204C (2200F)	---
NGK Insulators	SN-82	Sintered Silicon Nitride	1/86	As-Processed	1204C (2200F)	---
NGK Insulators	SN-84	Sintered Silicon Nitride	9/87	Machined	1204C (2200F)	---
NGK Insulators	SN-88	Sintered Silicon Nitride	7/91	As-Processed	1260C (2300F)	---
Norton Co.	NCX-34	Hot Pressed Silicon Nitride	6/78	Machined	1204C (2200F)	---
			6/78	Machined	1371C (2500F)	---
Norton Advanced Ceramics (NAC)	NT-154	HIPped Silicon Nitride	10/88	Machined	1204C (2200F)	---
			4/90	Machined	1260C (2300F)	---
			9/93	As-Processed	1316C (2400F)	---
NAC	NT-164	HIPped Silicon Nitride	8/93	As-Processed	1316C (2400F)	---
NAC	NT-230	Si-SiC	5/91	As-Processed	1260C (2300F)	---
Pure Carbon Co.	Refel	Siliconized Silicon Carbide (Si-SiC)	10/78	Machined	1204C (2200F)	---
			10/78	Machined	1260C (2300F)	---
			10/78	Machined	1316C (2400F)	---
			10/78	Machined	1371C (2500F)	---
			10/81	Machined	1093C (2000F)	---
			10/81	As-Processed	1093C (2000F)	---
Toshiba Corp.	Toshiba Si_3N_4	Sintered Silicon Nitride	7/84	Machined	1204C (2200F)	---

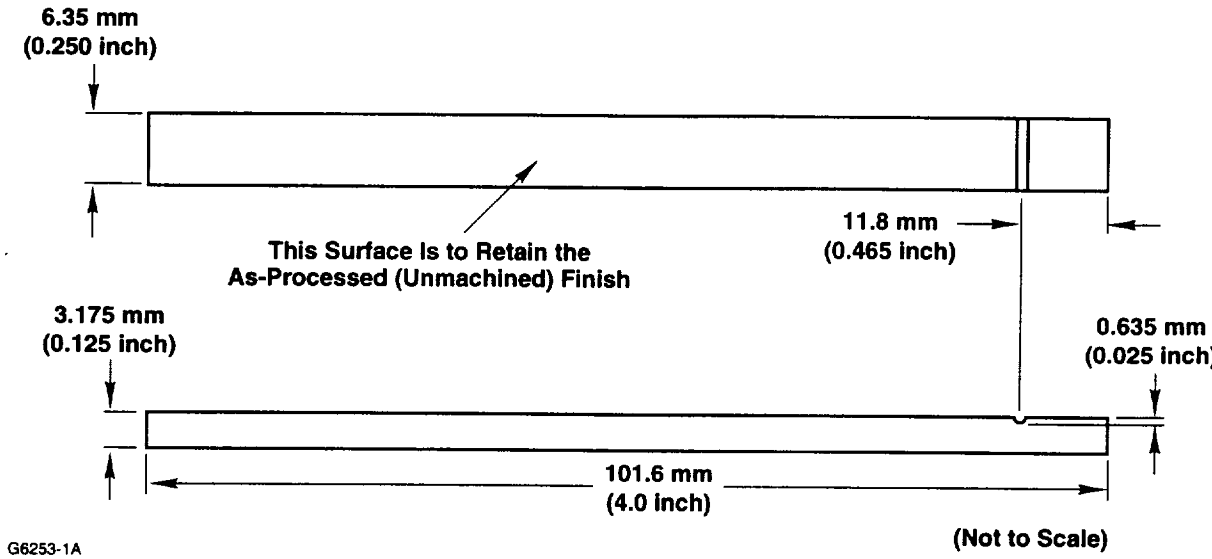

Figure 1. Schematic Of Ceramic Baseline Flexural Strength Test Specimens.

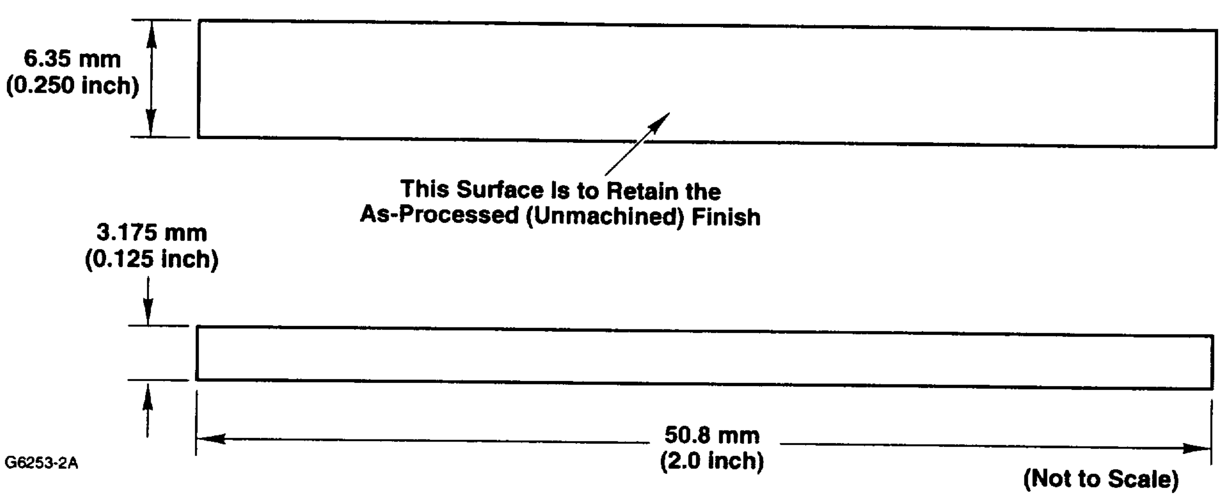

Figure 2. Schematic Of Ceramic Cyclic Oxidation Durability Test Specimens.

4.0 TEST FACILITIES AND EQUIPMENT

A test facility was specifically designed by AlliedSignal Engines (AE) to accomplish the long-term burner exposure testing required by this program. The burner test facility, located in the AE Engineering Test Laboratory in Phoenix, AZ consists of four burner rigs, each equipped with oil burners, firebrick-lined enclosures, and automatic fail-safe control systems. Each burner rig has an air-cooled specimen holder coated with a plasma-sprayed zirconia thermal barrier coating (TBC) which can be used to test 24 test specimens simultaneously.

4.1 Burner Rigs

Each of the four burner rigs consists of a Trane Thermal Company Model 2070 or 2085 high-velocity oil burner, a furnace enclosure, a specimen holder with drive and actuation systems, and associated cycle and temperature controls. The burners originally were operated using Jet A fuel, but since 1980, DF-2 diesel fuel has been used. A schematic illustration of the burner rig facilities is shown in Figure 3.

With this system, the elevated-temperature atmosphere is produced by the oil burner and furnace enclosure. Thermal cycling is accomplished by moving the specimen holder in and out of the furnace enclosure through a specimen port. After specimen withdrawal, cooling air is directed onto the test bars to reduce the temperature to the required 204C (400F). The specimen holder rotates at approximately 100 rpm, to ensure that all the specimens are exposed to similar conditions.

The furnace enclosure, illustrated in Figures 4 and 5, is fabricated from six-inch thick firebrick encased in stainless steel sheeting. Ports are provided in the enclosure assembly for burner installation, specimen holder insertion, pyrometer sighting, burner control, and hot gas exhaust. After specimen withdrawal, a sliding door on each specimen port closes to prevent furnace heat loss and to allow rapid specimen cooling.

The specimen holder actuation drive system provides direct drive to the specimen holder and allows an instrumented specimen holder and slip ring assembly to be mounted on the drive shaft for temperature calibration. The gearbox and motor drive are mounted on a baseplate supported by two slide shafts and ball bearing slides. For specimen translation into or out of the enclosure, the baseplate is moved with a pneumatic actuator.

The burner rig control system, illustrated in Figure 6, allows continuous, unattended cyclic testing. Originally, Mikron Instrument Company, Model 66, infrared pyrometers and Honeywell proportional controllers were used to monitor the specimen temperature and to control the burner heat output. After five years of continuous service, these instruments were replaced with Leeds and Northrup Electromax V microprocessor-controlled controllers and Williamson dual-wavelength optical pyrometers.

Additional fail-safe features of the burner rig facility include:

- A Fireye Combustion Controls ultraviolet scanner focused on the burner flame to initiate shutdown if a flameout should occur
- A rotation monitor to ensure that the specimen holder will not be inserted into the furnace if rotation stops
- A door-position monitor to ensure that the specimen holder cannot be actuated into the furnace unless the door is open
- An independent temperature sensing system located near the specimen holder, which is adjustable to a set input utilizing a thermocouple in the gas stream, to detect any possible over-temperature conditions and cause the specimens to be removed from the furnace
- External fuel shutoffs and safety features, included in the facility design.

4.2 Specimen Holders

To survive the planned long-term, high-temperature exposures, the air-cooled specimen holders were specially designed for use in this program. The specimen holder, illustrated in Figures 7 through 9, is designed to provide ceramic specimen support with minimal stress-concentrating effects and proper instrumentation cable routing for system calibration, as well as to endure the cyclic temperature extremes.

The specimen holder design incorporates a cylindrical Haynes HA188 cobalt-based superalloy housing, in which an HA188 body is positioned. The perimeter of this body is slotted, to accommodate fixturing of up to 24 ceramic specimens at one time. A tapered, slotted specimen spacer, located between the housing and body, provides additional support for the test bars and also provides room for a compressible ceramic packing material (woven ceramic fiber). When compressed between the body and specimen spacer, this packing material provides uniform radial pressure on each ceramic test bar. The ceramic test bars are then held firmly between the packing material and the outer housing. Compressive loading is maintained between the housing and body by conical spring washers regulated with an adjustment nut. The exposed surfaces of the specimen holder are flame-spray-coated with a Metco 201 BNS calcia-stabilized zirconia thermal barrier coating (TBC) for protection.

Air cooling and instrumentation passages are provided through the hollow body and housing shafts. Coolant air travels through the body shaft, through coolant passages in the specimen spacer, between and around the test bars, and then exits through ports in the housing. Coolant air is directed away from the high-temperature environment by the housing skirt. This airflow direction is noted on Figure 7.

The air-cooled specimen holder results in a large specimen thermal gradient, simulating the thermal gradients that turbine engine components may see; this provides the capability for qualitative assessment of material oxidation and corrosion over a broad temperature range.

4.3 Calibration

To ensure that the ceramic test bars reaches the required test temperatures during both the elevated-temperature exposures and cool-down periods, an instrumented specimen holder and slip ring assembly were fabricated. This instrumented assembly was used to calibrate the temperature control system during burner rig and facility checkout. The assembly is illustrated in Figures 10 and 11. The assembly consists of a modified specimen holder with a Lebow four-channel slip ring. Instrumentation consists of high-temperature platinum/platinum-rhodium (Pt/Pt-Rh) thermocouples imbedded in the faces of three ceramic specimens and connected to the slip ring assembly. The assembly is mounted on the drive shaft and actuation system in the same manner as the non-instrumented specimen holders. Thus, the instrumentation "package" does not require dismantling after each use, is usable on any of the four test rigs, and can be replaced with the other specimen holders carrying actual test bars without disturbing any burner control settings.

Once the instrumented specimen holder accuracy is confirmed, the burner rig control pyrometer is calibrated. This is accomplished with the instrumented specimen holder, by adjustment of the burner rig control pyrometer range and emissivity until the temperature controller reading matches that of the test bar thermocouples.

Thermal test cycle evaluations also were performed with the instrumentation package, to confirm that the ceramic test bars were cycled between the upper and lower temperature limits in the specified time. Test bar cycle temperatures were obtained by recording the instrumented test bar thermocouple outputs as the cycle sequence was performed.

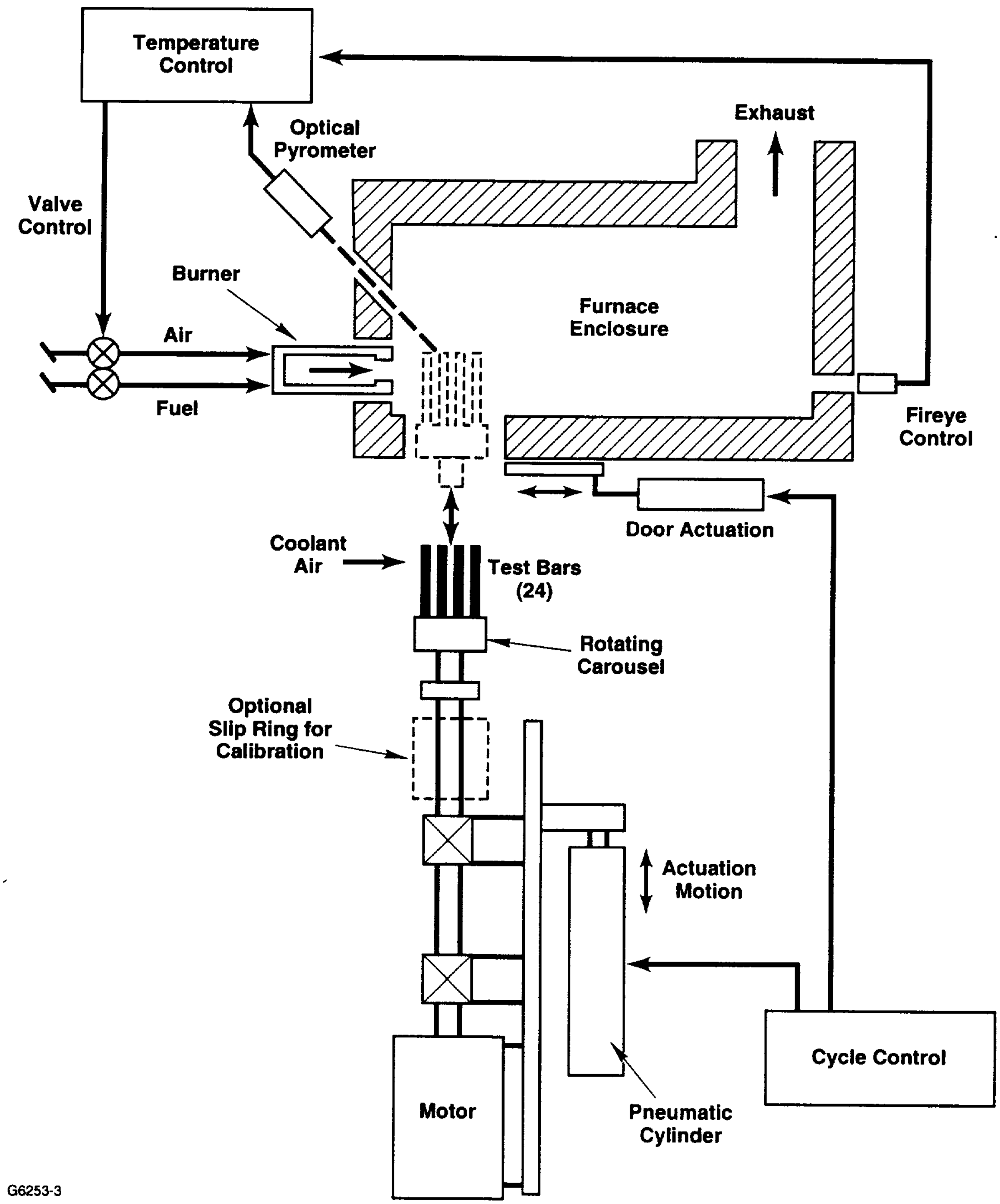

Figure 3. Schematic Of Ceramic Oxidation Durability Test Facility.

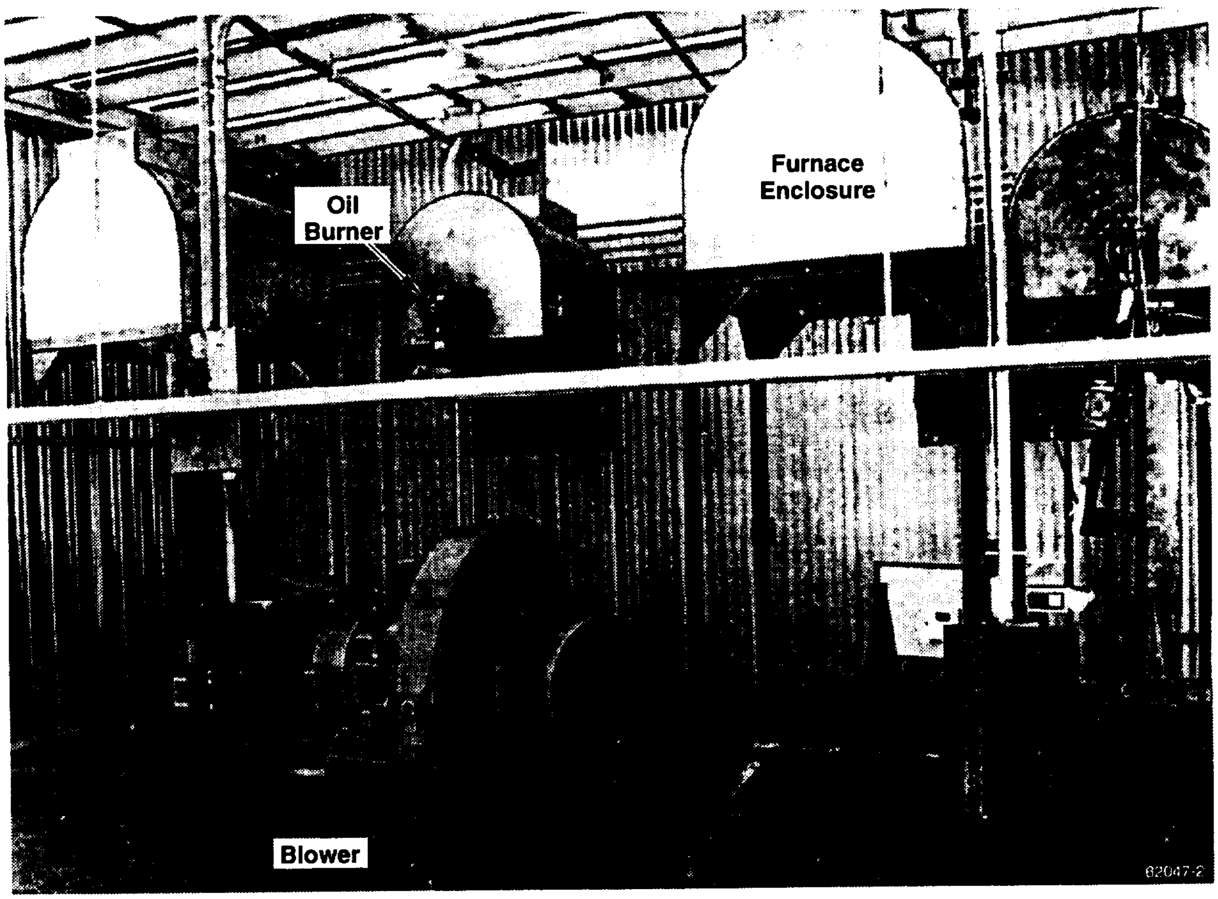

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Figure 4. View Of Burner Rig Test Facility (Prior To Installation Of Fuel And Air Supply).

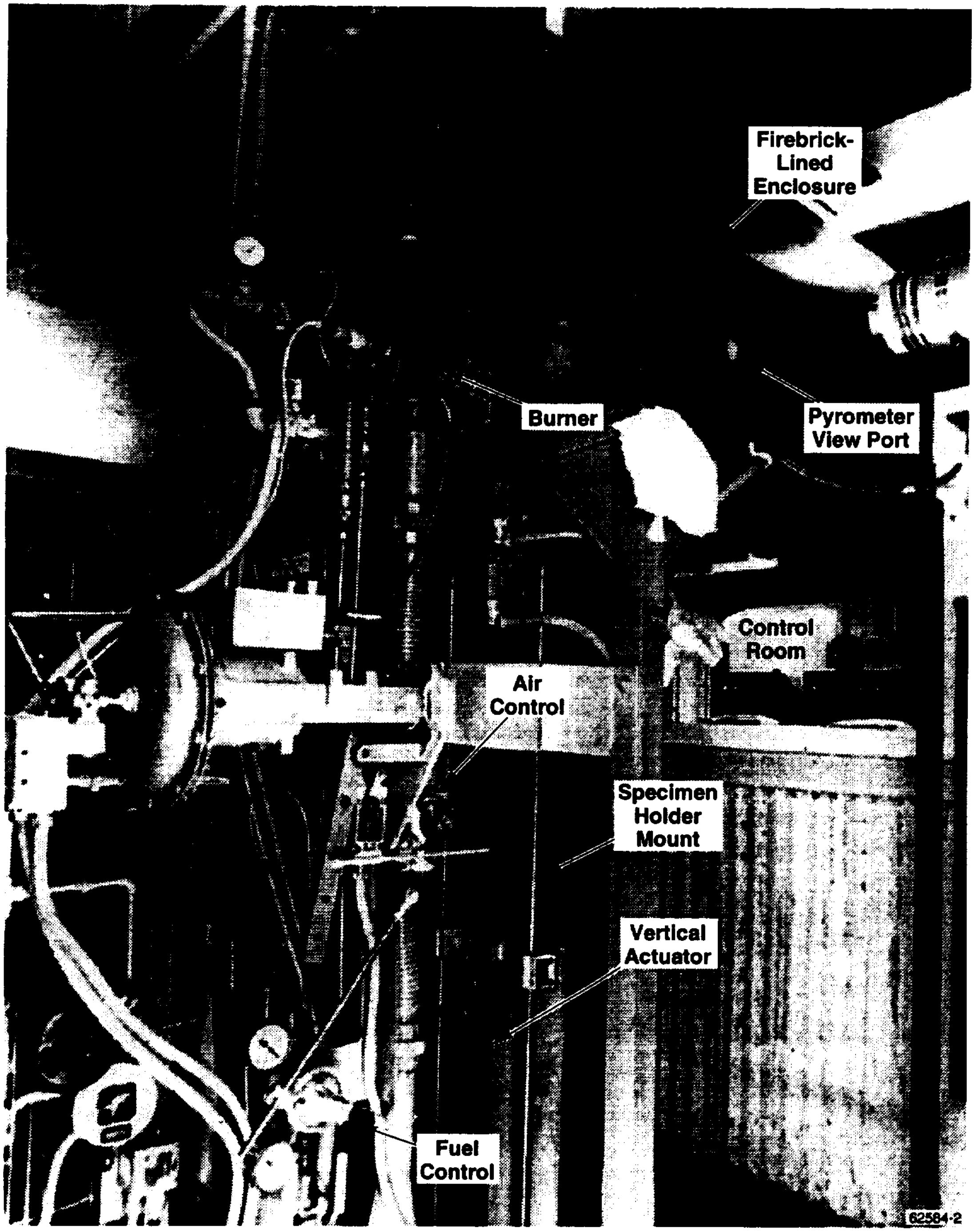

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Figure 5. Cyclic Oxidation Durability Test Rig No. 1.

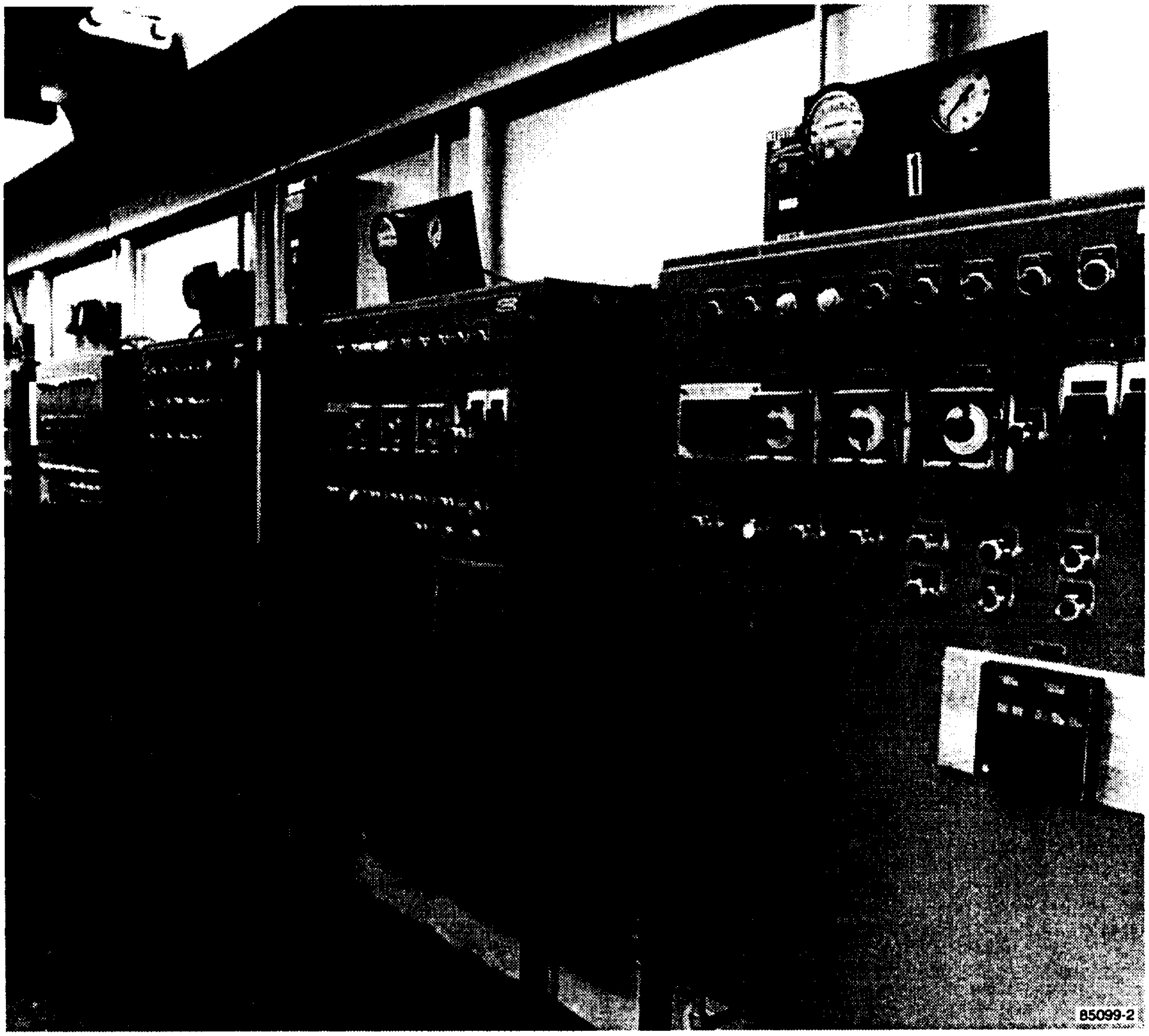

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Figure 6. Cyclic Oxidation Durability Test Facility Control Room.

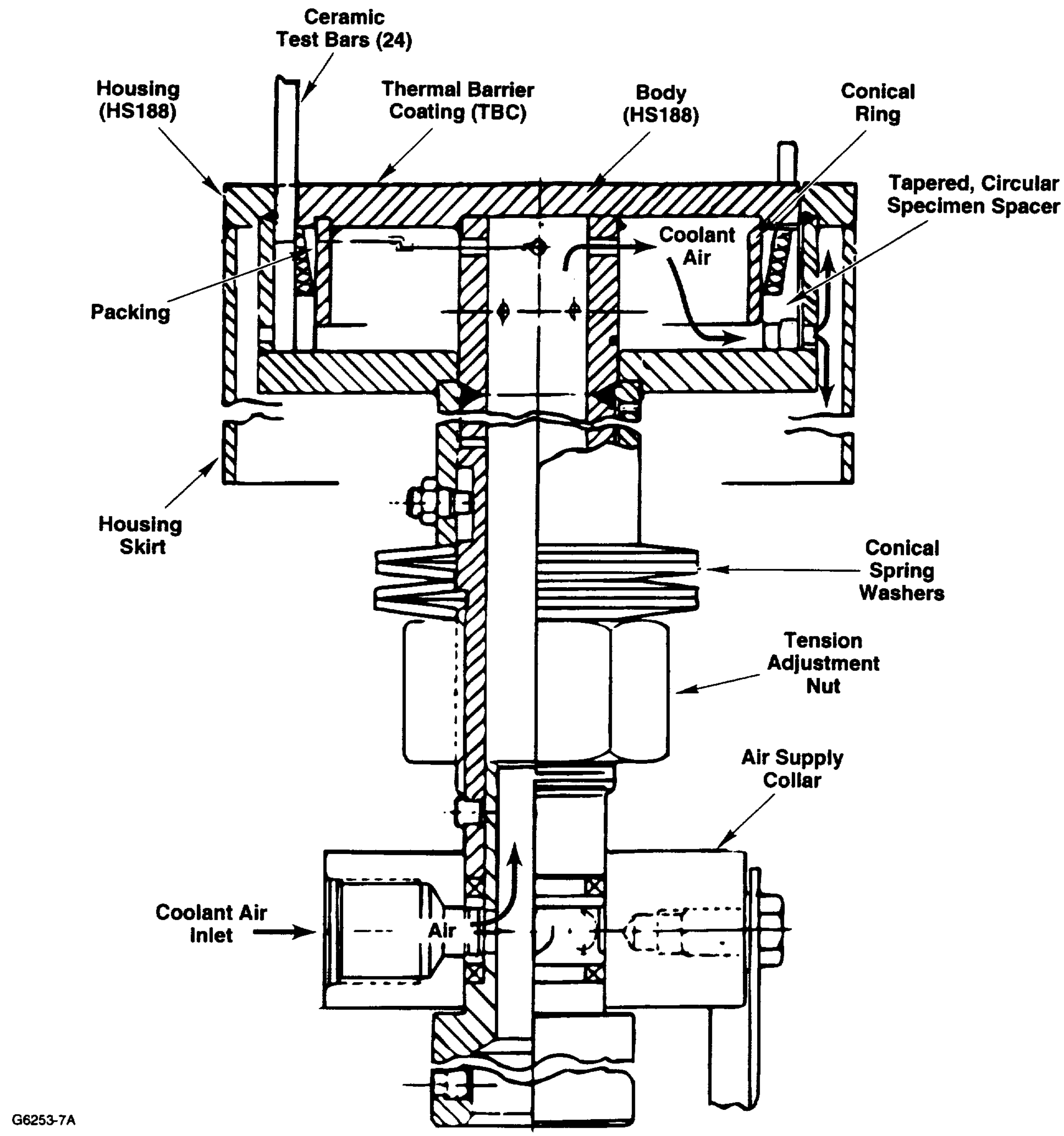

Figure 7. Schematic Of Air-Cooled Specimen Holder For Ceramic Test Bars.

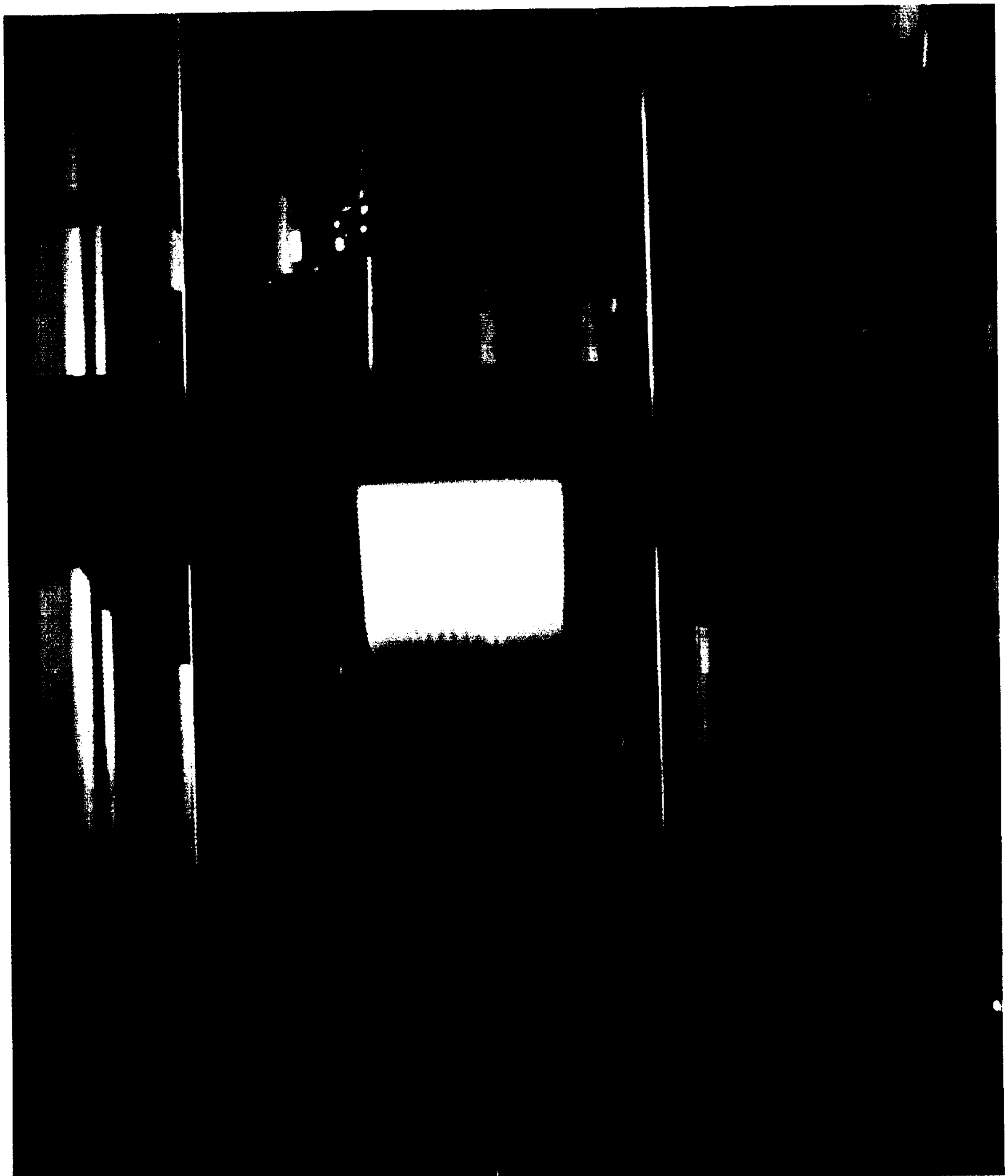

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Figure 8. Specimen Holder With Specimens Installed, During Durability Temperature Quench Test Cycle (Removed From Furnace Enclosure).

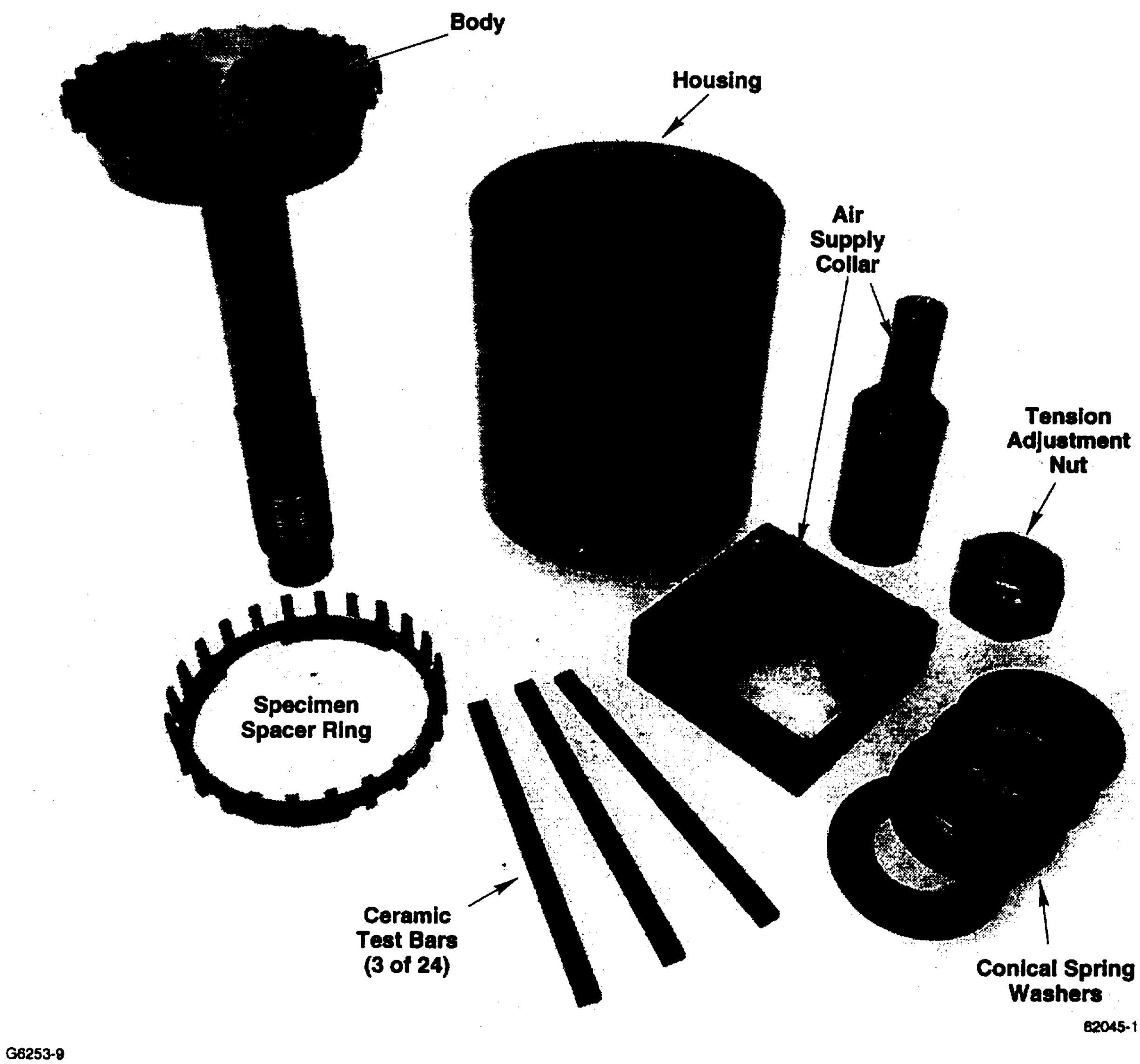


Figure 9. High-Temperature Specimen Holder Components.

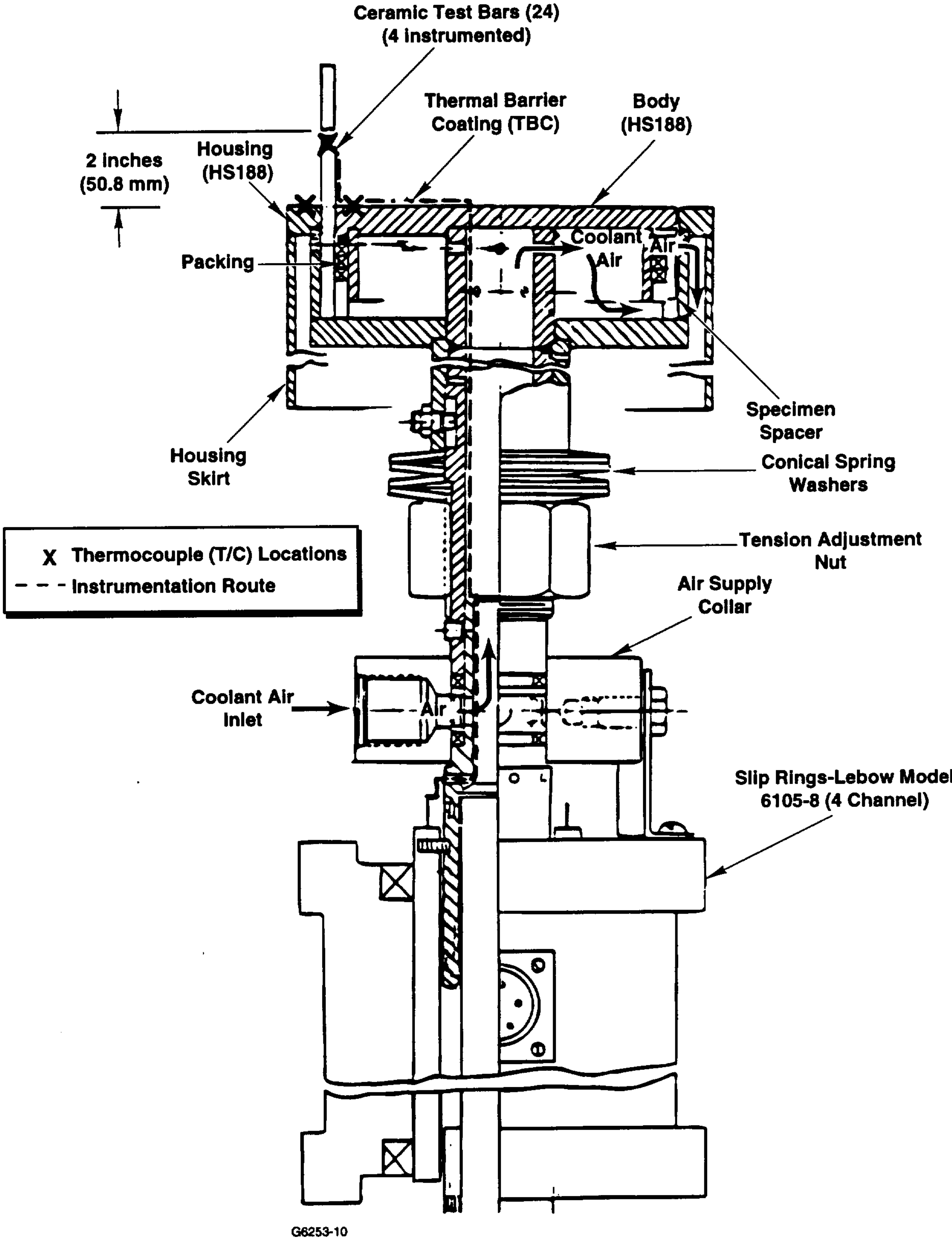


Figure 10. Schematic Of Instrumented Specimen Holder Assembly.

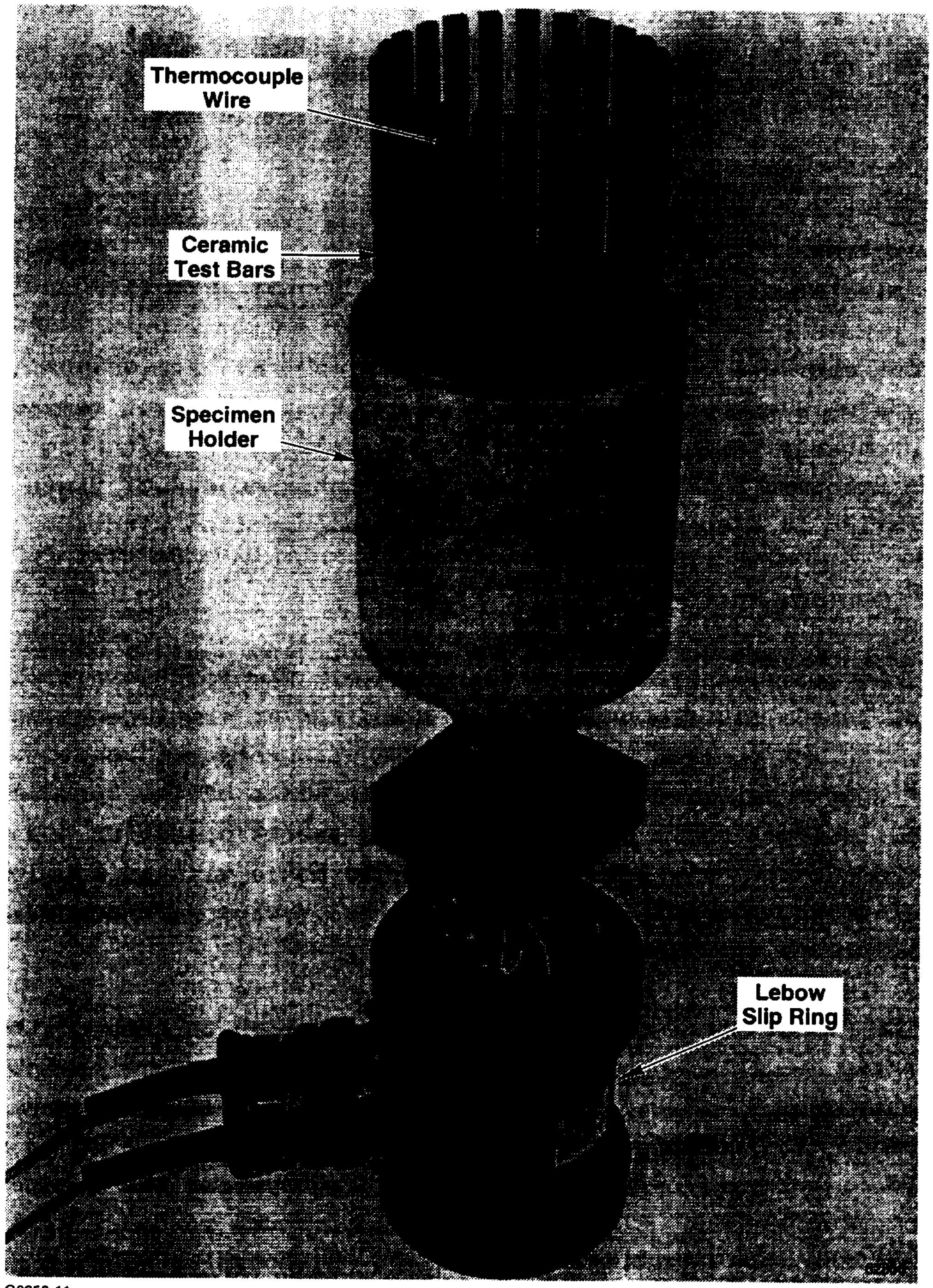


Figure 11. Instrumented Ceramic Test Specimen Holder.

5.0 TEST PROCEDURES

5.1 Pre-Exposure Evaluations

Baseline flexure strength values for all the ceramic materials tested were obtained at both room and elevated temperature, utilizing quarter-point bending tests. From 1978 through 1980, the baseline elevated-temperature flexure strength tests were conducted at 1204C (2200F). After 1980, the baseline elevated-temperature flexure tests were performed at the same temperature used for the cyclic oxidation durability test cycles for the particular material. The results of the baseline flexure strength tests for each of the materials are summarized in Section 6. The complete baseline flexure test results are given in Appendix I.

The baseline flexure strength values were determined using an inner span of 19.05 mm (0.75 inch) and an outer span of 38.10 mm (1.50 inch) at a cross-head displacement rate of 0.5 mm (0.02 inch) per minute. Twelve test bars of each material were tested at each test temperature. The elevated-temperature tests were conducted in a static air environment using a 10-minute soaking period at temperature prior to flexure test loading. All of the test bars were dimensionally inspected, weighed, and measured for density.

Following flexure testing to failure, optical fractography was performed on all of the baseline flexure strength test specimens to identify the fracture origins. Scanning electron microscopy (SEM) was performed on selected baseline strength specimen fracture surfaces to better document the typical fracture-originating flaws. Typical photomicrographs for the various materials are presented in Section 6.0 of this report.

5.2 Durability Exposures

All test bars to be exposed were cleaned prior to assembly into the burner rig specimen holders. Prior to each exposure sequence, the burner rig temperature controls were calibrated, using the instrumented specimen holder. After the calibration, the specimen holder carousels loaded with specimens were mounted on individual burner rigs adjusted to operate at the selected test temperature. The test cycle consisted of heating the test specimens to the specified test temperature within 30 seconds; holding at the selected temperature for 11 minutes, and then forced-air quenching to 204C (400F) in 30 seconds. Five thermal cycles were completed per hour.

Three primary test schedules for the cyclic oxidation durability test exposures were used over the 18-year span of this program, as shown in Figure 12. For tests performed from the inception of the program in 1978 until 1980, durability exposures of increasing duration were performed in series. Initially, twelve specimens each of two materials were assembled into the specimen holder and exposed for 350 hours. The test specimens were then evaluated for room-temperature retained strength. If the specimens had retained more than 50 percent of the baseline flexure strength, a 1050-hour test was conducted using new specimens of the same materials, followed by post-exposure strength testing at room temperature. If the materials exhibited greater than 50-percent strength retention after 1050 hours of exposure, a third test of 2100 hours duration was performed with additional specimens, again followed by post-exposure strength testing at room temperature.

Four ceramic materials were evaluated concurrently between 1978 and 1980. All the materials were evaluated at exposure temperatures of 1204C (2200F) and 1371C (2500F). The material exhibiting the best overall durability was then selected for 3500-hour exposure tests. For these tests, the test specimen carousel was loaded with 24 new specimens of the selected material. Following 3500 hours of exposure, 12 specimens each were tested for retained strength at room temperature and 1204C (2200F).

Since 1980, all durability testing was performed using a staggered test sequence, in which some of the test specimens were removed and replaced with new specimens at scheduled intervals. The test schedule for the 3500-hour tests performed after 1980 is shown in Figure 12. Initially, 24 test specimens were assembled into a test carousel and exposed for 350 hours. After 350 hours exposure, 6 of the test bars were removed for evaluation and replaced with 6 new, unexposed bars. Similarly, at 1400, 2100, and 2450 hours, six additional test bars were removed and replaced with new, unexposed bars. At the completion of 3500 hours of exposure, a total of 48 test bars had been exposed: 12 bars each for 350, 1050, 2100, and 3500 hours of exposure, respectively.

In 1984, the program transitioned to a 1050-hour durability test cycle. The test results from previous years indicated the cyclic durability exposure test sufficiently identified any major material problems within the first 350 hours of exposure. Also, durability exposures beyond 1050 hours typically provided little additional information with respect to oxidation durability. This change to a 1050-hour test cycle also permitted evaluation of more materials within the program funding limits. In the 1050-hour test, similar to the staggered 3500-hour test, 24 test specimens were assembled into a test carousel and exposed for 350 hours. After 350 hours exposure, 12 of the initial 24 test bars were removed for evaluation and replaced with 12 new, unexposed bars. At the completion of 1050 hours of exposure, a total of 36 test bars had been exposed: 12 bars each for 350, 700, and 1050 hours of exposure, respectively.

Some of the test schedules for certain materials were modified from the above-described procedures, to accommodate low specimen quantities or other problems encountered during testing. These special circumstances are described in the applicable parts of Section 6.0.

5.3 <u>Post-Exposure Evaluations</u>

After completing the specified exposure duration, the loaded specimen holders were removed and disassembled. The post-exposure weights and dimensions of the exposed test specimens were measured for comparison with the baseline values for each specimen. The surface topography of the as-exposed specimens was examined and documented using scanning electron microscopy (SEM).

Quarter-point flexure strength testing was then performed on the exposed specimens to measure post-exposure retained strength. The test procedures were the same as described in Section 5.1 for the baseline strength tests. The exposed durability test bars were tested with the flame-impinged surface of the bar centered between the support spans and in tension. For the durability test specimens exposed in tests during the period 1978 through 1980, the retained strength tests for specimens with exposure durations up to 2100 hours were performed at room temperature only. Following the 3500-hour exposures, 12 specimens each were tested at room temperature and 1204C (2200F) for retained strength. For the durability tests performed after 1980, room-temperature and elevated-temperature retained strength tests were performed for all specimen exposure durations. For each exposure duration, 12 specimens each were tested at room temperature and elevated temperature. Following 1980, the elevated-temperature retained strength flexure tests were performed at the same temperature used for the cyclic oxidation durability test exposures. The post-exposure strength test results for each material tested are summarized in Section 6. The complete post-exposure flexure strength test data is provided in Appendix II.

Following flexure strength testing, optical fractography was performed on all the post-exposure strength test specimens to identify the fracture origins for comparison with the baseline fracture characteristics. SEM was performed on selected post-exposure specimen strength test fracture surfaces to better document the typical fracture-originating flaws. Typical photomicrographs of the fracture surfaces are given following the text, at the end of Section 6.

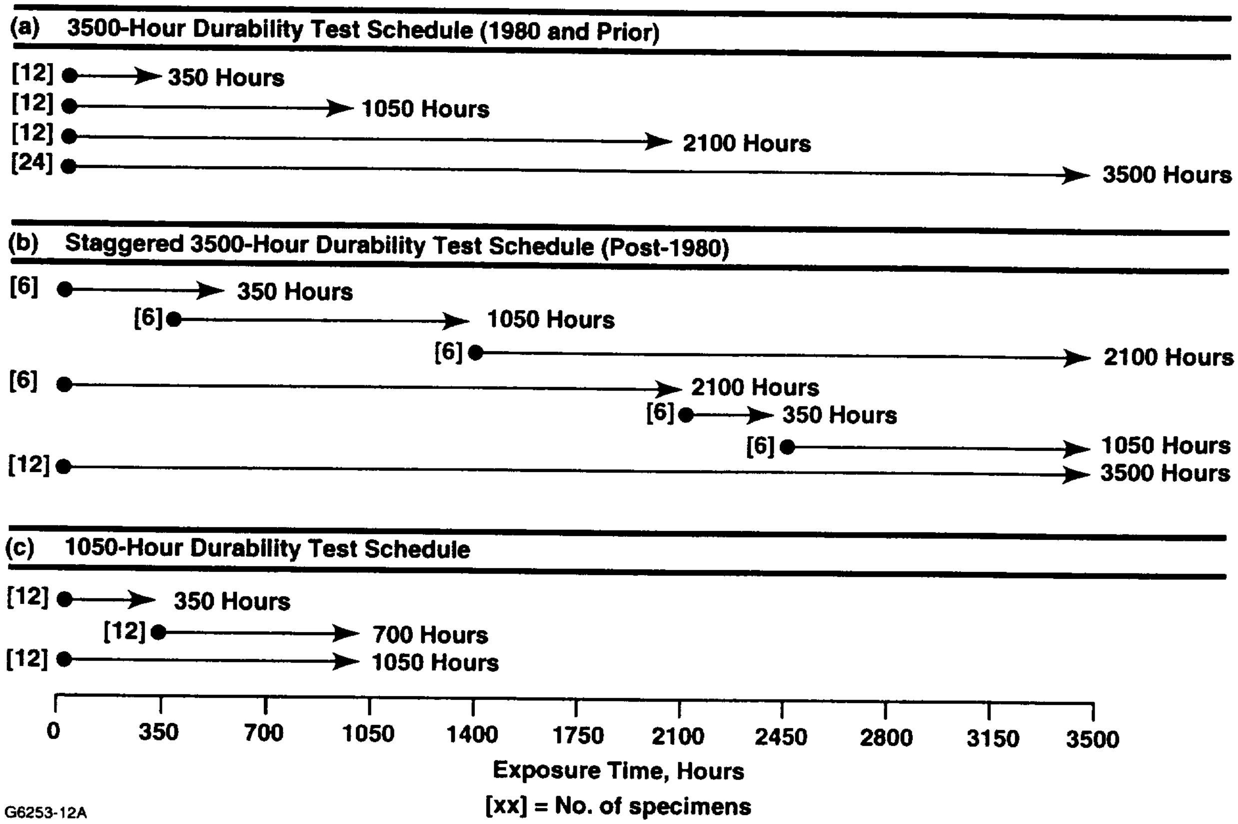


Figure 12. Specimen Exposure Schedules For Cyclic Oxidation Durability Testing.

6.0 TEST RESULTS

Detailed test results for each of the 29 ceramic materials evaluated in the 40 exposure tests during this program are described in the following sections. Separate sections on each material tested are given in alphabetical order by manufacturer and material identifier. Refer to Tables 1 and 2 for a complete listing of the materials tested. The baseline test results for each material are summarized in the following sections, and the complete pre-exposure flexure test results are given in Appendix I. The specific test conditions for the cyclic durability exposures accomplished for each material are then described, and the post-exposure test results are summarized. The complete post-exposure flexure test results for each material are given in Appendix II. All figures referenced in the discussion of the test results are included at the end of this section.

6.1 AiResearch Casting Company RBN101 Reaction Bonded Silicon Nitride

RBN101 reaction-bonded silicon nitride (RBSN) specimens were received from AiResearch Casting Company (ACC) (Torrance, CA) for evaluation during 1978, the first year of the program. All the test bars were received in the as-machined condition. RBN101 cyclic exposures were performed at both 1204C (2200F) and 1371C (2500F) for durations up to 2100 hours. Additionally, a second 2100-hour cyclic durability test at 1371C (2500F) was conducted to re-evaluate anomalous test results from the first 1371C (2500F) exposure.

6.1.1 RBN101 Baseline Test Results

The baseline properties of the longitudinally-machined RBN101 test specimens are summarized in Table 3. The measured density of the RBN101 test specimens ranged from 2.78 to 2.91 g/cm^3. The machined-surface finish ranged from 6 to 14 microinch rms.

The average room-temperature flexure strength for RBN101 was 37.4 ksi, with a standard deviation of 2.8 ksi. The flexure strength at 1204C (2200F) was 46.1 ksi, with a standard deviation of 4.1 ksi. The predominant fracture-originating flaws at both room and elevated temperatures were surface and subsurface porosity. Typical failure origins in RBN101 baseline flexure test specimens are illustrated in Figures 13 and 14.

TABLE 3. BASELINE PROPERTIES OF RBN101 SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms
RBN101		AiResearch Casting Co.		June 1978	2.78 to 2.91	6 to 14
Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined		
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins	
24	(75)	258 ± 20	(37.4 ± 2.8)	19	Surface and subsurface porosity	
1204	(2200)	318 ± 28	(46.1 ± 4.1)	12	Surface and subsurface porosity	

6.1.2 Results Of RBN101 Exposures At 1204C (2200F)

RBN101 test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 1050, and 2100 hours. Following exposure, the RBN101 test bars were flexure tested at room temperature to measure the retained strength. The post-exposure test results are summarized in Table 4 and Figure 15. The average strength of the RBN101 material dropped by 21 percent, from 37.4 ksi to 29.7 ksi, after 2100 hours of exposure at 1204C (2200F). No significant weight or dimensional losses occurred during these exposures.

Figures 16(a) and (b) illustrate the surface topography of the RBN101 specimen oxide layer following exposure at 1204C (2200F) for 350 hours and 1050 hours, respectively. The RBN101 specimens exhibited an increasingly coarse surface oxide with increased exposure duration. Examination of the RBN101 post-exposure flexure strength test fracture surfaces revealed that the fractures originated at both surface and subsurface locations. All surface origins were sites of oxide reaction, as illustrated in Figure 17. Several fractures originated at sites where the oxide had penetrated the test bar surface and interacted with pre-existing subsurface porosity, as illustrated in Figure 18.

TABLE 4. RBN101 POST-EXPOSURE TEST RESULTS SUMMARY (1204C).

Material	Surface Condition	Cyclic Oxidation Exposure Temperature
RBN101	Longitudinally Machined	1204C (2200F)

Post-Exposure Strength Measurements Summary

Exposure Duration, hrs	Test Temperature C	Test Temperature (F)	Post-Exposure Strength MPa	Post-Exposure Strength (ksi))	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	258 ± 20	(37.4 ± 2.8)	---	19	Surface and subsurface porosity
350	24	(75)	240 ± 24	(34.8 ± 3.4)	-7	12	Surface and subsurface porosity
1050	24	(75)	241 ± 20	(35.0 ± 3.0)	-7	12	Surface and subsurface oxidation reaction
2100	24	(75)	205 ± 31	(29.7 ± 4.5)	-21	12	Surface and subsurface oxidation reaction

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-0.1	0.0	12
1050	0.1	1.5	12
2100	-0.8	0.7	12

6.1.3 Results Of RBN101 Exposure At 1371C (2500F)

RBN101 test specimens were cyclically exposed at 1371C (2500F) for durations of 350, 1050, and 2100 hours. Following exposure, the RBN101 test bars were flexure tested at room temperature to measure retained strength. The post-exposure RBN101 test results are summarized in Table 5 and Figure 15. RBN101 exhibited progressive strength loss with increasing length of exposure. The average room-temperature strength of the RBN101 material dropped by 53 percent, from 37.4 ksi to 17.7 ksi, after 2100 hours of exposure at 1371C (2500F). No significant weight or dimensional losses occurred up to 1050 hours of exposure. However, following 2100 hours of exposure, large dimensional and weight loss of the specimens was measured. Note that Carborundum Co. Hexoloy SA sintered alpha-silicon carbide (α-SiC) test specimens were tested concurrently in the same burner rig as the degraded 2100-hour RBN101 test bars and exhibited similar results (refer to section 6.6.4). Subsequently, the large dimensional and weight losses of both materials were suspected to be a test anomaly.

TABLE 5. RBN101 POST-EXPOSURE TEST RESULTS SUMMARY (1371C).

Material		Surface Condition				Cyclic Oxidation Exposure Temperature
RBN101		Longitudinally Machined				1371C (2500F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	258 ± 20	(37.4 ± 2.8)	---	19	Surface and subsurface porosity
350	24	(75)	203 ± 24	(29.4 ± 3.4)	-21	12	Surface and subsurface oxidation reaction
1050	24	(75)	150 ± 14	(21.8 ± 2.0)	-42	9	Surface and subsurface oxidation reaction
2100	24	(75)	122 ± 10	(17.7 ± 1.5)	-53	10	Subsurface porosity

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-0.2	0.0	12
1050	-1.7	0.0	9
2100	-24.5	-25.0	10

Figures 19(a) through (c) illustrate the surface topography of the RBN101 oxide layer as a function of exposure time at 1371C (2500F). After 350 hours of exposure, RBN101 initially exhibited a coarse surface oxide. With increased exposure duration, the RBN101 specimens exhibited a glassy oxide layer with evidence of bubble formation. Examination of the specimen fracture surfaces following flexure testing after 350- and 1050-hour exposures revealed the failures originated primarily at surface oxide reaction sites. These oxide reactions often interacted with pre-existing subsurface pores. Typical RBN101 350- and 1050-hour specimen post-exposure flexure test fracture origins are illustrated in Figures 20 and 21, respectively.

RBN101 test bars exposed for 2100 hours at 1371C (2500F) failed exclusively from subsurface porosity sites, as illustrated in Figure 22. Figure 22 also shows the substantial material loss contributing to the large weight and dimensional losses discussed earlier. A review of possible sources of this test anomaly was conducted. The review included analysis of the exposure temperatures, air-fuel ratios, and fuel, and energy-dispersive X-ray (EDX) analysis and X-ray diffraction analyses for contaminants. However, a specific cause of material degradation was not identified. Subsequently, an additional 2100-hour test at 1371C (2500F) was conducted under carefully controlled and observed conditions to determine whether the degradation phenomena could be repeated.

6.1.4 Repeat Of RBN101 Exposures At 1371C (2500F)

To further evaluate the abnormally large weight and dimensional losses observed in RBN101 (and concurrently exposed Hexoloy SA) specimens after 2100 hours of exposure at 1371C (2500F), a second 2100-hour cyclic exposure test at 1371C (2500F) was performed. This repeat test used 12 test bars each of RBN101 and Hexoloy SA. (The Hexoloy SA results are discussed in Section 6.6.4). The test results are summarized in Table 6 and Figure 15, along with prior test results. The strength of the RBN101 specimens following the second test for 2100 hours exposure at 1371C (2500F) was markedly better than for the original test. The RBN101 specimens lost 36 percent of the room-temperature strength after the second 2100-hours exposure test, compared to 53 percent for the specimens in the initial 2100-hour test. Additionally, the weight and dimensional losses were substantially less in the second exposure test. The dimensional and weight losses were both 7 percent, compared to 25 percent measured previously. These results suggest that the anomalous conditions for the original 2100-hour exposure were not reproduced during the repeat test.

TABLE 6. RBN101 POST-EXPOSURE TEST RESULTS SUMMARY (1371C RETEST).

Material	Surface Condition	Cyclic Oxidation Exposure Temperature
RBN101	Longitudinally Machined	1371C (2500F)

Post-Exposure Strength Measurements Summary

Exposure Duration, hrs	Test Temperature C	Test Temperature (F)	Post-Exposure Strength MPa	Post-Exposure Strength (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	258 ± 20	(37.4 ± 2.8)	---	19	Surface and subsurface porosity
2100	24	(75)	164 ± 12	(23.8 ± 1.7)	-36	11	Surface oxide layer

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
2100	-7.8	-7.3	11

6.2 AiResearch Casting Company RBN104 Reaction Bonded Silicon Nitride

RBN104 reaction bonded silicon nitride (RBSN) specimens were procured from AiResearch Casting Company (ACC) in 1980 for durability exposure testing at 1371C (2500F) for 3500 hours. All the test bars were received in the as-nitrided condition, after having been machined from plates while in the green state. The RBN104 test bars were "flash-oxidized" at 1100C (2012F) for 2 hours to generate a protective oxide layer prior to baseline strength testing and durability exposure. The term "flash oxidized" is used for this treatment to denote that the test bars were rapidly raised to 1100C (2012F) to obtain a protective surface oxide coating without significant oxide penetration.(7) This treatment also had been shown to be effective in restoring material strength losses resulting from grinding operations and in improving the measured baseline strength properties.(8)

6.2.1 RBN104 Baseline Test Results

The baseline properties of the as-processed RBN104 test specimens are summarized in Table 7. The measured density of the RBN104 test specimens ranged from 2.77 to 2.85 g/cm^3. The as-processed specimen surface finish ranged from 40 to 60 microinch rms.

TABLE 7. BASELINE PROPERTIES OF RBN104 SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms
RBN104		AiResearch Casting Co.		December 1980	2.77 to 2.85	40 to 60
Test Temperature		Baseline Strength		Surface Condition: As-Processed		
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins	
24	(75)	345 ± 31	(50.0 ± 4.5)	12	Surface and subsurface pores and porosity	
1204	(2200)	405 ± 20	(58.7 ± 3.0)	11	Surface and subsurface pores and porosity	

The average room-temperature flexure strength for RBN104 was 50.0 ksi, with a standard deviation of 4.5 ksi. The flexure strength at 1204C (2200F) was 58.7 ksi, with a standard deviation of 3.0 ksi. The strength improvement observed at 1204C (2200F) is not clearly understood, but may indicate that the "flash-oxidation" treatment could be further optimized. The predominate fracture-originating flaws in the RBN104 specimens after baseline flexure testing were surface and subsurface pores and porosity. Representative scanning electron microscope (SEM) photomicrographs of the failure origins observed in the baseline RBN104 flexure test specimens are shown in Figures 23 and 24. As noted in Figures 23 and 24, aluminum contaminant was observed at the fracture origin in a few test bars. The source of this contaminant is unknown. An analysis showed aluminum in 7 of 20 test bar fracture origins that were evaluated.

6.2.2 Results of RBN104 Exposure At 1371C (2500F)

RBN104 test specimens were cyclically exposed at 1371C (2500F) for durations of 350, 1050, and 2100 hours. Following exposure, the RBN104 test bars were flexure tested at room temperature and 1204C (2200F) to measure retained strength. Post-exposure RBN104 test results are summarized in Table 8 and Figure 25.

TABLE 8. RBN104 POST-EXPOSURE TEST RESULTS SUMMARY (1371C).

Material		Surface Condition				Cyclic Oxidation Exposure Temperature
RBN104		As-Processed				1371C (2500F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C (F)		Post-Exposure Strength MPa (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	345 ± 31 (50.0 ± 4.5)	---	12	Surface and subsurface porosity
zero	1204	(2200)	405 ± 20 (58.7 ± 3.0)	---	11	Surface and subsurface porosity
350	24	(75)	261 ± 23 (37.9 ± 3.4)	-24	3	Surface pits, subsurface porosity
350	1204	(2200)	354 ± 53 (51.3 ± 7.7)	-12	3	Surface pits, subsurface porosity
1050	24	(75)	142 ± 24 (20.6 ± 3.5)	-59	3	Surface pits, subsurface porosity
1050	1204	(2200)	310 ± 26 (45.0 ± 3.8)	-23	3	Surface pits, subsurface porosity
2100	24	(75)	206 ± 12 (29.8 ± 1.8)	-40	3	Surface pits, subsurface porosity
2100	1204	(2200)	331 ± 36 (48.0 ± 5.3)	-18	3	Surface pits, subsurface porosity

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-0.3	0.6	6
1050	---	-0.1	6
2100	---	-2.1	6

The RBN104 specimens exhibited room-temperature strength losses of 24, 59, and 40 percent after 350, 1050, and 2100 hours exposure, respectively. At 1204C (2200F), RBN104 showed 12.5, 23.3, and 18 percent strength losses after 350, 1050, and 2100 hours exposure, respectively. This better strength retention at elevated temperature may be a result of oxide layer softening at 1204C (2200F), resulting in flaw blunting and/or increased strain tolerance at the surface. As illustrated in these results, the strength of the RBN104 increased after 2100 hours of exposure when compared with the 1050-hour exposure results. Due to the small number of test specimens evaluated (three per test condition), no firm conclusion should be drawn when comparing these post-1050- and 2100-hour exposure strength results. However, it is evident from all the test results that the room-temperature flexure strength of RBN104 is significantly degraded with exposure at 1371C (2500F). Therefore, evaluations of RBN104 at 1371C (2500F) were terminated after 2100 hours exposure.

Representative SEM and EDX analyses of RBN104 test specimens cyclically exposed at 1371C (2500F) 350 and 1050 hours are presented in Figures 26 and 27, respectively. Contrary to the baseline RBN104 fractography results, no aluminum contaminant was observed at the fracture origins of any of the exposed test bars. The predominant failure origins were surface pits and subsurface porosity. As illustrated in Figure 27, the surface irregularities and pits were primarily the remains of bubbles that formed in the glassy oxide layer during exposure.

6.3 AiResearch Casting Company Code 2 Sintered Silicon Nitride

Code 2 sintered silicon nitride (Si_3N_4) specimens were procured from AiResearch Casting Company (ACC) in 1985 for durability exposure at 1204C (2200F). The test bars were received in the as-processed (unmachined) condition. This particular batch of Code 2 exhibited poor flexure strength characteristics, and the batch was deemed not representative of the Code 2 material produced at ACC. Subsequently, the durability exposure testing was limited to 350 hours duration.

6.3.1 Code 2 Baseline Test Results

The baseline properties of the as-processed Code 2 Si_3N_4 specimens are presented in Table 9. The measured density of the Code 2 test specimens ranged from 3.23 to 3.25 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 15 to 40 microinch rms, and the transverse surface finish ranged from 15 to 65 microinch rms.

The room-temperature baseline flexure strength of Code 2 was 62.3 ksi with a standard deviation of 10.8 ksi. At 1204C (2200F), the baseline flexure strength was 43.0 ksi with a standard deviation of 3.8 ksi. The majority of the specimens failed at internal porosity. Visual inspection of the fracture surfaces showed that all the test specimens contained a small number of relatively large pores randomly distributed throughout the material. These large pores (~100 microns in size) were the fracture-originating flaws in all instances. Examples of large pore fracture origins are shown in Figures 28 (a) and (b).

This lot of Code 2 material was markedly weaker than Code 2 material characterized under other programs. Typically, the strength of Code 2 test specimens was between 90 and 120 ksi at room temperature and 60 and 80 ksi at 1204C (2200F). Additionally, the large porosity was not representative of the Code 2 material produced at ACC.

TABLE 9. BASELINE PROPERTIES OF CODE 2 SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
Code 2		AiResearch Casting Co.		March 1985	3.23 to 3.25	Longt.	15 to 40
						Transv.	15 to 65
Test Temperature		Baseline Strength		Surface Condition: As-Processed			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	430 ± 74	(62.3 ± 10.8)	12	Large pores (≈ 100 microns)		
1204	(2200)	297 ± 26	(43.0 ± 3.8)	12	Large pores (≈ 100 microns)		

6.3.2 Results Of Code 2 Exposures At 1204C (2200F)

Code 2 test material was originally procured for a 1050-hour duration cyclic durability test at 1204C (2200F). However, the durability test was limited to 350 hours, since the material was deemed not representative of typical Code 2 Si_3N_4 produced by ACC.

The post-exposure flexure test results for Code 2 Si_3N_4 cyclically exposed at 1204C (2200F) are summarized in Table 10 and Figure 29. Code 2 Si_3N_4 experienced little degradation in room-temperature and 1204C (2200F) flexure strength after 350 hours of cyclic durability exposure. In post-exposure tests at room temperature and 1204C (2200F), retained strength values averaged 61.4 ksi and 40.7 ksi, respectively. The large pores noted in the baseline strength test specimens were also the fracture-initiating flaws seen in the post-exposure strength test specimens (see Figures 30(a) and (b).

TABLE 10. ACC CODE 2 POST-EXPOSURE TEST RESULTS SUMMARY (1204C).

Material			Surface Condition				Cyclic Oxidation Exposure Temperature
Code 2			As-Processed				1204C (2200F)
Post-Exposure Strength Measurements Summary							
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	430 ± 74	(62.3 ± 10.8)	---	12	Large pores
zero	1204	(2200)	297 ± 26	(43.0 ± 3.8)	---	12	Large pores
350	24	(75)	423 ± 29	(61.4 ± 4.2)	-2	3	Large pores
350	1204	(2200)	281 ± 41	(40.7 ± 5.9)	-5	3	Large pores
Post-Exposure Weight and Dimensional Changes Summary							
Exposure Duration, hrs			Weight Change, percent		Dimensional Change, percent		Quantity Specimens Measured
350			0.0		1.4		6

6.4 AlliedSignal Ceramic Components GN-10 Hot Isostatically Pressed Silicon Nitride

GN-10 hot isostatically pressed (HIPped) silicon nitride specimens were procured from AlliedSignal Ceramic Components (ACC) (Torrance, CA) in 1989 for durability exposure at 1204C (2200F). The test bars were longitudinally machined on all sides. The test specimens were machined from pressure slip cast (PSC) and glass-encapsulated HIPped billets.

6.4.1 GN-10 Baseline Test Results

The baseline properties of the longitudinally-machined GN-10 test specimens are summarized in Table 11. The measured density of the GN-10 test specimens ranged from 3.30 to 3.38 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 7 to 15 microinch rms and the transverse surface finish ranged from 40 to 60 microinch rms.

The room-temperature baseline flexure strength of the GN-10 specimens was 128.0 ksi, with a standard deviation of 21.7 ksi. At 1204C (2200F), the baseline flexure strength was 108.7 ksi, with a standard deviation of 4.1 ksi. The majority of the specimens failed in flexure strength testing from the machined test surface (see Figure 31). A notable quantity of the flexure test specimen failures, particularly at 1204C (2200F), originated from internal inclusions.

TABLE 11. BASELINE PROPERTIES OF GN-10 SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, µ inch rms	
GN-10	AlliedSignal Ceramic Components	May 1989	3.30 to 3.38	Longt.	7 to 15
				Transv.	40 to 60

Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined	
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins
24	(75)	883 ± 150	(128.0 ± 21.7)	12	Machined Surface, Internal Inclusions
1204	(2200)	750 ± 28	(108.7 ± 4.1)	12	Machined Surface, Internal Inclusions

6.4.2 Results Of GN-10 Exposures At 1204C (2200F)

GN-10 test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 700, and 1050 hours. Following exposure, the GN-10 test bars were flexure tested at room temperature and 1204C (2200F) to measure the retained strength. The post-exposure test results for GN-10 are summarized in Table 12 and Figure 32. Initially, after 350 hours of exposure at 1204C (2200F), GN-10 exhibited relatively large losses in strength in post-exposure flexure tests performed at both room temperature and 1204C (2200F). With continued exposure, the strength characteristics of GN-10 remained constant up to 1050 hours of exposure. Following 1050 hours exposure, the average post-exposure room-temperature flexural strength dropped 37 percent, to 81.3 ksi, and the 1204C (2200F) retained flexural strength dropped 33 percent to 73.1 ksi. All fractures seen in the post-exposure tests originated from oxidation-induced pitting. Typical post-exposure fracture origins are shown in Figures 33 and 34.

TABLE 12. GN-10 POST-EXPOSURE TEST RESULTS SUMMARY (1204C).

Material				Surface Condition			Cyclic Oxidation Exposure Temperature
GN-10				Longitudinally Machined			1204C (2200F)
Post-Exposure Strength Measurements Summary							
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	883 ± 150	(128.0 ± 21.7)	---	12	Machined surface, internal inclusions
zero	1204	(2200)	750 ± 28	(108.7 ± 4.1)	---	12	Machined surface, internal inclusions
350	24	(75)	598 ± 27	(86.7 ± 3.9)	-32	6	Oxidation pits
350	1204	(2200)	540 ± 38	(78.3 ± 5.5)	-28	6	Oxidation pits
700	24	(75)	611 ± 24	(88.7 ± 3.6)	-31	6	Oxidation pits
700	1204	(2200)	559 ± 30	(81.0 ± 4.4)	-25	6	Oxidation pits
1050	24	(75)	560 ± 21	(81.3 ± 3.1)	-37	6	Oxidation pits
1050	1204	(2200)	504 ± 8	(73.1 ± 1.1)	-33	5	Oxidation pits

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-0.1	2.4	12
700	-0.2	2.7	12
1050	-0.2	2.8	11

6.5 Carborundum Co. Hexoloy KX01 Siliconized Silicon Carbide

Hexoloy KX01 siliconized silicon carbide (Si-SiC) specimens with as-processed surfaces were procured from the Carborundum Company (Niagara Falls, NY) in 1983 for durability testing at 1204C (2200F).

6.5.1 Hexoloy KX01 Baseline Test Results

The baseline properties of the as-processed Hexoloy KX01 Si-SiC test specimens are summarized in Table 13. The measured density of the KX01 test specimens ranged from 2.87 to 2.93 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions.

The longitudinal surface finish ranged from 30 to 35 microinch rms and the transverse surface finish ranged from 25 to 60 microinch rms.

The average room-temperature flexure strength was 57.4 ksi, with a standard deviation of 7.6 ksi. The baseline 1204C (2200F) flexure strength was 54.9 ksi, with a standard deviation of 9.5 ksi. Most of the fractures seen in the baseline flexure strength test specimens originated from the specimen as-processed test surfaces. A typical KX01 fracture origin is shown in Figure 35.

TABLE 13. BASELINE PROPERTIES OF HEXOLOY KX01 SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
Hexoloy KX01		Carborundum Co.		March 1983	2.87 to 2.93	Longt.	30 to 35
						Transv.	25 to 60
Test Temperature		Baseline Strength		Surface Condition: As-Processed			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	396 ± 53	(57.4 ± 7.6)	12	As-Processed Surface		
1204	(2200)	379 ± 66	(54.9 ± 9.5)	12	As-Processed Surface		

6.5.2 Results Of Hexoloy KX01 Exposures At 1204C (2200F)

Hexoloy KX01 test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 1050, 2100, and 3500 hours. Following exposure, the Hexoloy KX01 test bars were flexure tested at room temperature and 1204C (2200F) to measure the retained strength. The post-exposure test results for KX01 Si-SiC are summarized in Table 14 and Figure 36. The post-exposure flexure strength values were virtually constant over the entire 3500 hours of exposure. Following 3500 hours exposure, the average KX01 room-temperature flexural strength was 58.8 ksi compared to 57.4 ksi for the baseline tests. The 1204C (2200F) retained flexural strength was 53.9 ksi compared to 54.9 ksi for the baseline. All fractures seen in the post-exposure strength test specimens originated from the specimen tensile face at the rough oxide layer that formed during exposure. Typical post-exposure fracture origins are shown in Figure 37.

TABLE 14. HEXOLOY KX01 POST-EXPOSURE TEST RESULTS SUMMARY (1204C).

Material			Surface Condition			Cyclic Oxidation Exposure Temperature
Hexoloy KX01			As-Processed			1204C (2200F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	396 ± 53	(57.4 ± 7.6)	---	12	As-processed surface
zero	1204	(2200)	379 ± 66	(54.9 ± 9.5)	0	12	As-processed surface
350	24	(75)	361 ± 82	(52.3 ± 11.9)	-9	6	Rough oxide layer
350	1204	(2200)	430 ± 67	(62.4 ± 9.7)	14	6	Rough oxide layer
1050	24	(75)	428 ± 55	(62.1 ± 8.0)	8	6	Rough oxide layer
1050	1204	(2200)	426 ± 30	(61.8 ± 4.4)	13	6	Rough oxide layer
2100	24	(75)	435 ± 55	(63.1 ± 7.9)	10	6	Rough oxide layer
2100	1204	(2200)	402 ± 40	(58.3 ± 5.8)	6	6	Rough oxide layer
3500	24	(75)	406 ± 41	(58.8 ± 6.0)	2	6	Rough oxide layer
3500	1204	(2200)	372 ± 11	(53.9 ± 1.6)	-2	5	Rough oxide layer

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.1	1.0	12
1050	-0.1	2.3	12
2100	0.2	3.2	12
3500	-0.1	4.1	11

6.6 Carborundum Co. Hexoloy SA Sintered Alpha Silicon Carbide

Hexoloy SA sintered alpha silicon carbide (α-SiC) test specimens were procured from the Carborundum Co. for evaluation during the first year of the program, 1978. These test bars were machined from isopressed and sintered billets. Cyclic exposures of the Hexoloy SA specimens were performed at both 1204C (2200F) and 1371C (2500F) for durations up to 3500 hours. Additionally, a second (repeat) 2100-hour cyclic durability test at 1371C (2500F) was performed to re-evaluate anomalous test results from the first 1371C (2500F) exposure testing.

During 1983, injection-molded Hexoloy SA specimens with the test surface left in the as-processed (unmachined) condition were procured from the Carborundum Co. for a 3500-hour durability test at 1371C (2500F). This test was temporarily stopped after 580 hours of durability exposure, when a large piece of combustor carbon broke loose from the burner and impacted the test specimens in the rotating carousel. Several of the specimens incurred damage. AlliedSignal

Engines and NASA mutually decided to restructure the Hexoloy SA test schedule, lowering the total exposure time to 2700 hours, to accommodate the reduced quantity of remaining, undamaged injection-molded Hexoloy SA test specimens.

6.6.1 Machined Surface Hexoloy SA Baseline Test Results

The baseline properties of the longitudinally-machined Hexoloy SA test specimens are summarized in Table 15. The measured density of the Hexoloy SA test specimens ranged from 3.04 to 3.14 g/cm^3. The surface finish ranged from 4 to 9 microinch rms.

The average baseline room-temperature flexure strength of the Hexoloy SA specimens was 45.8 ksi, with a standard deviation of 9.7 ksi. The baseline flexure strength at 1204C (2200F) was 50.8 ksi, with a standard deviation of 6.9 ksi. The room-temperature specimen failures typically originated at the machined surface. No obvious material defects were noted. A typical room-temperature test fracture surface for Hexoloy SA is shown in Figure 38. At 1204C (2200F), Hexoloy SA flexure test specimens failed predominantly at surface and subsurface pores (Figures 39 and 40). The slightly-higher flexural strength and transition to pore defect failure origins in the 1204C (2200F) baseline flexure tests suggests the elevated-temperature oxidizing environment may provide Hexoloy SA with an oxidation-anneal that heals machining-induced flaws or reduces residual stress effects.

TABLE 15. BASELINE PROPERTIES OF LONGITUDINALLY MACHINED HEXOLOY SA SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, µ inch rms
Hexoloy SA		Carborundum Co.		June 1978	3.04 to 3.14	4 to 9
Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined		
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins	
24	(75)	316 ± 67	(45.8 ± 9.7)	12	Machined Surface	
1204	(2200)	350 ± 48	(50.8 ± 6.9)	12	Subsurface Pores	

6.6.2 Results Of Machined Surface Hexoloy SA Exposures At 1204C (2200F)

Machined-surface Hexoloy SA test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 1050, 2100, and 3500 hours. For all the exposure durations, the post-exposure retained strength values were measured at room temperature. For the 3500-hour specimens only, the retained strength at 1204C (2200F) was also measured.

Post-exposure test results for the machined-surface Hexoloy SA specimens cyclically exposed at 1204C (2200F) are summarized in Table 16 and Figure 41. Hexoloy SA exhibited 100-percent strength retention in post-exposure flexure strength tests at room temperature and 1204C (2200F) following 3500 hours of cyclic oxidation exposure at 1204C (2200F). Additionally, the Hexoloy SA specimens exhibited negligible weight and dimensional changes following exposure.

Following 3500 hours of exposure, Hexoloy SA exhibited an average room-temperature strength of 50.1 ksi, compared to 45.8 ksi for the baseline tests. At 1204C (2200F), Hexoloy SA exhibited a retained strength of 50.9 ksi, compared to 50.8 ksi for the baseline.

Fractures seen in the post-exposure strength tests of the cyclically-exposed Hexoloy SA test specimens typically originated at surface oxide pits or surface or subsurface porosity sites. Typical post-exposure fracture-originating flaws are illustrated in Figures 42 and 43. The surface topography of Hexoloy SA as a function of exposure time at 1204C (2200F) is shown in Figures 44(a) through (c). Initially, oxide nodules formed on the surface of the Hexoloy SA specimens, and with continued exposure, transitioned to a continuous scale of coarse oxide buildup.

TABLE 16. HEXOLOY SA POST-EXPOSURE TEST RESULTS SUMMARY (1204C, LONGITUDINALLY MACHINED SPECIMENS).

Material	Surface Condition	Cyclic Oxidation Exposure Temperature
Hexoloy SA	Longitudinally Machined	1204C (2200F)

Post-Exposure Strength Measurements Summary

Exposure Duration, hrs	Test Temperature C	Test Temperature (F)	Post-Exposure Strength MPa	Post-Exposure Strength (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	316 ± 67	(45.8 ± 9.7)	---	12	Machined surface
zero	1204	(2200)	350 ± 48	(50.8 ± 6.9)	---	12	Subsurface pores
350	24	(75)	359 ± 40	(52.0 ± 5.8)	14	11	Surface and subsurface pores
1050	24	(75)	368 ± 41	(53.4 ± 6.0)	16	12	Surface oxide, oxidation pits
2100	24	(75)	321 ± 45	(46.5 ± 6.6)	2	12	---
3500	24	(75)	345 ± 30	(50.1 ± 4.4)	9	9	Surface oxide, oxidation pits
3500	1204	(2200)	351 ± 29	(50.9 ± 4.2)	0	10	Subsurface pores and porosity

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.0	0.0	11
1050	0.0	1.7	12
2100	-0.7	0.7	12
3500	-0.8	0.4	19

6.6.3 <u>Results Of Machined-Surface Hexoloy SA Exposures At 1371C (2500F)</u>

Machined-surface Hexoloy SA test specimens were cyclically exposed at 1371C (2500F) for durations of 350, 1050, 2100, and 3500 hours. For all the exposure durations, the post-exposure retained strength values were measured at room temperature. For the 3500-hour specimens only, the retained strength at 1204C (2200F) was also measured.

Post-exposure test results for the machined-surface Hexoloy SA specimens cyclically exposed at 1371C (2500F) are summarized in Table 17 and Figure 45. The Hexoloy SA specimens exhibited 100-percent strength retention at room temperature following 3500 hours of cyclic oxidation exposure at 1371C (2500F). The average retained room-temperature strength was 47.4 ± 4.1 ksi, compared to 45.8 ± 9.7 ksi for the baseline. However, an undefined anomalous test condition during the 2100-hour exposure test resulted in a 35-percent strength loss, from 45.8 ksi to 29.7 ksi. This strength loss was accompanied by large weight and dimensional losses, -15 and -11 percent, respectively. As noted earlier in Section 6.1.2, RBN101 reaction-bonded Si_3N_4 (RBSN) test specimens were tested concurrently in the same test rig, and exhibited similar effects after 2100 hours exposure. Because negligible losses in weight, dimensions, and strength were observed up to 1050 hours exposure and after 3500 hours exposure, the degradation observed following 2100 hours exposure was believed to be a test anomaly.

TABLE 17. HEXOLOY SA POST-EXPOSURE TEST RESULTS SUMMARY (1371C, LONGITUDINALLY MACHINED SPECIMENS).

Material		Surface Condition			Cyclic Oxidation Exposure Temperature		
Hexoloy SA		Longitudinally Machined			1371C (2500F)		
Post-Exposure Strength Measurements Summary							
Exposure Duration, hrs	Test Temperature C	Test Temperature (F)	Post-Exposure Strength MPa	Post-Exposure Strength (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	316 ± 67	(45.8 ± 9.7)	---	12	Machined surface
zero	1204	(2200)	350 ± 48	(50.8 ± 6.9)	---	12	Subsurface pores
350	24	(75)	317 ± 22	(45.9 ± 3.2)	0	9	Surface and subsurface porosity
1050	24	(75)	323 ± 21	(46.8 ± 3.1)	2	10	Oxidation pits
2100	24	(75)	205 ± 18	(29.7 ± 2.7)	-35	11	Oxidation pits
3500	24	(75)	327 ± 28	(47.4 ± 4.1)	3	12	Oxidation pits
3500	1204	(2200)	223 ± 21	(32.3 ± 3.1)	-36	12	Flat, transgranular fracture

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-0.3	0.0	9
1050	-1.4	-0.1	10
2100	-14.8	-11.4	11
3500	-2.7	0.4	24

In contrast to the post-exposure room-temperature flexure strength results, Hexoloy SA did exhibit a loss in 1204C (2200F) flexure strength following 3500 hours of exposure at 1371C (2500F). The retained 1204C (2200F) strength exhibited a 36-percent strength loss, dropping from 50.8 ksi to 32.3 ksi.

Representative surfaces of Hexoloy SA test bars exposed to 1371C (2500F) are illustrated in Figures 46(a) through (c). The Hexoloy SA specimens exhibited a coarse, cracked oxide layer after 350 hours of exposure. After 1050 and 3500 hours of exposure, the oxide layer exhibited a smooth, glassy topography scattered with small pores and debris from fractured bubbles. A highly-porous surface oxide layer was observed after the anomalous 2100-hour 1371C (2500F) exposure.

Exposed Hexoloy SA specimens flexure tested at room temperature typically fractured at surface oxide pits or pores or subsurface porosity, as illustrated in Figures 47 and 48. Test bars that had sustained large material loss during the 2100-hours exposure typically fractured at surface pits (Figure 49). Figure 49 also illustrates the substantial material loss incurred, particularly at the test bar edges.

Hexoloy SA specimens that had been exposed for 3500 hours and then flexure tested at 1204C (2200F) exhibited flat, transgranular fracture surfaces with uniformly-distributed 10-micron pores (Figure 50). Large flaws or specific fracture origin sites were not identified in the exposed Hexoloy SA specimens flexure tested at elevated temperature. The strength reduction and change in fracture surface results suggest a different fracture mechanism than observed for room-temperature fractures, where large defects (pores or pits) control the strength. However, the nature of this mechanism has not been identified. Residual stress effects resulting from the oxidation durability exposure are suspected.

6.6.4 Repeat Test Of Machined Surface Hexoloy SA Exposures At 1371C (2500F)

To further evaluate the abnormally-large weight and dimensional losses observed in the first test of Hexoloy SA and RBN101 specimens after 2100 hours of exposure at 1371C (2500F), a second 2100-hour cyclic exposure test at 1371C (2500F) was conducted using 12 new test bars each of Hexoloy SA and RBN101. (The RBN101 results are discussed in Section 6.1.4). The results for this retest of Hexoloy SA specimens are summarized in Table 18 and shown in comparison to prior test results in Figure 45. Contrary to the large strength loss observed in the original 2100-hour exposure test, the Hexoloy SA specimens in the retest exhibited virtually no strength loss during the second 2100-hour exposure test at 1371C (2500F). The weight and dimensional losses in the second 2100-hour test were also markedly smaller than in the original 2100-hour exposure test. These results, in addition to similar results obtained for the concurrently-tested RBN101 specimens, suggest that the anomalous conditions for the original 2100-hour exposure test were not reproduced during the repeat test.

TABLE 18. HEXOLOY SA POST-EXPOSURE TEST RESULTS SUMMARY (1371C RETEST, LONGITUDINALLY MACHINED SPECIMENS).

Material			Surface Condition			Cyclic Oxidation Exposure Temperature
Hexoloy SA			Longitudinally Machined			1371C (2500F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	316 ± 67 (45.8 ± 9.7)	---	12	Machined surface
2100	24	(75)	309 ± 47 (44.8 ± 6.8)	-2	11	Oxide layer

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
2100	-6.1	-5.7	11

6.6.5 Injection Molded, As-Processed Surface Hexoloy SA Baseline Test Results

The baseline properties of the injection-molded Hexoloy SA as-processed surface test specimens are summarized in Table 19. The measured density of the as-processed Hexoloy SA test specimens ranged from 3.10 to 3.14 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 18 to 25 microinch rms, and the transverse surface finish ranged from 40 to 60 microinch rms.

The average baseline room-temperature flexure strength of the injection-molded Hexoloy SA specimens was 63.5 ksi, with a standard deviation of 9.2 ksi. The average flexure strength values at 1204C (2200F) and 1371C (2500F) were 60.7 ksi and 52.8 ksi, respectively. Both the room- and elevated-temperature baseline strength test results were substantially higher than the baseline strength values measured for the machined surface, isopressed Hexoloy SA specimens procured and evaluated earlier in the program. The predominant failure-initiation sites were surface and subsurface porosity. Typical fracture-initiating flaws are illustrated in Figures 51 through 53.

TABLE 19. BASELINE PROPERTIES OF INJECTION MOLDED, AS-PROCESSED SURFACE HEXOLOY SA SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, µ inch rms	
Hexoloy SA Injection Molded		Carborundum Co.		July 1983	3.10 to 3.14	Longt.	18 to 25
						Transv.	40 to 60
Test Temperature		Baseline Strength		Surface Condition: As-Processed			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	438 ± 63	(63.5 ± 9.2)	12	Surface and subsurface porosity		
1204	(2200)	419 ± 53	(60.7 ± 7.6)	12	Surface and subsurface porosity		
1371	(2500)	364 ± 57	(52.8 ± 8.2)	12	Surface and subsurface porosity		

6.6.6 Results Of Injection Molded, As-Processed Surface Hexoloy SA Exposures At 1371C (2500F)

Injection molded, as-processed surface Hexoloy SA test specimens were cyclically exposed at 1371C (2500F) for durations of 350, 1050, and 2700 hours. The exposure testing was originally targeted for 3500 hours. However, after 580 hours of exposure, a large piece of combustor carbon broke loose from the burner and impacted the specimens in the rotating carousel (see Figure 54). Several of the test specimens were damaged. AlliedSignal Engines and NASA mutually decided to restructure the Hexoloy SA test schedule, lowering the total exposure time to 2700 hours, to accommodate the reduced quantity of remaining, undamaged test specimens.

Following exposure, the Hexoloy SA test bars were flexure tested at room temperature and 1204C (2200F) to measure the retained strength. Post-exposure test results for the as-processed surface Hexoloy SA specimens cyclically exposed to 1371C (2500F) are summarized in Table 20 and Figure 55. The room-temperature flexure strength decreased as a function of exposure time, exhibiting 7, 13, and 26 percent strength loss after 350, 1050, and 2700 hours of exposure, respectively. The elevated-temperature strength fluctuated with exposure time, exhibiting 9 and 11 percent strength <u>loss</u> after 350 and 2700 hours exposure, respectively, and 6 percent strength <u>increase</u> after 1050 hours exposure. Following 2700 hours exposure at 1371C (2500F), the retained room-temperature flexure strength was 46.6 ± 6.4 ksi, compared to the baseline test value of 63.5 ± 9.2 ksi. The retained 1371C (2500F) flexural strength was 47.2 ± 4.4 ksi, compared to 52.8 ± 8.2 ksi for the baseline.

Two categories of post-exposure fracture origins for the as-processed surface Hexoloy SA specimens were observed: 1) internal pores and porous areas typical of the as-received material, and 2) surface defects resulting from or augmented by oxidation. Examples of fracture-initiating flaws pre-existing in the as-received material are shown in Figure 56. Examples of oxidation-induced fracture-initiating flaws are shown in Figures 57 and 58.

Representative surfaces of Hexoloy SA test bars exposed to 1371C (2500F) are illustrated in Figure 59. Following 1050 hours of exposure, the as-processed surface Hexoloy SA specimens exhibited a smooth, glassy oxide layer with some bubbles and oxidation pits as shown in Figure 59(a). With continued exposure up to 2700 hours, the surface topography coarsened, with increased formation of bubbles and oxidation pits, as shown in Figure 59(b).

TABLE 20. INJECTION MOLDED HEXOLOY SA POST-EXPOSURE TEST RESULTS SUMMARY (1371C, AS-PROCESSED SURFACE SPECIMENS).

Material			Surface Condition				Cyclic Oxidation Exposure Temperature
Hexoloy SA			Injection Molded, As-Processed				1371C (2500F)
Post-Exposure Strength Measurements Summary							
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	438 ± 63	(63.5 ± 9.2)	---	12	Surface and subsurface porosity
zero	1371	(2500)	364 ± 57	(52.8 ± 8.2)	---	12	Surface and subsurface porosity
350	24	(75)	409 ± 62	(59.3 ± 9.0)	-7	3	Surface and subsurface porosity
350	1371	(2500)	331 ± 71	(48.0 ± 10.3)	-9	2	Surface and subsurface porosity
1050	24	(75)	383 ± 35	(55.5 ± 5.1)	-13	6	Oxidation pits, internal porosity
1050	1371	(2500)	385 ± 44	(55.8 ± 6.4)	6	5	Oxidation pits, internal porosity
2700	24	(75)	321 ± 44	(46.6 ± 6.4)	-27	3	Oxidation pits, internal porosity
2700	1371	(2500)	326 ± 30	(47.2 ± 4.4)	-11	3	Oxidation pits, internal porosity

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	3.2	2.3	5
1050	-0.7	1.7	11
2700	-6.5	-4.4	6

6.7 Carborundum Co. Hexoloy ST Titanium Diboride Toughened Sintered Silicon Carbide

Hexoloy ST titanium diboride (TiB_2)-toughened sintered alpha-silicon carbide (α-SiC) specimens with the test surface left in the as-processed condition were procured from the Carborundum Co. in 1987 for durability exposure testing at 1204C (2200F) for 1050 hours. Hexoloy ST contains 20 weight-percent of TiB_2 particulates, added to increase the toughness of the sintered α-SiC matrix. The test specimens were received with green-machined, as-sintered test surfaces. Based on encouraging 1204C (2200F) durability test results, additional Hexoloy ST specimens were procured during 1988 for further durability test exposures at 1260C (2300F). These later specimens also had the test surfaces left in the green-machined, as-sintered condition.

6.7.1 Hexoloy ST Baseline (Pre-1204C Exposure) Test Results

The baseline properties of the as-processed surface Hexoloy ST test specimens are summarized in Table 21. The measured density of these Hexoloy ST test specimens ranged from 3.33 to 3.34 g/cm^3. The as-processed surface finish ranged from 12 to 20 microinch rms.

The baseline average room-temperature flexure strength of the Hexoloy ST specimens was 55.1 ksi, with a standard deviation of 6.3 ksi. The baseline flexure strength at 1204C (2200F) was 55.9 ksi, with a standard deviation of 7.3 ksi. These strength values are comparable to the non-toughened Hexoloy SA material tested earlier in the program (see Section 6.6.5).

The predominant failure-initiating flaws seen in these baseline flexure tests were surface connected and internal porosity. Typical fracture-initiating flaws are illustrated in Figures 60 and 61. In Figure 61, note that the TiB_2 particles can be readily seen on the fracture surface, following the brief exposure to the static air oxidizing environment of the flexure test furnace.

TABLE 21. BASELINE PROPERTIES OF HEXOLOY ST AS-PROCESSED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms
Hexoloy ST		Carborundum Co.		October 1987	3.33 to 3.34	12 to 20
Test Temperature		Baseline Strength		Surface Condition: As-Processed		
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins	
24	(75)	380 ± 44	(55.1 ± 6.3)	12	Surface and internal porosity	
1204	(2200)	386 ± 50	(55.9 ± 7.3)	12	Surface and internal porosity	

6.7.2 Results Of Machined-Surface Hexoloy ST Exposures At 1204C (2200F)

As-processed surface Hexoloy ST test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 587, and 937 hours. The test was originally targeted for 1050 hours exposure. However, the test was terminated after 937 hours exposure, when the specimens contacted the furnace door, which failed to open following a temperature quench cycle. All of the specimens failed at the attachment, preventing re-fixturing of the bars for continued exposure testing. However, the test gage sections of the specimens were intact, enabling measurement of post-exposure strength.

Following exposure, the Hexoloy ST test bars were flexure tested at room temperature and 1204C (2200F) to measure retained strength. The Hexoloy ST post-exposure test results are summarized in Table 22 and Figure 62. The measured room-temperature and 1204C (2200F) flexure strength decreased gradually, as a function of specimen exposure time. After 937 hours exposure, the retained room-temperature flexure strength of these Hexoloy ST specimens had decreased 18 percent, to 45.3 ksi, and at 1204C (2200F), the retained flexure strength had decreased 22 percent, to 43.6 ksi.

TABLE 22. HEXOLOY ST POST-EXPOSURE TEST RESULTS SUMMARY (1204C, AS-PROCESSED SURFACE SPECIMENS).

Material			Surface Condition				Cyclic Oxidation Exposure Temperature
Hexoloy ST			As-Processed				1204C (2200F)
Post-Exposure Strength Measurements Summary							
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	380 ± 44	(55.1 ± 6.3)	---	12	Surface and internal porosity
zero	1204	(2200)	386 ± 50	(55.9 ± 7.3)	---	12	Surface and internal porosity
350	24	(75)	393 ± 19	(57.0 ± 2.7)	3	6	Internal porosity
350	1204	(2200)	356 ± 27	(51.6 ± 4.0)	-8	6	Internal porosity
587	24	(75)	356 ± 39	(51.6 ± 5.7)	-6	6	Rough oxide layer, internal porosity
587	1204	(2200)	339 ± 19	(49.1 ± 2.8)	-12	5	Rough oxide layer, internal porosity
937	24	(75)	312 ± 54	(45.3 ± 7.8)	-18	6	Rough oxide layer, internal porosity
937	1204	(2200)	301 ± 19	(43.6 ± 2.7)	-22	5	Rough oxide layer, internal porosity

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.2	2.1	12
587	---	2.5	11
937	---	4.4	11

Figure 63 shows a flexure strength test fracture origin on a Hexoloy ST specimen exposed for 350 hours, which fractured at an internal pore. This fracture origin is typical of the baseline, unexposed Hexoloy ST specimen flexure test results. Following 587 and 937 hours of exposure, the fracture-initiating flaws had shifted from flaws inherent in the baseline material to surface flaws associated with a thick oxide layer (50 microns). Figures 64 and 65 illustrate typical fracture origins for Hexoloy ST specimens flexure tested following 587-hour and 937-hour exposures at 1204C (2200F), respectively.

The surface topography of Hexoloy ST as a function of exposure time at 1204C (2200F) is illustrated in Figure 66. Following 350 hours exposure at 1204C (2200F), the oxide layer partially covered the test specimen surface. Following 587 and 937 hours of exposure, a continuous, rough oxide layer was seen covering the specimen surface.

6.7.3 Hexoloy ST Baseline (Pre-1260C [2300F] Exposure) Test Results

The baseline properties of the as-processed surface Hexoloy ST test specimens are summarized in Table 23. The measured density of the Hexoloy ST test specimens ranged from 3.33 to 3.35 g/cm^3. The as-processed specimen surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 29 to 76 microinch rms, and the transverse surface finish ranged from 27 to 83 microinch rms.

The baseline average room-temperature flexure strength of Hexoloy ST was 58.8 ksi, with a standard deviation of 7.9 ksi. The strength at 1260C (2300F) was 56.2 ksi, with a standard deviation of 6.1 ksi. The predominant failure-initiation sites were surface-connected and internal pores. Typical fracture-initiating flaws are illustrated in Figures 67 and 68. These pre-exposure strength values and fracture characteristics were comparable to the baseline values for Hexoloy ST material procured and tested earlier in the program (see Section 6.7.1).

TABLE 23. BASELINE (PRE-1260C EXPOSURE) PROPERTIES OF HEXOLOY ST AS-PROCESSED SURFACE SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, µ inch rms	
Hexoloy ST	Carborundum Co.	November 1988	3.33 to 3.35	Longt.	29 to 76
				Transv.	27 to 83

Test Temperature		Baseline Strength		Surface Condition: As-Processed	
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins
24	(75)	405 ± 54	(58.8 ± 7.9)	12	Surface and internal porosity
1260	(2300)	387 ± 42	(56.2 ± 6.1)	12	Surface and internal porosity

6.7.4 Results Of As-Processed Surface Hexoloy ST Exposures At 1260C (2300F)

Hexoloy ST test specimens were cyclically exposed at 1260C (2300F) for durations of 350, 700, and 1050 hours. Following exposure, the Hexoloy ST test bars were flexure tested at room temperature and 1260C (2300F) to measure retained strength. The Hexoloy ST post-exposure test results are summarized in Table 24 and Figure 69. After 1050 hours of exposure, the room-temperature strength of Hexoloy ST decreased 22 percent, to 46.2 ksi, and the 1260C (2300F) strength decreased 33 percent, to 37.7 ksi.

TABLE 24. HEXOLOY ST POST-EXPOSURE TEST RESULTS SUMMARY (1260C, AS-PROCESSED SURFACE SPECIMENS).

Material		Surface Condition				Cyclic Oxidation Exposure Temperature
Hexoloy ST		As-Processed				1260C (2300F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C (F)		Post-Exposure Strength MPa (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24 (75)		405 ± 54 (58.8 ± 7.9)	---	12	Surface and internal porosity
zero	1260 (2300)		387 ± 42 (56.2 ± 6.1)	---	12	Surface and internal porosity
350	24 (75)		374 ± 37 (54.2 ± 5.3)	-8	6	Rough oxide layer
350	1260 (2300)		294 ± 10 (42.7 ± 1.4)	-24	6	Rough oxide layer
700	24 (75)		342 ± 20 (49.6 ± 2.9)	-16	6	Rough oxide layer
700	1260 (2300)		298 ± 10 (43.2 ± 1.5)	-23	6	Rough oxide layer
1050	24 (75)		318 ± 17 (46.2 ± 2.4)	-22	6	Rough oxide layer
1050	1260 (2300)		260 ± 16 (37.7 ± 2.3)	-33	5	Rough oxide layer

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.2	2.4	12
700	0.3	2.5	12
1050	0.2	0.1	11

Following exposure at 1260C (2300F), the Hexoloy ST strength test specimens typically failed at the surface at the rough oxide layer that had formed during exposure. It was difficult to perform fractography on the exposed Hexoloy ST flexure specimens, because the TiB_2 oxidized rapidly on the fracture surfaces, obscuring many of the fracture features. Figure 70 shows the fracture origin of a specimen exposed for 350 hours at 1260C (2300F). The fracture origin, somewhat obscured by the oxidized TiB_2 on the fracture surface, is at the oxidized tensile surface. This is typical of the majority of the Hexoloy ST specimens tested. A few specimens exhibited fractures at large internal pores (Figure 71). Similar pores were noted in the baseline Hexoloy ST material.

Figure 72 shows the oxidized surfaces of the Hexoloy ST specimens following 350, 700, and 1050 hours of exposure at 1260C (2300F). The TiB_2 oxidized rapidly at 1260C (2300F), giving the material a white-green appearance. A heavy oxide layer was present after only 350 hours of exposure. This layer became thicker with increased length of exposure. Following 1050 hours of exposure, the oxide layer typically had a crazed appearance.

6.8 Corning Code 9458 Lithium Aluminum Silicate

Code 9458 Lithium Aluminum Silicate (LAS) glass-ceramic material was procured in 1981 from the Corning Glass Works (Corning, NY) for durability testing at (1093C) 2000F. The specimens were received in the as-machined condition. Durability testing of this LAS material was not successfully completed during this program due to burner rig and temperature measurement problems. The low test temperature and high reflectivity of the LAS material were deemed to be the cause of the temperature measurement problems.

6.8.1 LAS Baseline Test Results

The baseline properties of the longitudinally-machined Corning LAS test specimens are summarized in Table 25. The measured density of the LAS test specimens ranged from 2.24 to 2.29 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 15 to 21 microinch rms, and the transverse surface finish ranged from 35 to 44 microinch rms. The measured surface finish values were relatively high, compared to typical machined ceramic specimen surfaces.

The average LAS room-temperature flexure strength was 13.7 ksi, with a standard deviation of 0.8 ksi. The strength at 1093C (2000F) was 13.0 ksi, with a standard deviation of 1.3 ksi. Most of the specimen failures originated at large surface porosity sites. Figure 73 shows a representative fracture origin for the LAS material. Also shown in Figure 73 is a view of a typical LAS machined test bar surface, illustrating the large amount of 10 to 20 micron size pores in this material. The high level of surface-connected porosity may also be responsible for the high surface finish values.

TABLE 25. BASELINE PROPERTIES OF CODE 9458 LAS SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, µ inch rms	
Code 9458 LAS	Corning Glass Works	August 1981	2.24 to 2.29	Longt.	15 to 21
				Transv.	35 to 44

Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined	
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins
24	(75)	94 ± 5	(13.7 ± 0.8)	11	Surface pores
1093	(200)	90 ± 9	(13.0 ± 1.3)	11	Surface pores

6.8.2 Cyclic Exposure Evaluations Of Corning LAS

The durability test rigs used in this program were originally designed for use at temperatures in the range of 1204C to 1370C (2200F to 2500F), utilizing 400,000 Btu/hr burners. One burner rig was modified with reduced-capacity fuel and air nozzles, dropping the burner output to 250,000 Btu/hr, which lowered the operating temperature to permit a 1093C (2000F) burner rig test.

A cyclic exposure test of Corning LAS test bars at 1093C (2000F) was initiated and successfully completed 350 hours of exposure. The post-exposure test results are summarized in Table 26 and Figure 74. Following 350 hours exposure, the LAS specimens exhibited a 27 percent decrease in average room-temperature strength, to 10.0 ksi. The predominant fracture-originating flaws seen in the post-exposure flexure testing were surface pits and porosity. Examples of the LAS post-exposure failure origins are shown in Figure 75.

TABLE 26. CODE 9458 LAS POST-EXPOSURE TEST RESULTS SUMMARY (1093C).

Material		Surface Condition				Cyclic Oxidation Exposure Temperature
Code 9458 LAS		Longitudinally Machined				1093C (2000F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C (F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24 (75)	94 ± 5	(13.7 ± 0.8)	---	11	Surface pores
350	24 (75)	69 ± 7	(10.0 ± 1.1)	-27	6	Surface pits and porosity

The LAS durability exposure testing was terminated after 732 hours, due to a brief, unplanned overtemperature excursion of approximately 65C (150F). This overtemperature resulted in cracking and swelling of the LAS material, as illustrated in Figure 76. The aging Mikron 66 infrared pyrometers were suspected as the cause of the temperature control problem. A more sensitive "dual spectrum" pyrometer was then procured from the Williamson Co., after evaluation of several competitive models. The Williamson pyrometer satisfactorily detected the temperature of several ceramic materials in calibrated furnace tests, and was installed in a durability test rig for further evaluation. However, the pyrometer output was erratic in initial tests using LAS. Further consultation with Williamson revealed that the temperature of "some materials" could not be detected satisfactorily with this type pyrometer, because of high "reflectivity" of the materials.

Subsequently, LAS durability exposure tests utilizing standard thermocouple controls were attempted; however, this method proved unreliable as well. Further durability exposure testing of LAS was postponed indefinitely, due to the poor operation of the durability burner rigs.

6.9 Ford Motor Co. Reaction Bonded Silicon Nitride

Reaction-bonded silicon nitride (RBSN) test specimens were procured in 1981 from Ford Motor Company (Detroit, MI) for a 3500-hour durability test at 1204C (2200F). The test specimens were supplied in the as-processed (as-nitrided) and "flash-oxidized" condition. Following completion of baseline strength evaluations, spalling problems were encountered in other NASA-monitored programs using Ford RBSN for gas turbine components. Subsequently, the durability exposure testing of Ford RBSN was postponed indefinitely, at NASA's request.

6.9.1 Ford RBSN Baseline Test Results

The baseline properties of the as-processed surface Ford RBSN test specimens are summarized in Table 27. The measured density of the Ford RBSN test specimens ranged from 2.77 to 2.85 g/cm^3. The surface finish ranged from 25 to 40 microinch rms.

The average room-temperature flexure strength of the Ford RBSN test specimens was 41.8 ksi, with a standard deviation of 2.6 ksi. The strength at 1204C (2200F) was 44.2 ksi, with a standard deviation of 3.9 ksi. The predominant failure-initiation sites seen in the flexure test specimens were internal porosity and oxide-filled, surface-connected pores. A typical fracture-originating flaw in Ford RBSN is shown in Figure 77.

TABLE 27. BASELINE PROPERTIES OF FORD RBSN SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms
Ford RBSN		Ford Motor Co.		November 1982	2.77 to 2.85	25 to 40
Test Temperature		Baseline Strength		Surface Condition: As-Processed		
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins	
24	(75)	288 ± 18)	(41.8 ± 2.6)	12	Internal porosity and surface pores	
1204	(2200)	305 ± 27)	(44.2 ± 3.9)	12	Internal porosity and surface pores	

6.10 General Electric Co. Sintered Beta Silicon Carbide

Sintered beta silicon carbide (β-SiC) specimens with as-processed surfaces were procured from the General Electric Company (GE) (Schenectady, NY) in 1984 for a 1400-hour durability test at 1371C (2500F). All the test bars were received with the test surface left in the green-machined and sintered condition.

6.10.1 As-Processed GE β-SiC Baseline Test Results

The baseline properties of the as-processed surface GE β-SiC test specimens are summarized in Table 28. The measured density of the GE β-SiC test specimens ranged from 3.05 to 3.12 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 7 to 8 microinch rms, and the transverse surface finish ranged from 9 to 11 microinch rms.

The average room-temperature flexure strength was 61.3 ksi, with a standard deviation of 4.6 ksi. The flexure strength at 1371C (2500F) was 61.2 ksi, with a standard deviation of 8.9 ksi. The majority of the GE β-SiC specimen failures originated from internal porosity (Figure 78). Additionally, a notable quantity of failures originating from the as-processed surface were observed in these specimens.

TABLE 28. BASELINE PROPERTIES OF BETA-SILICON CARBIDE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
Beta- SiC		General Electric Co.		December 1984	3.05 to 3.12	Longt.	7 to 8
						Transv.	9 to 11
Test Temperature		Baseline Strength		Surface Condition: As-Processed			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	423 ± 32	(61.3 ± 4.6)	12	Internal porosity and as-processed surface		
1371	(2500)	422 ± 61	(61.2 ± 8.9)	12	Internal porosity and as-processed surface		

6.10.2 Results Of As-Processed GE β-SiC Exposures At 1371C (2500F)

GE β-SiC test specimens were cyclically exposed at 1371C (2500F) for durations of 350, 1050, and 1400 hours. Following exposure, the β-SiC test bars were flexure tested at room temperature and 1371C (2500F) to measure retained strength. The β-SiC post-exposure test results are summarized in Table 29 and Figure 79.

The GE β-SiC specimens exhibited little change in strength and fracture characteristics over the 1400 hours of durability test exposure at 1371C (2500F). After 1400 hours of exposure, the room-temperature flexure strength of the β-SiC specimens had decreased 8 percent, to 56.7 ksi; and the 1371C (2500F) strength had decreased 3 percent, to 59.5 ksi. The predominant fracture-originating flaw types seen in post-exposure flexure test specimens were internal pores or porous areas. Typical fracture-originating flaws for the exposed β-SiC specimens are shown in Figures 80 and 81. These flaws were similar to the fracture-initiating flaws seen in the baseline, unexposed test specimens.

TABLE 29. BETA SINTERED SILICON CARBIDE POST-EXPOSURE TEST RESULTS SUMMARY (1371C).

Material			Surface Condition			Cyclic Oxidation Exposure Temperature
β-SiC			As-Processed			1371C (2500F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	423 ± 32	(61.3 ± 4.6)	---	12	Internal porosity, as-processed surface
zero	1371	(2500)	422 ± 61	(61.2 ± 8.9)	---	12	Internal porosity, as-processed surface
350	24	(75)	382 ± 56	(55.4 ± 8.1)	-10	6	Internal porosity
350	1371	(2500)	393 ± 37	(56.9 ± 5.4)	-7	6	Internal porosity
1050	24	(75)	416 ± 31	(60.3 ± 4.4)	-2	4	Internal porosity
1050	1371	(2500)	406 ± 43	(58.9 ± 6.2)	-4	4	Internal porosity
1400	24	(75)	391 ± 19	(56.7 ± 2.7)	-8	4	Internal porosity
1400	1371	(2500)	410 ± 21	(59.5 ± 3.0)	-3	4	Internal porosity

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	1.8	2.2	12
1050	-0.3	1.6	8
1400	-0.6	1.3	8

6.11 GTE AY6 Sintered Silicon Nitride

Test specimens of AY6 sintered silicon nitride with machined test surfaces were procured from GTE Sylvania Laboratories, Inc. (GTE) (Waltham, MA) in 1983 for durability testing at 1204C (2200F). The test specimens were machined from isopressed, green-machined, and sintered billets.

6.11.1 GTE AY6 Baseline Test Results

The baseline properties of the longitudinally-machined GTE AY6 test specimens are summarized in Table 30. The measured density of the AY6 test specimens ranged from 3.15 to 3.17 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 4 to 5 microinch rms, and the transverse surface finish ranged from 8 to 10 microinch rms.

The average baseline (unexposed) AY6 flexure strength at room temperature was 87.3 ksi, with a standard deviation of 6.3 ksi. The flexure strength at 1204C (2200F) was 40.8 ksi, with a standard deviation of 5.3 ksi. The majority of the AY6 baseline specimen failures originated from the tensile surface. At room temperature, the fractures typically originated from porous areas (Figure 82). At 1204C (2200F), the baseline specimens exhibited a region of slow crack growth at the failure origins (Figure 83).

TABLE 30. BASELINE PROPERTIES OF AY6 SPECIMENS.

<table>
<tr><th colspan="2">Material</th><th colspan="2">Supplier</th><th>Delivery Date</th><th>Density, g/cm^3</th><th colspan="2">Surface Finish, μ inch rms</th></tr>
<tr><td colspan="2" rowspan="2">AY6</td><td colspan="2" rowspan="2">GTE Laboratories</td><td rowspan="2">July 1983</td><td rowspan="2">3.15 to 3.17</td><td>Longt.</td><td>4 to 5</td></tr>
<tr><td>Transv.</td><td>8 to 10</td></tr>
<tr><td colspan="2">Test Temperature</td><td colspan="2">Baseline Strength</td><td colspan="4">Surface Condition: Longitudinally Machined</td></tr>
<tr><td>C</td><td>(F)</td><td>MPa</td><td>(ksi)</td><td>Quantity</td><td colspan="3">Primary Failure Origins</td></tr>
<tr><td>24</td><td>(75)</td><td>602 ± 44</td><td>(87.3 ± 6.3)</td><td>12</td><td colspan="3">Surface porosity</td></tr>
<tr><td>1204</td><td>(2200)</td><td>282 ± 37</td><td>(40.8 ± 5.3)</td><td>12</td><td colspan="3">Slow crack growth</td></tr>
</table>

6.11.2 Results Of AY6 Exposures At 1204C (2200F)

GTE AY6 test specimens were cyclically exposed at 1204C (2200F) for 377 hours. The exposed test specimens were then flexure tested at room temperature and 1204C (2200F) to measure the retained strength. The post-exposure test results are summarized in Table 31 and Figure 84. After 377 hours exposure, the AY6 room-temperature strength was reduced by 18 percent, from 87.3 ksi to 71.3 ksi, and the 1204C (2200F) strength was reduced 12 percent, to 36.1 ksi. Inspection of the fracture surfaces revealed that most of the fractures originated from the rough surface oxide layer. Typical AY6 post-exposure fracture origins are shown in Figure 85.

Due to the low baseline strength measured at 1204C (2200F), and further strength reduction resulting from the cyclic exposure at 1204C (2200F), the GTE AY6 durability testing was terminated at 377 hours.

TABLE 31. AY6 POST-EXPOSURE TEST RESULTS SUMMARY (1204C).

Material				Surface Condition			Cyclic Oxidation Exposure Temperature
AY6				Longitudinally Machined			1204C (2200F)
Post-Exposure Strength Measurements Summary							
Exposure Duration,	Test Temperature		Post-Exposure Strength		Strength Change,	Qty.	
hrs	C	(F)	MPa	(ksi)	percent	Tested	Primary Failure Origins
zero	24	(75)	602 ± 44	(87.3 ± 6.3)	---	12	Surface porosity
zero	1204	(2200)	282 ± 37	(40.8 ± 5.3)	---	12	Slow crack growth
377	24	(75)	492 ± 28	(71.3 ± 4.0)	-18	6	Rough oxide layer
377	1204	(2200)	249 ± 23	(36.1 ± 3.3)	-12	6	Rough oxide layer

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
377	2.8	2.9	12

6.12 GTE PY6 Sintered Silicon Nitride

PY6 sintered silicon nitride specimens with machined test surfaces were procured from GTE in 1981 for 3500-hours durability testing at 1204C (2200F). The PY6 test specimens were machined from isopressed, green-machined, and sintered billets. Durability testing of the specimens of this vintage of PY6 material was terminated after 350 hours, due to the poor strength exhibited by the baseline material.

Specimens of a hot isostatically pressed (HIPped) version of the PY6 composition was procured from GTE in 1990, for 1050 hours of durability testing at 1204C (2200F). The HIPped PY6 specimens retained the as-processed (as-HIPped) surface on the test surface of each bar. The test specimens were machined from isopressed, green-machined, and sintered billets, preserving the test surface of the specimen in the as-green-machined, and as-sintered condition.

6.12.1 Machined-Surface Sintered PY6 Baseline Test Results

The baseline properties of the longitudinally-machined PY6 test specimens are summarized in Table 32. The measured density of the PY6 test specimens ranged from 3.16 to 3.20 g/cm^3. The measured machined-surface finish ranged from 10 to 20 microinch rms.

The average flexure strength of PY6 measured at room temperature was 39.9 ksi, with a standard deviation of 8.0 ksi; and the flexure strength at 1204C (2200F) was 47.6 ksi, with a standard deviation of 6.2 ksi. PY6 baseline specimen fractures typically originated from surface or subsurface pores (Figure 86). A few fractures originating at iron-based metallic inclusions were also noted (Figure 87).

These measured strength values for the baseline PY6 specimens were considerably below the strength values demonstrated with prior batches of PY6 material. The lower strength values obtained during this evaluation were identified by GTE as a result of the scale-up from laboratory-size batches, and scaling up of the test bar samples to the size required for the NASA durability evaluations. The specific source of the scale-up problems was not identified.

TABLE 32. BASELINE PROPERTIES OF SINTERED PY6 MACHINED-SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms
PY6		GTE Laboratories		April 1981	3.16 to 3.20	10 to 20
Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined		
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins	
24	(75)	275 ± 55	(39.9 ± 8.0)	12	Surface and subsurface pores, iron inclusions	
1204	(2200)	328 ± 43	(47.6 ± 6.2)	12	Surface and subsurface pores, iron inclusions	

6.12.2 Results Of Machined-Surface Sintered PY6 Exposures At 1204C (2200F)

Based on the low baseline strength values measured for these PY6 test specimens, the full-term 3500-hour durability testing was postponed, pending recovery of PY6 strength characteristics. However, a 350-hour 1204C (2200F) exposure was performed for a preliminary evaluation of this material. Following 350 hours exposure, the retained strength of the PY6 test specimens was measured at room temperature and 1204C (2200F). The post-exposure test results are summarized in Table 33 and Figure 88. After 350 hours exposure, the measured room-temperature strength of the PY6 specimens had dropped 7 percent, to 36.9 ksi; and the 1204C (2200F) retained strength had dropped 8 percent, to 43.7 ksi. Post-exposure weight and dimensional differences were minimal.

The PY6 specimen failures seen in post-exposure flexure tests typically originated from the flame-exposed surfaces (Figure 89). A surface reaction associated with the oxidation exposure appeared to have penetrated up to 100 microns deep in the vicinity of surface-connected and near-surface porosity.

TABLE 33. SINTERED PY6 POST-EXPOSURE TEST RESULTS SUMMARY (1204C, LONGITUDINALLY-MACHINED SPECIMENS).

Material		Surface Condition			Cyclic Oxidation Exposure Temperature
Sintered PY6		Longitudinally Machined			1204C (2200F)
Post-Exposure Strength Measurements Summary					
Exposure Duration, hrs	Test Temperature C (F)	Post-Exposure Strength MPa (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24 (75)	275 ± 55 (39.9 ± 8.0)	---	12	Subsurface and surface pores, iron inclusions
zero	1204 (2200)	328 ± 43 (47.6 ± 6.2)	---	12	Subsurface and surface pores, iron inclusions
350	24 (75)	255 ± 39 (36.9 ± 5.6)	-7	3	Oxidation surface reaction
350	1204 (2200)	302 ± 18 (43.7 ± 2.5)	-8	3	Oxidation surface reaction

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-0.1	0.9	6

6.12.3 As-Processed Surface HIPped PY6 Baseline Test Results

The baseline properties of as-processed surface HIPped PY6 test specimens are summarized in Table 34. The measured density of the HIPped PY6 test specimens ranged from 3.22 to 3.26 g/cm^3, which is higher than the 3.16 to 3.20 g/cm^3 values measured for the sintered version of PY6. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 90 to 100 microinch rms, and the transverse surface finish ranged from 75 to 100 microinch rms. These surface finish values for HIPped PY6 were very high, compared to as-processed surface finish values measured for other ceramic materials under this program.

The average flexure strength of HIPped PY6 measured at room temperature was 83.1 ksi, with a standard deviation of 12.0 ksi; and the flexure strength at 1204C (2200F) was 57.5 ksi, with a standard deviation of 4.4 ksi. The majority of the PY6 specimen failures originated from the tensile surface.

TABLE 34. BASELINE PROPERTIES OF HIPped PY6 AS-PROCESSED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
HIPped PY6		GTE Laboratories		January 1990	3.22 to 3.26	Longt.	90 to 100
						Transv.	75 to 100
Test Temperature		Baseline Strength		Surface Condition: As-Processed			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	573 ± 83	(83.1 ± 12.0)	12	As-processed surface		
1204	(2200)	397 ± 30	(57.5 ± 4.4)	12	As-processed surface		

6.12.4 Results Of As-Processed Surface HIPped PY6 Exposures At 1204C (2200F)

HIPped PY6 test specimens were cyclically exposed at 2200F (1204C) for 350, 700, and 1050 hours. Following exposure, the retained strength was measured at room temperature and 1204C (2200F). The post-exposure test results are summarized in Table 35 and Figure 90. The room-temperature strength initially decreased 14 percent, to 71.2 ksi after 350 hours exposure. With continued exposure, the room-temperature strength remained relatively constant, exhibiting average strengths of 71.4 ksi and 72.7 ksi following 700 and 1050 hours of exposure, respectively. The 1204C (2200F) strength increased 28 percent to 73.6 ksi, after 350 hours of cyclic exposure, and increased further to 78.6 ksi, a 36 percent total increase, after 1050 hours of exposure. The large increase in elevated-temperature strength following cyclic exposure was highly unusual. The results suggest some residual stresses in the as-processed surface may exist, and that an oxidation-annealing heat treatment may improve the baseline material elevated-temperature properties.

The predominant fracture-originating flaws seen in PY6 post-exposure flexure test specimens for all exposure times and strength test temperatures were oxidation pits in the flame-exposed specimen surface. Typical fracture-originating flaws are shown in Figure 91. The oxide layer thickness increased with exposure time, growing to approximately 75 microns in thickness following 1050 hours of exposure. Figure 92 shows the typical surface topography of PY6 flame-exposed surfaces for different exposure times. The PY6 specimens exhibited a pitted surface topography for all exposure times, which is consistent with the post-exposure strength and fractography results.

TABLE 35. HIPped PY6 POST-EXPOSURE TEST RESULTS SUMMARY (1204C, AS-PROCESSED SURFACE SPECIMENS).

Material		Surface Condition				Cyclic Oxidation Exposure Temperature
HIPped PY6		As-Processed				1204C (2200F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	573 ± 83	(83.1 ± 12.0)	---	12	As-processed surface
zero	1204	(2200)	397 ± 30	(57.5 ± 4.4)	---	12	As-processed surface
350	24	(75)	491 ± 39	(71.2 ± 5.7)	-14	6	Oxidation pits
350	1204	(2200)	508 ± 34	(73.6 ± 4.9)	28	6	Oxidation pits
700	24	(75)	493 ± 12	(71.4 ± 1.8)	-14	6	Oxidation pits
700	1204	(2200)	473 ± 36	(68.5 ± 5.2)	19	6	Oxidation pits
1050	24	(75)	501 ± 54	(72.7 ± 7.9)	-12	6	Oxidation pits
1050	1204	(2200)	542 ± 31	(78.6 ± 4.6)	36	6	Oxidation pits

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.1	0.9	12
700	0.0	1.4	12
1050	0.0	2.3	12

6.13 Kyocera SC-201 Silicon Carbide

As-processed surface SC-201 sintered silicon carbide specimens were procured from Kyocera Ceramics Corp. (Kokubu, Japan) in 1984 for durability testing at 1371C (2500F).

6.13.1 As-Processed Surface SC-201 Baseline Test Results

The baseline properties of the Kyocera as-processed surface SC-201 test specimens are summarized in Table 36. The measured density of the SC-201 test specimens ranged from 3.06 to 3.15 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 6 to 11 microinch rms and the transverse surface finish ranged from 10 to 13 microinch rms.

The baseline flexural strength of SC-201 was measured at room temperature, 1204C (2200F), and 1371C (2500F). The measured SC-201 strength values increased with increasing test temperature. The average room-temperature flexure strength was 61.9 ksi, with a standard deviation of 11.4 ksi. The average strength values measured at 1204C (2200F) and 1371C

(2500F) were 66.2 ksi and 71.3 ksi, respectively. The majority of the SC-201 specimen failures originated from surface-connected and internal porosity. Typical fracture-initiating flaws for SC-201 are shown in Figures 93 and 94.

TABLE 36. BASELINE PROPERTIES OF SC-201 AS-PROCESSED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
SC-201		Kyocera Ceramics Corp.		May 1984	3.06 to 3.15	Longt.	6 to 11
						Transv.	10 to 13
Test Temperature		Baseline Strength		Surface Condition: As-Processed			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	427 ± 79	(61.9 ± 11.4)	12	Surface and internal porosity		
1204	(2200)	456 ± 57	(66.2 ± 8.2)	12	Surface and internal porosity		
1371	(2500)	491 ± 61	(71.3 ± 8.8)	12	Surface and internal porosity		

6.13.2 Results Of As-Processed Surface SC-201 Exposures At 1371C (2500F)

As-processed surface SC-201 test specimens were cyclically exposed at 1371C (2500F) for durations of 350, 1050, 2100, and 2270 hours. The testing was terminated at 2270 hours, short of the planned 3500-hours exposure, after a piece of the refractory furnace lining broke loose and damaged the specimens. Following exposure, the retained strength was measured at room temperature and 1371C (2500F). The post-exposure strength testing included some of the specimens which were damaged in the test that was terminated after 2270 hours exposure. For those damaged specimens, the test gage section was preserved in most instances, enabling measurement of post-exposure strength.

The post-exposure test results are summarized in Table 37 and Figure 95. The SC-201 specimens initially showed an increase in both room-temperature and 1371C (2500F) retained strength, up to 1050 hours exposure. After 1050 hours of exposure, the room-temperature strength increased 22 percent, to 75.2 ksi, and the 1371C (2500F) strength increased 9 percent, to 77.5 ksi. However, with continued exposure, the retained strength began to diminish. After 2270 hours exposure, the SC-201 specimens exhibited a 7-percent increase in room-temperature strength, to 66.2 ksi, and the 1371C (2500F) strength decreased 22 percent, to 55.6 ksi. The majority of the post-exposure specimen failures originated from the flame-exposed specimen surface, many of which originated from the chamfered edge of the flame-exposed side (Figure 96). Several specimens failures originated from subsurface or internal porosity (Figure 97).

Typical post-exposure surface topography of the SC-201 specimens is shown in Figure 98. After 1050 hours exposure, the SC-201 specimen surfaces typically exhibited a glassy morphology with localized bubble formation. After 2100 hours of exposure, the bubbles in the glassy layer were typically distributed over the entire surface.

TABLE 37. SC-201 POST-EXPOSURE TEST RESULTS SUMMARY.

Material		Surface Condition			Cyclic Oxidation Exposure Temperature
SC-201		As-Processed			1371C (2500F)
Post-Exposure Strength Measurements Summary					
Exposure Duration, hrs	Test Temperature C (F)	Post-Exposure Strength MPa (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24 (75)	427 ± 79 (61.9 ± 11.4)	---	12	Surface and internal porosity
zero	1371 (2500)	491 ± 61 (71.3 ± 8.8)	---	12	Surface and internal porosity
350	24 (75)	473 ± 12 (68.6 ± 1.7)	11	3	Surface and internal porosity
350	1371 (2500)	483 ± 40 (70.0 ± 5.8)	-2	3	Surface and internal porosity
1050	24 (75)	519 ± 22 (75.2 ± 3.2)	22	3	Surface and internal porosity
1050	1371 (2500)	535 ± 69 (77.5 ± 10.1)	9	3	Surface and internal porosity
2100	24 (75)	391 ± 41 (56.8 ± 5.9)	-8	3	Surface and internal porosity
2100	1371 (2500)	406 ± 6 (58.9 ± 0.9)	-17	3	Surface and internal porosity
2270	24 (75)	457 ± 40 (66.2 ± 5.7)	7	3	Surface and internal porosity
2270	1371 (2500)	383 ± 73 (55.6 ± 10.6)	-22	3	Surface and internal porosity

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-1.2	1.9	6
1050	-1.8	1.4	6
2100	-3.1	4.3	5
2270	---	2.7	6

6.14 Kyocera SN-250M Sintered Silicon Nitride

Machined-surface SN-250M sintered silicon nitride specimens with longitudinally-machined test surfaces were procured from Kyocera Ceramics Corp. (Japan) in 1990 for durability testing at 1204C (2200F).

6.14.1 Machined-Surface SN-250M Baseline Test Results

The baseline properties of the longitudinally-machined SN-250M test specimens are summarized in Table 38. The measured density of the SN-250M test specimens ranged from 3.27 to 3.34 g/cm3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 5 to 8 microinch rms, and the transverse surface finish ranged from 8 to 12 microinch rms.

The baseline flexural strength of SN-250M was measured at room temperature, 982C (1800F), and 1204C (2200F). The average measured room-temperature flexure strength was 128.3 ksi, with a standard deviation of 6.9 ksi. The average strength values measured at 982C (1800F) and 1204C (2200F) were 83.1 ksi and 81.4 ksi, respectively. In the pre-exposure flexure tests, the SN-250M specimens typically fractured from the surface, either at the chamfer or the tensile surface. A typical SN-250M specimen baseline test fracture origin is shown in Figure 99.

TABLE 38. BASELINE PROPERTIES OF SN-250M MACHINED-SURFACE SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, µ inch rms	
SN-250M	Kyocera Ceramics Corp.	October 1986	3.27 to 3.34	Longt.	5 to 8
				Transv.	8 to 12

Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined	
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins
24	(75)	885 ± 47	(128.3 ± 6.9)	12	Machined surface, chamfer
982	(1800)	573 ± 65	(83.1 ± 9.4)	12	Machined surface, chamfer
1204	(2200)	562 ± 43	(81.4 ± 6.3)	12	Machined surface, chamfer

6.14.2 Results Of Machined-Surface SN-250M Exposures At 1204C (2200F)

Machined-surface SN-250M test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 700, and 1050 hours. Following exposure, the SN-250M test bars were flexure tested at room temperature and 1204C (2200F) to measure the retained strength. The SN-250M post-exposure test results are summarized in Table 39 and Figure 100.

The post-exposure room-temperature strength of the SN-250M specimens initially dropped 21 percent, to 101.0 ksi following 350 hours exposure. SN-250M showed no further reduction in room-temperature strength with continued exposure, and exhibited an average room-temperature strength of 106.0 ksi after 1050 hours exposure. The 1204C (2200F) strength was relatively stable up to 1050 hours of exposure. After 1050 hours of exposure, the 1204C (2200F) strength was 76.5 ksi, which was 6 percent below the baseline value.

The strength-controlling flaws for exposed SN-250M specimens were predominantly oxidation pits in the flame-exposed surface for all exposure durations. Typical post-exposure failure origins for SN-250M are shown in Figures 101 through 103. The oxidation pits became progressively deeper with increasing exposure time. However, there was no strong correlation between the size of the oxidation pits and the retained strength level. With exposure beyond 1050 hours, strength loss with continued growth of the oxidation pits would be expected.

The typical surface topography of SN-250M specimens following 350, 700, and 1050 hours exposure is shown in Figures 104(a), (b), and (c), respectively. A very rough, glassy, pitted surface oxide layer was present on the specimens following 350 hours of exposure. Little change in this surface oxide layer was observed with increasing exposure time.

TABLE 39. SN-250M POST-EXPOSURE TEST RESULTS SUMMARY.

Material		Surface Condition				Cyclic Oxidation Exposure Temperature
SN-250M		Longitudinally Machined				1204C (2200F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	885 ± 47	(128.3 ± 6.9)	---	12	Machined surface, chamfer
zero	1204	(2200)	562 ± 43	(81.4 ± 6.3)	---	12	Machined surface, chamfer
350	24	(75)	696 ± 65	(101.0 ± 9.4)	-21	6	Oxidation pits
350	1204	(2200)	563 ± 29	(81.6 ± 4.2)	0	6	Oxidation pits
700	24	(75)	797 ± 37	(115.6 ± 5.4)	-10	6	Oxidation pits
700	1204	(2200)	586 ± 30	(85.0 ± 4.4)	4	6	Oxidation pits
1050	24	(75)	731 ± 43	(106.0 ± 6.2)	-17	6	Oxidation pits
1050	1204	(2200)	528 ± 54	(76.5 ± 7.8)	-6	6	Oxidation pits

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.2	3.0	12
700	0.2	1.7	12
1050	0.1	2.3	12

6.15 Kyocera SN-251 Sintered Silicon Nitride

SN-251 sintered silicon nitride specimens with machined test surfaces were procured from Kyocera Ceramics Corp. (Japan) in 1990 for durability testing at 1204C (2200F). The SN-251 specimens were procured and tested concurrently with Kyocera SN-252 specimens. SN-252 is a sintered, reaction-bonded silicon nitride (SRBSN) version of the nominal SN-251 composition. (The SN-252 results are reported in Section 6.16). Both SN-251 and SN-252 are in-situ toughened silicon nitrides with elongated-grain microstructures for enhanced fracture toughness.

6.15.1 Machined-Surface SN-251 Baseline Test Results

The baseline properties of the longitudinally-machined SN-251 test specimens are summarized in Table 40. The measured density of the SN-251 test specimens ranged from 3.38 to 3.43 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 9 to 11 microinch rms, and the transverse surface finish ranged from 12 to 14 microinch rms.

The baseline flexural strength of SN-251 was measured at room temperature and 1204C (2200F). The average baseline room-temperature flexure strength was 114.1 ksi, with a standard deviation of 8.4 ksi, and the average strength at 1204C (2200F) was 84.9 ksi, with a standard deviation of 4.7 ksi. The majority of the baseline SN-251 specimen failures originated from large acicular grains, typically 100 microns in length (Figure 105).

TABLE 40. BASELINE PROPERTIES OF SN-251 MACHINED-SURFACE SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
SN-251	Kyocera Ceramics Corp.	February 1990	3.38 to 3.43	Longt.	9 to 11
				Transv.	12 to 14

Test Temperature		Baseline Strength		Surface Condition: longitudinally Machined	
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins
24	(75)	787 ± 58	(114.1 ± 8.4)	12	Large acicular grains
1204	(2200)	585 ± 33	(84.9 ± 4.7)	12	Large acicular grains

6.15.2 Results Of Machined-Surface SN-251 Exposures At 1204C (2200F)

Machined-surface SN-251 test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 700, and 1050 hours. SN-251 specimens were exposed concurrently with Kyocera SN-252 specimens in the same test carousel (the SN-252 results are reported in Section 6.16). Following exposure, the retained strength was measured at room temperature and 1204C (2200F). The SN-251 post-exposure test results are summarized in Table 41 and Figure 106.

Following 1050 hours of exposure, the SN-251 specimens exhibited a small decrease (7 percent) in room-temperature strength, from 114.1 ksi to 106.4 ksi, and a small increase (6 percent) in 1204C (2200F) strength, from 84.9 ksi to 89.8 ksi. Following exposure, the specimen failures originated primarily from the surface oxide layer, although several SN-251 specimens did fail at the long acicular grains typical of the baseline fracture origins. Typical post-exposure failure origins for SN-251 are shown in Figures 107 through 108.

The typical surface topography of SN-251 specimens following 350, 700, and 1050 hours exposure is shown in Figures 109(a), (b), and (c), respectively. The flame-exposed surface roughened with increasing exposure time. Pitting was evident after 1050 hours exposure.

TABLE 41. SN-251 POST-EXPOSURE TEST RESULTS SUMMARY.

Material		Surface Condition				Cyclic Oxidation Exposure Temperature
SN-251		Longitudinally Machined				1204C (2200F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	787 ± 58	(114.1 ± 8.4)	---	12	Large acicular grains
zero	1204	(2200)	585 ± 33	(84.9 ± 4.7)	---	12	Large acicular grains
350	24	(75)	746 ± 17	(108.2 ± 2.5)	-5	3	Oxide layer
350	1204	(2200)	673 ± 25	(97.6 ± 3.7)	15	3	Oxide layer
700	24	(75)	735 ± 90	(106.5 ± 13.0)	-7	3	Oxide layer
700	1204	(2200)	624 ± 53	(90.5 ± 7.7)	7	3	Oxide layer
1050	24	(75)	734 ± 32	(106.4 ± 4.7)	-7	3	Oxide layer
1050	1204	(2200)	619 ± 11	(89.8 ± 1.7)	6	3	Oxide layer

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.1	1.5	6
700	0.1	1.6	6
1050	0.0	1.7	6

6.16 Kyocera SN-252 Sintered Reaction Bonded Silicon Nitride

Machined-surface SN-252 sintered, reaction-bonded silicon nitride (SRBSN) specimens with machined test surfaces were procured from Kyocera Ceramics Corp. (Japan) in 1990 for durability testing at 1204C (2200F). The SN-251 specimens were procured and tested concurrently with the Kyocera SN-252 specimens. (Refer to Section 6.15 for the SN-251 results). SN-251 is a sintered silicon nitride with the same nominal composition as SN-252. Both SN-251 and SN-252 are in-situ toughened silicon nitrides with elongated-grain microstructures for enhanced fracture toughness.

6.16.1 Machined-Surface SN-252 Baseline Test Results

The baseline properties of the longitudinally-machined SN-252 test specimens are summarized in Table 42. The measured density of the SN-252 test specimens ranged from 3.36 to 3.40 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 9 to 11 microinch rms, and the transverse surface finish surface ranged from 12 to 14 microinch rms.

The baseline flexural strength of SN-252 was measured at room temperature and 1204C (2200F). The baseline strength characteristics of these SN-252 specimens were lower than SN-251 at both room and elevated temperature. The average room-temperature flexure strength was 93.4 ksi, with a standard deviation of 7.7 ksi. The average strength at 1204C (2200F) was 72.8 ksi, with a standard deviation of 3.4 ksi. Similar to SN-251, the predominant fracture-originating flaws were large acicular grains.

TABLE 42. BASELINE PROPERTIES OF SN-252 MACHINED-SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
SN-252		Kyocera Ceramics Corp.		May 1990	3.36 to 3.40	Longt.	9 to 11
						Transv.	12 to 14
Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	644 ± 53	(93.4 ± 7.7)	20	Large acicular grains		
1204	(2200)	502 ± 23	(72.8 ± 3.4)	7	Large acicular grains		

6.16.2 Results Of Machined-Surface SN-252 Exposures At 1204C (2200F)

Machined-surface SN-252 test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 700, and 1050 hours. The SN-252 specimens were exposed concurrently with the Kyocera SN-251 specimens in the same test carousel. (The SN-251 results are reported in Section 6.15). Following exposure, the retained strength was measured at room temperature and 1204C (2200F). The SN-252 post-exposure test results are summarized in Table 43 and Figure 110.

Following 1050 hours exposure, SN-252 exhibited a small decrease in both room-temperature and 1204C (2200F) strength. At room temperature, the flexure strength of SN-252 decreased 14 percent, from 93.4 ksi to 80.7 ksi, and the 1204C (2200F) strength decreased 11 percent, from 72.8 ksi to 64.8 ksi. Following exposure, the SN-252 specimen failures originated primarily from the large silicon nitride grains intersecting the rough surface oxide layer. A few failures from internal silicon nitride grains were also observed. Typical post-exposure failure origins for SN-252 are shown in Figures 111 through 112.

The typical surface topography of SN-252 specimens following 350, 700, and 1050 hours exposure is shown in Figures 113(a), (b), and (c), respectively. The flame-exposed surface roughened with increasing exposure time. The oxide thickness for all exposure times was approximately 25 microns.

TABLE 43. SN-252 POST-EXPOSURE TEST RESULTS SUMMARY.

Material			Surface Condition				Cyclic Oxidation Exposure Temperature
SN-252			Longitudinally Machined				1204C (2200F)
Post-Exposure Strength Measurements Summary							
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	644 ± 53	(93.4 ± 7.7)	---	20	Large acicular grains
zero	1204	(2200)	502 ± 23	(72.8 ± 3.4)	---	7	Large acicular grains
350	24	(75)	573 ± 21	(83.0 ± 3.0)	-11	3	Large grains, oxide layer
350	1204	(2200)	482 ± 19	(69.9 ± 2.8)	-4	3	Large grains, oxide layer
700	24	(75)	580 ± 22	(84.1 ± 3.2)	-10	3	Large grains, oxide layer
700	1204	(2200)	463 ± 7	(67.1 ± 1.0)	-8	3	Large grains, oxide layer
1050	24	(75)	557 ± 37	(80.7 ± 5.4)	-14	3	Large grains, oxide layer
1050	1204	(2200)	447 ± 28	(64.8 ± 4.1)	-11	3	Large grains, oxide layer

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.0	1.5	6
700	0.0	1.6	6
1050	-0.1	1.6	6

6.17 Kyocera SN-253 Sintered Silicon Nitride

SN-253 sintered silicon nitride specimens with as-processed test surfaces were procured from Kyocera Industrial Ceramics Corp. (Vancouver, WA) in 1995 for durability testing at 1316C (2400F). The SN-253 specimens were procured and tested concurrently with Kyocera SN-281 specimens. (The SN-281 results are described in Section 6.19).

6.17.1 As-Processed Surface SN-253 Baseline Test Results

The baseline properties of the as-processed surface SN-253 test specimens are summarized in Table 44. The measured density of the SN-253 test specimens ranged from 3.44 to 3.46 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 56 to 74 microinch rms and the transverse surface finish ranged from 64 to 82 microinch rms.

The pre-exposure flexural strength of the as-processed SN-253 specimens was measured at room temperature and 1316C (2400F). The average baseline room-temperature SN-253 flexure strength was 94.2 ksi, with a standard deviation of 9.9 ksi, and the 1316C (2400F) flexure strength was 96.2 ksi, with a standard deviation of 5.2 ksi. The majority of the baseline specimen failures originated from the as-processed specimen surface. Small pits were present at the fracture origination site on several specimens. Figure 114 illustrates a typical SN-253 specimen fracture originating from a pit approximately 25 microns deep. Figure 115 shows a pock (a partially-enclosed surface cavity) fracture origin on a lower-strength (78 ksi) specimen. The pock was approximately 75 microns deep.

TABLE 44. BASELINE PROPERTIES OF SN-253 AS-PROCESSED SURFACE SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
SN-253	Kyocera Ceramics Corp.	May 1995	3.44 to 3.46	Longt.	56 to 74
				Transv.	64 to 82

Test Temperature		Baseline Strength		Surface Condition: As-Processed	
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins
24	(75)	650 ± 68	(94.2 ± 9.9)	6	As-processed surface, small pits
1316	(2400)	664 ± 36	(96.2 ± 5.2)	6	As-processed surface, small pits

6.17.2 <u>Results Of As-Processed Surface SN-253 Exposures At 1316C (2400F)</u>

As-processed surface SN-253 test specimens were cyclically exposed at 1316C (2400F) for durations of 350, 700, and 1050 hours. The SN-253 test specimens were assembled into the same durability test fixture with the SN-281 specimens and exposed concurrently. (Test results for SN-281 are discussed in Section 6.19). The SN-253 post-exposure test results are summarized in Table 45 and Figure 116.

Following exposure, SN-253 retained flexural strength was measured at room temperature and 1316C (2400F) for each exposure duration. Overall, the SN-253 specimens retained approximately 75 percent of the baseline room-temperature and 1316C (2400F) flexural strength. The average room-temperature and 1316C (2400F) strength values measured after 1050 hours of exposure were 71.7 ksi and 72.0 ksi, respectively, compared to 94.2 ksi and 96.2 ksi, respectively, for the baseline pre-exposure tests. For reference, SN-253 specimens tested previously in the AlliedSignal Engines oxidation durability rig at 1260C (2300F) under internal funding exhibited 100-percent strength retention following exposure for various periods.

TABLE 45. SN-253 POST-EXPOSURE TEST RESULTS SUMMARY.

Material	Surface Condition	Cyclic Oxidation Exposure Temperature
SN-253	As-Processed	1316C (2400F)

Post-Exposure Strength Measurements Summary

Exposure Duration, hrs	Test Temperature C	Test Temperature (F)	Post-Exposure Strength MPa	Post-Exposure Strength (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	650 ± 68	(94.2 ± 9.9)	---	6	As-processed surface, small pits
zero	1316	(2400)	664 ± 36	(96.2 ± 5.2)	---	6	As-processed surface, small pits
350	24	(75)	612 ± 25	(88.7 ± 3.6)	-6	3	Oxidation pits
350	1316	(2400)	578 ± 43	(83.8 ± 6.2)	-13	3	Oxidation pits
700	24	(75)	508 ± 56	(73.6 ± 8.1)	-22	3	Oxidation pits
700	1316	(2400)	484 ± 54	(70.2 ± 7.8)	-27	3	Oxidation pits
1050	24	(75)	494 ± 100	(71.7 ± 14.5)	-24	3	Oxidation pits
1050	1316	(2400)	496 ± 54	(72.0 ± 7.8)	-25	3	Oxidation pits

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-0.2	0.2	6
700	-0.3	1.8	6
1050	-0.5	1.4	6

Failure origins seen in the post-exposure flexure tests on the SN-253 specimens were located predominately at pits in the flame-exposed surface. The pitting was relatively severe, up to 200 microns deep. The edges of the specimens appeared to be particularly susceptible to oxidation-induced pitting. Examples of typical failure origins for SN-253 following cyclic exposure at 1316C (2400F) are shown in Figures 117 through 119.

Additionally, the SN-253 specimens exhibited some signs of intermediate-temperature (400C to 900C [752F to 1652F]) oxidation instability in the attachment area of the specimens. Three of the SN-253 durability specimens exhibited localized discoloration (white spots) in the cooler attachment area. One of the three specimens exhibited cracks emanating from a discolored area (Figure 120). It should be noted that SN-253 specimens exhibited similar oxidation-induced cracking in a previous AlliedSignal Engines internally-funded oxidation durability test performed at 1260C (2300F). It was believed these oxidation instability problems with SN-253 had been resolved, based on further extensive static air furnace experiments. The present NASA-sponsored long-duration durability test results suggest static air furnace tests may not be adequate for oxidation screening of ceramic materials targeted for gas turbine applications.

The surface topography of the oxidized SN-253 test specimens was documented using scanning electron microscopy (SEM). Figure 121 shows the typical SN-253 specimen surface topography of a baseline (unexposed) specimen and specimens exposed for 350, 700, and 1050 hours. After 350 hours of exposure, the SN-253 specimens exhibited a relatively rough scale of oxide nodules. After 700 hours of exposure, the oxide exhibited a glassy morphology and the onset of pitting. After 1050 hours of exposure, the oxide scale was relatively rough and exhibited localized spalling. The typical SN-253 oxide layer thickness was approximately 20 microns after 350 hours and 50 microns after 1050 hours of exposure.

6.18 Kyocera SN-260 Sintered Silicon Nitride

SN-260 sintered silicon nitride specimens with as-processed test surfaces were procured from Kyocera Ceramics Corp. (Japan) in 1991 for durability testing at 1260C (2300F).

6.18.1 As-Processed Surface SN-260 Baseline Test Results

The baseline properties of the as-processed surface SN-260 test specimens are summarized in Table 46. The measured density of the SN-253 test specimens was 3.38 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 26 to 38 microinch rms and the transverse surface finish ranged from 24 to 47 microinch rms.

The average baseline SN-260 room-temperature flexure strength was 94.1 ksi, with a standard deviation of 10.5 ksi, and the 1260C (2300F) flexure strength was 80.7 ksi, with a standard deviation of 11.0 ksi. The majority of the baseline specimen fractures originated from the as-processed surface. Figure 122 shows a typical SN-260 fracture origin at a pit in the as-processed surface. Some failures from internal porosity were also documented (Figure 123).

TABLE 46. BASELINE PROPERTIES OF SN-260 AS-PROCESSED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, µ inch rms	
SN-260		Kyocera Ceramics Corp.		February 1991	3.38	Longt.	26 to 38
						Transv.	24 to 47
Test Temperature		Baseline Strength		Surface Condition: As-Processed			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	649 ± 72	(94.1 ± 10.5)	12	As-processed surface, surface pits		
1260	(2300)	556 ± 76	(80.7 ± 11.0)	12	As-processed surface, surface pits		

6.18.2 Results of As-Processed Surface SN-260 Exposures At 1260C (2300F)

A 1050-hour cyclic durability exposure test at 1260C (2300F) was initiated on the SN-260 specimens. However, the test was terminated after 303 hours, due to a cracking problem in the cooler attachment area of the SN-260 test specimens. Cracks had originated at the specimen notch used for fixturing the bars in the test carousel (Figure 124). This cracking resulted from an oxidation-induced phase change and associated expansion of the grain boundaries in the attachment area. Kyocera SN-260 requires a "flash oxidation" heat treatment for phase stability. However, this heat treatment had not been re-applied after notching of these specimens at AlliedSignal Engines for the durability rig fixturing. Therefore, the specimens were locally unprotected in the notch region. The results of oxidation studies performed by Kyocera suggested that re-applying the "flash oxidation" treatment after notching would eliminate the cracking problem.

Subsequently, 12 spare SN-260 specimens were "flash oxidized" and a new 1050-hour cyclic durability test at 1260C (2300F) was initiated, to verify the cracking problem had been eliminated. Hexoloy SA specimens were used as "dummy" bars to fill the remaining 12 positions in the burner carousel. However, this second SN-260 cyclic oxidation test was also terminated, after 333 hours, due to reoccurrence of the cracking problem observed during the initial testing. In contrast to the first test, the cracking observed in the second test had originated about 0.25 inch (0.6 cm) above the notch (Figure 125). Based on these results from the second durability test, all work on SN-260 was terminated.

Since only the attachment region of the SN-260 specimens was affected by the cracking problem, the flame-exposed test portions of the specimens were suitable for post-exposure evaluations. Therefore, the retained strength of the SN-260 specimens exposed for 303 hours was measured, and the results are summarized in Table 47 and Figure 126. Following 303 hours of exposure at 1260C (2300F), the average SN-260 room-temperature strength had decreased 11 percent, from 94.1 ksi to 83.6 ksi, and the average 1260C (2300F) strength had dropped 8 percent, from 80.7 ksi to 74.0 ksi. The fracture origins of the exposed SN-260 specimens originated mostly at pitting below the oxide layer (Figure 127). Some failures from pre-existing material defects, such as internal porosity or large Si_3N_4 grains were also noted.

TABLE 47. SN-260 POST-EXPOSURE TEST RESULTS SUMMARY.

Material		Surface Condition			Cyclic Oxidation Exposure Temperature
SN-260		As-Processed			1260C (2300F)
Post-Exposure Strength Measurements Summary					
Exposure Duration, hrs	Test Temperature C (F)	Post-Exposure Strength MPa (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24 (75)	649 ± 72 (94.1 ± 10.5)	---	12	As-processed surface, surface pits
zero	1260 (2300)	556 ± 76 (80.7 ± 11.0)	---	12	As-processed surface, surface pits
303	24 (75)	577 ± 63 (83.6 ± 9.1)	-11	6	Pits beneath oxide layer
303	1260 (2300)	511 ± 44 (74.0 ± 6.4)	-8	6	Pits beneath oxide layer

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
303	0.4	1.7	11

6.19 Kyocera SN-281 Sintered Silicon Nitride

SN-281 sintered silicon nitride specimens with as-processed test surfaces were procured from Kyocera Ceramics Corp. (Japan) in 1995 for durability testing at 1316C (2400F). The SN-281 specimens were procured and tested concurrently with Kyocera SN-253 specimens. (The SN-253 results are discussed in Section 6.17).

6.19.1 As-Processed Surface SN-281 Baseline Test Results

The baseline properties of the as-processed surface SN-281 test specimens are summarized in Table 48. The measured density of the SN-281 test specimens ranged from 3.39 to 3.40 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 34 to 53 microinch rms and the transverse surface finish ranged from 32 to 53 microinch rms.

The average baseline room-temperature flexure strength was 104.5 ksi, with a standard deviation of 6.8 ksi, and the 1316C (2400F) flexure strength was 85.4 ksi, with a standard deviation of 2.8 ksi. All baseline SN-281 specimen fractures originated from the as-processed surface. No pits or other surface anomalies were noted in optical examinations or SEM of the fracture surfaces. Figure 128 illustrates a typical SN-281 specimen fracture originating from the as-processed surface. A single specimen exhibited a stringer-like inclusion in the vicinity of a surface failure origin. Wavelength-dispersive X-ray (WDX) analysis revealed the stringer was a concentration of sintering additive (Figure 129).

TABLE 48. BASELINE PROPERTIES OF SN-281 AS-PROCESSED SURFACE SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, µ inch rms	
SN-281	Kyocera Ceramics Corp.	May 1995	3.39 to 3.40	Longt.	34 to 53
				Transv.	32 to 53

Test Temperature		Baseline Strength		Surface Condition: As-Processed	
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins
24	(75)	720 ± 47	(104.5 ± 6.8)	6	As-processed surface
1316	(2400)	589 ± 20	(85.4 ± 2.8)	6	As-processed surface

6.19.2 Results Of As-Processed Surface SN-281 Exposures At 1316C (2400F)

As-processed surface SN-281 test specimens were cyclically exposed at 1316C (2400F) for durations of 350, 700, and 1050 hours. Note that both the SN-281 and SN-253 test specimens were assembled into the same durability test fixture and were exposed concurrently. (The test results for SN-253 are discussed in Section 6.17). The SN-281 post-exposure test results are summarized in Table 49 and Figure 130.

Overall, after exposure the Kyocera SN-281 specimens retained approximately 65 percent of the baseline room-temperature strength and 75 percent of the 1316C (2400F) flexural strength. The average room-temperature and 1316C (2400F) strength values measured after 1050 hours of exposure were 67.8 ksi and 64.1 ksi, respectively, compared to 104.5 ksi and 85.4 ksi, respectively, for the baseline tests.

The post-exposure fractography results for SN-281 were similar to SN-253. The failure origins for the SN-281 specimens were located predominately at pits in the flame-exposed surfaces. The pitting was relatively severe, up to 150 microns deep. Additionally, the edges of the specimens appeared to be particularly susceptible to oxidation-induced pitting. Examples of typical failure origins for SN-281 following cyclic exposure at 1316C (2400F) are shown in Figures 131 through 133. Unlike SN-253, the SN-281 specimens exhibited no evidence of intermediate-temperature oxidation instability.

The surface topography of the oxidized SN-281 specimens was documented using SEM. Figure 134 shows typical SN-281 surface topography of a baseline (unexposed) specimen and specimens exposed for 350, 700, and 1050 hours. After 350 hours of exposure, the SN-281 specimens exhibited a relatively rough scale of oxide nodules. After 700 and 1050 of hours exposure, the SN-281 specimens exhibited a pitted, glassy oxide scale. The typical oxide thickness was approximately 15 microns after 350 hours and 30 microns after 1050 hours of exposure, respectively.

TABLE 49. SN-281 POST-EXPOSURE TEST RESULTS SUMMARY.

Material		Surface Condition				Cyclic Oxidation Exposure Temperature
SN-281		As-Processed				1316C (2400F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C (F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24 (75)	720 ± 47	(104.5 ± 6.8)	---	6	As-processed surface
zero	1316 (2400)	589 ± 20	(85.4 ± 2.8)	---	6	As-processed surface
350	24 (75)	509 ± 60	(73.9 ± 8.7)	-29	3	Exposed surface, chamfer
350	1316 (2400)	525 ± 32	(76.2 ± 4.7)	-11	3	Exposed surface, chamfer
700	24 75)	472 ± 28	(68.5 ± 4.0)	-34	3	Oxidation pits
700	1316 (2400)	489 ± 21	(71.0 ± 3.0)	-17	3	Oxidation pits
1050	24 (75)	468 ± 37	(67.8 ± 5.4)	-35	3	Oxidation pits
1050	1316 (2400)	442 ± 11	(64.1 ± 1.6)	-25	3	Oxidation pits

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-0.2	0.4	6
700	-0.2	1.4	6
1050	-0.5	1.2	6

6.20 NGK SN-50 Sintered Silicon Nitride

SN-50 sintered silicon nitride specimens with as-processed test surfaces were procured from NGK Insulators (Nagoya, Japan) in 1984 for durability testing at 1204C (2200F).

6.20.1 As-Processed Surface SN-50 Baseline Test Results

The baseline properties of the as-processed surface SN-50 test specimens are summarized in Table 50. The measured density of the SN-50 test specimens ranged from 3.11 to 3.14 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 7 to 15 microinch rms and the transverse surface finish ranged from 10 to 15 microinch rms.

The baseline flexural strength of the SN-50 specimens was measured at room temperature and 1204C (2200F). The average baseline room-temperature flexure strength was 96.7 ksi, with a standard deviation of 7.0 ksi, and the average strength at 1204C (2200F) was 46.8 ksi, with a standard deviation of 3.1 ksi. Based on optical examination of the fracture surfaces at 40X magnification, the majority of the SN-50 specimen failures in flexure tests originated from the tensile surface. Subsequent SEM examination of selected fracture surfaces revealed that fractures appearing to originate at the tensile surface actually originated at subsurface porosity (Figure 135). In specimens flexure tested at 1204C (2200F), the fracture origins had an area of slow crack growth visible (Figure 136).

TABLE 50. BASELINE PROPERTIES OF SN-50 AS-PROCESSED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
SN-50		NGK Insulators		September 1984	3.11 to 3.14	Longt.	7 to 15
						Transv.	10 to 15
Test Temperature		Baseline Strength		Surface Condition: As-Processed			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	667 ± 48	(96.7 ± 7.0)	12	As-Processed surface, subsurface porosity		
1204	(2200)	323 ± 21	(46.8 ± 3.1)	12	Slow crack growth		

6.20.2 Results Of As-Processed Surface SN-50 Exposures At 1204C (2200F)

A cyclic durability test at 1204C (2200F) was initiated for as-processed surface SN-50 test specimens. The test was terminated after 350 hours, based on low elevated-temperature baseline properties and degradation of both room- and elevated-temperature properties observed after 350 hours of exposure. The post-exposure test results for SN-50 are summarized in Table 51 and Figure 137.

The room-temperature flexure strength decreased 36 percent, from 96.7 ksi to 62.3 ksi after 350 hours of exposure, and the 1204C (2200F) strength decreased 66 percent, from 46.8 ksi to 15.8 ksi. All of the SN-50 specimen failures originated from the flame-exposed surface, although the thick surface oxide layer and flat, featureless fracture surfaces made determination of the exact failure origin locations difficult. A typical post-exposure fracture surface for SN-50 is shown in Figure 138. The exposed specimens tested at 1204C (2200F) all revealed signs of slow crack growth, similar to the baseline SN-50 elevated-temperature test specimens.

TABLE 51. SN-50 POST-EXPOSURE TEST RESULTS SUMMARY.

Material			Surface Condition			Cyclic Oxidation Exposure Temperature
SN-50			As-Processed			1204C (2200F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	667 ± 48	(96.7 ± 7.0)	---	12	As-processed surface, subsurface porosity
zero	1204	(2200)	323 ± 21	(46.8 ± 3.1)	---	12	Slow crack growth
350	24	(75)	430 ± 33	(62.3 ± 4.7)	-36	6	Oxide layer
350	1204	(2200)	109 ± 14	(15.8 ± 2.0)	-66	6	Slow crack growth

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.0	1.9	12

6.21 NGK SN-82 Sintered Silicon Nitride

SN-82 sintered silicon nitride specimens with as-processed test surfaces were procured from NGK in 1986 for durability testing at 1204C (2200F).

6.21.1 As-Processed Surface SN-82 Baseline Test Results

The baseline properties of the as-processed SN-82 test specimens are summarized in Table 52. The measured density of the SN-82 test specimens ranged from 3.23 to 3.26 g/cm^3. The surface finish ranged from 5 to 10 microinch rms.

The baseline flexural strength of SN-82 was measured at room temperature, 982C (1800F), and 1204C (2200F). The average room-temperature flexure strength was 120.4 ksi, with a standard deviation of 14.0 ksi. The average strength values measured at 982C (1800F) and 1204C (2200F) were 103.9 ksi and 97.3 ksi, respectively. The majority of the SN-82 specimen failures originated from the as-processed surface. In most instances, no obvious material defect was noted at the failure origin (Figure 139). However, several specimen failures originated at pores or porous areas, as shown in Figure 140.

TABLE 52. BASELINE PROPERTIES OF SN-82 AS-PROCESSED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms
SN-82		NGK Insulators		January 1986	3.23 to 3.26	5 to 10
Test Temperature		Baseline Strength		Surface Condition: As-Processed		
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins	
24	(75)	831 ± 97	(120.4 ± 14.0)	12	As-processed surface, porosity	
982	(1800)	717 ± 63	(103.9 ± 9.2)	12	As-processed surface, porosity	
1204	(2200)	671 ± 38	(97.3 ± 5.5)	12	As-processed surface, porosity	

6.21.2 Results Of As-Processed Surface SN-82 Exposures At 1204C (2200F)

As-processed surface SN-82 test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 1050, 2100, and 3500 hours. For all exposure durations, the retained strength of SN-82 was measured at room temperature and 1204C (2200F). The post-exposure test results are summarized in Table 53 and Figure 141.

The NGK SN-82 specimens initially exhibited large losses in strength following the first 350 hours of exposure. After 350 hours of exposure, the SN-82 specimens had lost 26 percent and 42 percent of the baseline room-temperature and 1204C (2200F) strength, respectively. With continued exposure, the SN-82 specimens exhibited minimal change in post-exposure strength at both room and elevated temperatures. After 350 hours of exposure, the room-temperature strength dropped 36 percent, from 120.4 ksi to 77.6 ksi, and the 1204C (2200F) strength dropped 36 percent, from 97.3 ksi to 62.4 ksi. All of the post-exposure specimen failures originated from oxidation-induced defects on the flame-exposed surface. Typical post-exposure fracture-originating flaws for SN-82 are shown in Figures 142 and 143.

Figure 144 shows the oxidized surface of an SN-82 specimen exposed for 2100 hours. The oxide layer is well bonded to the specimen surface, and glassy in appearance with many surface pits. Following 3500 hours of exposure, SN-82 exhibited localized areas of oxide spalling (Figure 145).

TABLE 53. SN-82 POST-EXPOSURE TEST RESULTS SUMMARY.

Material		Surface Condition			Cyclic Oxidation Exposure Temperature
SN-82		As-Processed			1204C (2200F)
Post-Exposure Strength Measurements Summary					

Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	831 ± 97	(120.4 ± 14.0)	---	12	As-processed surface, porosity
zero	1204	(2200)	671 ± 38	(97.3 ± 5.5)	---	12	As-processed surface, porosity
350	24	(75)	611 ± 43	(88.6 ± 6.2)	-26	3	Oxidation induced surface defects
350	1204	(2200)	392 ± 6	(56.9 ± 0.9)	-42	3	Oxidation induced surface defects
1050	24	(75)	515 ± 44	(74.6 ± 6.4)	-38	6	Oxidation induced surface defects
1050	1204	(2200)	471 ± 56	(68.3 ± 8.2)	-30	6	Oxidation induced surface defects
2100	24	(75)	514 ± 22	(74.5 ± 3.1)	-38	6	Oxidation induced surface defects
2100	1204	(2200)	492 ± 27	(71.3 ± 3.9)	-27	6	Oxidation induced surface defects
3500	24	(75)	525 ± 30	(77.6 ± 4.3)	-36	6	Oxidation induced surface defects
3500	1204	(2200)	430 ± 22	(62.4 ± 3.2)	-36	5	Oxidation induced surface defects

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-0.1	1.9	6
1050	1.1	2.5	12
2100	0.9	2.3	12
3500	2.2	3.0	11

6.22 NGK SN-84 Sintered Silicon Nitride

SN-84 sintered silicon nitride specimens with machined test surfaces were procured from NGK in 1987 for durability testing at 1204C (2200F).

6.22.1 Machined Surface SN-84 Baseline Test Results

The baseline properties of the longitudinally-machined SN-84 test specimens are summarized in Table 54. The measured density of the SN-84 test specimens ranged from 3.25 to 3.26 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 8 to 12 microinch rms and the transverse surface finish ranged from 10 to 18 microinch rms.

The baseline flexural strength of SN-84 was measured at room temperature and 1204C (2200F). The average room-temperature flexure strength was 139.7 ksi, with a standard deviation of 21.5 ksi, and the average strength at 1204C (2200F) was 134.5 ksi, with a standard deviation of 15.8 ksi. The majority of the SN-84 specimen failures originated from the machined surface (Figure 146). Several specimens failed from internal inclusions composed of iron, chromium, and nickel (Figure 147).

TABLE 54. BASELINE PROPERTIES OF SN-84 MACHINED SURFACE SPECIMENS.

<table>
<tr><th colspan="2">Material</th><th colspan="2">Supplier</th><th>Delivery Date</th><th>Density, g/cm^3</th><th colspan="2">Surface Finish, µ inch rms</th></tr>
<tr><td colspan="2" rowspan="2">SN-84</td><td colspan="2" rowspan="2">NGK Insulators</td><td rowspan="2">September 1987</td><td rowspan="2">3.25 to 3.26</td><td>Longt.</td><td>8 to 12</td></tr>
<tr><td>Transv.</td><td>10 to 18</td></tr>
<tr><th colspan="2">Test Temperature</th><th colspan="2">Baseline Strength</th><th colspan="4">Surface Condition: Longitudinally Machined</th></tr>
<tr><th>C</th><th>(F)</th><th>MPa</th><th>(ksi)</th><th>Quantity</th><th colspan="3">Primary Failure Origins</th></tr>
<tr><td>24</td><td>(75)</td><td>964 ± 148</td><td>(139.7 ± 21.5)</td><td>12</td><td colspan="3">Machined surface, metallic inclusions</td></tr>
<tr><td>1204</td><td>(2200)</td><td>927 ± 109</td><td>(134.5 ± 15.8)</td><td>12</td><td colspan="3">Machined surface, metallic inclusions</td></tr>
</table>

6.22.2 Results Of Machined Surface SN-84 Exposed At 1204C (2200F)

Machined-surface SN-84 test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 700, and 1050 hours. Following exposure, the retained strength of SN-84 was measured at room temperature and 1204C (2200F) for all exposure durations. The SN-84 post-exposure test results are summarized in Table 55 and Figure 148.

The NGK SN-84 specimens initially exhibited large losses in strength during the first 350 hours of exposure. After 350 hours of exposure, the SN-84 specimens had lost 56 percent and 47 percent of the pre-exposure baseline room-temperature and 1204C (2200F) strength, respectively. With continued exposure, SN-84 exhibited less changes in post-exposure strength at both room and elevated temperature. After 1050 hours of exposure, the SN-84 room-temperature strength dropped a total of 64 percent, from 139.7 ksi to 50.8 ksi, and the 1204C (2200F) strength dropped 41 percent, from 134.5 ksi to 79.1 ksi. All of the post-exposure specimen failures originated from oxidation pits beneath the rough oxide layer formed during exposure. Typical post-exposure fracture-originating flaws for SN-84 are shown in Figures 149 and 150.

Surface topography of SN-84 specimens as a function of exposure time is illustrated in Figure 151. The NGK SN-84 specimens exposed at 2200F (1204C) exhibited an oxide layer approximately 50 microns thick for all exposure durations, though the oxide layer appearance changed with increased exposure. A coarse oxide layer was present following 350 hours of exposure. After 700 hours, glassy pools were present on the surface of the oxide layer. After 1050 hours of exposure, several oxidation pits had formed within the glassy pools, which had increased in coverage.

TABLE 55. SN-84 POST-EXPOSURE TEST RESULTS SUMMARY.

Material	Surface Condition	Cyclic Oxidation Exposure Temperature
SN-84	Longitudinally Machined	1204C (2200F)

Post-Exposure Strength Measurements Summary

Exposure Duration, hrs	Test Temperature C	Test Temperature (F)	Post-Exposure Strength MPa	Post-Exposure Strength (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	964 ± 148	(139.7 ± 21.5)	---	12	Machined surface, metallic inclusions
zero	1204	(2200)	927 ± 109	(134.5 ± 15.8)	---	12	Machined surface, metallic inclusions
350	24	(75)	422 ± 35	(61.2 ± 5.1)	-56	6	Oxidation pits beneath rough oxide
350	1204	(2200)	495 ± 18	(71.8 ± 2.7)	-47	5	Oxidation pits beneath rough oxide
700	24	(75)	486 ± 31	(70.5 ± 4.5)	-50	6	Oxidation pits beneath rough oxide
700	1204	(2200)	600 ± 92	(87.0 ± 13.4)	-35	7	Oxidation pits beneath rough oxide
1050	24	(75)	350 ± 17	(50.8 ± 2.4)	-64	6	Oxidation pits beneath rough oxide
1050	1204	(2200)	545 ± 43	(79.1 ± 6.3)	-41	6	Oxidation pits beneath rough oxide

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.2	2.3	11
700	0.2	2.2	13
1050	0.1	3.1	12

6.23 NGK SN-88 Sintered Silicon Nitride

As-processed surface SN-88 sintered silicon nitride specimens were procured from NGK in 1991 for durability testing at 1260C (2300F).

6.23.1 As-Processed Surface SN-88 Baseline Test Results

The baseline properties of the as-processed surface SN-88 test specimens are summarized in Table 56. The measured density of the SN-88 test specimens ranged from 3.43 to 3.52 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 39 to 63 microinch rms, and the transverse surface finish ranged from 22 to 34 microinch rms.

The baseline flexural strength of SN-88 was measured at room temperature and 1260C (2300F). The average room-temperature flexure strength was 98.4 ksi, with a standard deviation of 8.8 ksi, and the average strength at 1260C (2300F) was 95.8 ksi, with a standard deviation of 6.0 ksi. The majority of the baseline specimen fractures originated from the as-processed surface. At room temperature, the predominant fracture-originating flaws were pits in the as-processed surface (Figure 152). At 1260C (2300F), a majority of the specimen failure origins were large silicon nitride grains at the as-processed surface (Figure 153). A few specimen failures originating at internal silicon nitride grains were also noted (Figure 154).

TABLE 56. BASELINE PROPERTIES OF SN-88 AS-PROCESSED SURFACE SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, µ inch rms	
SN-88	NGK Insulators	July 1991	3.43 to 3.52	Longt.	39 to 63
				Transv.	22 to 34

Test Temperature		Baseline Strength		Surface Condition: As-Processed	
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins
24	(75)	679 ± 61	(98.4 ± 8.8	12	Surface pits
1260	(2300)	661 ± 42	(95.8 ±6.0)	12	Large acicular grains

6.23.2 Results Of As-Processed Surface SN-88 Exposures At 1260C (2300F)

As-processed surface SN-88 test specimens were cyclically exposed at 1260C (2300F) for durations of 350, 700, and 1050 hours. Post-exposure retained flexural strength was measured at room temperature and 2300F (1260C) for all exposure durations. The post-exposure test results are summarized in Table 57 and Figure 155. Overall, the NGK SN-88 specimens exhibited good strength retention following cyclic durability exposure. The average post-exposure room-temperature strength decreased slightly, from 98.4 ksi to 84.1 ksi (15 percent loss), and the average 1260C (2300F) strength decreased from 95.8 ksi to 85.0 ksi (11 percent loss).

TABLE 57. SN-88 POST-EXPOSURE TEST RESULTS SUMMARY.

Material	Surface Condition	Cyclic Oxidation Exposure Temperature
SN-88	As-Processed	1260C (2300F)

Post-Exposure Strength Measurements Summary

Exposure Duration, hrs	Test Temperature C	Test Temperature (F)	Post-Exposure Strength MPa	Post-Exposure Strength (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	679 ± 61	(98.4 ± 8.8)	---	12	Surface pits
zero	1260	(2300)	661 ± 42	(95.8 ± 6.0)	---	12	Surface pits
350	24	(75)	643 ± 39	(93.1 ± 5.7)	-5	7	Oxide layer, acicular grains
350	1260	(2300)	571 ± 35	(82.9 ± 5.1)	-13	6	Oxide layer, acicular grains
700	24	(75)	624 ± 34	(90.5 ± 4.9)	-8	7	Oxidation pits
700	1260	(2300)	610 ± 45	(88.5 ± 6.6)	-8	6	Oxidation pits
1050	24	(75)	580 ± 37	(84.1 ± 5.4)	-15	5	Oxidation pits
1050	1260	(2300)	586 ± 31	(85.0 ± 4.5)	-11	6	Oxidation pits

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.1	1.8	12
700	0.2	1.8	13
1050	0.0	1.9	11

The post-exposure SN-88 specimen fracture origins were located predominately at the flame-exposed surface. For short exposure times, the fractures originated from the oxidized surface or from acicular silicon nitride grains (Figure 156). After longer exposure times, the predominate fracture-originating flaw types were pits in the flame-exposed surface (Figure 157). A few internal failure origins at silicon nitride grains were noted in 1260C (2300F) flexural test specimens with longer exposure times (Figure 158).

The surface topography of an SN-88 specimen following exposure is illustrated in Figure 159. After 350 hours of exposure, the SN-88 specimens exhibited a relatively rough, glassy oxide scale. Little change was noted in the surface topography with further exposure. The typical oxide thickness was between 25 and 30 microns for all exposure times.

6.24 Norton NCX-34 Hot Pressed Silicon Nitride

NCX-34 sintered silicon nitride specimens with machined test surfaces were received from the Norton Company (Worcestor, MA) for evaluation during the first year of the program, 1978. NCX-34 cyclic exposures were initiated at both 1204C (2200F) and 1371C (2500F). Both oxidation durability tests were terminated early, due to spontaneous material degradation during exposure.

6.24.1 Machined Surface NCX-34 Baseline Test Results

The baseline properties of the longitudinally-machined NCX-34 test specimens are summarized in Table 58. The measured density of the NCX-34 test specimens ranged from 3.34 to 3.37 g/cm^3. The surface finish ranged from 4 to 9 microinch rms.

The baseline flexural strength of NCX-34 was measured at room temperature and 1204C (2200F). The average baseline room-temperature flexure strength was 121.0 ksi, with a standard deviation of 7.3 ksi, and the average strength at 1204C (2200F) was 78.8 ksi, with a standard deviation of 9.4 ksi. The majority of the NCX-34 specimen failures originated from the machined surface (Figure 160). A few specimens showed failures initiating from subsurface porosity (Figures 161).

TABLE 58. BASELINE PROPERTIES OF NCX-34 MACHINED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms
NCX-34		Norton Co.		June 1978	3.34 to 3.37	4 to 9
Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined		
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins	
24	(75)	834 ± 51	(121.0 ± 7.3)	12	Machined surface, subsurface porosity	
1204	(2200)	543 ± 65	(78.8 ± 9.4)	12	Machined surface, subsurface porosity	

6.24.2 Results Of NCX-34 Exposures At 1204C (2200F) and 1371C (2500F)

Oxidation durability tests with Norton NCX-34 test bars were initiated at 1204C (2200F) and 1371C (2500F). In both tests, NCX-34 specimens were exposed concurrently and in the same specimen holder with RBN101 test bars. However, testing was suspended after 25.1 hours at 1204C (2200F) and after 47.1 hours at 1371C (2500F), since noticeable cracking, expansion, and discoloration was visible on each NCX-34 test bar just above the specimen holder. Specimen holder disassembly revealed extensive material degradation for all the NCX-34 test bars, as illustrated in Figure 162, but no damage to the RBN101 material had occurred. These oxidation results indicated that spontaneous material degradation during the durability exposure was responsible for the phenomenon observed. Based on these results, further durability testing of NCX-34 was suspended.

Comparing NCX-34 specimens exposed to 1204C (2200F) and 1371C (2500F), the cracking in specimens exposed at 1204C (2200F) generally was closer to the middle of the test bar, as shown in Figure 163. The difference in location for the observed reactions at different exposure temperatures suggests the degradation mechanism was a temperature-sensitive phenomenon. Similar material cracking had been observed by Lange, et al.[9] in which oxidation at 1000C (1832F) of four unstable phases (notably the $Y_4Si_2O_7N_2$ "J" phase and the $Y_5Si_3O_{12}N$ "H" phase) of the Si-Y-O-N system was proposed as responsible for the cracking and disintegration.

To further evaluate this phenomenon, an NCX-34 test bar was exposed for 24 hours in an oxidizing gradient furnace at temperatures ranging from 465C to 865C (869F to 1589F). The results of this exposure are illustrated in Figure 164, in which severe cracking, distortion, and discoloration of the test bar is shown. The test bar temperatures for which the reactions are the most severe are from 580C to 820C (1080 to 1505F).

6.25 Norton Advanced Ceramics NT-154 Hot Isostatically Pressed Silicon Nitride

Machined-surface NT-154 sintered silicon nitride specimens were procured from Norton Advanced Ceramics (NAC) (Northboro, MA) in 1988 for durability testing at 1204C (2200F). NT-154 was developed as a high-temperature, low sintering additive silicon nitride composition, and requires encapsulated, hot isostatic pressing (HIPping) for densification. The 1988 vintage NT-154 test specimens were machined from isopressed and glass-encapsulated HIPped billets.

Based upon encouraging durability results seen in tests at 1204C (2200F), machined NT-154 specimens were procured in 1990 for durability testing at 1260C (2300F). Specimens from this vintage of NT-154 were machined from pressure slip cast (PSC) and glass-encapsulated HIPped billets.

In 1993, NT-154 specimens with as-processed surfaces were procured for durability testing at 1316C (2400F). These NT-154 test specimens were machined from pressure slip cast (PSC) and glass-encapsulated HIPped billets, preserving the test surface in the as-HIPped condition.

6.25.1 Machined Surface NT-154 Baseline (Pre-1204C Exposure) Test Results

The baseline properties of longitudinally-machined NT-154 test specimens are summarized in Table 59. The measured density of the NT-154 test specimens ranged from 3.23 to 3.24 g/cm^3. The surface finish ranged from 8 to 15 microinch rms.

The baseline flexural strength of NT-154 was measured at room temperature and 1204C (2200F). The average baseline room-temperature flexure strength was 152.1 ksi, with a standard deviation of 29.5 ksi, and the average strength at 1204C (2200F) was 102.0 ksi, with a standard deviation of 9.1 ksi. The majority of the baseline NT-154 specimen failures originated from the machined surface. A typical fracture origin for NT-154 is shown in Figure 165.

TABLE 59. BASELINE PROPERTIES OF NT-154 MACHINED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm³	Surface Finish, μ inch rms
NT-154		Norton Advanced Ceramics		October 1988	3.23 to 3.24	8 to 15
Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined		
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins	
24	(75)	1049 ± 204	(152.1 ± 29.5)	12	Machined surface	
1204	(2200)	704 ± 62	(102.0 ± 9.1)	12	Machined surface	

6.25.2 Results of Machined-Surface NT-154 Exposures At 1204C (2200F)

Machined-surface NT-154 test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 700, and 1050 hours. The post-exposure retained flexure strength was measured at room temperature and 1204C (2200F) for all exposure durations. The post-exposure test results are summarized in Table 60 and Figure 166.

TABLE 60. NT-154 POST-EXPOSURE TEST RESULTS SUMMARY (1204C).

Material			Surface Condition				Cyclic Oxidation Exposure Temperature
NT-154			Longitudinally Machined				1204C (2200F)
Post-Exposure Strength Measurements Summary							
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	1049 ± 204	(152.1 ± 29.5)	---	12	Machined surface
zero	1204	(2200)	704 ± 62	(102.0 ± 9.1)	---	12	Machined surface
350	24	(75)	735 ± 50	(106.5 ± 7.3)	-30	6	Exposed surface, chamfer
350	1204	(2200)	764 ± 60	(110.7 ± 8.7)	9	6	Exposed surface, chamfer
700	24	(75)	626 ± 30	(90.7 ± 4.3)	-40	6	Exposed surface, chamfer
700	1204	(2200)	821 ± 13	(119.1 ± 1.9)	17	6	Exposed surface, chamfer
1050	24	(75)	616 ± 57	(89.4 ± 8.3)	-41	6	Exposed surface, chamfer
1050	1204	(2200)	735 ± 46	(106.6 ± 6.7)	5	6	Exposed surface, chamfer

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.1	1.0	12
700	0.1	1.6	12
1050	0.0	2.0	12

The NT-154 room-temperature flexure strength decreased with increasing exposure time. After 350 hours, the room-temperature strength had decreased 30 percent, from 152.1 ksi to 106.5 ksi. With continued exposure, the room-temperature strength decreased further, to 89.4 ksi with 41 percent strength loss overall. The 1204C (2200F) strength increased with exposure up to 700 hours. After 700 hours, the NT-154 specimens exhibited a 1204C (2200F) strength increase of 17 percent, from 102.0 ksi to 119.1 ksi. With continued exposure up to 1050 hours, the 1204C (2200F) strength decreased to 106.6 ksi, which is 5 percent higher than the baseline strength. All the machined-surface NT-154 post-exposure specimen failures originated at the flame-exposed surface, either from the tensile surface or the edge chamfer. Typical post-exposure fracture origins are shown in Figures 167 and 168.

The surface topography of the NT-154 specimens as a function of exposure time is shown in Figure 169. The surface oxide roughened with increasing exposure. The oxide layer grew to a thickness of approximately 10 microns after 1050 hours exposure.

6.25.3 Machined-Surface NT-154 Baseline (Pre-1260C Exposure) Test Results

The baseline properties of the longitudinally-machined NT-154 test specimens are summarized in Table 61. The measured density of the NT-154 test specimens ranged from 3.23 to 3.24 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 6 to 8 microinch rms, and the transverse surface finish ranged from 10 to 11 microinch rms.

The baseline flexural strength of these machined-surface NT-154 specimens was measured at room temperature and 1260C (2300F). The average baseline room-temperature flexure strength was 112.4 ksi, with a standard deviation of 12.2 ksi, and the average strength at 1260C (2300F) was 103.1 ksi, with a standard deviation of 8.5 ksi. The room-temperature strength of this vintage of NT-154 was much lower than for the isopressed material evaluated earlier in the program, whereas the elevated-temperature properties were equivalent. The majority of the NT-154 baseline specimen failures typically originated from either the machined tensile surface or the chamfer. A typical fracture origin for these NT-154 specimens is shown in Figure 170.

TABLE 61. BASELINE (PRE- 1260C EXPOSURE) PROPERTIES OF NT-154 MACHINED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, µ inch rms	
NT-154		Norton Advanced Ceramics		April 1990	3.23 to 3.24	Longt.	6 to 8
						Transv.	10 to 11
Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	775 ± 84	112.4 ± 12.2)	12	Machined surface, chamfer		
1260	(2300)	711 ± 59	(103.1 ± 8.5)	12	Machined surface, chamfer		

6.25.4 Results Of Machined-Surface NT-154 Exposures At 1260C (2300F)

Machined-surface NT-154 test specimens were cyclically exposed at 1260C (2300F) for durations of 350, 700, and 1050 hours. The post-exposure retained strength of the NT-154 specimens was measured at room temperature and 2300F (1260C) for all exposure durations. The post-exposure test results are summarized in Table 62 and Figure 171. The room-temperature and 1260C (2300F) strength decreased gradually with increasing exposure. After 1050 hours, the room-temperature strength dropped 23 percent, from 112.4 ksi to 86.3 ksi, and the 1260C (2300F) strength dropped 15 percent, from 103.1 ksi to 87.6 ksi. The fracture origins of the exposed NT-154 specimens originated at the pitting beneath the rough oxide layer (Figures 172 and 173).

Figure 174 shows oxidized NT-154 specimen surfaces following 350, 700, and 1050 hours of exposure at 1260C (2300F). Following 350 hours, the oxide layer was relatively thin and smooth. With continued exposure, the oxide layer thickened and became pitted.

TABLE 62. NT-154 POST-EXPOSURE TEST RESULTS SUMMARY (1260C, LONGITUDINALLY MACHINED SPECIMENS).

Material		Surface Condition				Cyclic Oxidation Exposure Temperature
NT-154		Longitudinally Machined				1260C (2300F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	775 ± 84	(112.4 ± 12.2)	---	12	Machined surface, chamfer
zero	1260	(2300)	711 ± 59	(103.1 ± 8.5)	---	12	Machined surface, chamfer
350	24	(75)	623 ± 34	(90.4 ± 4.9)	-20	6	Pits beneath oxide layer
350	1260	(2300)	690 ± 68	(100.1 ± 9.8)	-3	6	Pits beneath oxide layer
700	24	(75)	581 ± 52	(84.3 ± 7.6)	-25	6	Pits beneath oxide layer
700	1260	(2300)	629 ± 47	(91.3 ± 6.8)	-11	6	Pits beneath oxide layer
1050	24	(75)	595 ± 56	(86.3 ± 8.2)	-23	6	Pits beneath oxide layer
1050	1260	(2300)	604 ± 35	(87.6 ± 5.1)	-15	6	Pits beneath oxide layer

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.0	0.6	12
700	-0.1	0.9	12
1050	-0.2	0.9	12

6.25.5 As-Processed Surface NT-154 Baseline (Pre-1316C [2400F] Exposure) Test Results

The baseline properties of the as-processed surface NT-154 test specimens are summarized in Table 63. The measured density of the NT-154 test specimens ranged from 3.22 to 3.23 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 40 to 81 microinch rms, and the transverse surface finish ranged from 41 to 92 microinch rms.

The baseline flexural strength of these NT-154 specimens was measured at room temperature and 1316C (2400F). The average room-temperature flexure strength was 95.5 ksi, with a standard deviation of 7.4 ksi, and the average strength at 1316C (2400F) was 71.8 ksi, with a standard deviation of 14.8 ksi. The baseline NT-154 specimen failures originated mostly from the as-processed test surface (Figure 175). A few failures originating at surface pits or surface connected porosity were noted (Figure 176). A single specimen failed from an iron-carbon inclusion intersecting the as-processed test surface (Figure 177).

TABLE 63. BASELINE PROPERTIES OF NT-154 AS-PROCESSED SURFACE SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, µ inch rms	
NT-154	Norton Advanced Ceramics	September 1993	3.22 to 3.23	Longt.	40 to 81
				Transv.	81 to 92

Test Temperature		Baseline Strength		Surface Condition: As-Processed	
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins
24	(75)	658 ± 51	(95.5 ± 7.4)	12	As-processed surface
1316	(2400)	495 ± 102	(71.8 ± 14.8)	12	As-processed surface

6.25.6 Results Of As-Processed Surface NT-154 Exposures At 1316C (2400F)

As-processed surface NT-154 test specimens were cyclically exposed at 1316C (2400F) for durations of 350, 700, and 1050 hours. The post-exposure retained flexural strength was measured at room temperature and 1316C (2400F) after 350, 700, and 1050 hours of exposure. The post-exposure strength test results are summarized in Table 64 and Figure 178.

The average post-exposure NT-154 room-temperature strength decreased gradually over the 1050 hours of exposure. After 1050 hours, the NT-154 specimens exhibited a 26-percent strength loss, dropping from 95.5 ksi to 70.6 ksi. The average 1316C (2400F) strength increased initially, then remained relatively constant with further exposure. Overall, the 1316C (2400F) strength increased 12 percent, from 71.8 ksi to 80.5 ksi. The post-exposure NT-154 specimen fracture origins were located predominately at the flame-exposed surface. For short exposure times, the specimen failures originated at the same types of as-processed surface anomalies observed in the baseline material. At longer exposure times, specimen failures originated predominately from edge chamfers (Figure 179) and from pits in the flame-exposed surface (Figures 180 and 181).

The surface topography of the exposed NT-154 specimens is shown in Figure 182. Oxide nodules had formed after 350 hours of exposure. After 700 and 1050 hours of exposure, the NT-154 specimens exhibited a rough oxide scale. The typical oxide thickness was approximately 10 microns after 350 hours of exposure, and between 15 and 20 microns following 700 and 1050 hours of exposure.

TABLE 64. NT-154 POST-EXPOSURE TEST RESULTS SUMMARY (1316C, AS-PROCESSED SURFACE SPECIMENS).

Material	Surface Condition	Cyclic Oxidation Exposure Temperature
NT-154	As-Processed	1316C (2400F)

Post-Exposure Strength Measurements Summary

Exposure Duration, hrs	Test Temperature C	Test Temperature (F)	Post-Exposure Strength MPa	Post-Exposure Strength (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	658 ± 51	(95.5 ± 7.4)	---	12	As-processed surface
zero	1316	(2400)	495 ± 102	(71.8 ± 14.8)	---	12	As-processed surface
350	24	(75)	638 ± 124	(92.5 ± 17.9)	-3	6	As-processed surface
350	1316	(2400)	590 ± 99	(85.5 ± 14.3)	19	6	As-processed surface
700	24	(75)	579 ± 77	(83.9 ± 11.2)	-12	6	Chamfer, oxidation pits
700	1316	(2400)	568 ± 73	(82.4 ± 10.6)	15	6	Chamfer, oxidation pits
1050	24	(75)	487± 102	(70.6 ± 14.8)	-26	6	Chamfer, oxidation pits
1050	1316	(2400)	555 ± 104	(80.5 ± 15.1)	12	6	Chamfer, oxidation pits

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-0.1	0.8	12
700	-0.4	1.0	12
1050	-0.4	1.0	12

6.26 Norton Advanced Ceramics NT-164 Hot Isostatically Pressed Silicon Nitride

As-processed surface NT-164 sintered silicon nitride specimens were procured from Norton Advanced Ceramics (NAC) in 1993 for durability testing at 1316C (2400F). NT-164 is a derivative of NT-154, developed for improved high-temperature mechanical properties. The NT-164 test specimens were machined from pressure slip cast (PSC) and glass-encapsulated HIPped billets, preserving the test surface in the as-HIPped condition.

6.26.1 As-Processed Surface NT-164 Baseline Test Results

The baseline properties of the as-processed NT-164 test specimens are summarized in Table 65. The measured density of the NT-164 specimens was 3.18 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 44 to 54 microinch rms, and the transverse surface finish ranged from 46 to 60 microinch rms.

The baseline flexural strength of the NT-164 specimens was measured at room temperature and 1316C (2400F). The average room-temperature flexure strength was 103.3 ksi, with a standard deviation of 16.5 ksi, and the average strength at 1316C (2400F) was 96.7 ksi, with a standard deviation of 13.8 ksi. The majority of the baseline specimen fractures originated from the as-processed surface (Figure 183). A notable quantity of the baseline test specimen failures originated from anomalies in the as-processed surface and were categorized as shallow pits (Figure 184). These shallow pits had little impact on specimen strength, since the pit aspect ratio (depth/width) was relatively low. A few failures originating from internal inclusions composed of iron, carbon, and nickel were noted in several specimens flexure tested at 1316C (2400F) (Figure 185).

TABLE 65. BASELINE PROPERTIES OF NT-164 AS-PROCESSED SURFACE SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
NT-164	Norton Advanced Ceramics	August 1993	3.18	Longt.	44 to 54
				Transv.	46 to 60

Test Temperature C	(F)	Baseline Strength MPa	(ksi)	Surface Condition: As-Processed Quantity	Primary Failure Origins
24	(75)	712 ± 114	(103.3 ± 16.5)	12	As-processed surface
1316	(2400)	667 ± 95	(96.7 ± 13.8)	12	As-processed surface, metallic inclusions

6.26.2 Results Of As-Processed Surface NT-164 Exposures At 1316C (2400F)

As-processed surface NT-164 test specimens were cyclically exposed at 1316C (2400F) for durations of 350, 700, and 1050 hours. The post-exposure retained flexural strength was measured at room temperature and 1316C (2400F) after 350, 700, and 1050 hours of exposure. The post-exposure test results are summarized in Tables 66 and Figure 186.

Overall, the post-exposure retained flexural strength results for NT-164 were excellent. The NT-164 specimens exhibited virtually no strength loss for all exposure times. The average room-temperature and 1316C (2400F) strength values measured after 1050 hours of exposure were 99.3 ksi and 96.2 ksi, respectively, compared to 103.2 ksi and 96.7 ksi, respectively, for the baseline tests.

TABLE 66. NT-164 POST-EXPOSURE TEST RESULTS SUMMARY.

Material		Surface Condition			Cyclic Oxidation Exposure Temperature
NT-164		As-Processed			1316C (2400F)
Post-Exposure Strength Measurements Summary					
Exposure Duration, hrs	Test Temperature C (F)	Post-Exposure Strength MPa (ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24 (75)	712 ± 114 (103.3 ± 16.5)	---	12	As-processed surface, metallic inclusions
zero	1316 (2400)	667 ± 95 (96.7 ± 13.8)	---	12	As-processed surface, metallic inclusions
350	24 (75)	657 ± 74 (95.3 ± 10.8)	-8	6	As-processed surface
350	1316 (2400)	680 ± 164 (98.6 ± 23.7)	2	6	Metallic inclusions
700	24 (75)	673 ± 108 (97.7 ± 15.7)	-5	6	As-processed surface
700	1316 (2400)	710 ± 152 (102.9 ± 22.0)	6	6	Metallic inclusions
1050	24 (75)	685 ± 105 (99.3 ± 15.2)	-4	6	As-processed surface
1050	1316 (2400)	663 ± 130 (96.2 ± 18.9)	0	6	Metallic inclusions

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.0	0.3	12
700	0.0	0.5	12
1050	-0.1	1.1	12

Post-exposure failure origins for NT-164 specimens flexure tested at room temperature were located predominately at the flame-exposed surface, as illustrated in Figure 187. For post-exposure flexural strength tests performed at 1316C (2400F), the predominate fracture-originating flaws were iron inclusions (Figure 188). These surface failure origins were similar to those identified in the baseline material tests, although the occurrence of failures from iron-based inclusions was more frequent in the post-exposure strength test specimens.

The surface topography of the exposed NT-164 specimens is documented in Figure 189. After 350 hours exposure, the NT-164 specimens exhibited a relatively rough scale of oxide nodules. After 700 and 1050 hours of exposure, the oxide scale exhibited a pitted topography. The typical oxide thickness was approximately 5 microns after 350 hours of exposure, and between 10 and 15 microns for specimens with 700 and 1050 hours exposure.

6.27 Norton Advanced Ceramics NT-230 Siliconized Silicon Carbide

As-processed surface NT-230 siliconized silicon carbide (Si-SiC) specimens were procured from Norton Advanced Ceramic (NAC) in 1991 for durability testing at 1260C (2300F). The test specimens were machined from billets, preserving the specimen test surfaces in the as-processed (unmachined) condition.

6.27.1 As-Processed Surface NT-230 Baseline Test Results

The baseline properties of the longitudinally-machined NT-230 test specimens are summarized in Table 67. The measured density of the NT-230 test specimens ranged from 3.10 to 3.11 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 2 to 9 microinch rms, and the transverse surface finish ranged from 13 to 27 microinch rms.

The baseline flexural strength of the NT-230 specimens was measured at room temperature and 1260C (2300F). The average baseline room-temperature flexure strength was 57.2 ksi, with a standard deviation of 9.6 ksi, and the average strength at 1260C (2300F) was 73.9 ksi, with a standard deviation of 9.8 ksi. The NT-230 specimens exhibited a relatively equal number of surface and internal failure origins in the pre-exposure flexure tests. Both the surface and internal failures originated from pores (Figures 190 and 191).

TABLE 67. BASELINE PROPERTIES OF NT-230 MACHINED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
NT-230		Norton Advanced Ceramics		May 1991	3.10 to 3.11	Longt.	2 to 9
						Transv.	13 to 27
Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	394 ± 66	(57.2 ± 9.6)	12	Surface and internal pores		
1260	(2300)	509 ± 67	(73.9 ± 9.8)	12	Surface and internal pores		

6.27.2 Results Of As-Processed Surface NT-230 Exposures At 1260C (2300F)

As-processed surface NT-230 test specimens were cyclically exposed at 1260C (2300F) for durations of 350, 700, and 1050 hours. The post-exposure retained strengths for NT-230 were measured at room temperature and 1260C (2300F) for all exposure times. The post-exposure test results are summarized in Table 68 and Figure 192.

Overall, the strength characteristics of NT-230 remained relatively constant as a function of exposure time. The average post-exposure room-temperature strength increased 6 percent, from 57.2 ksi to 60.7 ksi, and the average 1260C (2300F) strength decreased 9 percent, from 73.9 ksi to 67.0 ksi, after 1050 hours of cyclic exposure. All the post-exposure strength test data was within the range of strength values measured in the baseline NT-230 material tests.

TABLE 68. NT-230 POST-EXPOSURE TEST RESULTS SUMMARY.

Material			Surface Condition				Cyclic Oxidation Exposure Temperature
NT-230			Longitudinally Machined				1260C (2300F)
Post-Exposure Strength Measurements Summary							
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	394 ± 66	(57.2 ± 9.6)	---	12	Surface and internal pores
zero	1260	(2300)	509 ± 67	(73.9 ± 9.8)	---	12	Surface and internal pores
350	24	(75)	387 ± 62	(56.1 ± 9.0)	-2	6	Surface and internal pores
350	1260	(2300)	446 ± 37	(64.7 ± 5.3)	-12	5	Surface and internal pores
700	24	(75)	402 ± 60	(58.3 ± 8.7)	2	6	Surface and internal pores
700	1260	(2300)	509 ± 73	(73.8 ± 10.6)	0	6	Surface and internal pores
1050	24	(75)	418 ± 77	(60.7 ± 11.2)	6	6	Surface and internal pores
1050	1260	(2300)	462 ± 87	(67.0 ± 12.6)	-9	6	Surface and internal pores

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.2	1.4	12
700	0.2	1.4	12
1050	0.2	1.7	12

The NT-230 specimens delivered for durability testing were fabricated in two processing lots, designated as SC-96 and SC-101, respectively, by NAC. Although no differences in baseline strength characteristics were measured, some differences in post-exposure retained strength were observed for these two lots. Balanced quantities of test bars from each lot were included in each test to provide a comparison. However, specimens from Lot SC-96 did exhibit better post-exposure strength properties, compared to specimens from Lot SC-101. The average retained strength for Lot SC-96 specimens was approximately 10 to 20 ksi higher at room temperature for all exposure times, and 10 ksi higher at 1260C (2300F) after 700 and 1050 hours of exposure. Subsequent microstructural evaluations revealed coarser porosity for Lot SC-101 compared to Lot SC-96 (Figure 193).

The predominant fracture-originating flaw types for the exposed NT-230 specimens were pores, the same as observed in the baseline NT-230 material tests. Higher frequencies of internal failure origins were observed in the post-exposure test specimens, compared to the baseline (unexposed) test specimens. No failure origins associated with the surface oxide were observed. Pore failure origins for specimens from Lot SC-101 were typically larger than for Lot SC-96, which is consistent with the microstructural differences discussed above. Typical failure origins for the exposed NT-230 test specimens are shown in Figures 194 through 196.

The change in NT-230 surface topography following cyclic oxidation exposure at 1260C (2300F) is documented in Figure 197. After 350 hours of exposure, the NT-230 specimens exhibited a relatively rough oxide layer, with local areas of oxide spalling. Little change was noted in the surface topography with further exposure. The oxide thickness after 350, 700, and 1050 hours of exposure was 15, 20, and 30 microns, respectively.

6.28 Pure Carbon/Refel Siliconized Silicon Carbide

Refel siliconized silicon carbide (Si-SiC) specimens with longitudinally-machined test surfaces were procured from the Pure Carbon Co. (St. Marys, PA) during the first year of the program (1978) for durability testing at 1204C (2200F) and 1371C (2500F). However, the 1371C (2500F) testing was terminated early, due to test bar cracking. The unused specimens from the terminated test were subsequently used for lower-temperature exposure tests, to determine the maximum use temperature for Refel Si-SiC.

Additional machined-surface and as-processed surface specimens of injection-molded Refel Si-SiC were procured in 1981 for a 350-hour durability test at 1093C (2000F).

6.28.1 Machined-Surface Refel Si-SiC Baseline Test Results

The baseline properties of the longitudinally-machined Refel Si-SiC test specimens are summarized in Table 69. The measured density of the Refel Si-SiC test specimens ranged from 3.05 to 3.10 g/cm^3. The measured surface finish ranged from 3 to 5 microinch rms.

The baseline flexural strength of the Refel Si-SiC specimens was measured at room temperature and 1204C (2200F). The average baseline room-temperature flexure strength was 55.4 ksi, with a standard deviation of 10.2 ksi, and the average strength at 1204C (2200F) was 69.6 ksi, with a standard deviation of 6.6 ksi. At room temperature, the Refel Si-SiC specimen failures typically originated from surface and subsurface porosity. A representative room-temperature fracture surface is shown in Figure 198. The 1204C (2200F) baseline fracture origins were not clearly identifiable. Figure 199 illustrates a typical 1204C (2200F) fracture surface for the Refel test bars, showing a possible fracture origin.

TABLE 69. BASELINE PROPERTIES OF REFEL Si-SiC MACHINED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms
Refel Si-SiC		Pure Carbon Co.		October 1978	3.05 to 3.10	3 to 5
Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined		
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins	
24	(75)	382 ± 70	(55.4 ± 10.2)	12	Surface and subsurface porosity	
1204	(2200)	480 ± 46	(69.6 ± 6.6)	12	Not clearly identifiable	

6.28.2 Results Of Machined-Surface Refel Si-SiC Exposures At 1204C (2200F)

Longitudinally-machined Refel Si-SiC test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 1050, and 2100 hours. The post-exposure retained room-temperature flexural strength was measured for all exposure durations. The post-exposure test results are summarized in Table 70 and Figure 200.

TABLE 70. REFEL Si-SiC POST-EXPOSURE TEST RESULTS SUMMARY (1204C).

Material			Surface Condition				Cyclic Oxidation Exposure Temperature
Refel Si-SiC			Longitudinally Machined				1204C (2200F)
Post-Exposure Strength Measurements Summary							
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	ksi	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	382 ± 70	(55.4 ± 10.2)	---	12	Surface and subsurface porosity
350	24	(75)	332 ± 48	(48.1 ± 6.9)	-13	12	Surface and subsurface porosity
1050	24	(75)	304 ± 62	(44.1 ± 9.0)	-20	12	Surface and subsurface porosity
2100	24	(75)	255 ± 46	(37.0 ± 6.6)	-33	12	Surface and subsurface porosity

Post-Exposure Weight and Dimensional Changes Summary			
Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-2.0	0.3	12
1050	0.1	2.8	12
2100	-0.9	1.7	12

The retained room-temperature strength of the Refel Si-SiC specimens decreased with increasing exposure time. After 2100 hours of exposure at 1204C (2200F), the room-temperature strength of Refel Si-SiC had dropped a total of 33 percent, from 55.4 ksi to 37.0 ksi. The post-exposure specimen failures typically originated from surface-connected and subsurface pores (Figures 201 and 202).

The typical surface topography of the Refel Si-SiC specimens after 350 hours and 1050 hours of exposure is shown in Figure 203. A dense, coarse surface oxide layer approximately 6 microns thick was present after 350 hours of exposure. The oxide layer roughened and increased in thickness to approximately 10 microns after 1050 hours of exposure.

6.28.3 Results Of Machined-Surface Refel Si-SiC Exposures At 1371C (2500F)

Cyclic exposure testing of machined-surface Refel Si-SiC specimens was initiated at 1371C (2500F). However, the testing was terminated after 168 hours of exposure, when test bar cracking and silicon material exuding from exposed specimen areas became evident (Figure 204). Static furnace exposure tests were performed to study the degradation of Refel Si-SiC specimens. However, unlike the NCX-34 static furnace tests (see Section 6.24), the cracking problems observed in the cyclic durability tests could not be reproduced in the static furnace environment. These results indicated that the "active" environment conditions in the cyclic durability testing are different and more severe than the conditions in the static furnace test environment. Subsequently, the unused Refel Si-SiC specimens from the 1371C (2500F) testing were used in lower-temperature cyclic oxidation durability tests to determine the maximum use temperature for this material.

6.28.4 Maximum-Use Temperature Study For Refel Siliconized Silicon Carbide

A maximum-use temperature study for Refel Si-SiC was conducted using 350-hour cyclic durability exposures. First, a cyclic durability test was initiated at 1316C (2400F). However, the exposure was discontinued after 143 hours, when cracking became evident on all the test bars (Figure 205). The degradation was similar to that observed following Refel Si-SiC specimen durability exposure at 1371C (2500F).

A 350-hour cyclic exposure at 1260C (2300F) was then conducted, to better define the onset of the cracking problem previously observed. One Refel Si-SiC test specimen cracked on the back (the non-flame impingement) side, as shown in Figure 206. The balance of the exposed Refel Si-SiC specimens exhibited no evidence of cracking, and were subsequently tested for post-exposure retained room-temperature flexural strength. The post-exposure test results are summarized in Table 71 and Figure 207. The retained room-temperature strength averaged 25.1 ksi, significantly lower than the value of 48.1 ksi for bars exposed for 350 hours at 1204C (2200F), and 55 percent below the baseline room-temperature strength. Figure 208 shows a typical post-exposure flexure test fracture origin. All post-exposure flexure test fractures originated from irregularities in the surface oxide layer and associated surface porosity.

TABLE 71. REFEL Si-SiC POST-EXPOSURE TEST RESULTS SUMMARY (1260C).

Material			Surface Condition			Cyclic Oxidation Exposure Temperature
Refel Si-SiC			Longitudinally Machined			1260C (2300F)
Post-Exposure Strength Measurements Summary						
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	382 ± 70	(55.4 ± 10.2)	---	12	Surface and subsurface porosity
350	24	(75)	173 ± 32	(25.1 ± 4.6)	-55	11	Rough oxide layer, porosity

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.3	-0.1	11

6.28.5 Machined And As-Processed Surface Injection-Molded Refel Si-SiC Baseline Test Results

The baseline properties of the longitudinally-machined, injection molded Refel Si-SiC test specimens are summarized in Table 72. The measured density of the Refel Si-SiC test specimens ranged from 3.05 to 3.10 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 5 to 6 microinch rms, and the transverse surface finish ranged from 10 to 11 microinch rms.

TABLE 72. BASELINE PROPERTIES OF INJECTION MOLDED REFEL Si-SiC MACHINED SURFACE SPECIMENS.

Material		Supplier		Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
Refel Si-SiC Injection Molded		Pure Carbon Co.		October 1981	3.05 to 3.10	Longt.	5 to 6
						Transv.	10 to 11
Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined			
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins		
24	(75)	332 ± 95	(48.1 ± 13.8)	10	Surface and subsurface porosity		
1093	(2000)	368 ± 45	(53.4 ± 6.5)	10	Surface and subsurface porosity		

The baseline flexural strength of the longitudinally-machined, injection molded Refel Si-SiC specimens was measured at room temperature and 1093C (2000F). The average baseline room-temperature flexure strength was 48.1 ksi, with a standard deviation of 13.8 ksi, and the average strength at 1093C (2000F) was 53.4 ksi, with a standard deviation of 6.5 ksi. The majority of the Refel Si-SiC specimen failures originated from surface and subsurface porosity. Typical fracture-initiating flaws for Refel Si-SiC are shown in Figure 209.

The baseline properties of the as-processed surface, injection-molded Refel Si-SiC test specimens are summarized in Table 73. The measured density of the Refel Si-SiC test specimens ranged from 3.05 to 3.09 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 60 to 110 microinch rms and the transverse surface finish ranged from 60 to 120 microinch rms.

The baseline flexural strength of the as-processed surface, injection-molded Refel Si-SiC specimens was measured at room temperature and 1093C (2000F). The average baseline room-temperature flexure strength was 33.0 ksi, with a standard deviation of 6.5 ksi, and the average strength at 1093C (2000F) was 61.8 ksi, with a standard deviation of 8.9 ksi. The majority of the baseline specimen failures originated from the as-processed surface and subsurface porosity. A typical fracture origin for the as-processed surface, injection molded Refel Si-SiC specimens is shown in Figure 210.

TABLE 73. BASELINE PROPERTIES OF INJECTION-MOLDED REFEL Si-SiC AS-PROCESSED SURFACE SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
Refel Si-SiC Injection Molded	Pure Carbon Co.	October 1981	3.05 to 3.09	Longt.	60 to 110
				Transv.	60 to 120

Test Temperature		Baseline Strength		Surface Condition: As-Processed	
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins
24	(75)	227 ± 45	(33.0 ± 6.5)	10	As-processed surface and subsurface porosity
1093	(2000)	426 ± 61	(61.8 ± 8.9)	10	As-processed surface and subsurface porosity

6.28.6 Results Of Machined And As-Processed Surface, Injection-Molded Refel Si-SiC Exposures At 1093C (2000F)

Injection-molded Refel Si-SiC test bars were cyclically exposed for 350 hours at 1093C (2000F). The as-processed surface specimens were tested together with longitudinally-machined surface specimens, to obtain a direct comparison of material performance. Following exposure, the retained strength values were measured at room temperature and 1093C (2000F). The post-exposure test results are summarized in Tables 74 and 75 and Figure 207.

TABLE 74. INJECTION-MOLDED REFEL Si-SiC POST-EXPOSURE TEST RESULTS SUMMARY (1093C, LONGITUDINALLY MACHINED SPECIMENS).

Material	Surface Condition	Cyclic Oxidation Exposure Temperature
Refel Si-SiC	Injection Molded, Longitudinally Machined	1093C (2000F)

Post-Exposure Strength Measurements Summary

Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	332 ± 95	(48.1 ± 13.8)	---	10	Surface and subsurface porosity
zero	1093	(2000)	368 ± 45	(53.4 ± 6.5)	---	10	Surface and subsurface porosity
350	24	(75)	490 ± 59	(71.0 ± 8.6)	48	6	Surface and subsurface porosity
350	1093	(2000)	415 ± 38	(60.1 ± 5.5)	13	6	Surface and subsurface porosity

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.1	0.9	12

TABLE 75. INJECTION-MOLDED REFEL Si-SiC POST-EXPOSURE TEST RESULTS SUMMARY (1093C, AS-PROCESSED SURFACE SPECIMENS).

Material	Surface Condition	Cyclic Oxidation Exposure Temperature
Refel Si-SiC	Injection Molded, As-Processed	1093C (2000F)

Post-Exposure Strength Measurements Summary

Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	227± 45	(33.0 ± 6.5)	---	10	As-processed surface , subsurface porosity
zero	1093	(2000)	426 ± 61	(61.8 ± 8.9)	---	10	As-processed surface , subsurface porosity
350	24	(75)	321 ± 49	(46.5 ± 7.1)	41	5	As-processed surface
350	1093	(2000)	344 ± 76	(49.8 ± 11.0)	-19	6	As-processed surface

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	0.0	0.7	12

The exposed injection-molded Refel Si-SiC specimens with longitudinally-machined test surfaces exhibited increases in both room-temperature and 1093C (2000F) strength following the 350-hour exposure at 1093C. The room-temperature strength increased 48 percent, from 48.1 ksi to 71.0 ksi, and the 1093C (2000F) strength increased 11 percent, from 53.4 ksi to 60.1 ksi. The exposed Refel Si-SiC specimens with machined surfaces frequently fractured at porosity, either surface or internal. The failure origin of a machined-surface specimen is shown in Figure 211. Energy-dispersive X-ray (EDX) analysis was performed on the porosity at the failure origin and calcium (Ca) and small amounts of iron (Fe) were detected at the porosity.

The exposed injection-molded Refel Si-SiC specimens with as-processed surfaces exhibited an increase in room-temperature strength, but exhibited a strength loss at 1093C (2000F) following the 350-hour exposure at 1093C. The room-temperature strength increased 41 percent, from 33.0 ksi to 46.5 ksi, and the 1093C (2000F) strength decreased 19 percent, from 61.8 ksi to 49.8 ksi. Exposed Refel Si-SiC specimens with as-processed surfaces typically fractured at the tensile face surface of the specimen. Typical fracture origins are shown in Figure 212.

6.29 Toshiba Sintered Silicon Nitride

Sintered silicon nitride specimens with machined test surfaces were procured from Toshiba Corp. (Japan) in 1984 for durability testing at 1204C (2200F).

6.29.1 Machined-Surface Toshiba Sintered Silicon Nitride Baseline Test Results

The baseline properties of the longitudinally-machined Toshiba sintered silicon nitride test specimens are summarized in Table 76. The measured density of the Toshiba sintered Si_3N_4 test specimens ranged from 3.22 to 3.24 g/cm^3. The surface finish was measured in both the longitudinal and transverse directions. The longitudinal surface finish ranged from 4 to 7 microinch rms, and the transverse surface finish ranged from 5 to 7 microinch rms.

The baseline flexural strength of the Toshiba sintered Si_3N_4 specimens was measured at room temperature and 1204C (2200F). The average baseline room-temperature flexure strength was 112.6 ksi, with a standard deviation of 6.4 ksi, and the average strength at 1204C (2200F) was 61.0 ksi, with a standard deviation of 4.4 ksi. The majority of the sintered Si_3N_4 specimen failures originated from surface and subsurface porosity. Typical fracture-initiating flaws for Toshiba sintered Si_3N_4 are shown in Figure 213.

TABLE 76. BASELINE PROPERTIES OF TOSHIBA SINTERED SILICON NITRIDE MACHINED-SURFACE SPECIMENS.

Material	Supplier	Delivery Date	Density, g/cm^3	Surface Finish, μ inch rms	
Toshiba Sintered Si_3N_4	Toshiba Corp.	July 1984	3.22 to 3.24	Longt.	4 to 7
				Transv.	5 to 7

Test Temperature		Baseline Strength		Surface Condition: Longitudinally Machined	
C	(F)	MPa	(ksi)	Quantity	Primary Failure Origins
24	(75)	777 ± 44	(112.6 ± 6.4)	12	Surface and subsurface porosity
1204	(2200)	421 ± 30	(61.0 ± 4.4)	12	Surface and subsurface porosity

6.29.2 Results Of Machined-Surface Toshiba Sintered Si_3N_4 Exposures At 1204C (2200F)

Machined-surface Toshiba sintered Si_3N_4 test specimens were cyclically exposed at 1204C (2200F) for durations of 350, 700, and 1050 hours. The retained strength of the exposed Toshiba Si_3N_4 test specimens was measured at room temperature and 1204C (2200F) for all exposure durations. The post-exposure test results are summarized in Table 77 and Figure 214.

The Toshiba Si_3N_4 specimens initially exhibited large losses in strength following the first 350 hours of exposure. After 350 hours, the Toshiba Si_3N_4 specimens lost 45 percent and 46 percent of the baseline room-temperature and 1204C (2200F) strength values, respectively. With continued exposure, Toshiba Si_3N_4 exhibited minimal change in retained room-temperature strength and some recovery in 1204C (2200F) strength. Overall, the room-temperature strength dropped 53 percent, from 112.6 ksi to 53.0 ksi, and the 1204C (2200F) strength dropped 14 percent, from 61.0 ksi to 52.7 ksi after 1050 hours of cyclic exposure. All of the post-exposure specimen failures originated from oxidation-induced pitting on the flame-exposed surface. Typical post-exposure fracture-originating flaws for Toshiba Si_3N_4 are shown in Figures 215 and 216.

The surface topography of Toshiba Si_3N_4 specimens cyclically exposed at 1204C (2200F) is shown in Figure 217. After 350 hours of exposure, the specimen surface was covered with a rough oxide layer approximately 50 microns thick. After continued exposure, the layer appeared considerably more smooth and continuous. The oxide layer thickness grew to approximately 100 microns after 1050 hours of exposure.

TABLE 77. TOSHIBA SINTERED SILICON NITRIDE POST-EXPOSURE TEST RESULTS SUMMARY.

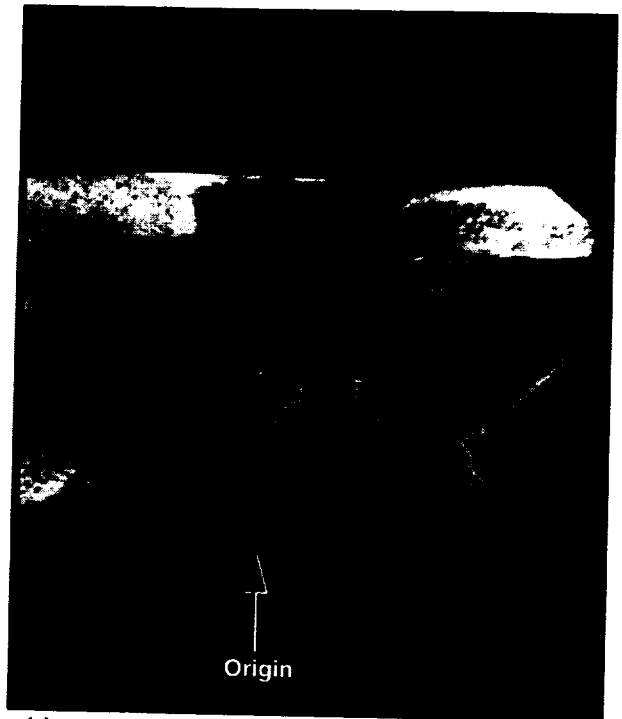
Material	Surface Condition	Cyclic Oxidation Exposure Temperature
Toshiba Sintered Si_3N_4	Longitudinally Machined	1204C (2200F)

Post-Exposure Strength Measurements Summary

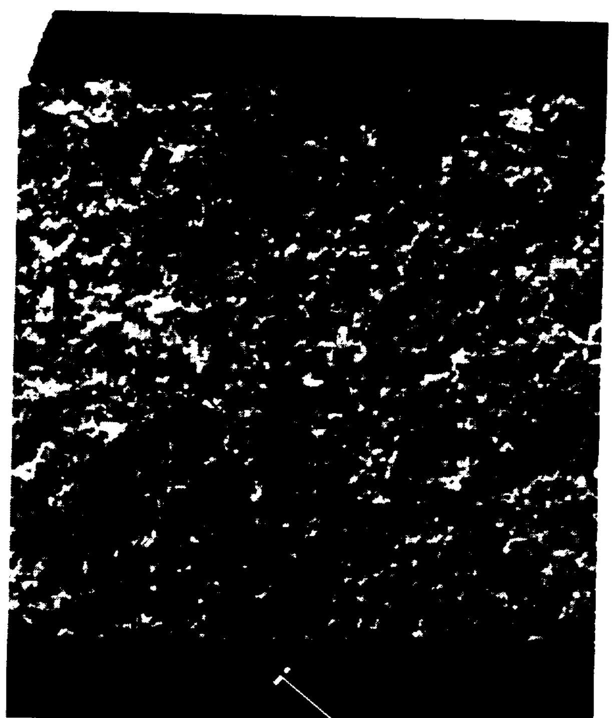
Exposure Duration, hrs	Test Temperature C	(F)	Post-Exposure Strength MPa	(ksi)	Strength Change, percent	Qty. Tested	Primary Failure Origins
zero	24	(75)	777 ± 44	(112.6 ± 6.4)	---	12	As-processed surface, subsurface porosity
zero	1204	(2200)	421 ± 30	(61.0 ± 4.4)	---	12	As-processed surface, subsurface porosity
350	24	(75)	425 ± 36	(61.6 ± 5.2)	-45	3	Oxidation pits
350	1204	(2200)	229 ± 25	(33.2 ± 3.6)	-46	3	Oxidation pits
700	24	(75)	443 ± 40	(64.2 ± 5.8)	-43	3	Oxidation pits
700	1204	(2200)	388 ± 39	(56.3 ± 5.6)	-8	3	Oxidation pits
1050	24	(75)	365 ± 43	(53.0 ± 6.2)	-53	6	Oxidation pits
1050	1204	(2200)	363 ± 59	(52.7 ± 8.6)	-14	6	Oxidation pits

Post-Exposure Weight and Dimensional Changes Summary

Exposure Duration, hrs	Weight Change, percent	Dimensional Change, percent	Quantity Specimens Measured
350	-0.6	5.6	6
700	-0.1	5.0	6
1050	-0.2	5.8	12



(a) 20x



(b) Origin 400x

G6253-13 Surface/Subsurface Porosity Origin

Figure 13. RBN101 Room-Temperature Baseline Test Specimen Failure Originating From Subsurface Porosity.

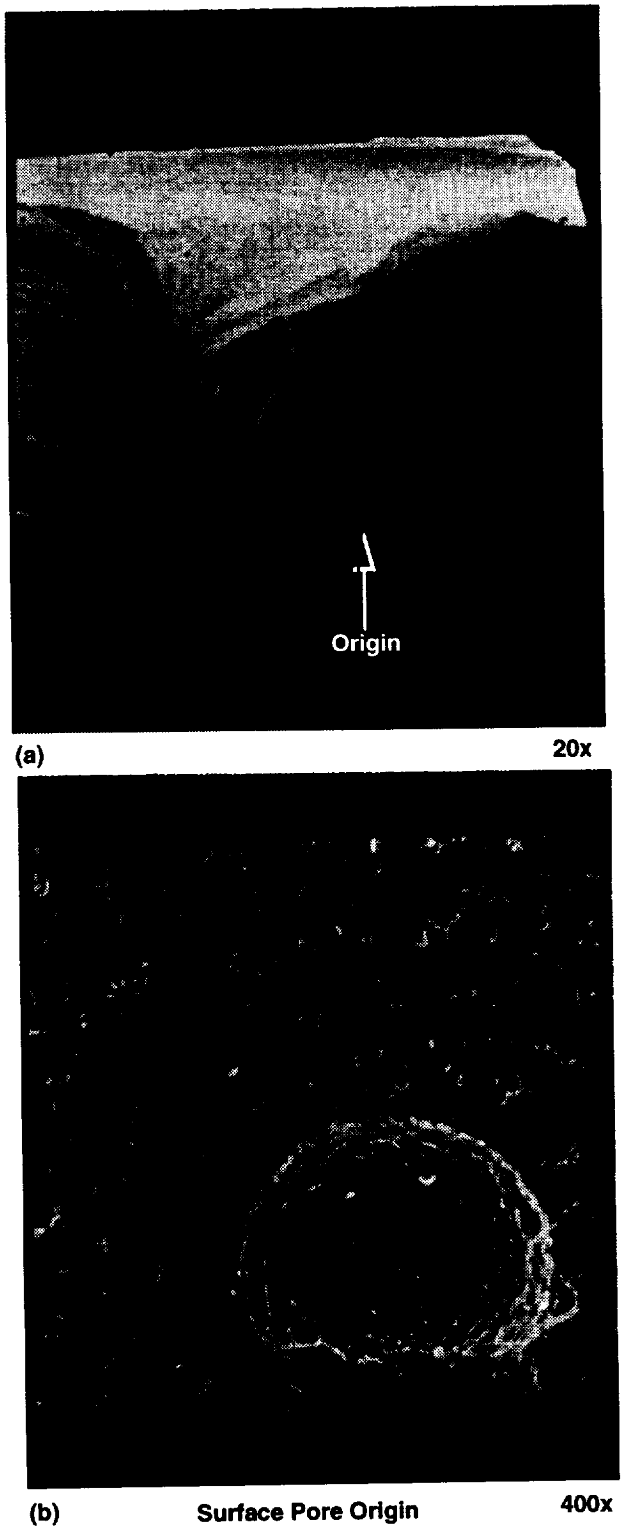


Figure 14. RBN101 1204C (2200F) Baseline Test Specimen Failure Originating From Surface-Connected Pore.

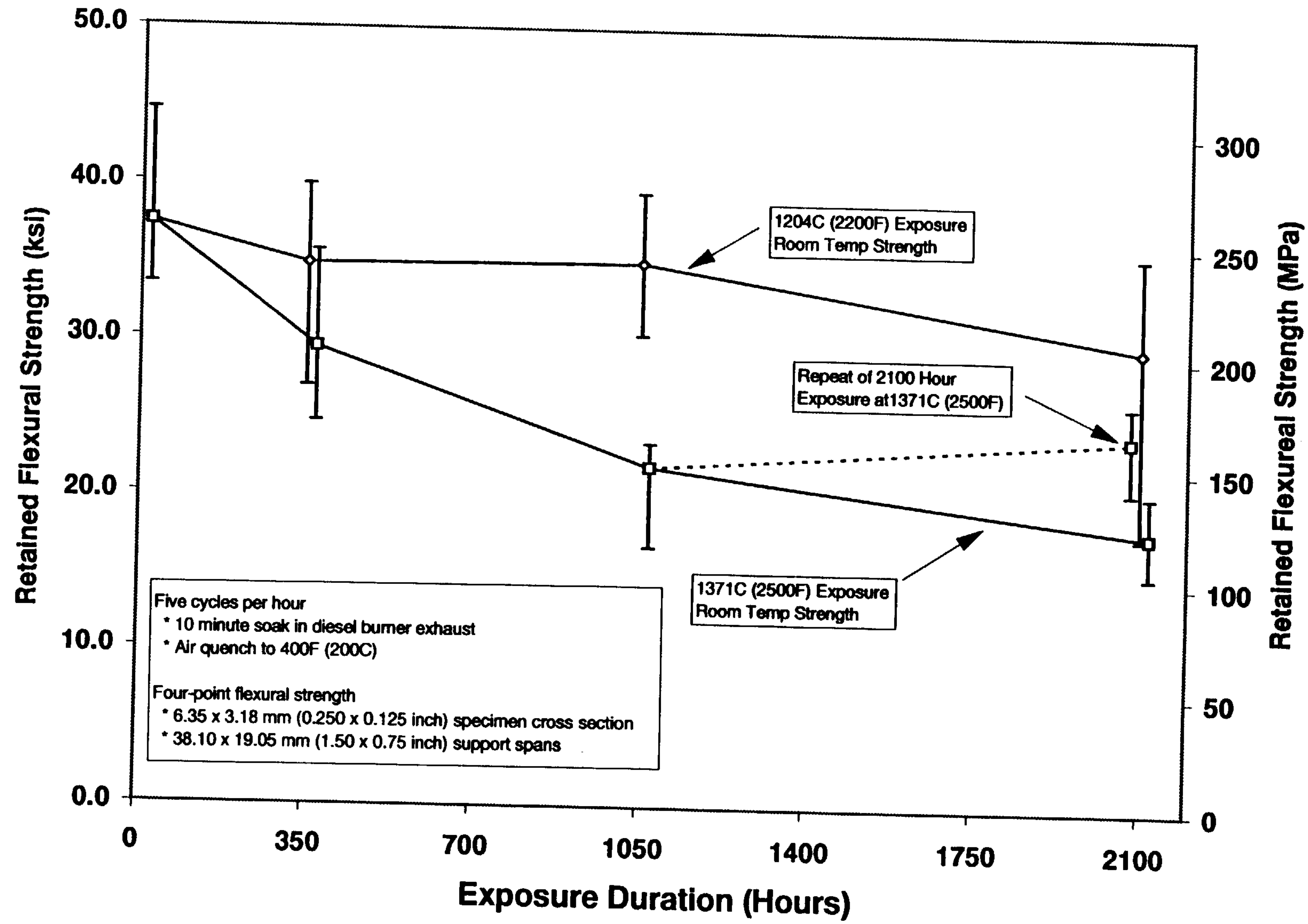
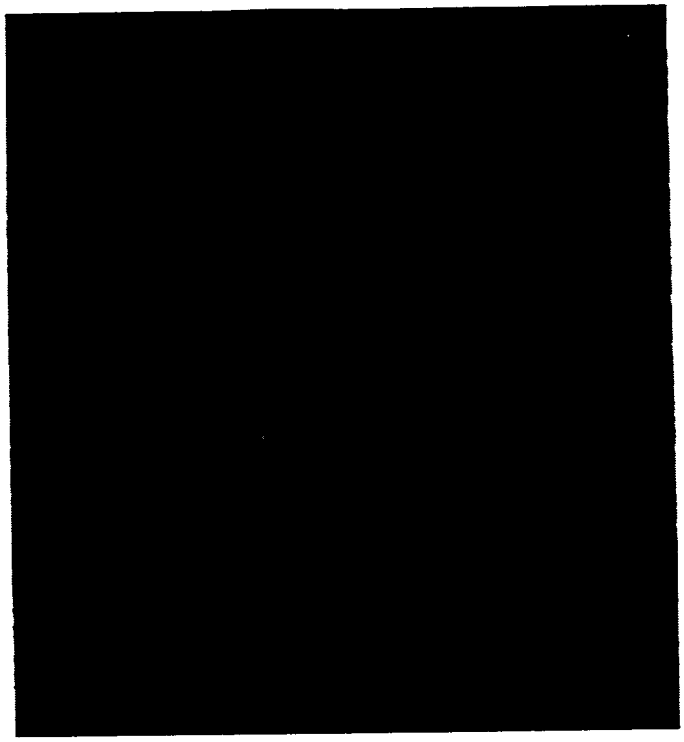
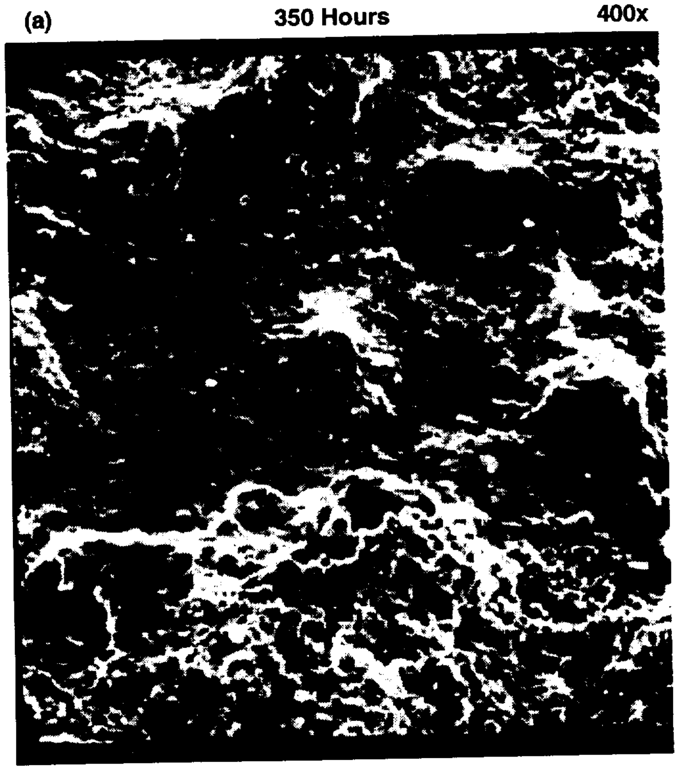


Figure 15. Room-Temperature Post-Exposure Strength Test Results For RBN101 Following 1204C (2200F) And 1371C (2500F) Cyclic Oxidation Durability Testing.



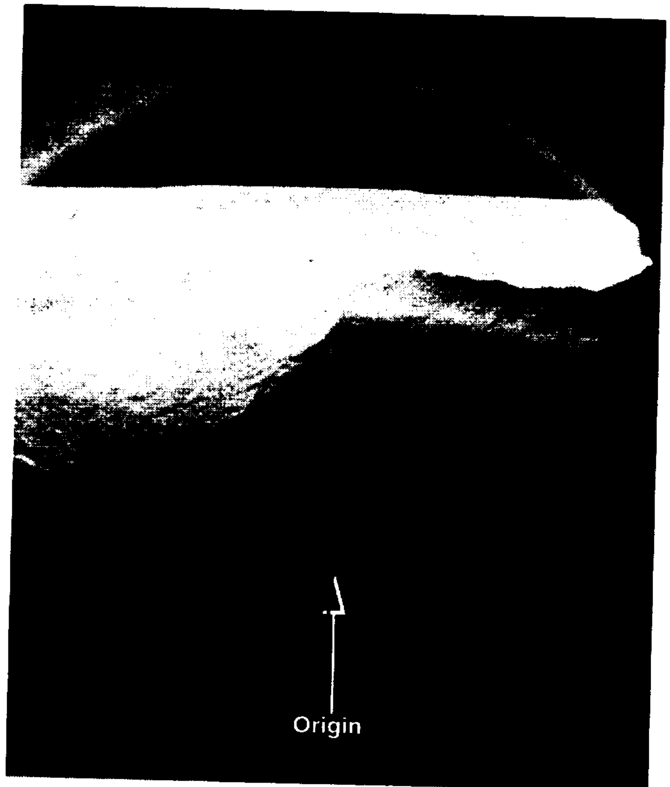
(a) 350 Hours 400x



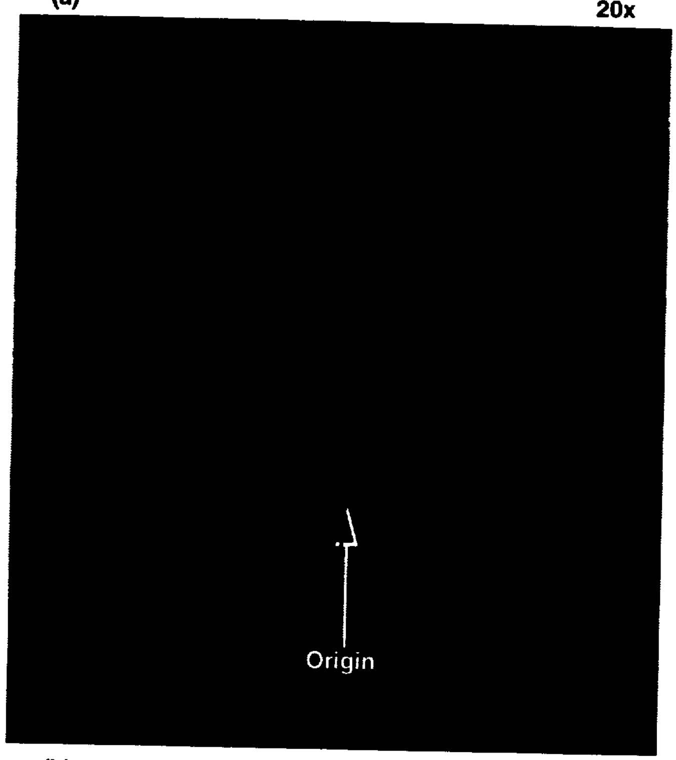
(b) 1050 Hours 400x

G6253-16A

Figure 16. Surface Topography Of RBN101 Specimen After Cyclic Oxidation Durability Exposure At 1204C (2200F): (a) 350 Hours; (b) 1050 Hours.



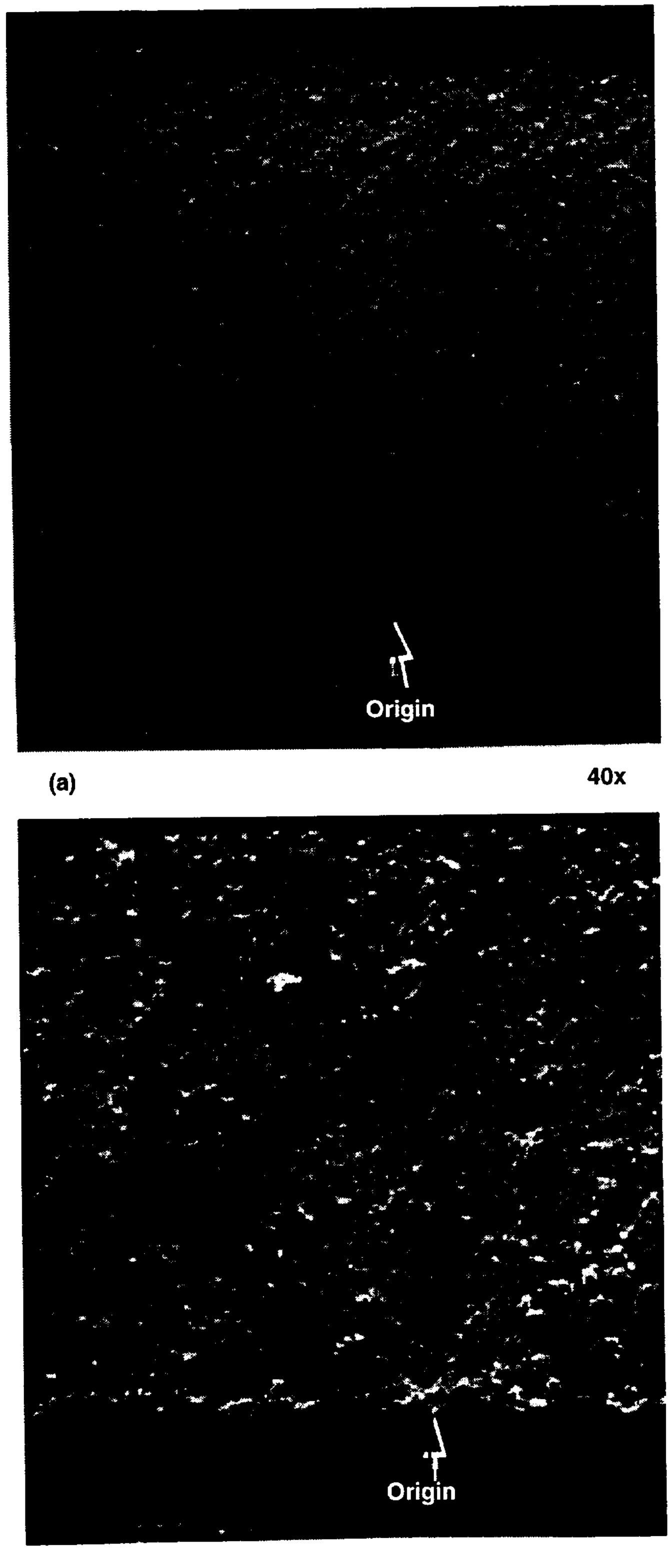
(a) 20x



(b) 400x

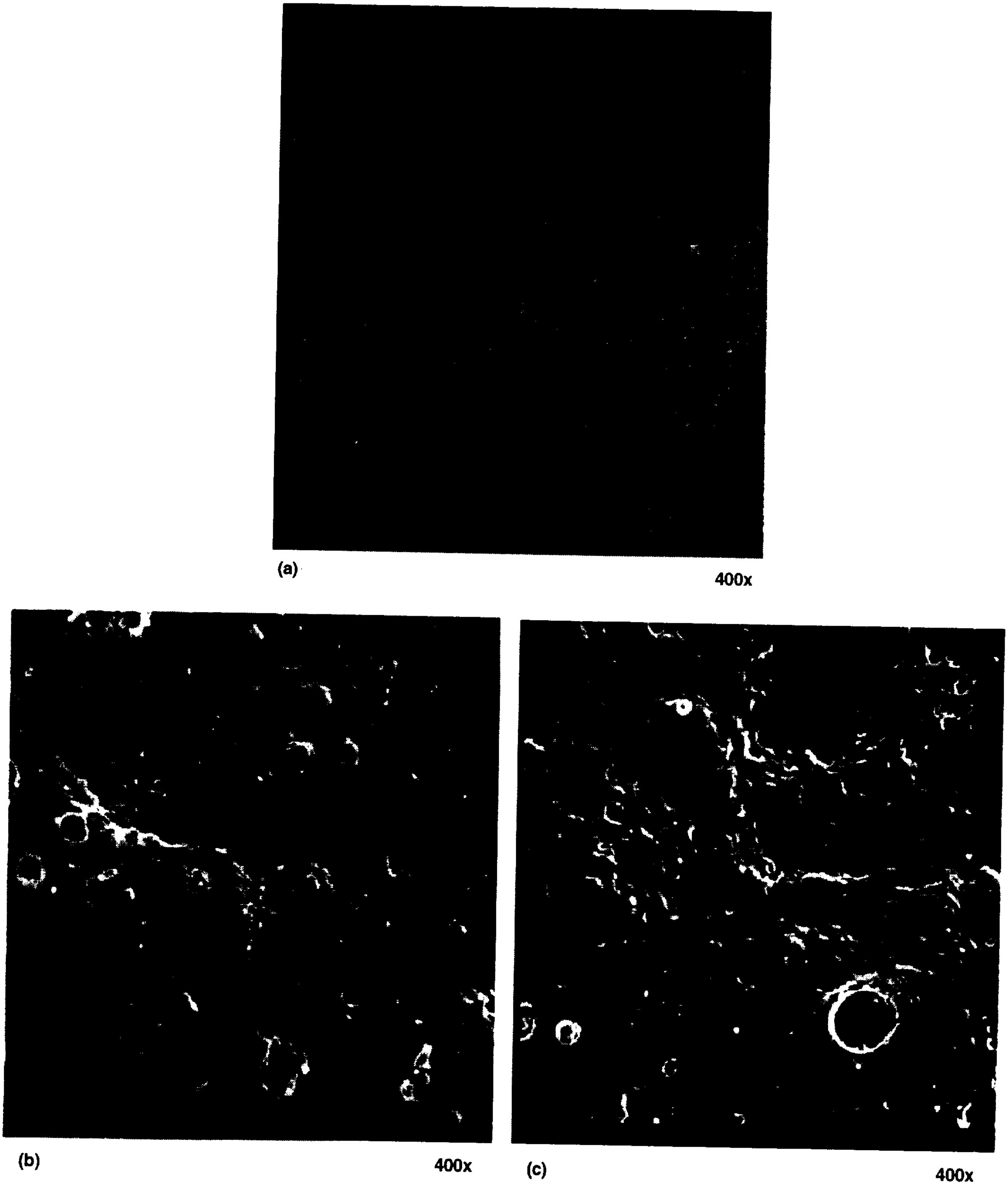
G6253-17A

Figure 17. RBN101 Specimen Failure Originating At Surface Oxide Reaction Following 350 Hours Exposure At 1204C (2200F).



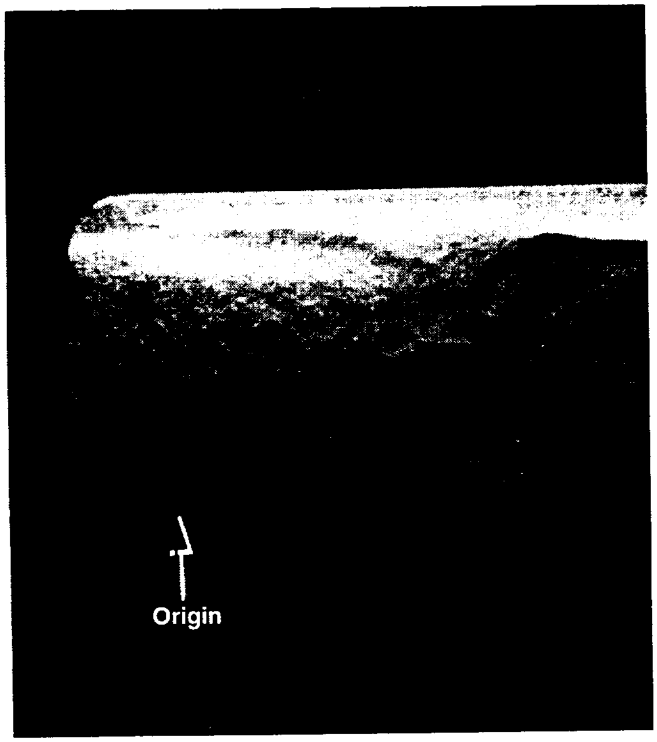
G6253-18

Figure 18. RBN101 Specimen Failure Originating At Oxide Reaction Of Subsurface Pore Following 350 Hours Exposure At 1204C (2200F).

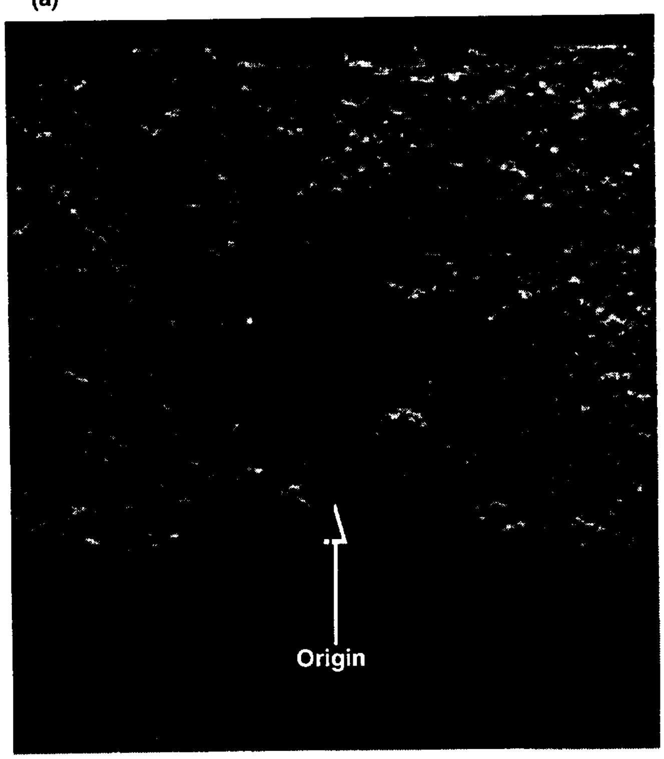


G6253-19

Figure 19. Surface Topography Of RBN101 Following Cyclic Oxidation Durability Exposure At 1371C (2500F): (a) 350 Hours; (b) 1050 Hours; (c) 2100 Hours.



(a) 20x



(b) 400x

Surface Oxide Reaction
and Subsurface Pore Origin

G6253-20

Figure 20. RBN101 Specimen Failure Originating At Surface Oxide Reaction (Pit) Following 350 Hours Exposure At 1371C (2500F).

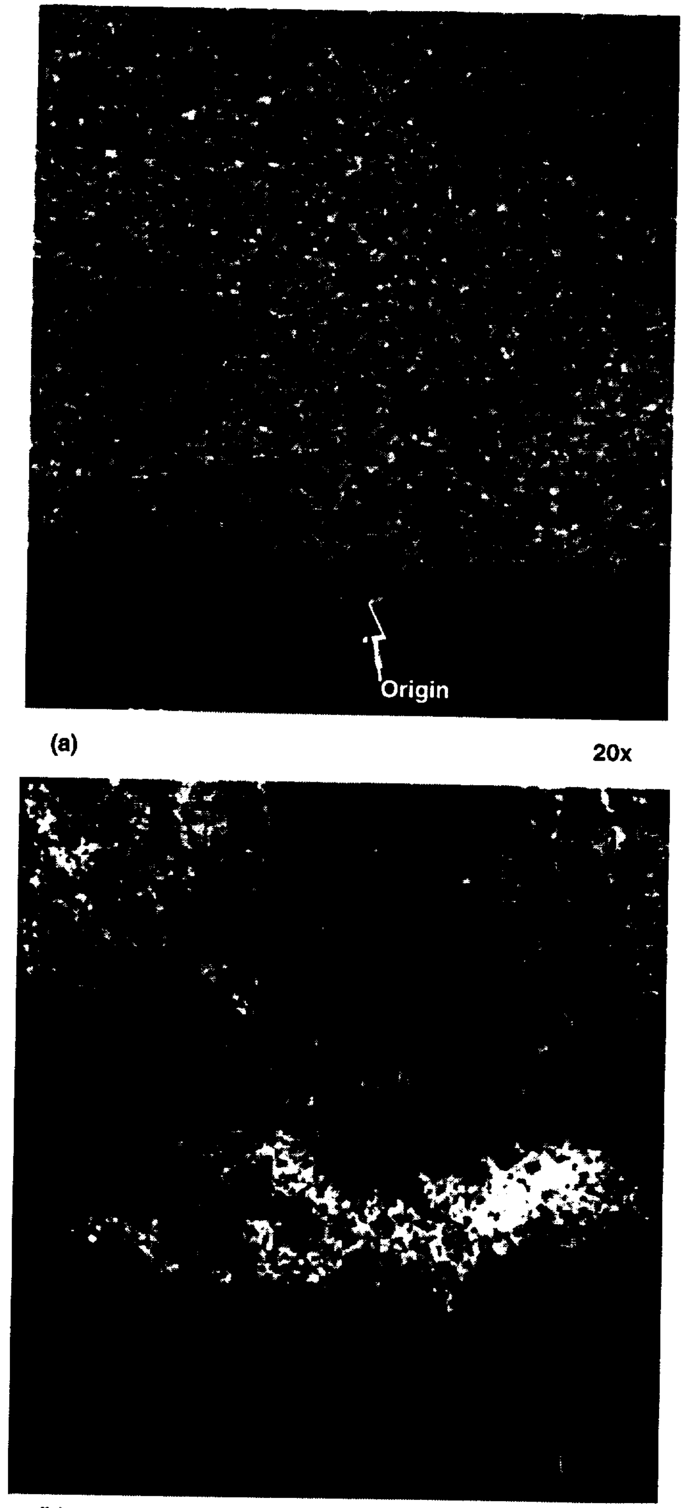
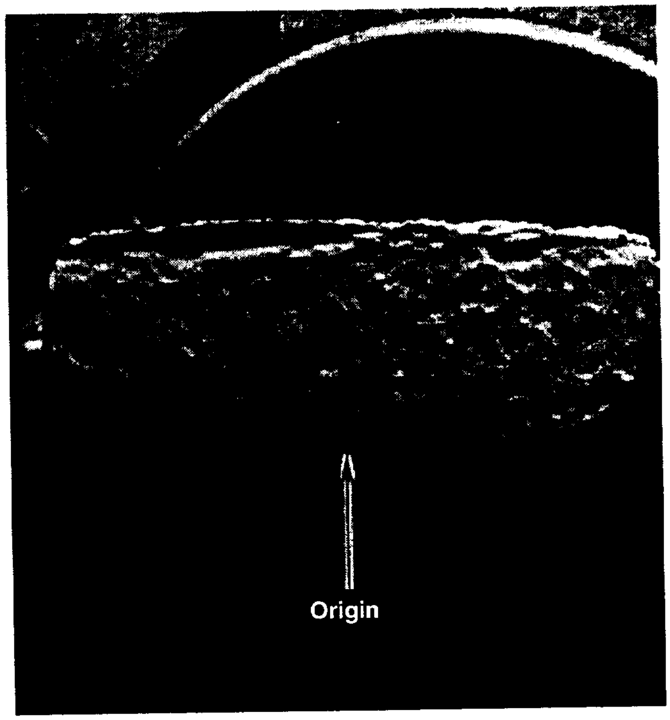
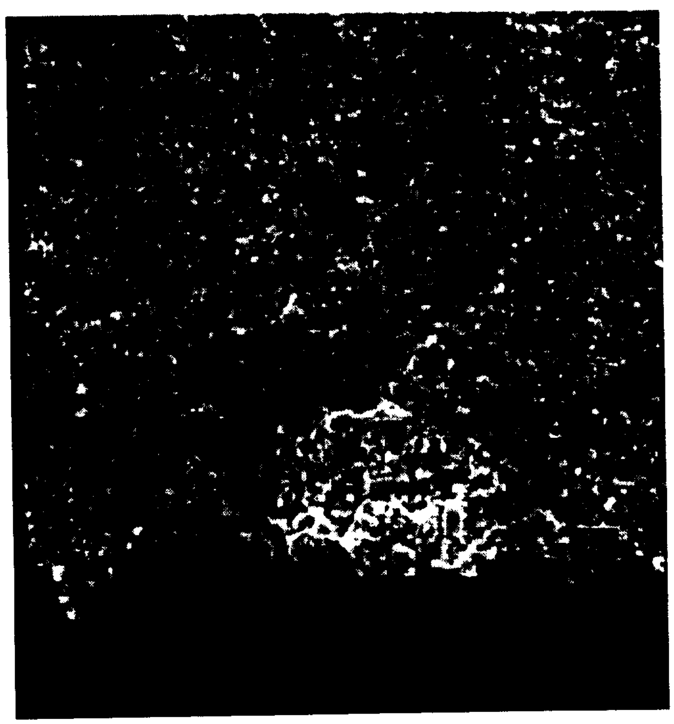


Figure 21. RBN101 Specimen Failure Originating At Oxidation Reaction With Pre-Existing Subsurface Porosity Following 1050 Hours Exposure At 1371C (2500F).



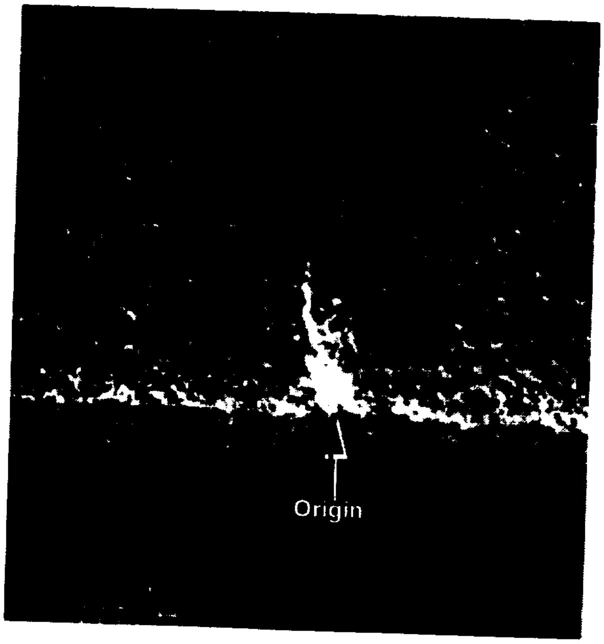
(a) 200x



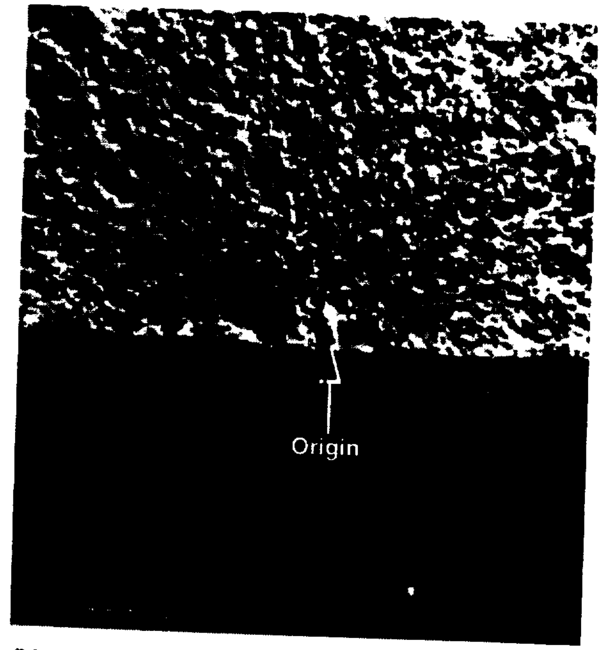
(b) 400x

G6253-22

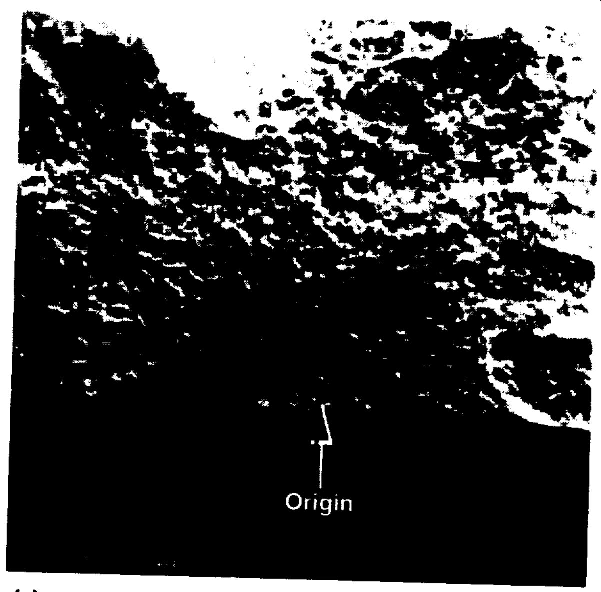
Figure 22. **RBN101 Specimen Failure Originating At Subsurface Porosity Following 2100 Hours Exposure At 1371C (2500F).**



(a) Low Density Region 20x



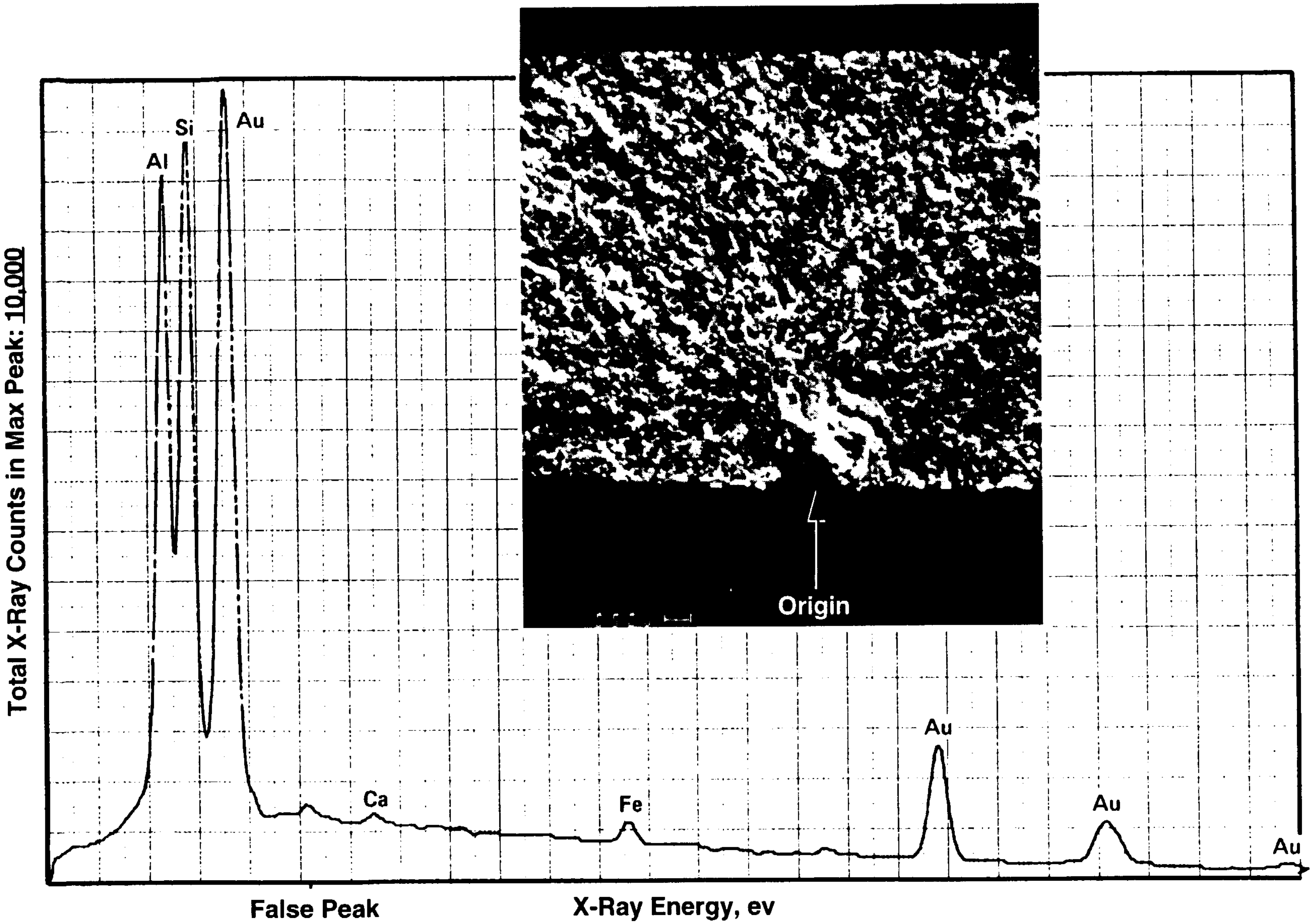
(b) Low Density Region Containing Al 20x



(c) Subsurface Porosity 20x

G6253-23A

Figure 23. Typical RBN104 Baseline Test Specimen Failures Originating From Surface And Subsurface Porosity.



G6253-24

Figure 24. RBN104 Room-Temperature Baseline Test Specimen Failure Originating From Low-Density Region Containing Aluminum.

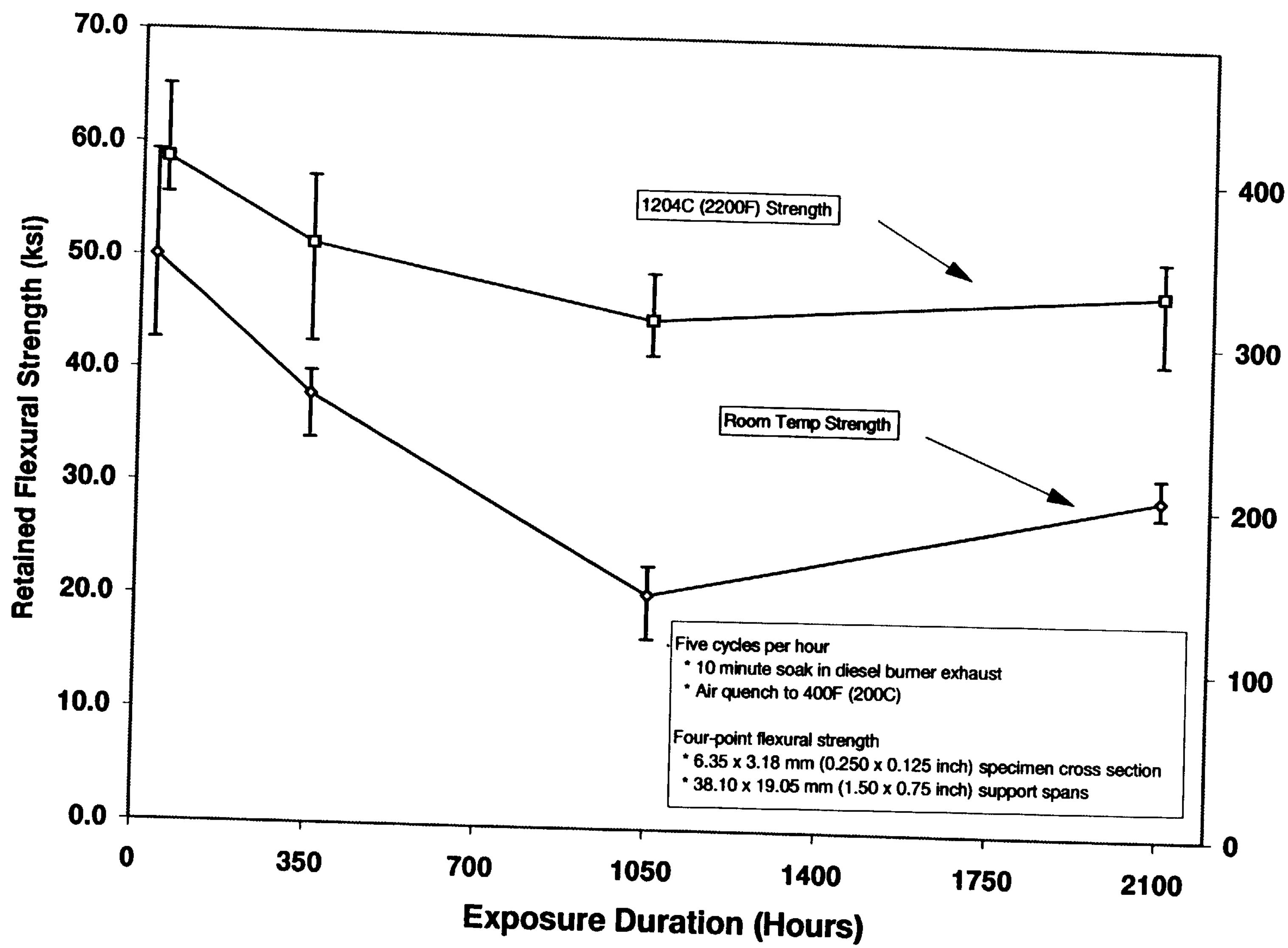


Figure 25. Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results For RBN104 Following 1371C (2500F) Cyclic Oxidation Durability Testing.

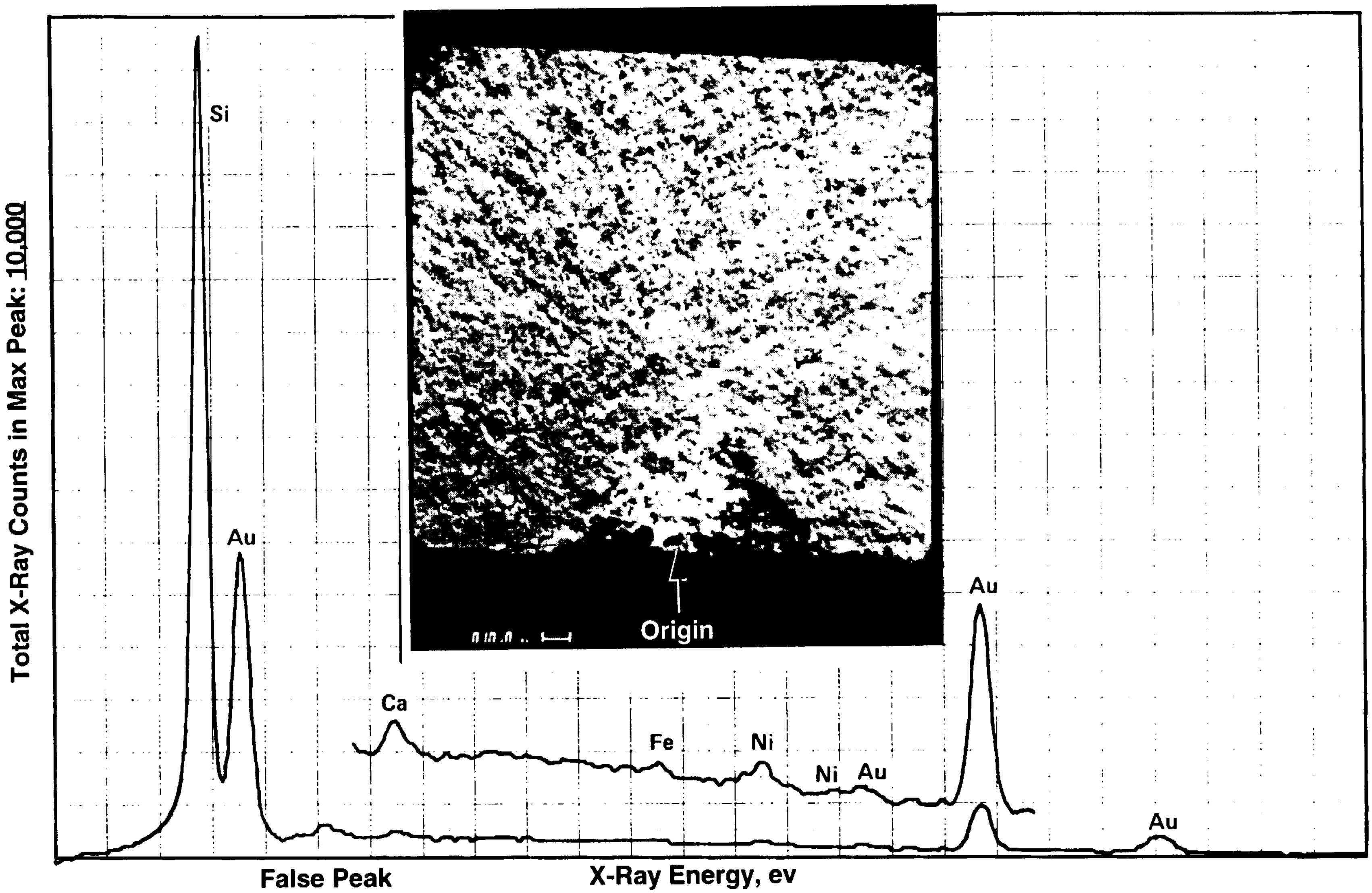
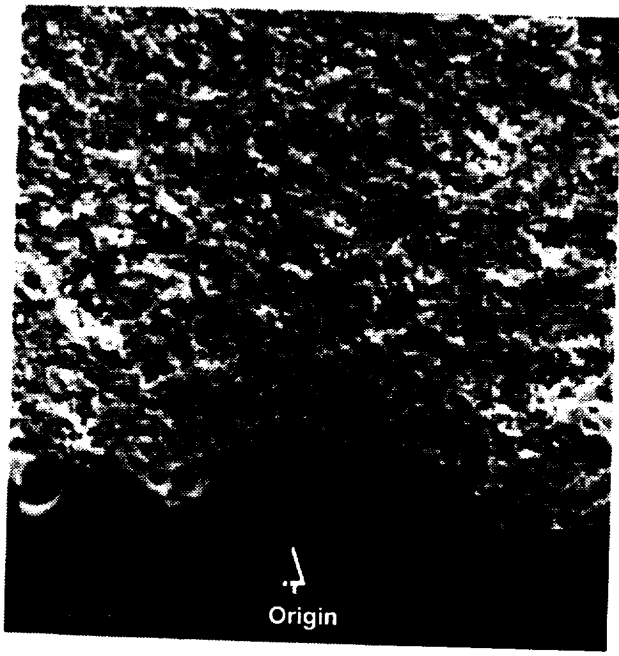
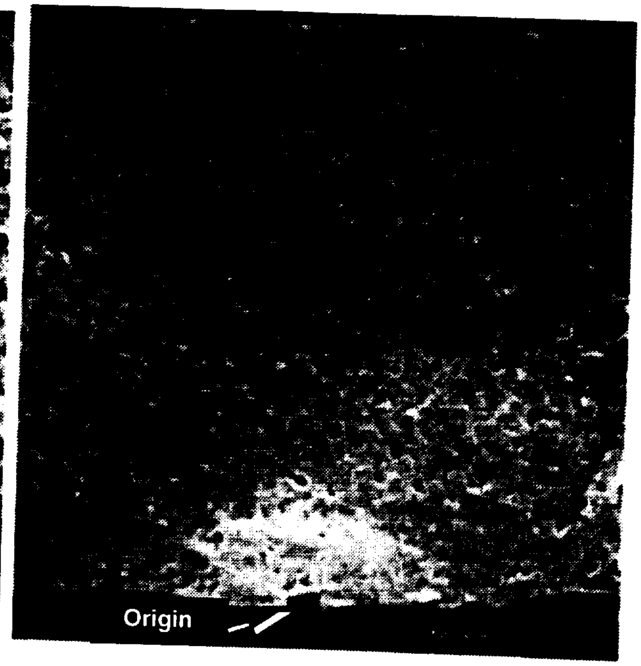


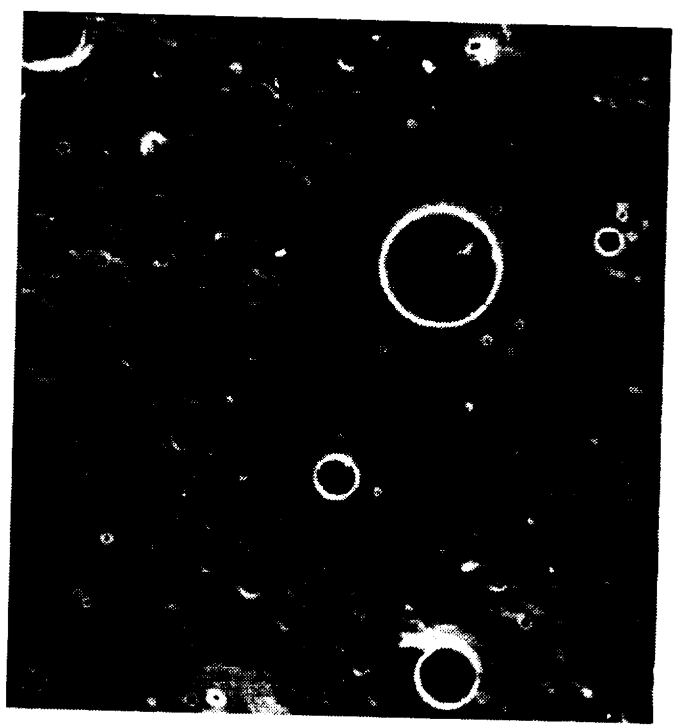
Figure 26. RBN104 Specimen Failure Originating At Surface Porosity Following 350 Hours Exposure At 1371C (2500F).



(a) Room-Temperature Test S/N 9084 400x



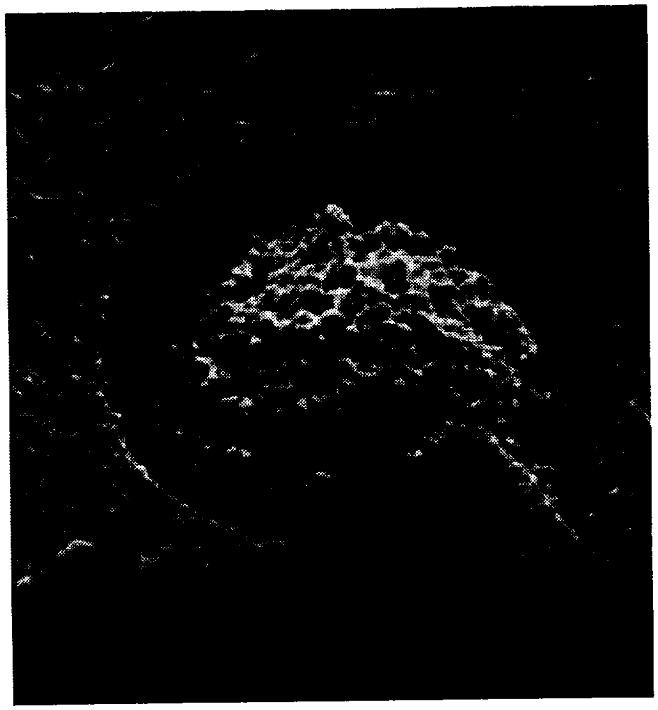
(b) 1204°C (2200°F) Test S/N 7680 400x



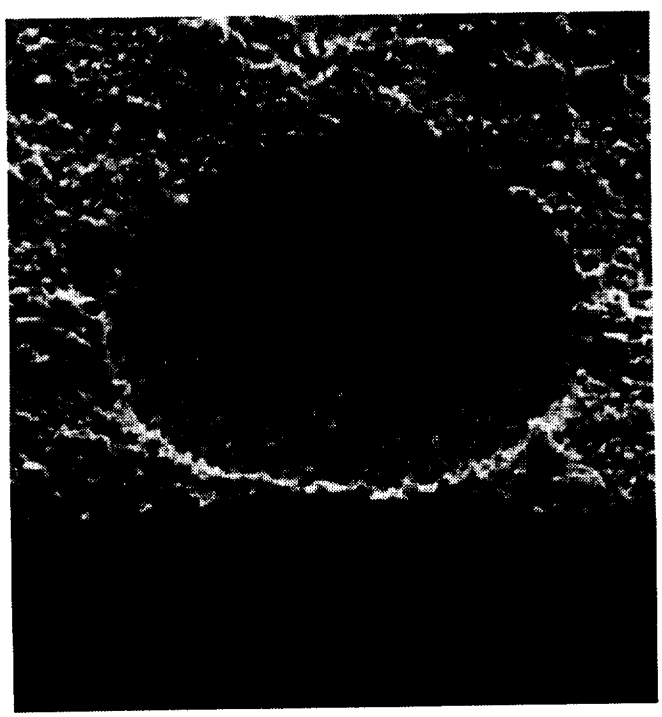
(c) As-Exposed Surface 400x

G6253-27

Figure 27. Typical RBN104 Specimen Failure Origins And Surface Topography Following 1050 Hours Exposure At 1371C (2500F).



400x



400x

G6253-28

Figure 28. Typical Code 2 Si_3N_4 Baseline Test Specimen Failures Originating From Large Pores.

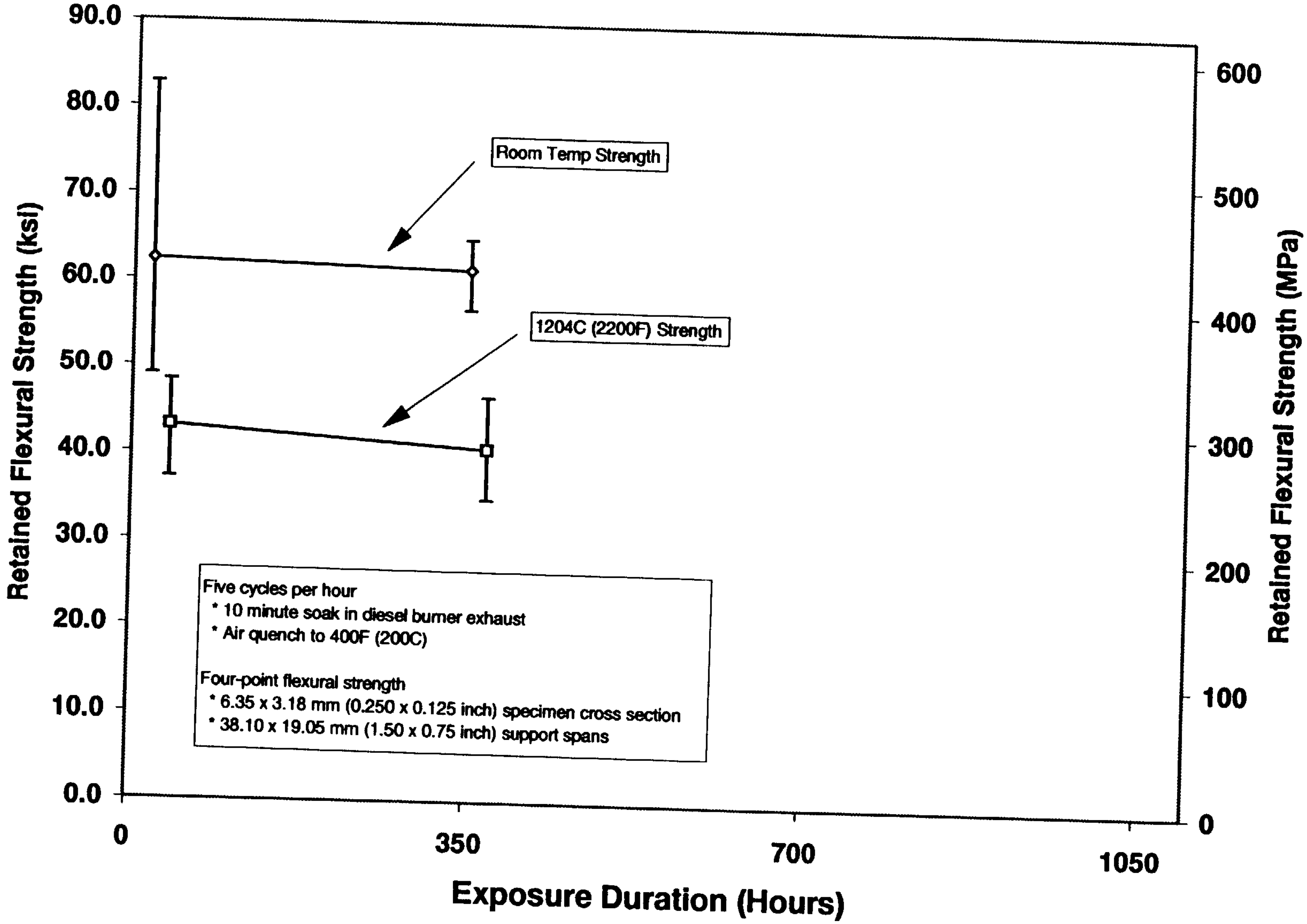
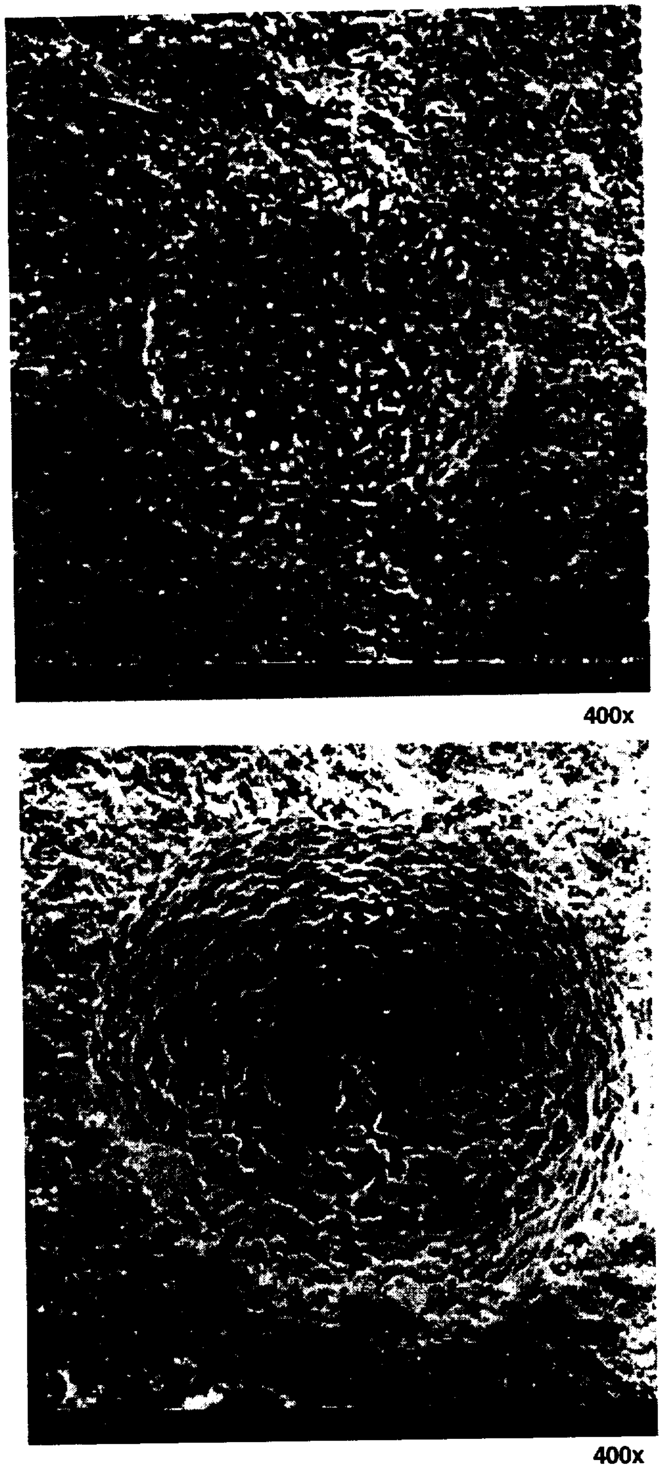


Figure 29. Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results For Code 2 Si_3N_4 Following 1204C (2200F) Cyclic Oxidation Durability Testing.



G6253-30A

Figure 30. Typical Code 2 Si_3N_4 Specimen Failures Originating From Large Pores Following 350 Hours Exposure At 1204C (2200F).

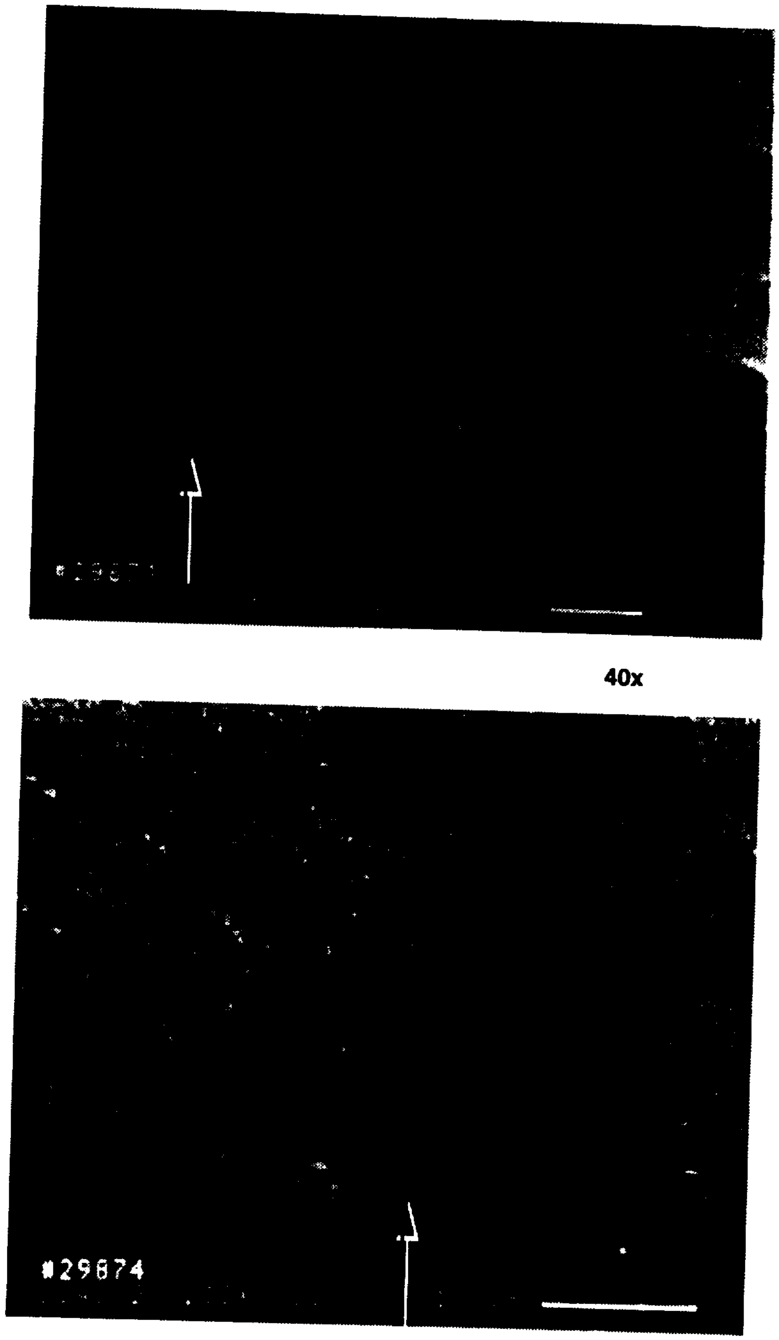


Figure 31. Typical GN-10 Baseline Test Specimen Failure Originating From Machined Surface.

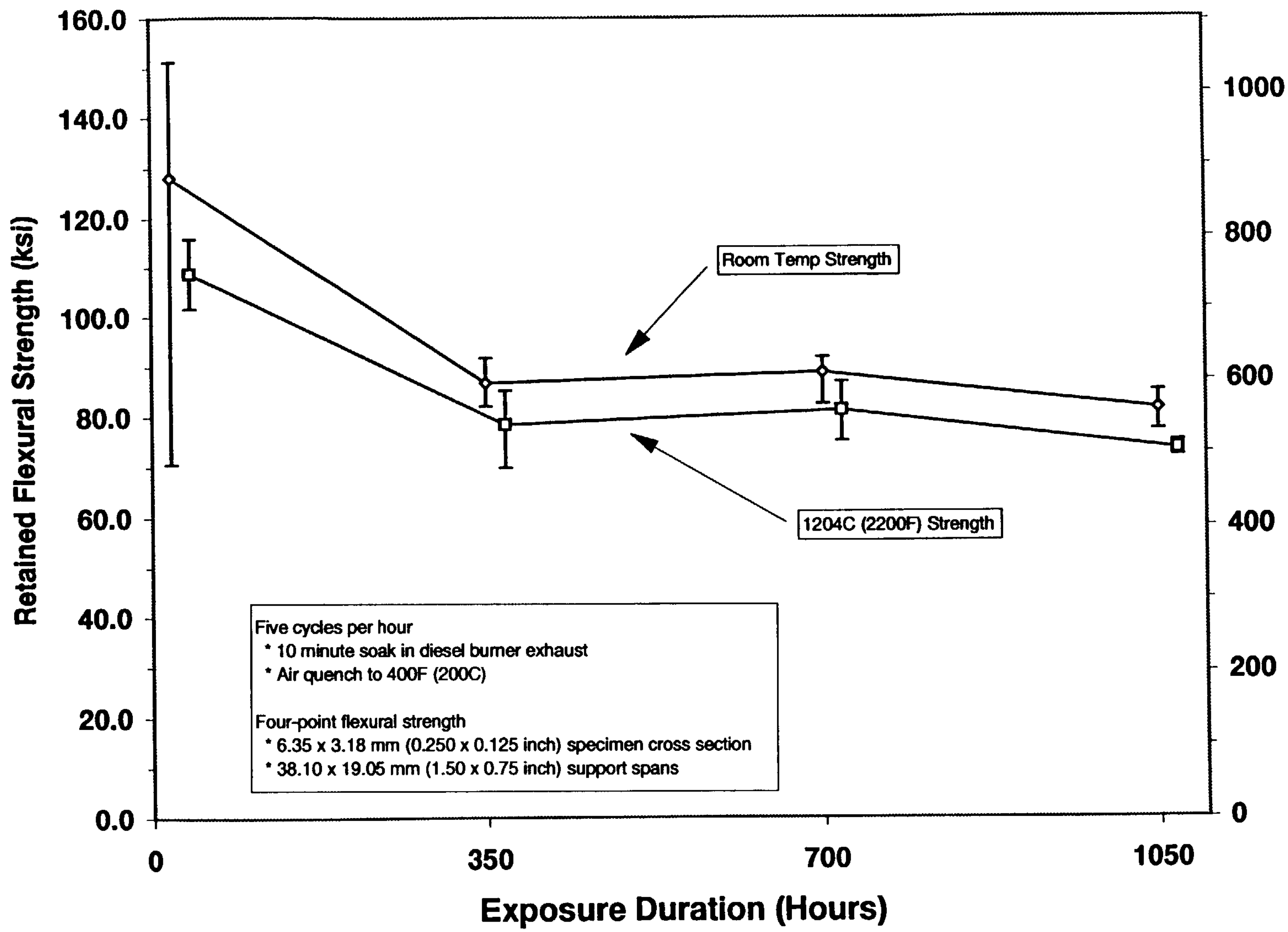
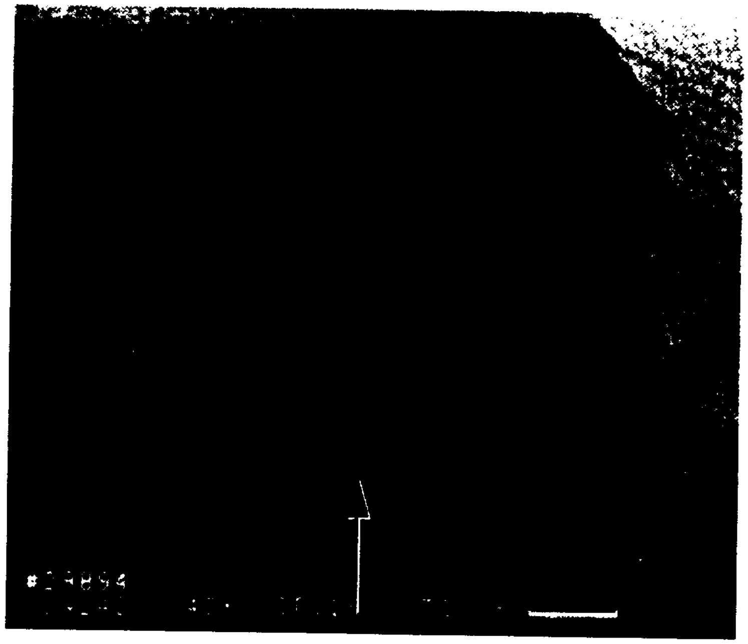
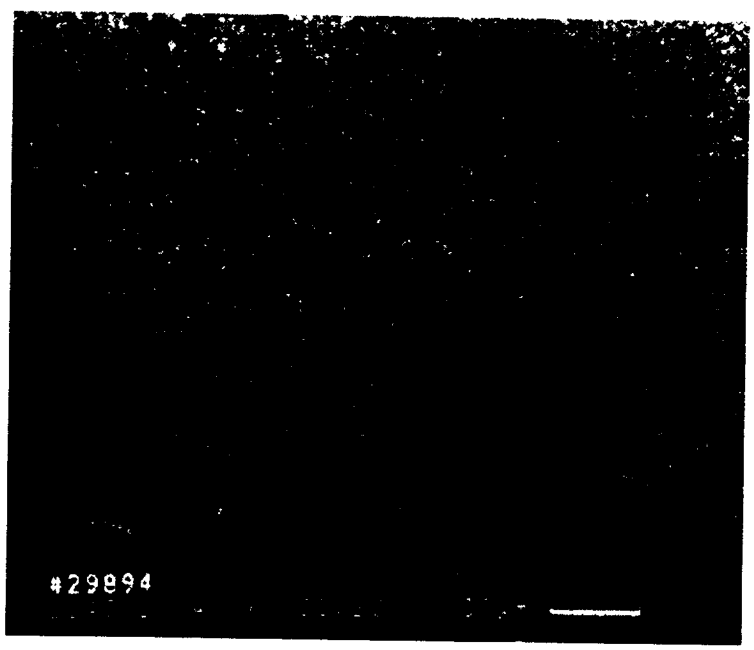


Figure 32. Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results For GN-10 Si_3N_4 Following 1204C (2200F) Cyclic Oxidation Durability Testing.



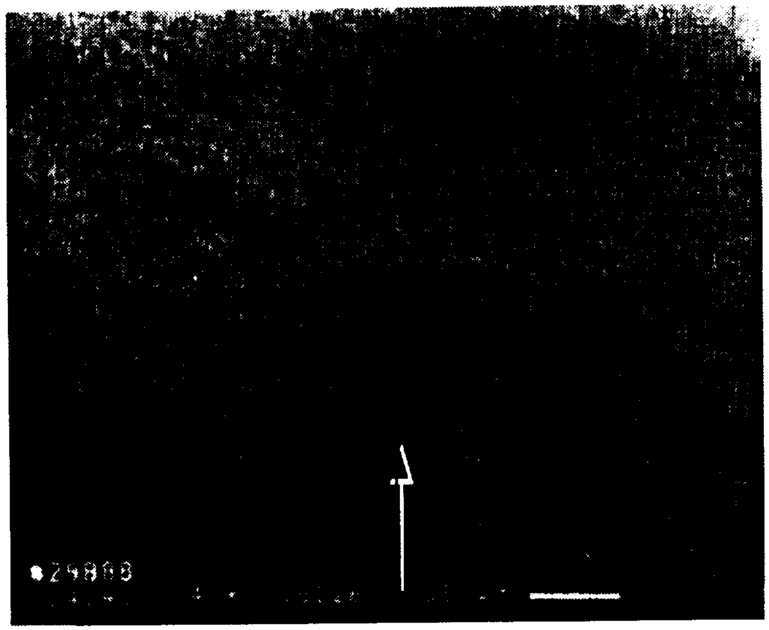
(a) 40x



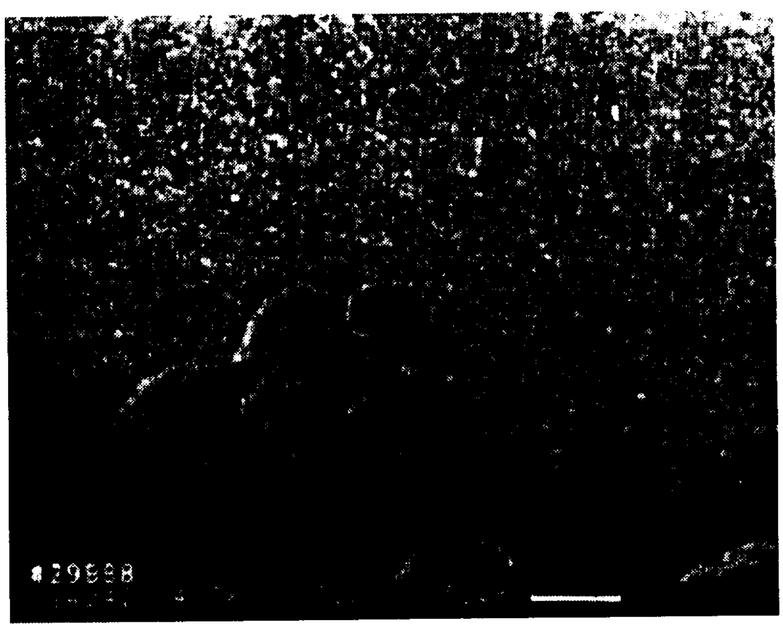
(a) 400x

G6253-33A

Figure 33. GN-10 Specimen Failure Originating At Surface Oxidation Pit Following 350 Hours Exposure At 1204C (2200F).



(a) 40x



(b) 400x

G6253-34

Figure 34. **GN-10 Specimen Failure Originating At Surface Oxidation Pit Following 1050 Hours Exposure At 1204C (2200F).**

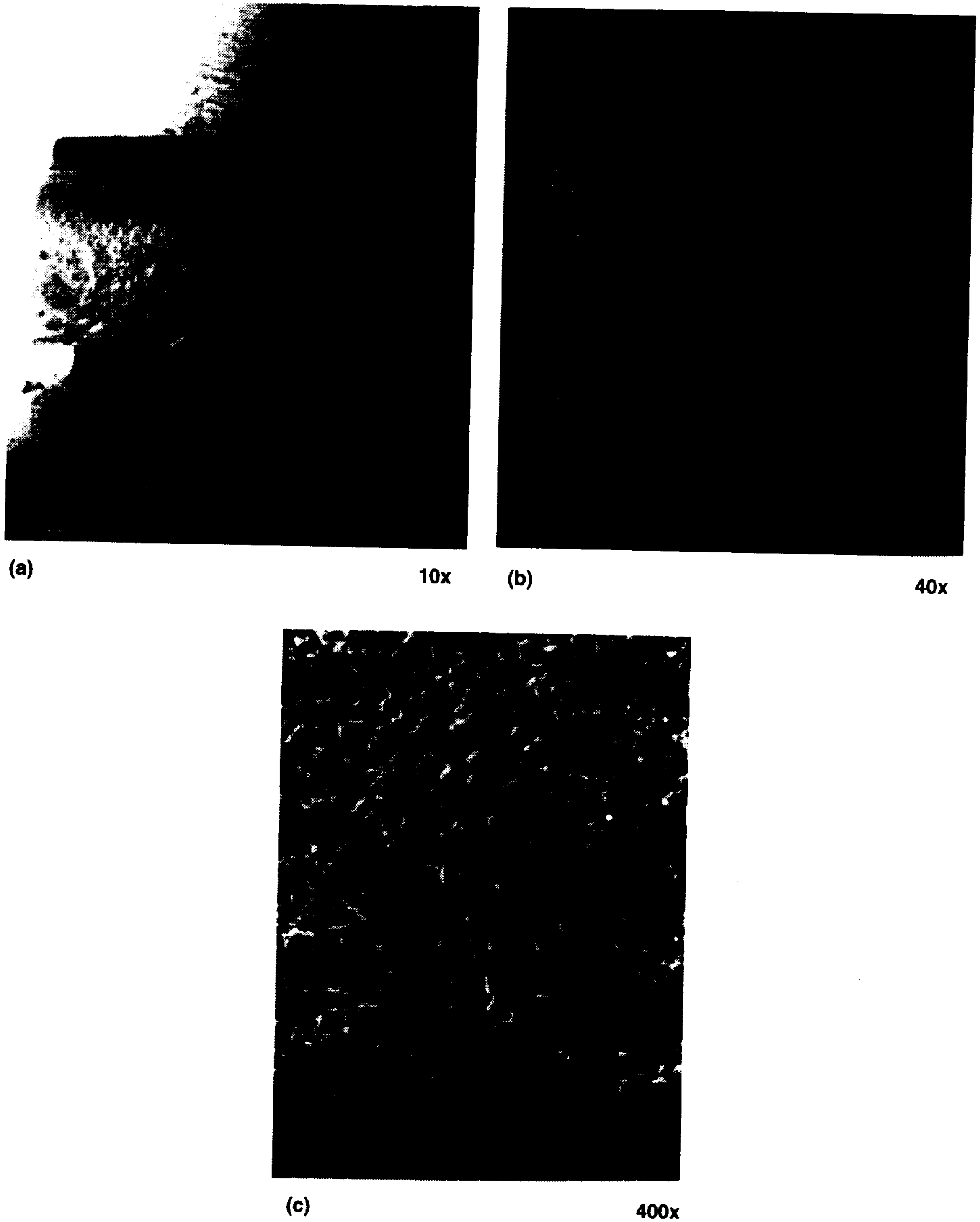


Figure 35. Typical KX01 Baseline Test Specimen Failure Originating From As-Processed Surface.

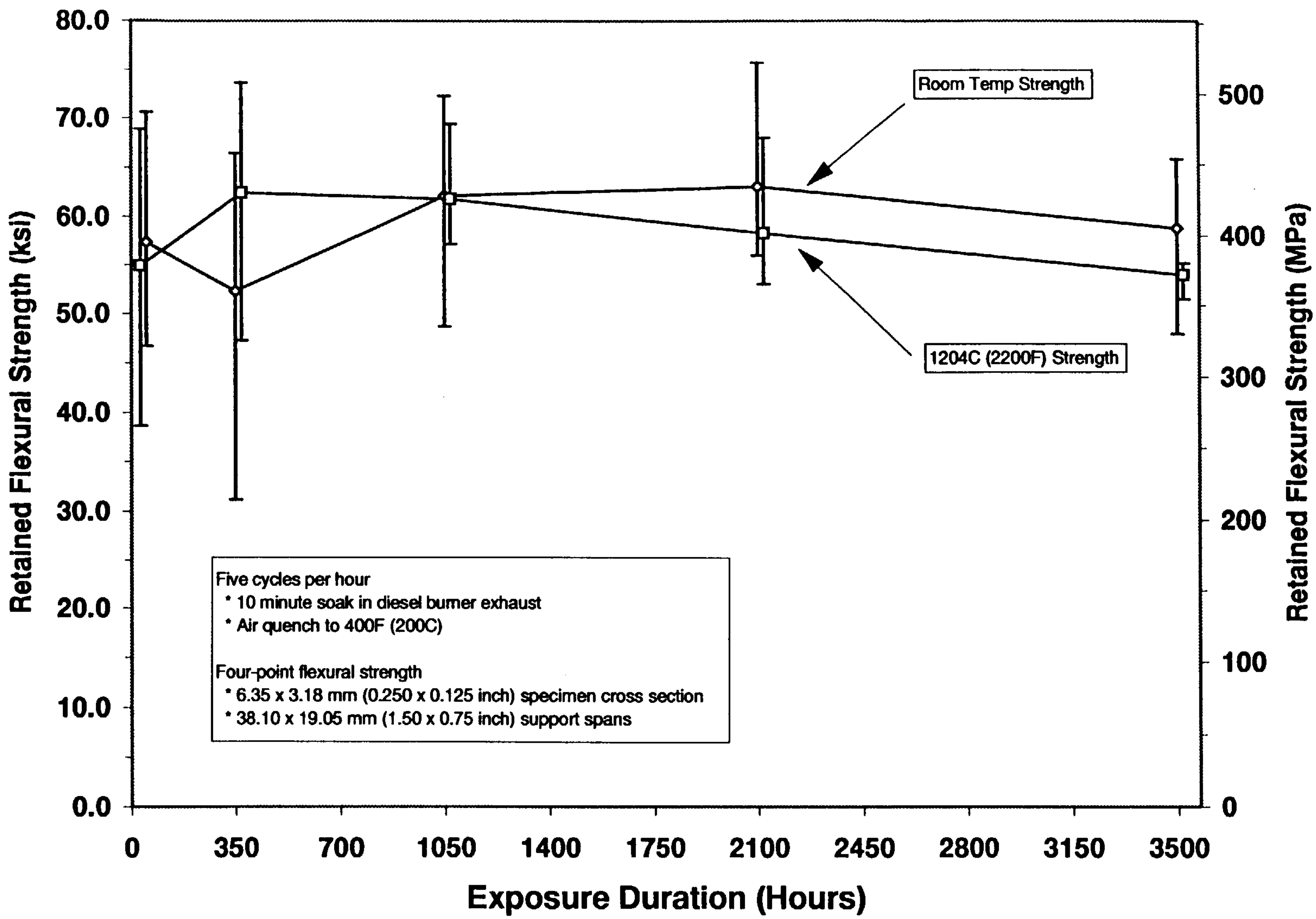


Figure 36. KX01 Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.

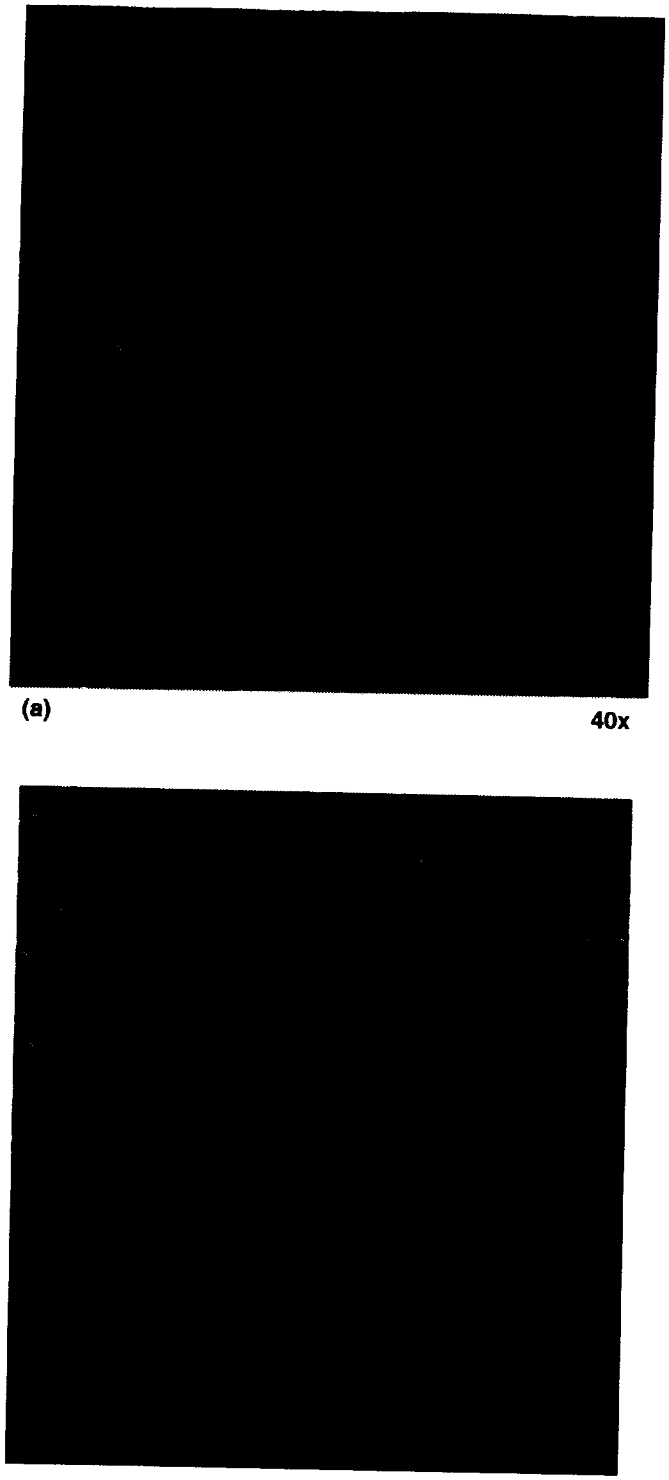


Figure 37. Typical KX01 Specimen Failure Originating From Flame-Exposed Surface Following 2100 Hours Exposure At 1204C (2200F).

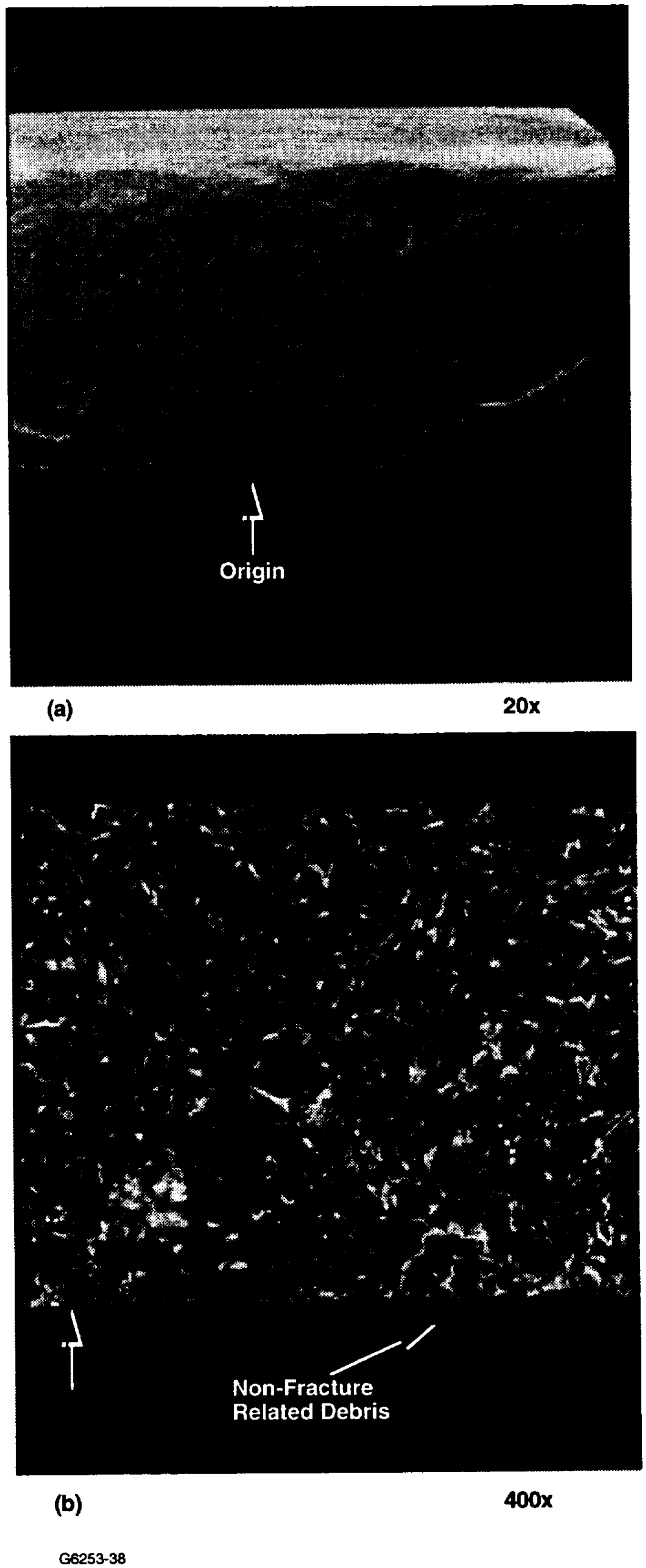
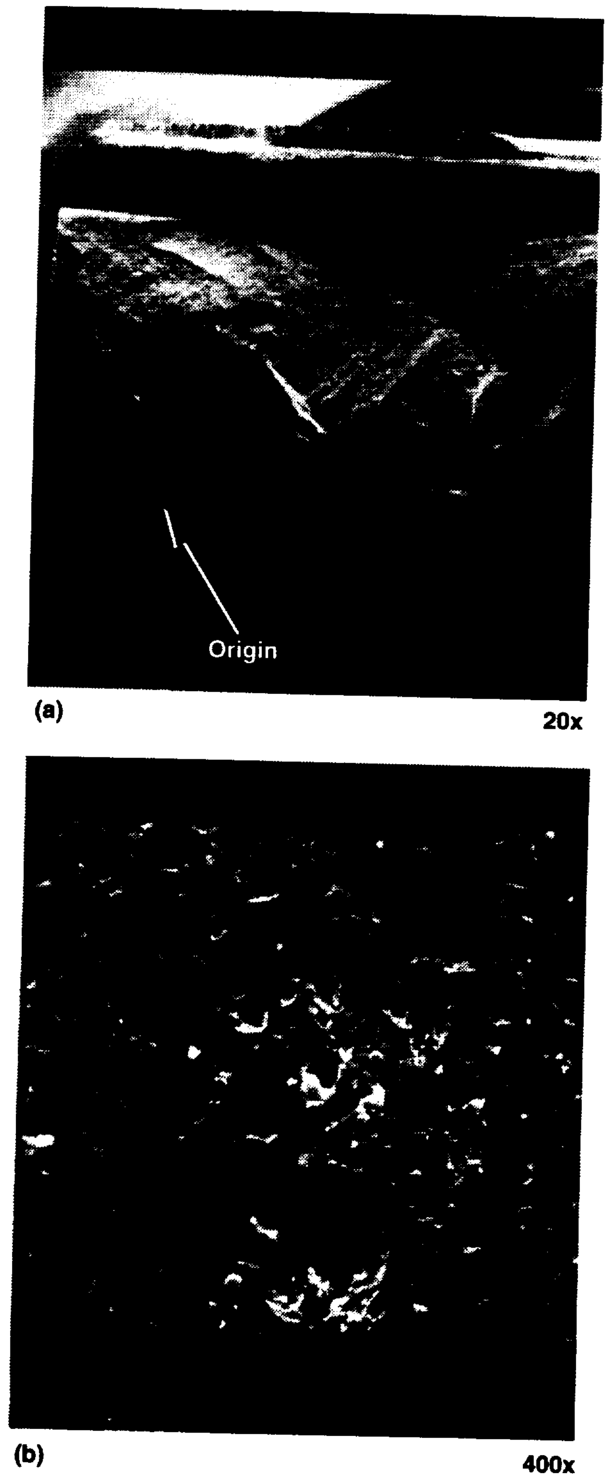


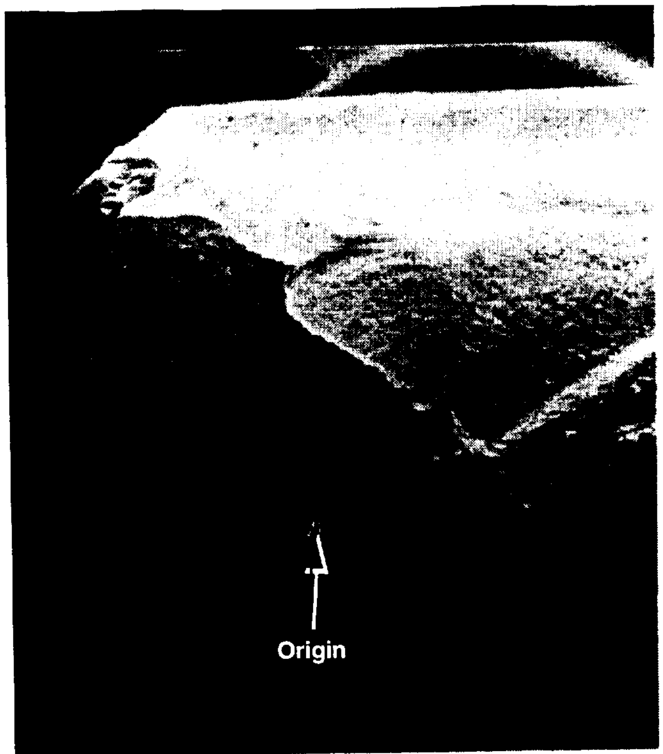
Figure 38. Typical Hexoloy SA Room-Temperature Baseline Test Specimen Failure Originating From Machined Surface; No Prominent Material Defects Were Noted.



Surface/Subsurface Pore at Origin

G6253-39

Figure 39. Hexoloy SA 1204C (2200F) Baseline Test Specimen Failure Originating From Surface-Connected Pore.



(a) 20x

(b) Surface Porosity at Origin 400x

G6253-40

Figure 40. Hexoloy SA 1204C (2200F) Baseline Test Specimen Failure Originating From Subsurface Porosity.

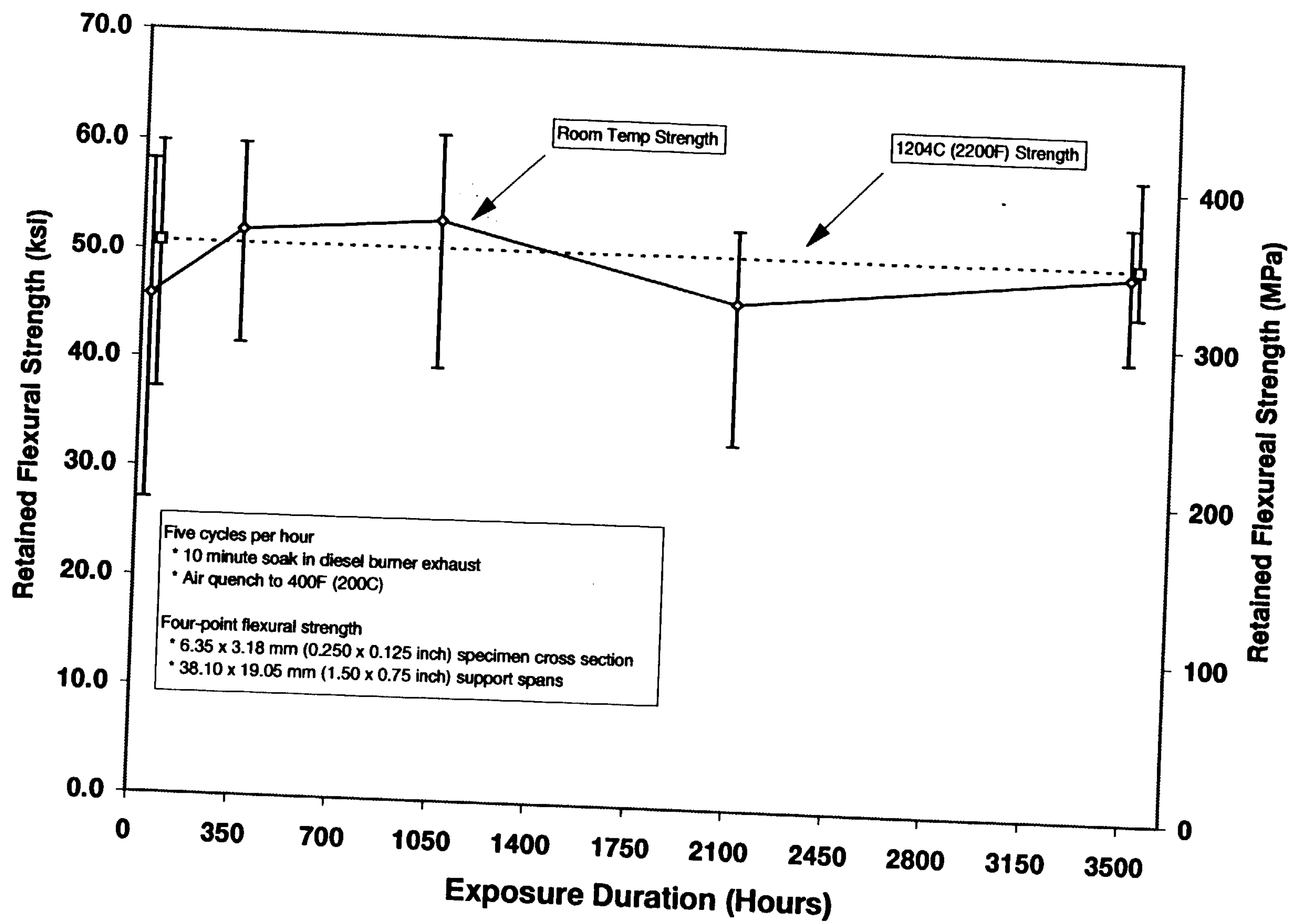
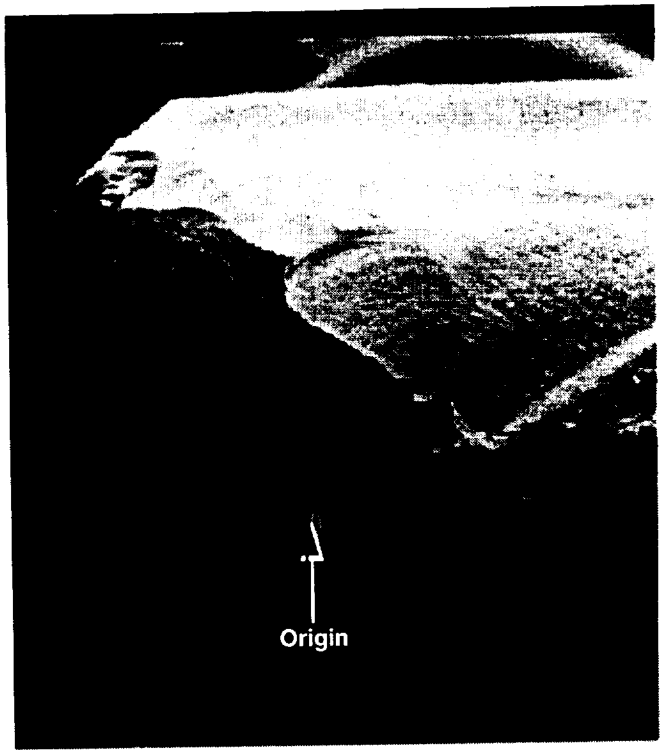


Figure 41. Hexoloy SA Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.

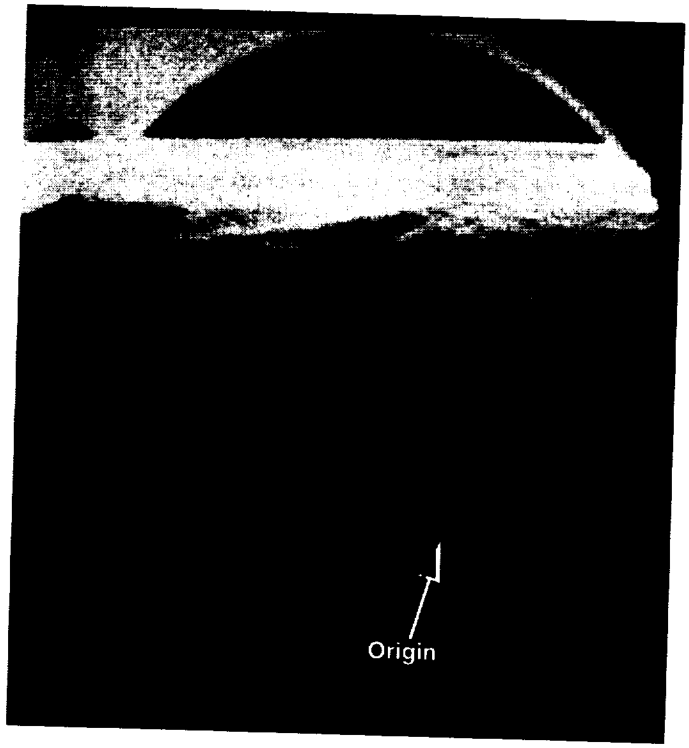


(a) 40x

(b) Surface Oxide Pit Origin 400x

G6253-42

Figure 42. Hexoloy SA Specimen Failure Originating At Surface Pit Following 3500 Hours Exposure At 1204C (2200F).

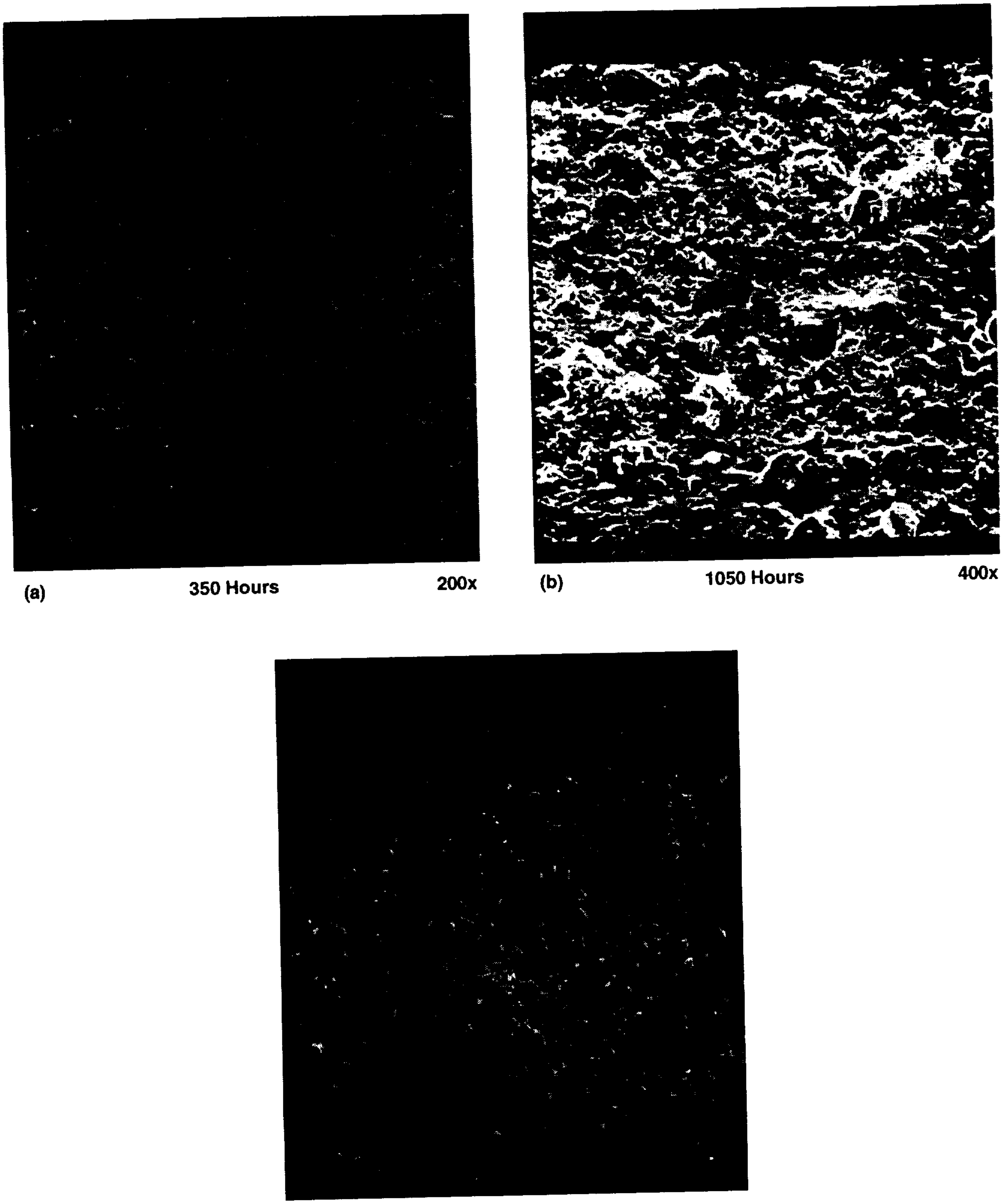


(a) 20x

(b) Subsurface Pore/Inclusion Origin 400x

G6253-43A

Figure 43. Hexoloy SA Specimen Failure Originating From Subsurface Porosity Following 350 Hours Exposure At 1204C (2200F).



(a) 350 Hours 200x

(b) 1050 Hours 400x

(c) 3500 Hours 400x

G6253-44A

Figure 44. Surface Topography Of Hexoloy SA Following Cyclic Oxidation Durability Exposures At 1204C (2200F): (a) 350 Hours; (b) 1050 Hours; (c) 3500 Hours.

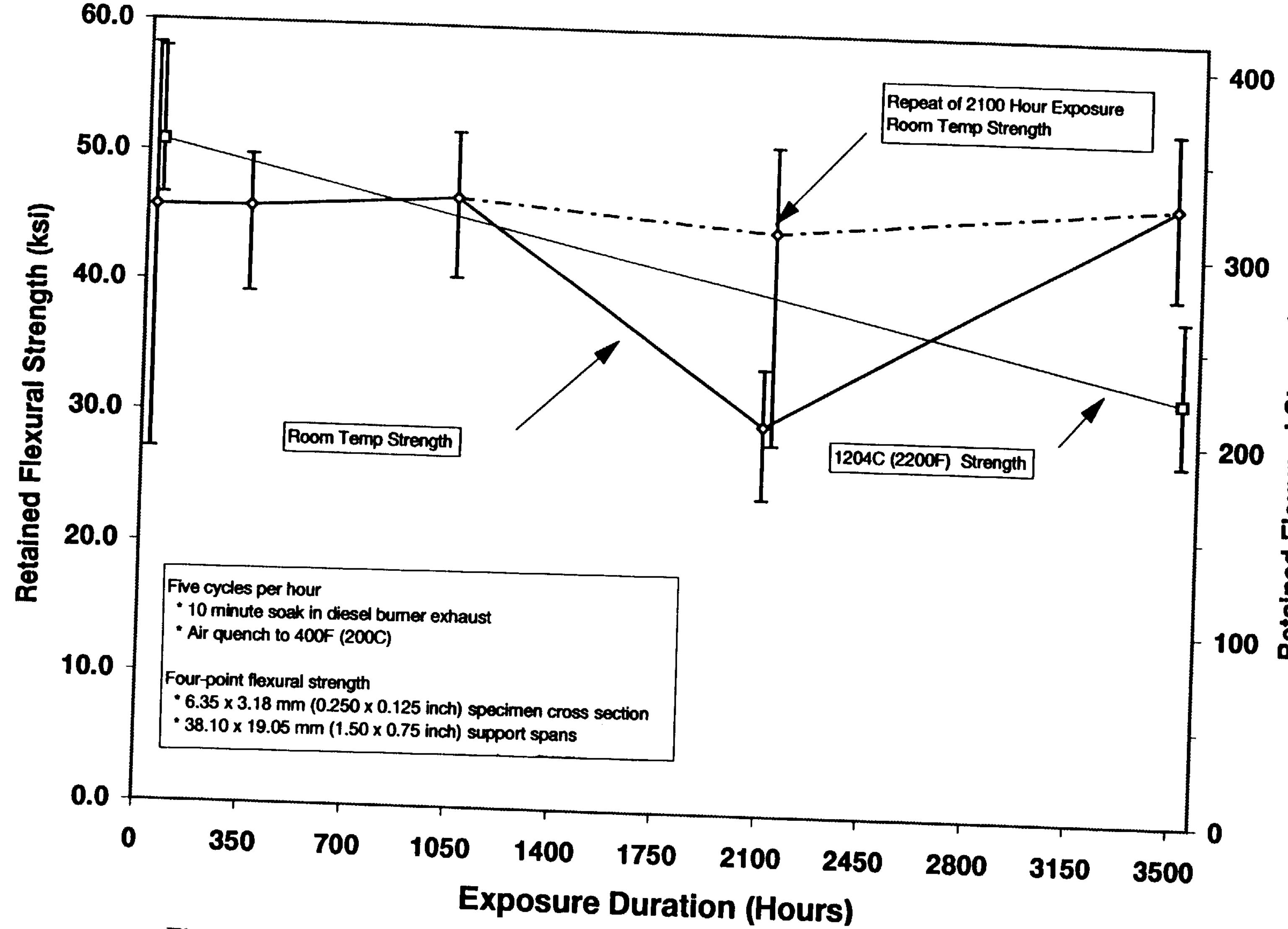
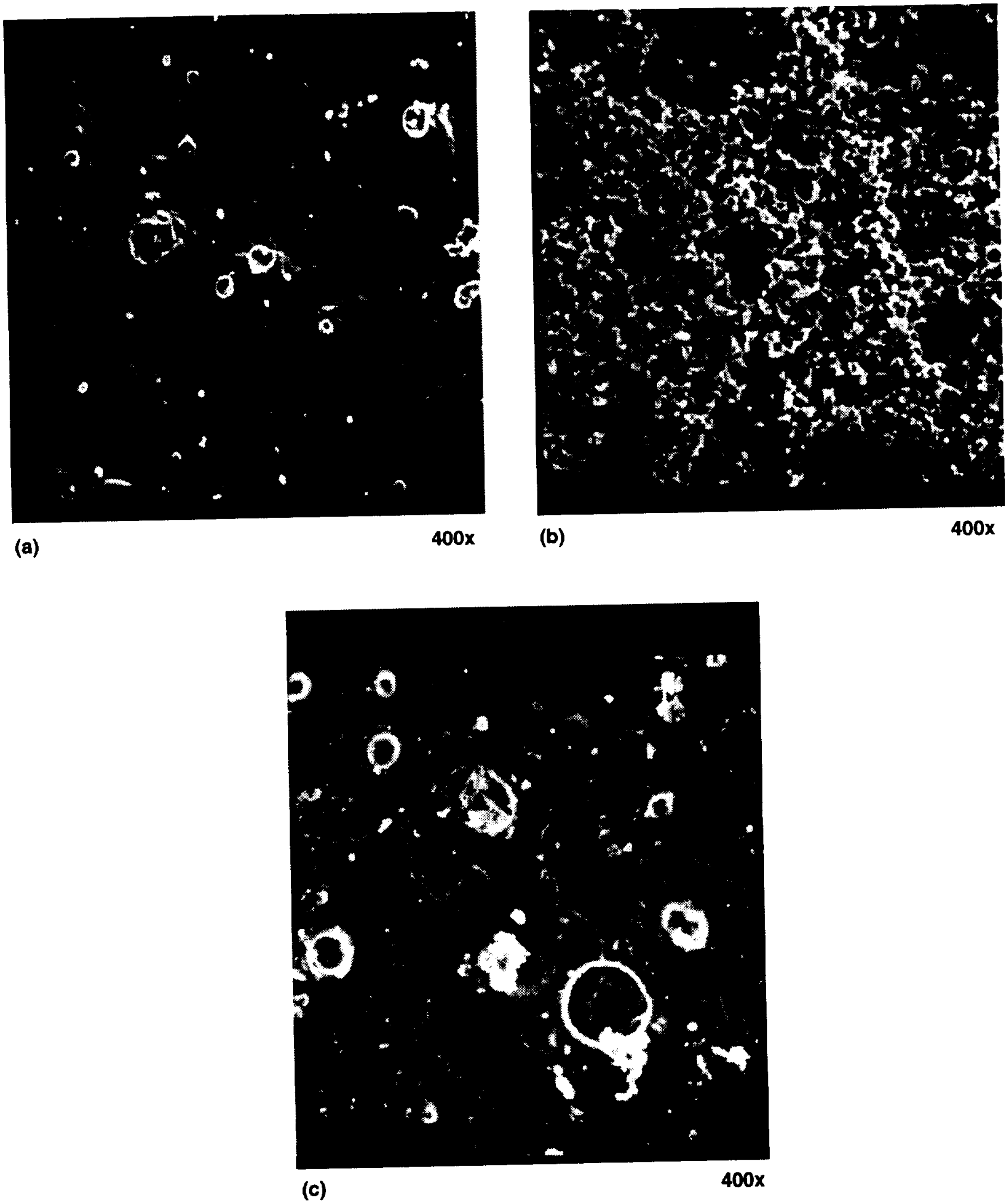
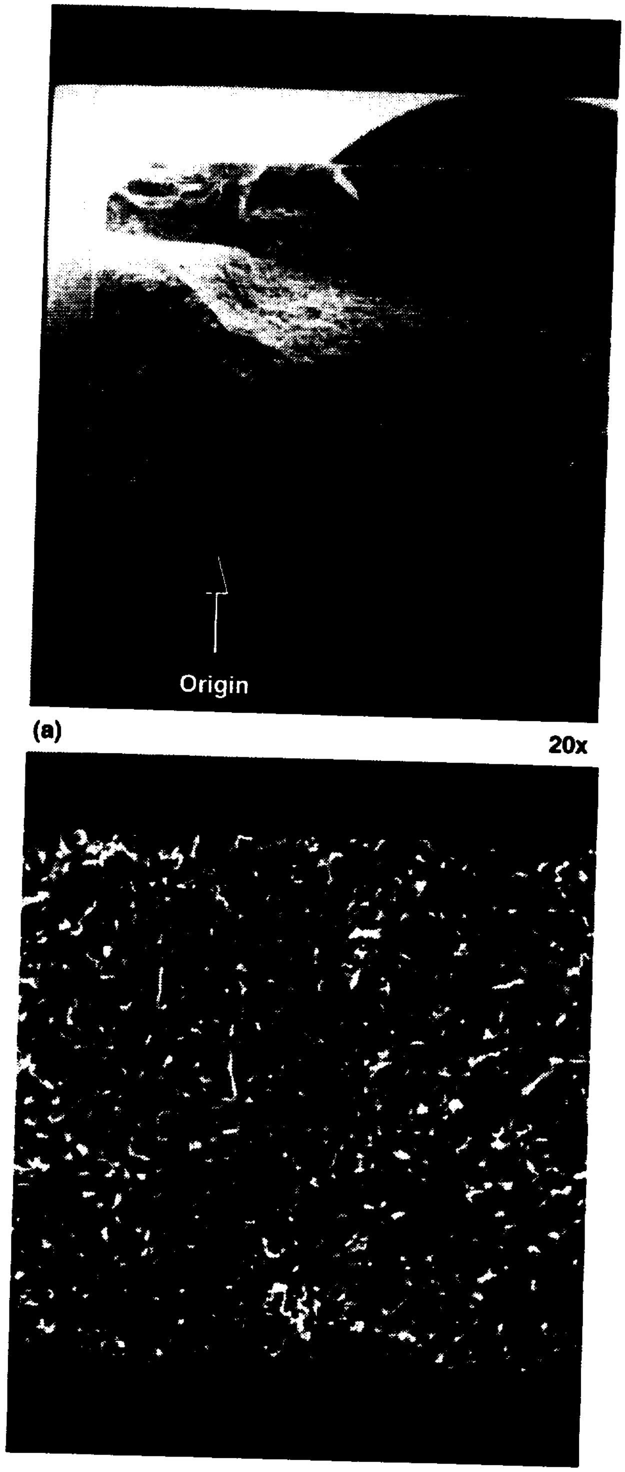


Figure 45. Hexoloy SA Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1371C (2500F) Cyclic Oxidation Durability Testing.



G6253-46

Figure 46. Surface Topography Of Hexoloy SA Following Cyclic Oxidation Durability Exposures At 1371C (2500F): (a) 1050 Hours; (b) 2100 Hours; (c) 3500 Hours.



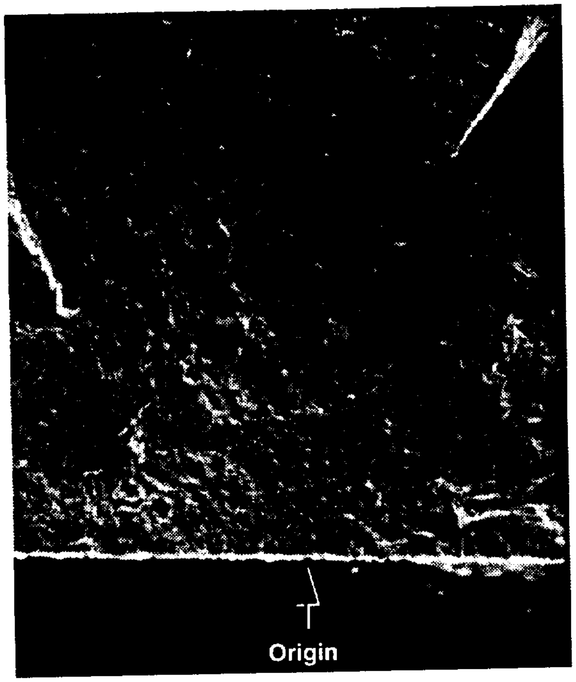
(a) 20x

(b) 400x

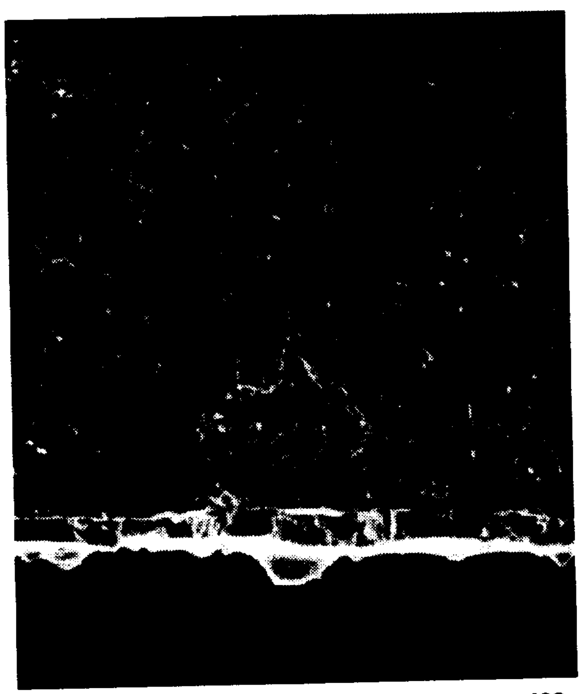
Surface Porosity Origin

G6253-47

Figure 47. Hexoloy SA Specimen Failure Originating From Surface Porosity Following 350 Hours Exposure At 1371C (2500F).



(a) 40x

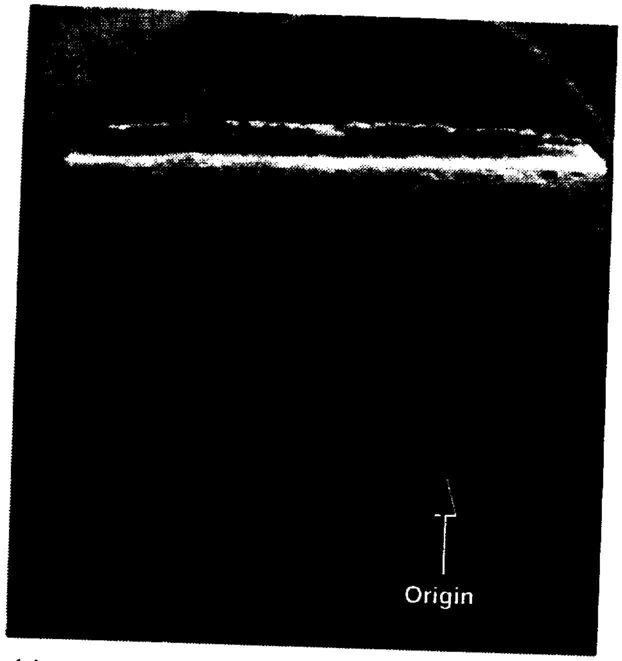


(b) 400x

Subsurface Porosity Origin

G6253-48

Figure 48. Hexoloy SA Specimen Failure Originating From Subsurface Porosity Following 3500 Hours Exposure At 1371C (2500F).



(a) 20x

(a) 400x

Surface Porosity Origin

G6253-49

Figure 49. Hexoloy SA Specimen Failure From Surface Pit, Exhibiting Substantial Material Loss Following 2100 Hours Exposure At 1371C (2500F).

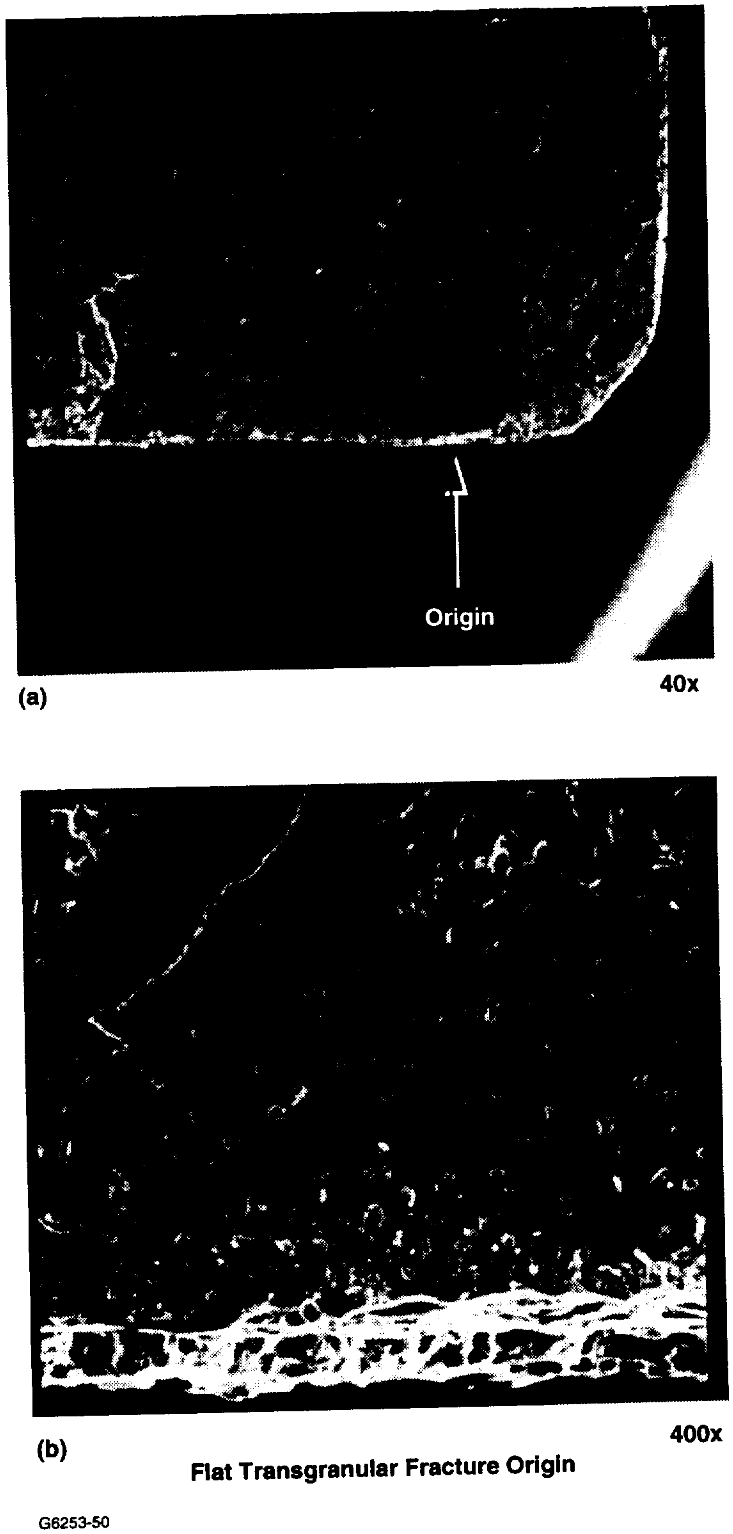
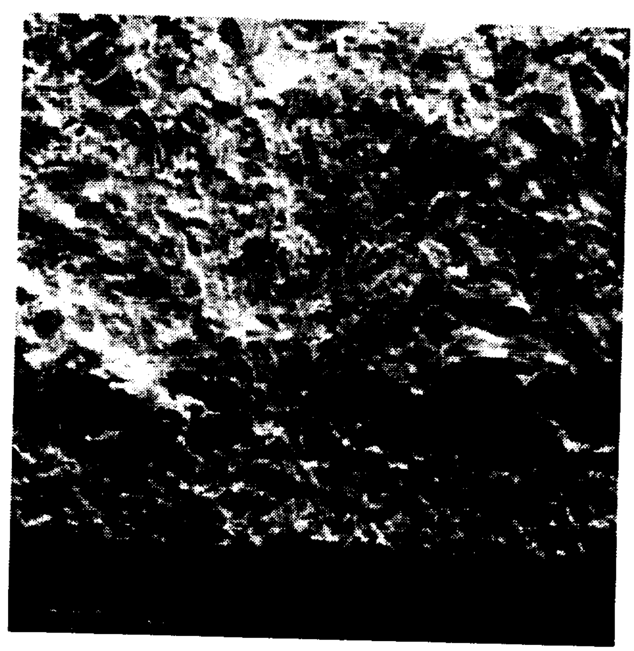


Figure 50. Hexoloy SA Specimen Flexure Tested At 1204C (2200F) Exhibiting Flat, Transgranular Fracture Following 2100 Hours Exposure At 1371C (2500F).

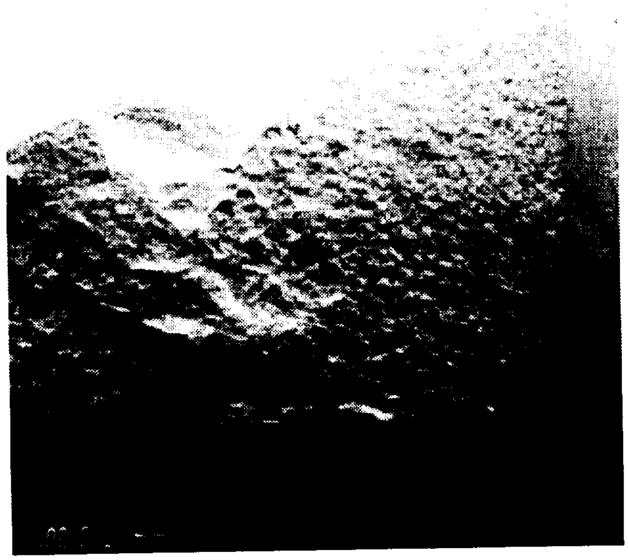
40x



400x

G6253-51

Figure 51. Hexoloy SA As-Processed Surface Baseline Test Specimen Failure Originating From Subsurface Porosity.



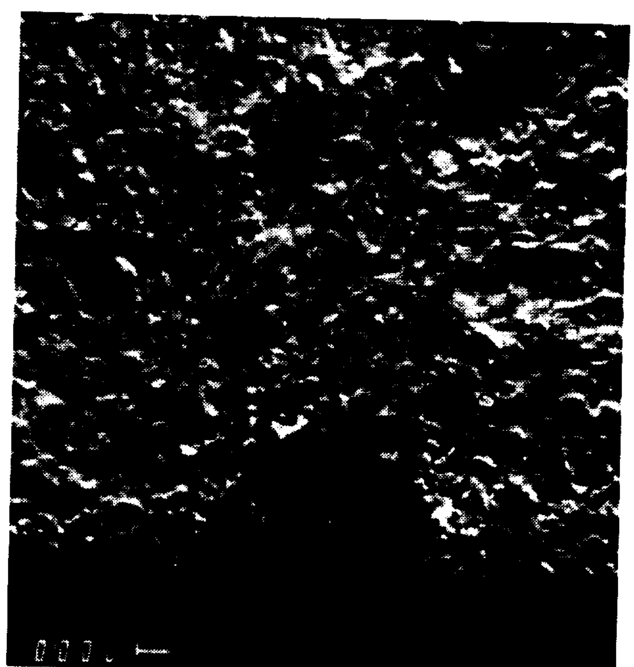
40x

400x

G6253-52

Figure 52. **Hexoloy SA As-Processed Surface Baseline Test Specimen Failure Originating From Porosity At Specimen Chamfer.**

40x



400x

G6253-53

Figure 53. Hexoloy SA As-Processed Surface Baseline Test Specimen Failure Originating From Surface-Connected Pore.

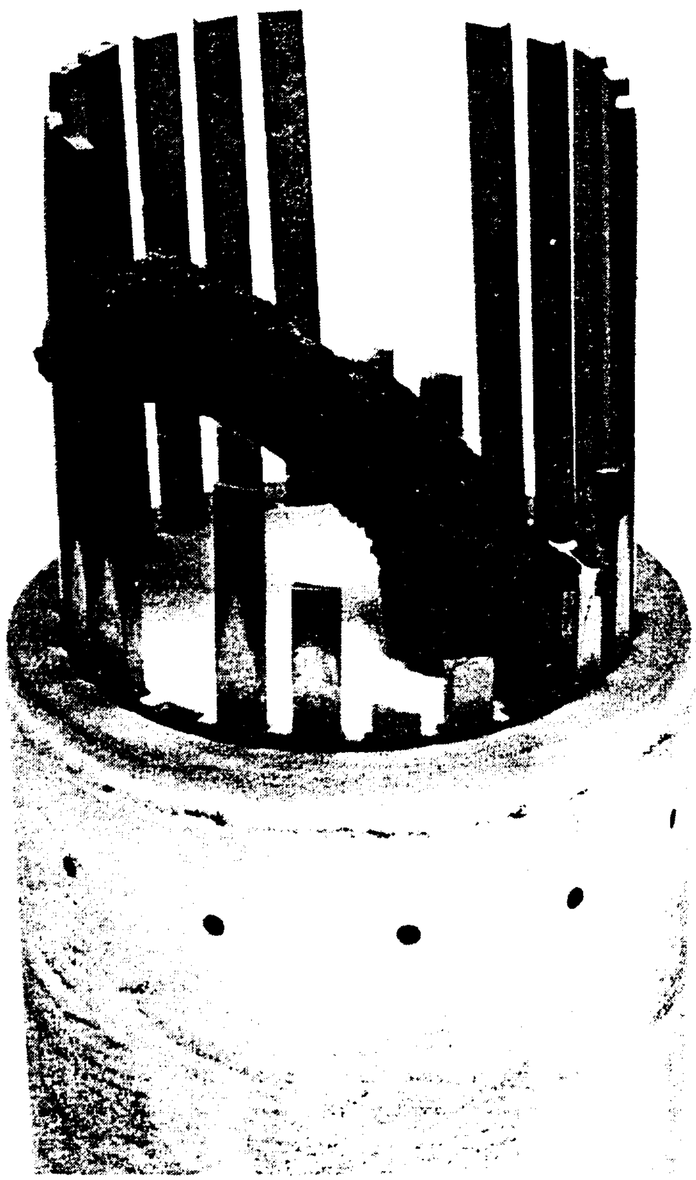


Figure 54. Hexoloy SA Test Specimens Damaged By Piece Of Combustor Carbon.

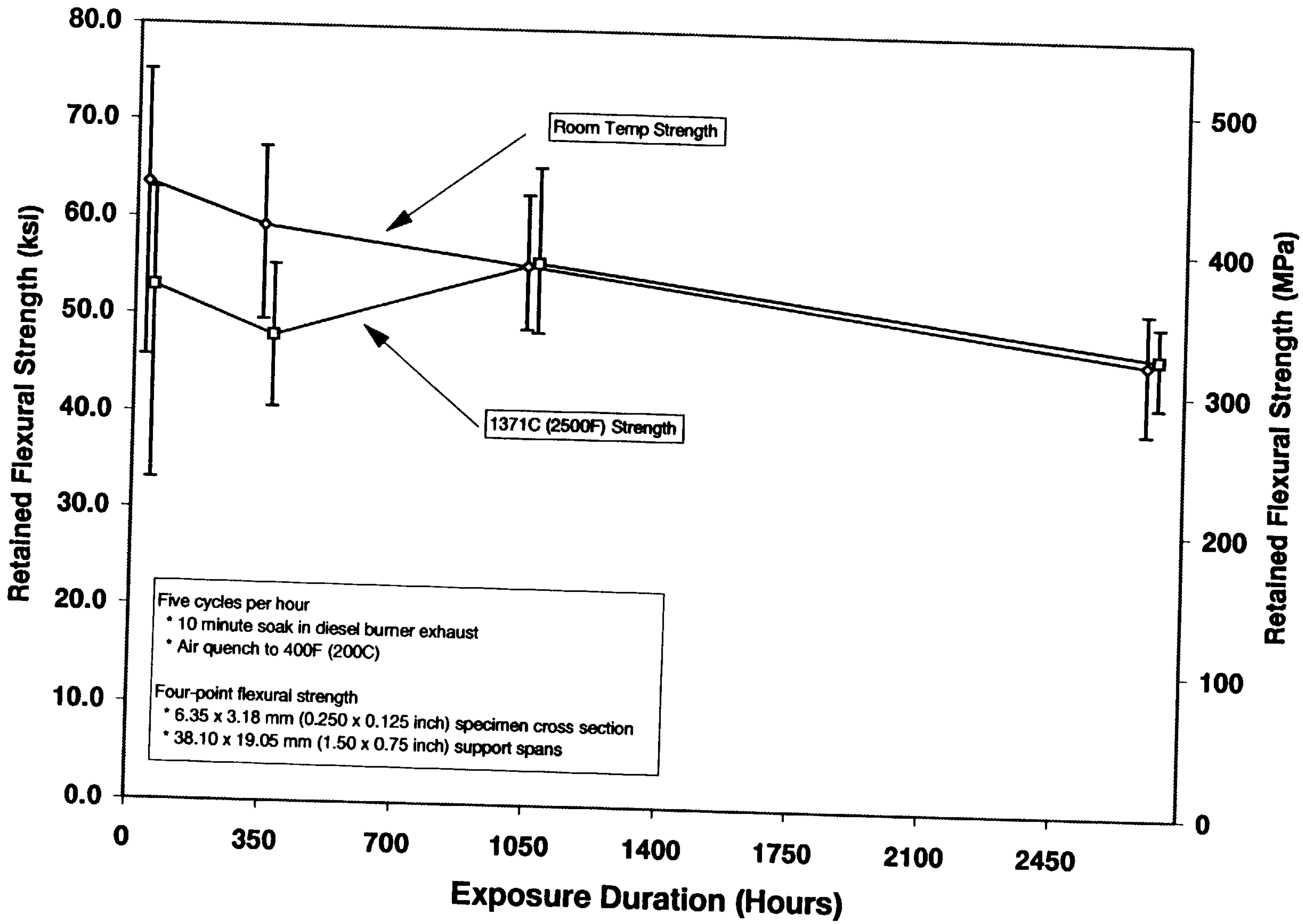


Figure 55. Injection-Molded Hexoloy SA Post-Exposure Room-Temperature And 1371C (2500F) Strength Test Results Following 1371C (2500F) Cyclic Oxidation Durability Testing.

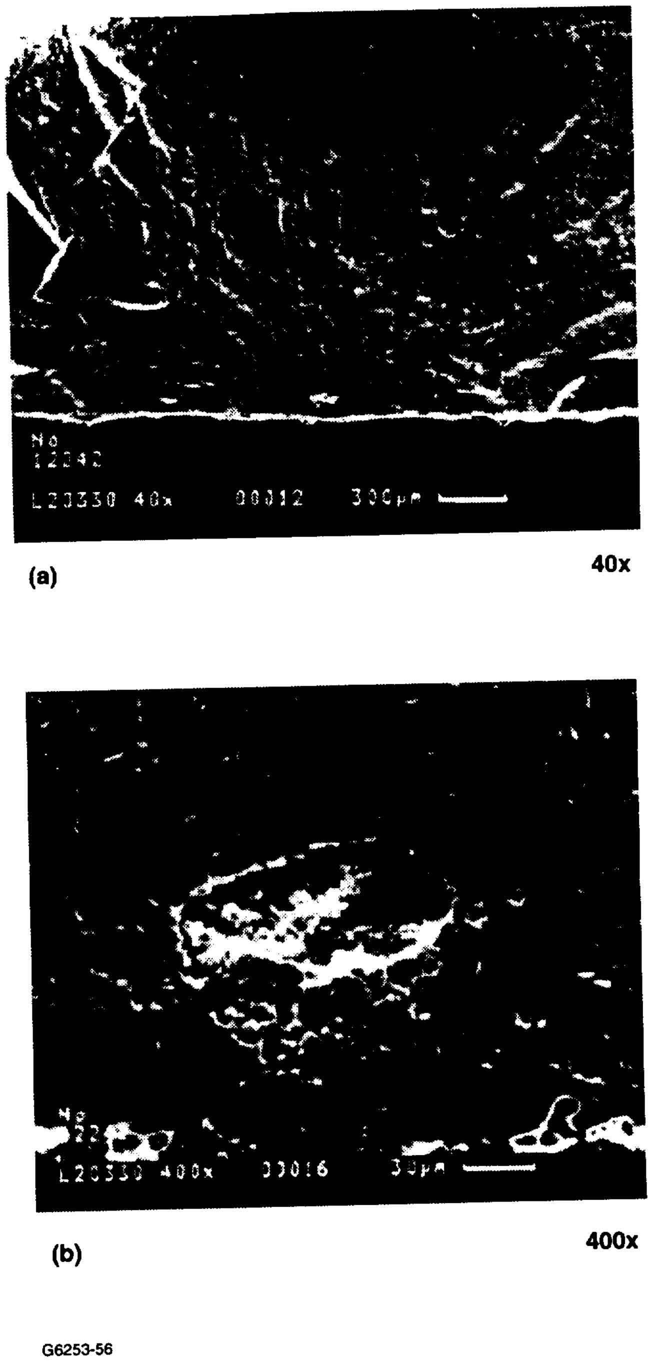
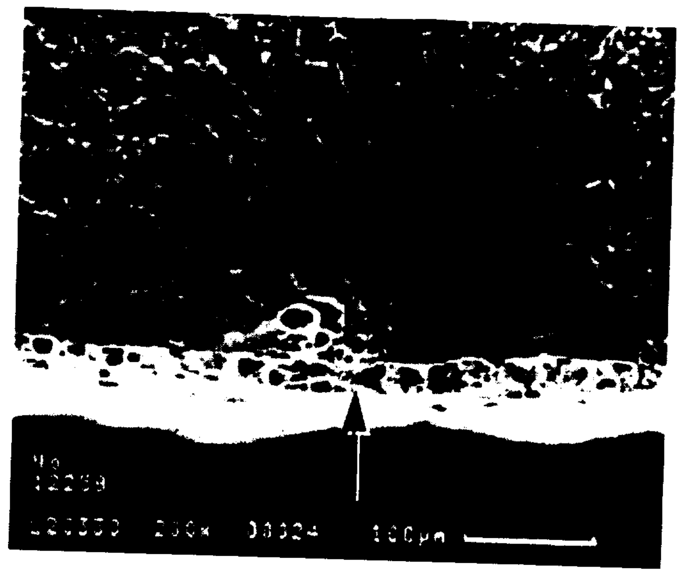
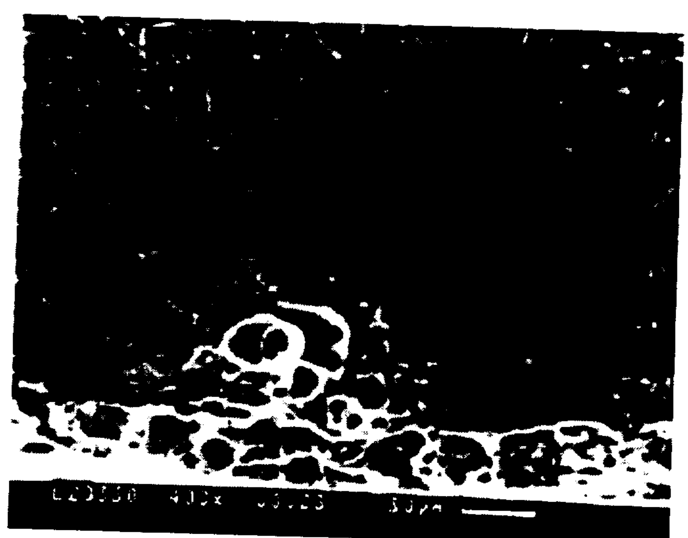


Figure 56. Hexoloy SA Specimen Failure Originating From Pre-Existing Subsurface Pore Following 1050 Hours Exposure At 1371C (2500F).



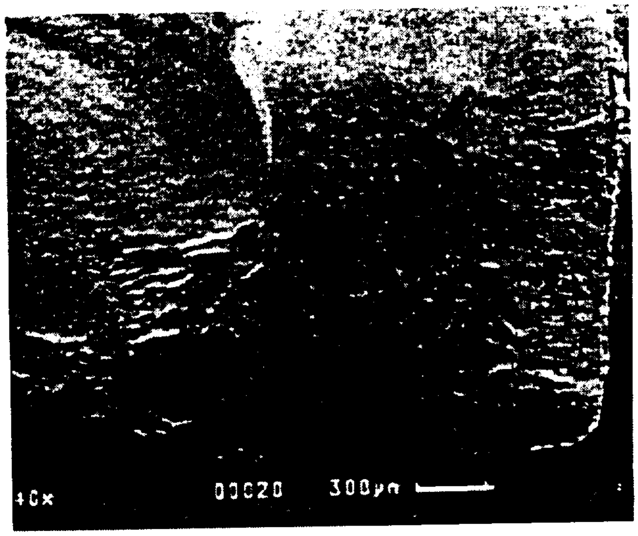
(a) 200x



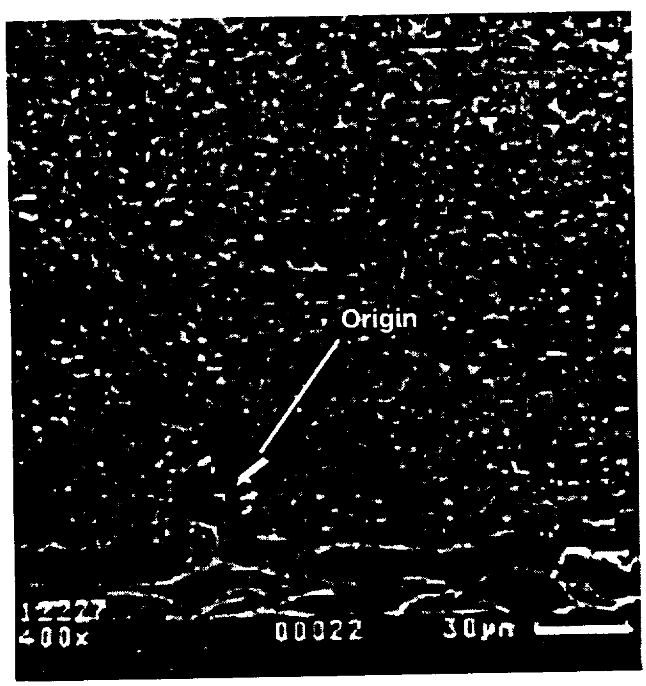
(b) 400x

G6253-57A

Figure 57. Hexoloy SA Specimen Failure Originating From Oxidation Pit And Adjacent Region Of Porosity Following 1050 Hours Exposure At 1371C (2500F).



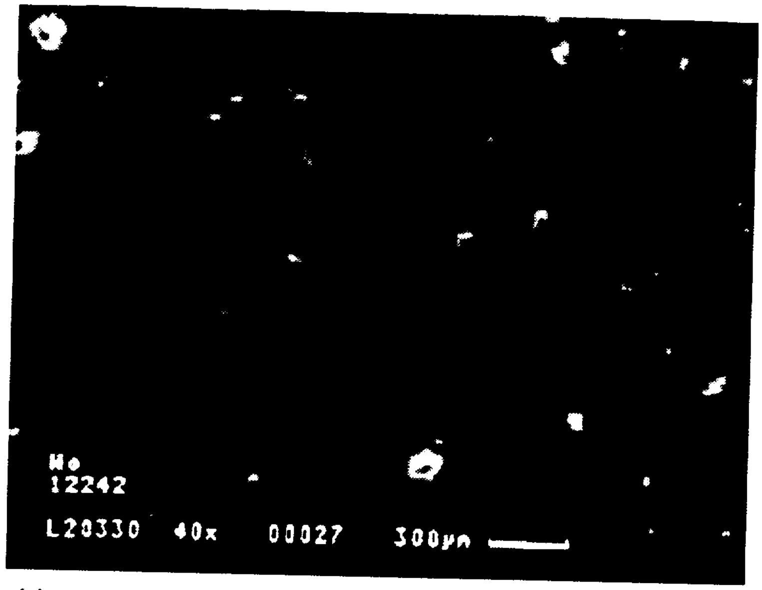
(a) 40x



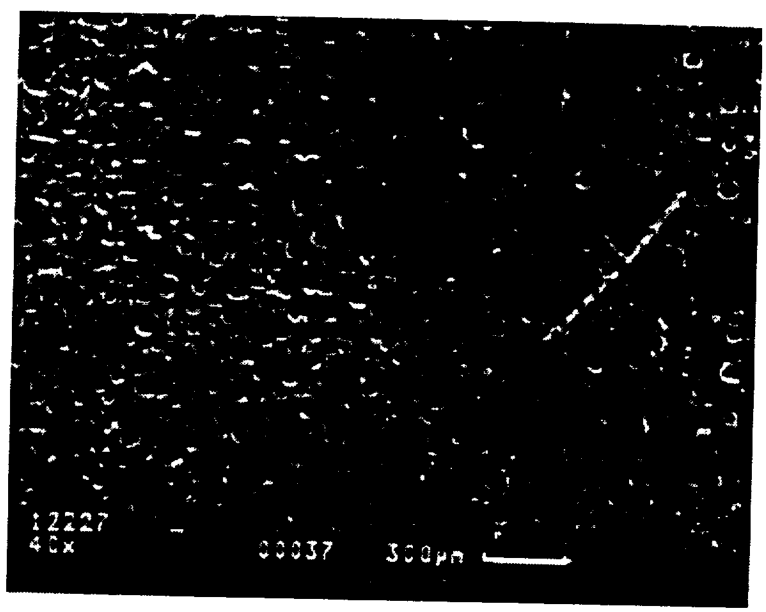
(b) 400x

G6253-58A

Figure 58. Hexoloy SA Specimen Failure Originating From Surface-Connected Pore Beneath Surface Oxide Layer Following 2700 Hours Exposure At 1371C (2500F).



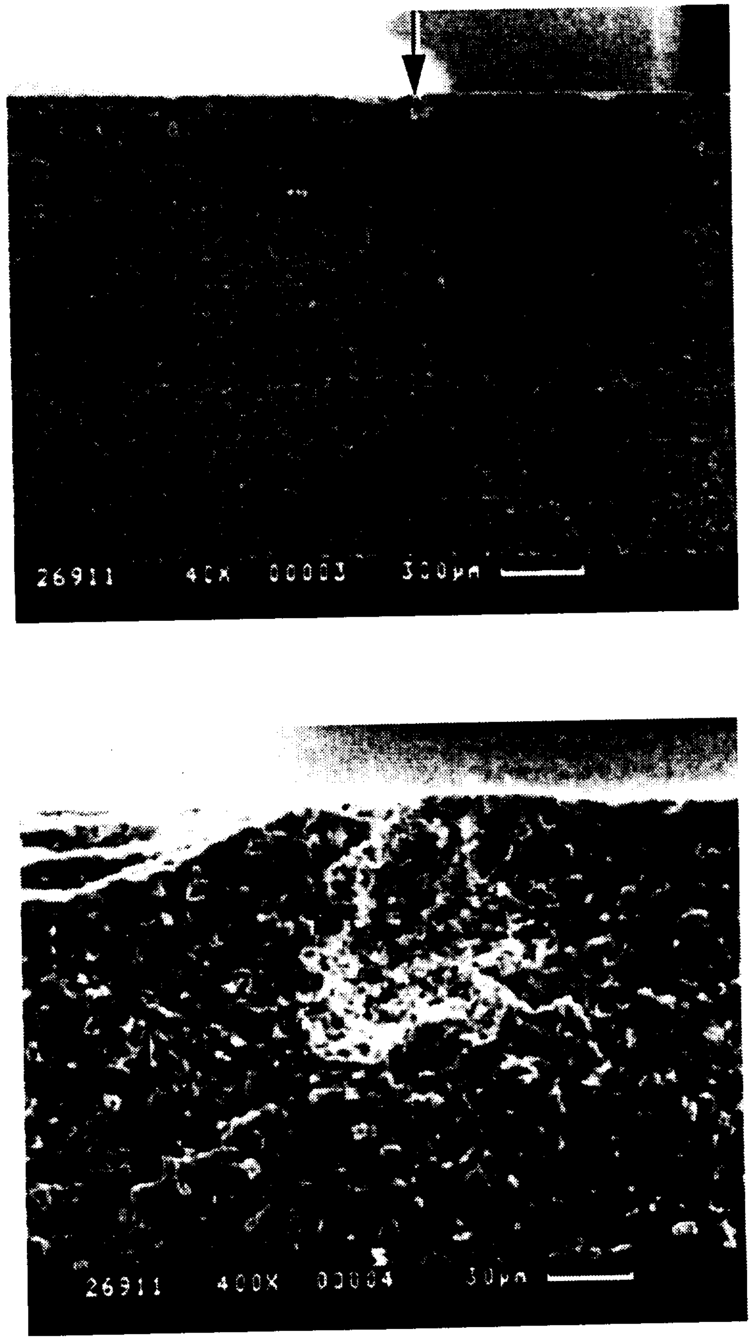
(a) **1050 Hours**



(b) **2700 Hours**

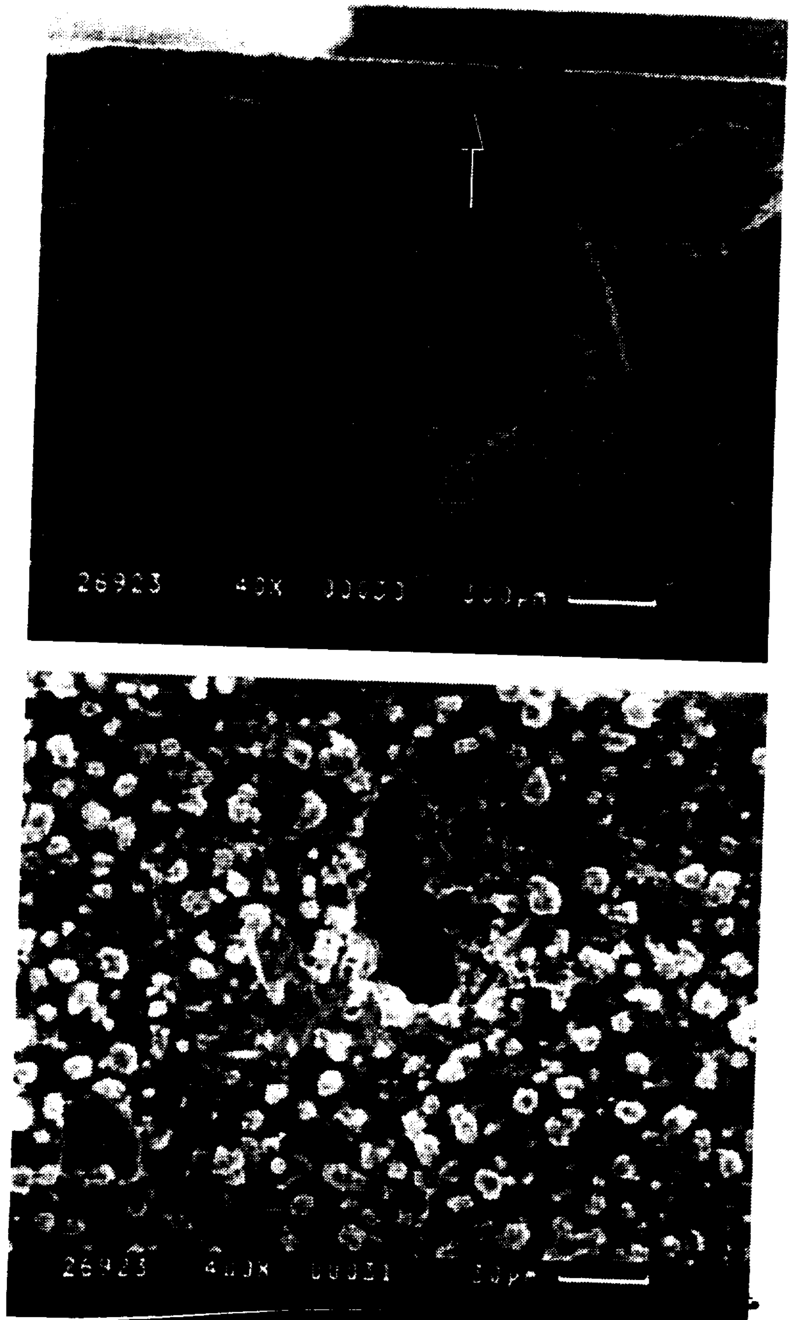
G6253-59

Figure 59. Surface Topography Of Hexoloy SA Following Cyclic Oxidation Durability Exposures At 1371C (2500F): (a) 1050 Hours; (b) 2700 Hours.



G6253-60

Figure 60. Hexoloy ST Room-Temperature Baseline Test Specimen Failure Originating From Subsurface Pore.



G6253-61

Figure 61. Hexoloy ST 1204C (2200F) Baseline Test Specimen Failure Originating From Subsurface Pore.

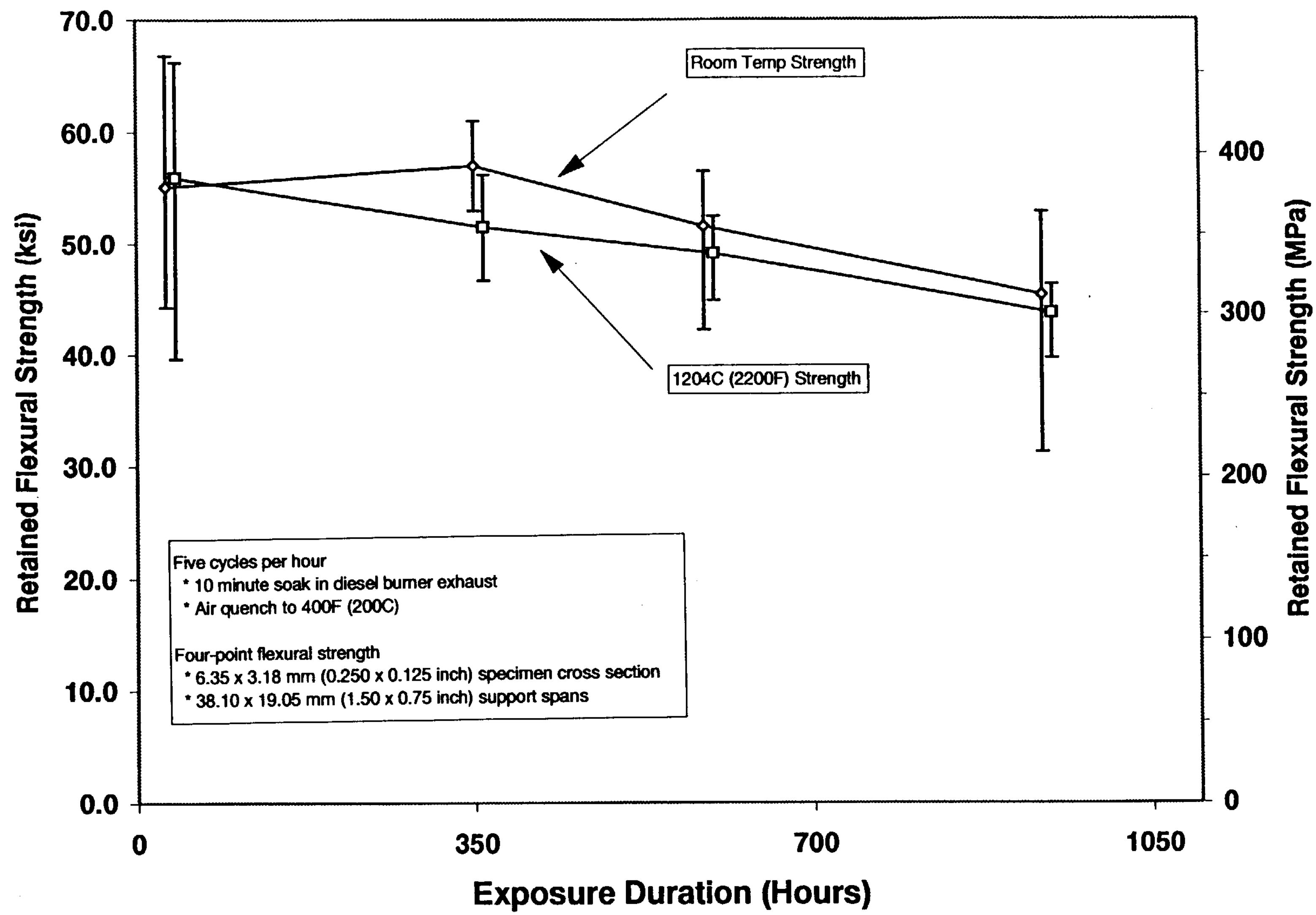
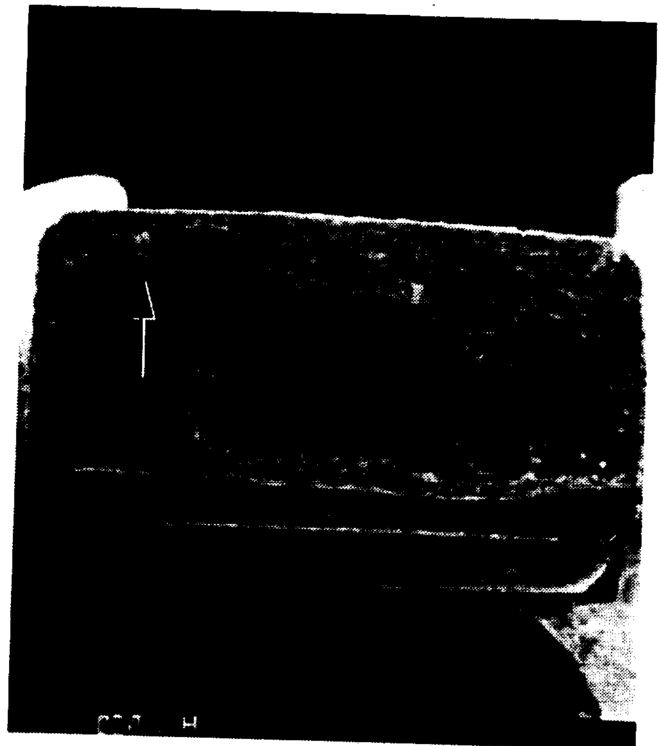
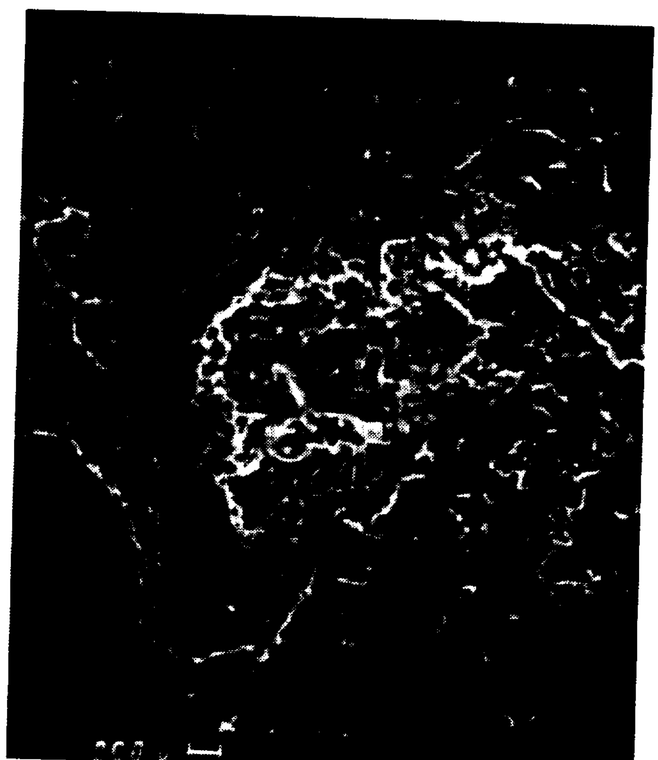


Figure 62. Hexoloy ST Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.



10x

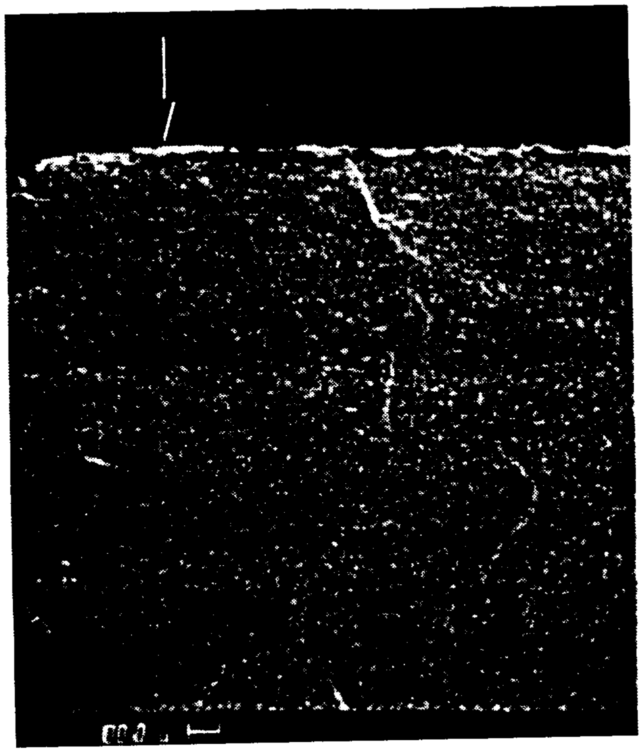


400x

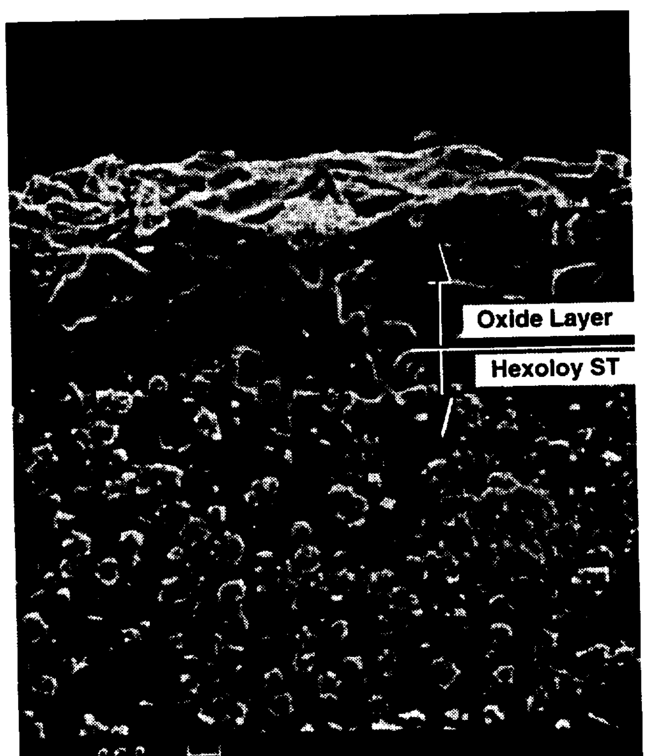
G6253-63

106230-4

Figure 63. Hexoloy ST Specimen Failure Originating From Internal Pore Following 350 Hours Exposure At 1204C (2200F).



40x



400x

106230-5

G6253-64

Figure 64. Hexoloy ST Specimen Failure Originating From Surface At Thick Oxide Layer Following 587 Hours Exposure At 1204C (2200F).

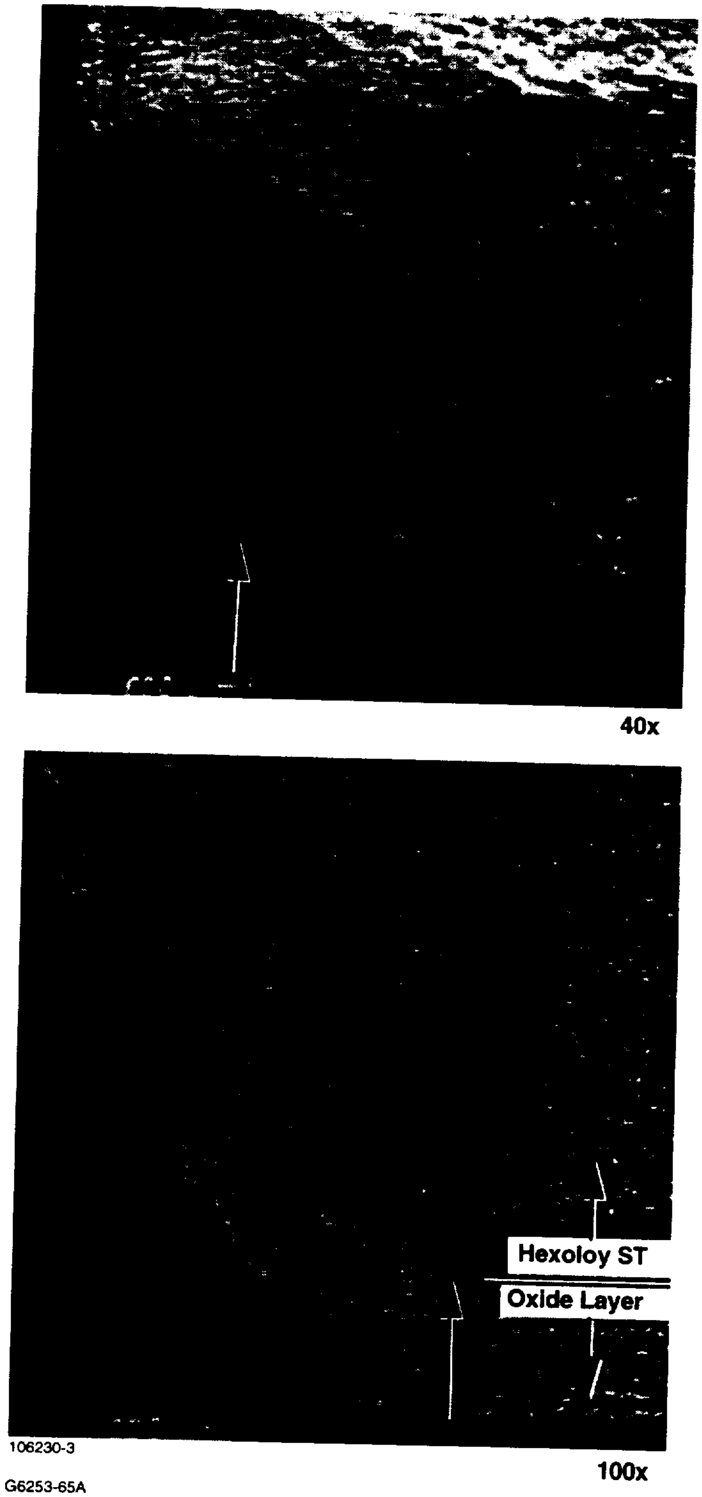
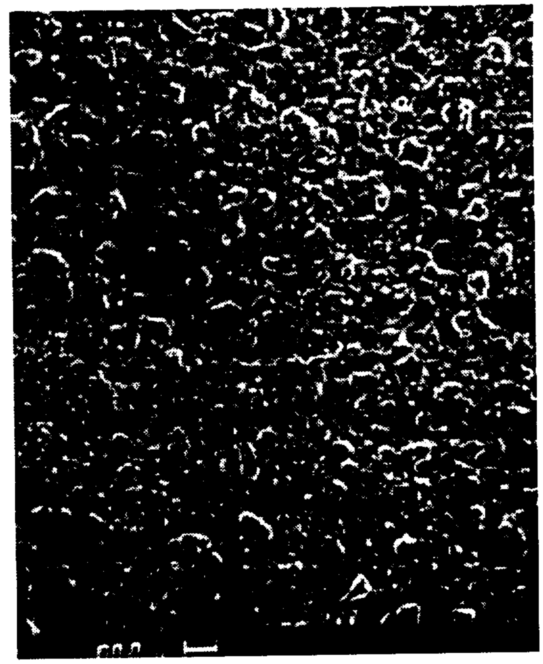
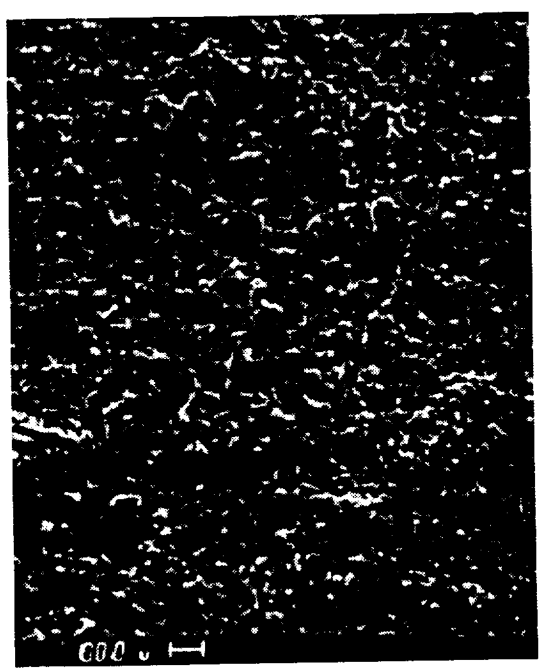


Figure 65. Hexoloy ST Specimen Failure Originating From Chamfer At Thick Oxide Layer Following 937 Hours Exposure At 1204C (2200F).

40x (a) 350-Hour Exposure



40x (b) 587-Hour Exposure



40x (c) 937-Hour Exposure 106230-8

G6253-66

Figure 66. Surface Topography Of Hexoloy ST Following Cyclic Oxidation Durability Exposures At 1204C (2200F): (a) 350 Hours; (b) 587 Hours; (c) 937 Hours.

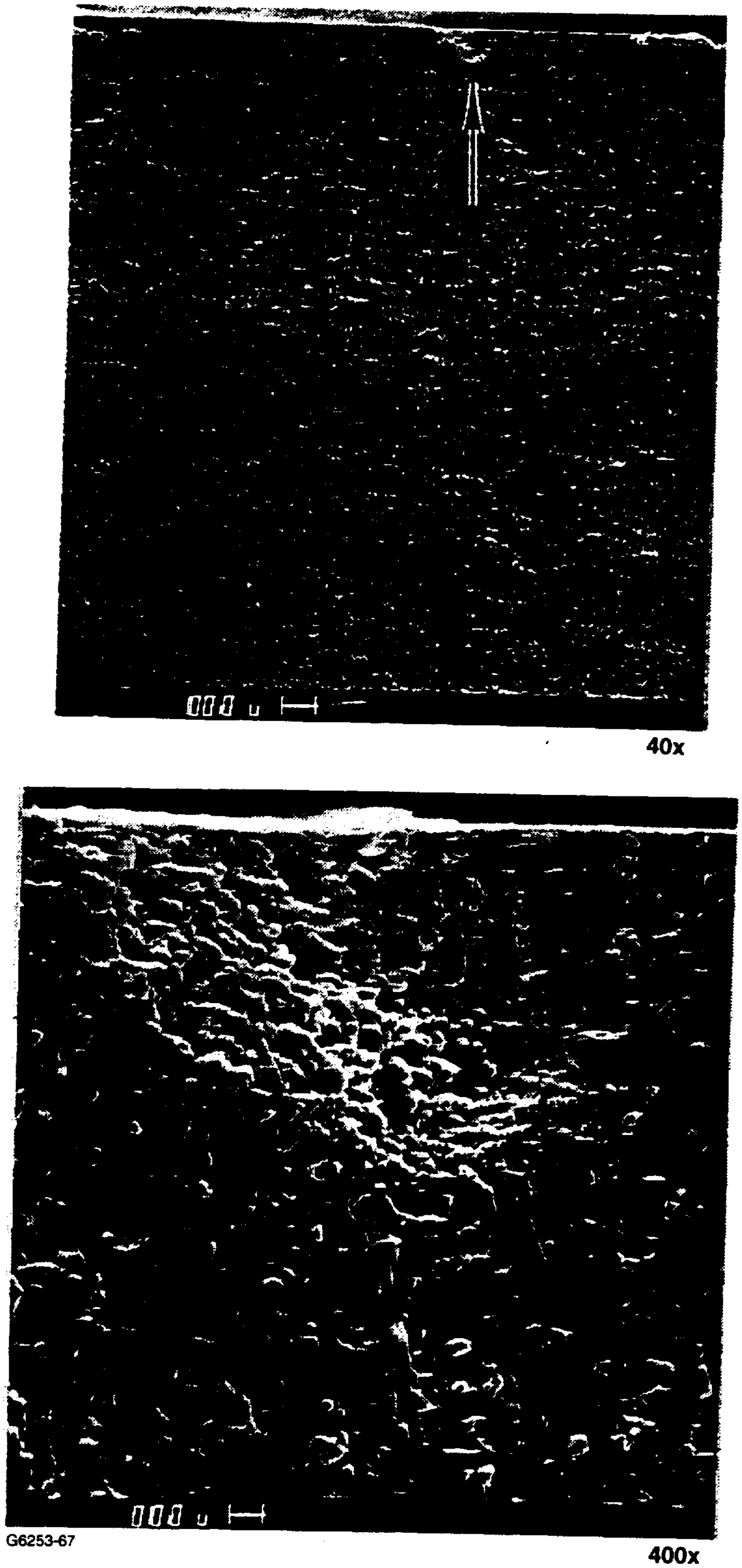


Figure 67. Hexoloy ST Room-Temperature Baseline Test Specimen Failure Originating From Surface-Connected Pore.

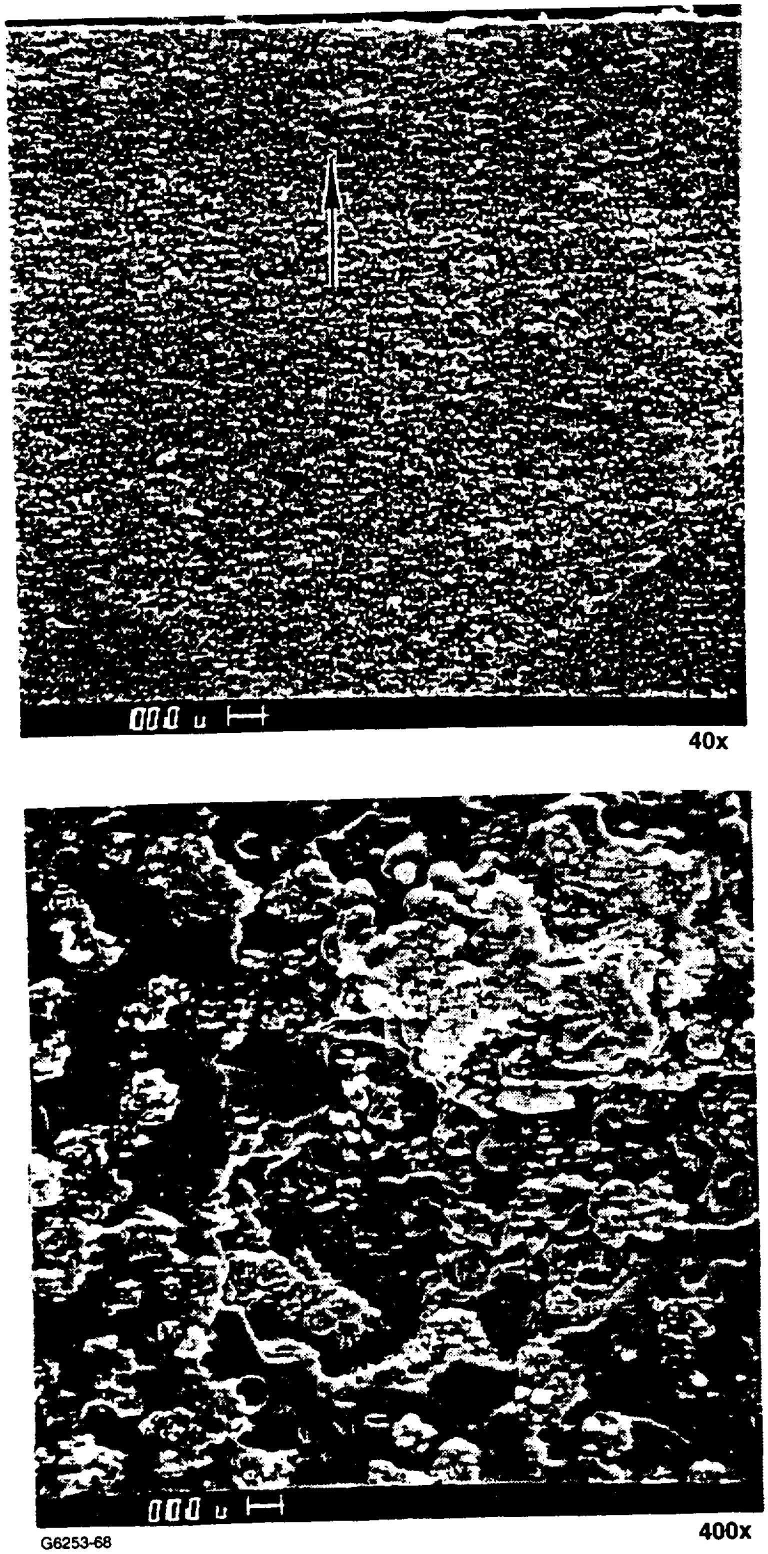


Figure 68. Hexoloy ST 1260C (2300F) Baseline Test Specimen Failure Originating From Internal Pore.

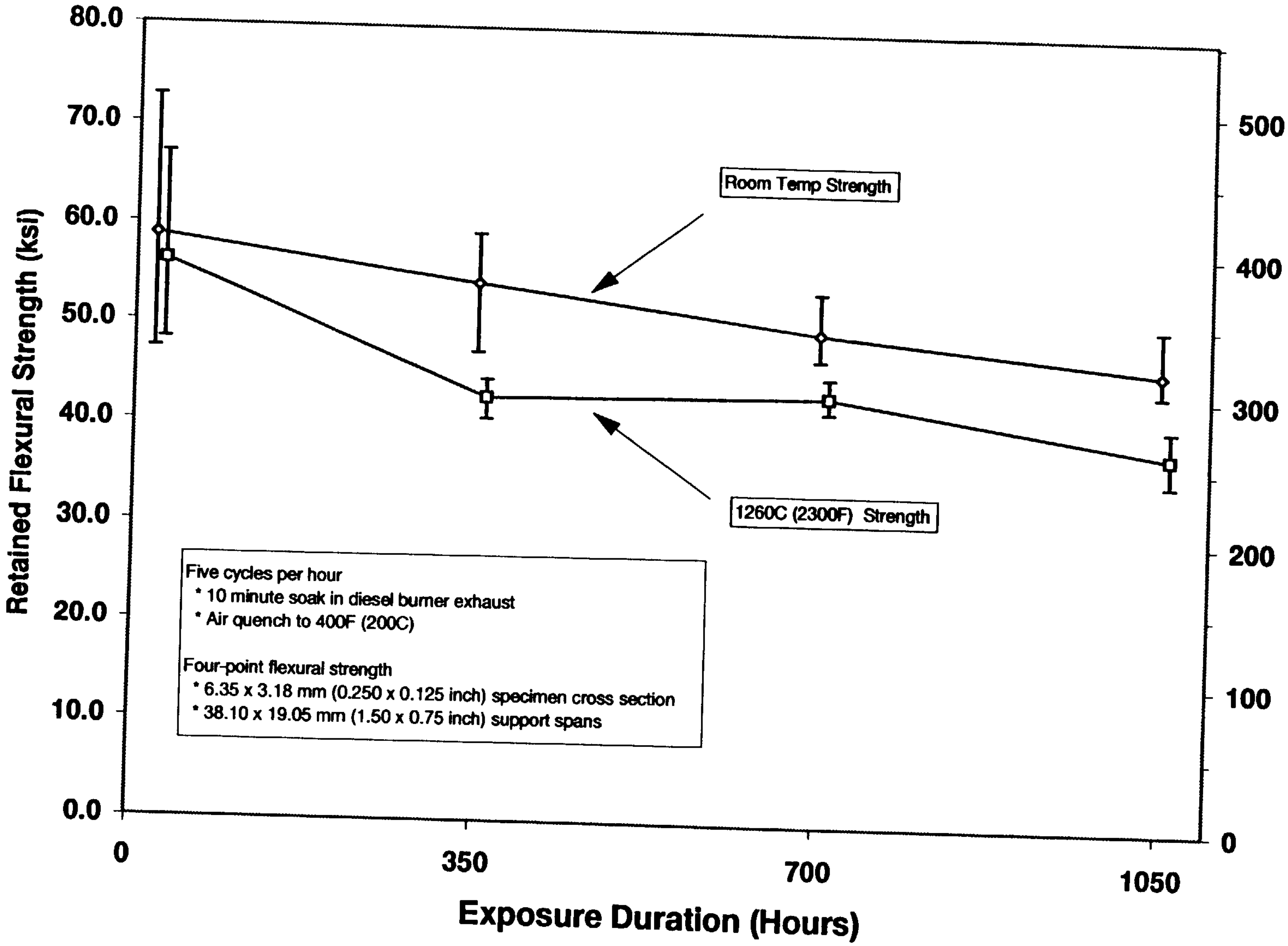
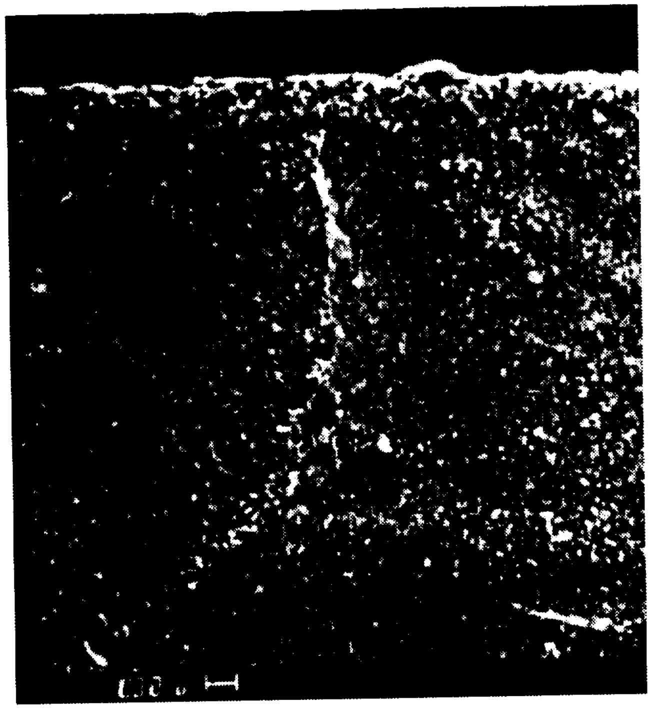
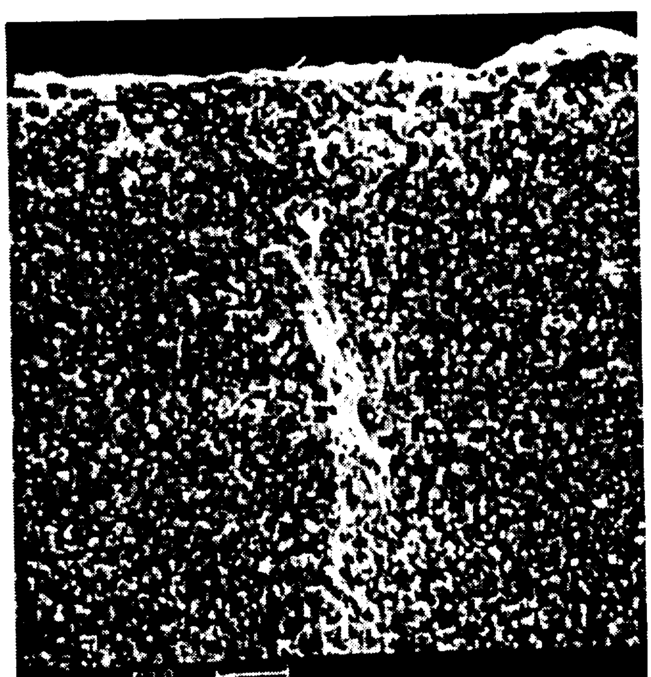


Figure 69. Hexoloy ST Post-Exposure Room-Temperature And 1260C (2300F) Strength Test Results Following 1260C (2300F) Cyclic Oxidation Durability Testing.



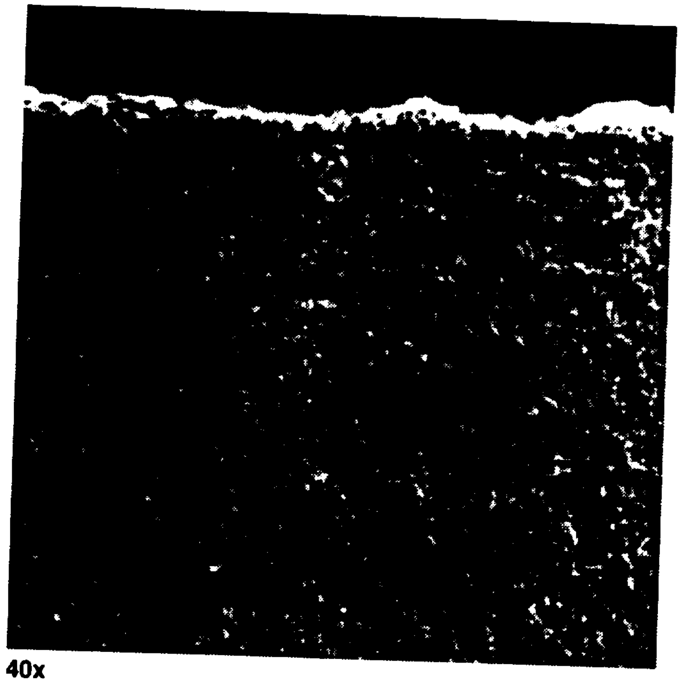
40x



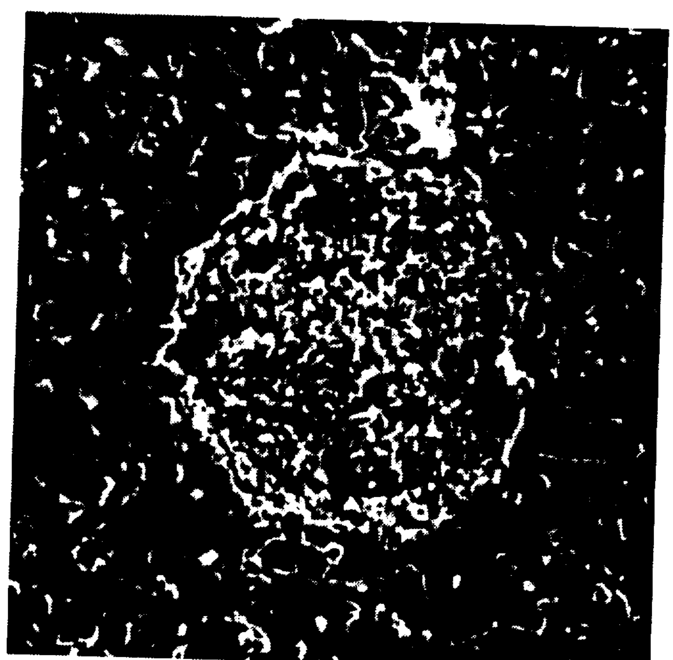
100x

G6253-70

Figure 70. Hexoloy ST Specimen Failure Originating From Rough Oxide Layer Following 350 Hours Exposure At 1260C (2300F).



40x



400x

G6253-71

Figure 71. Hexoloy ST Specimen Failure Originating From Internal Pore Following 1050 Hours Exposure At 1260C (2300F).

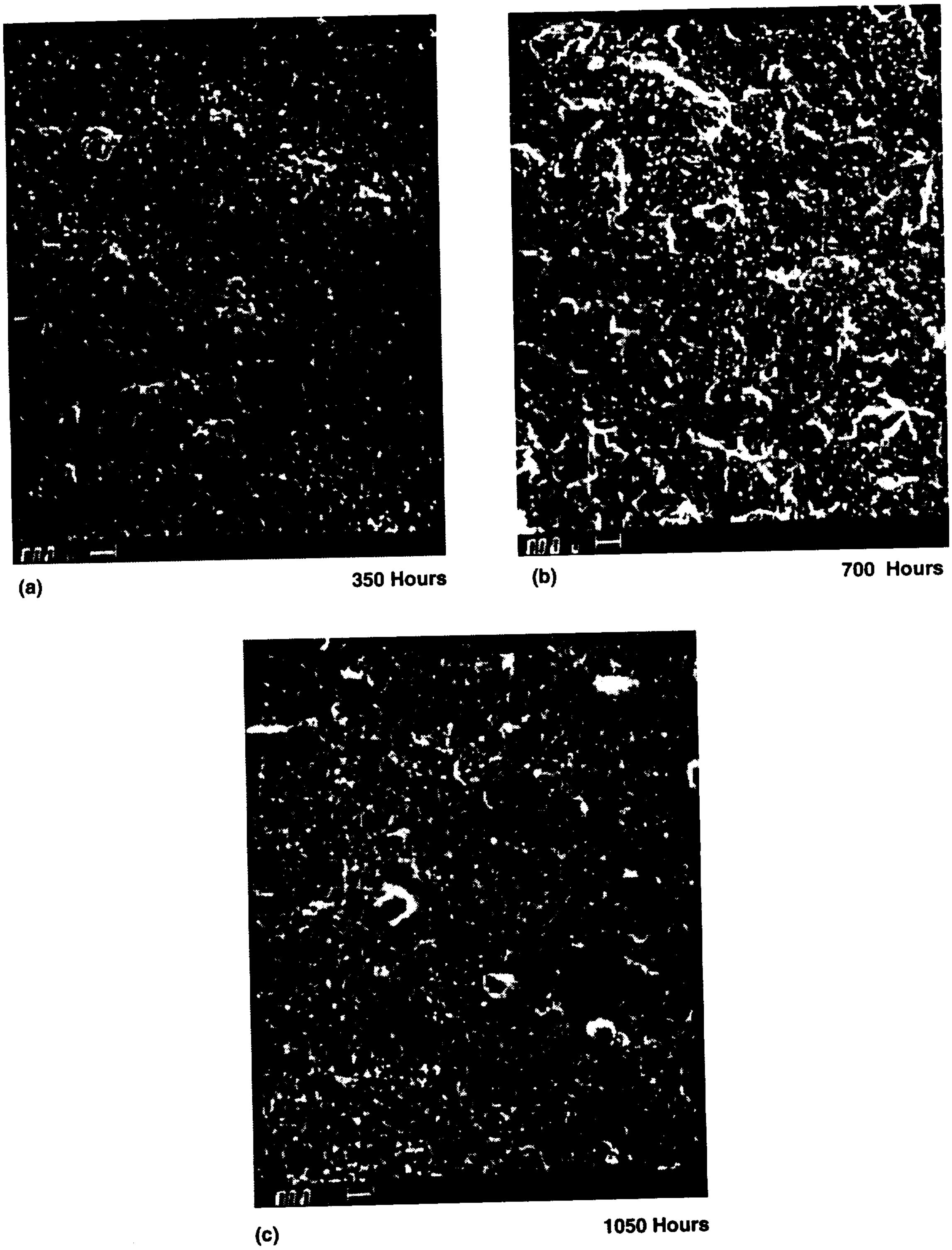


Figure 72. Hexoloy ST Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1260C (2300F): (a) 350 Hours; (b) 700 Hours; (c) 1050 Hours.

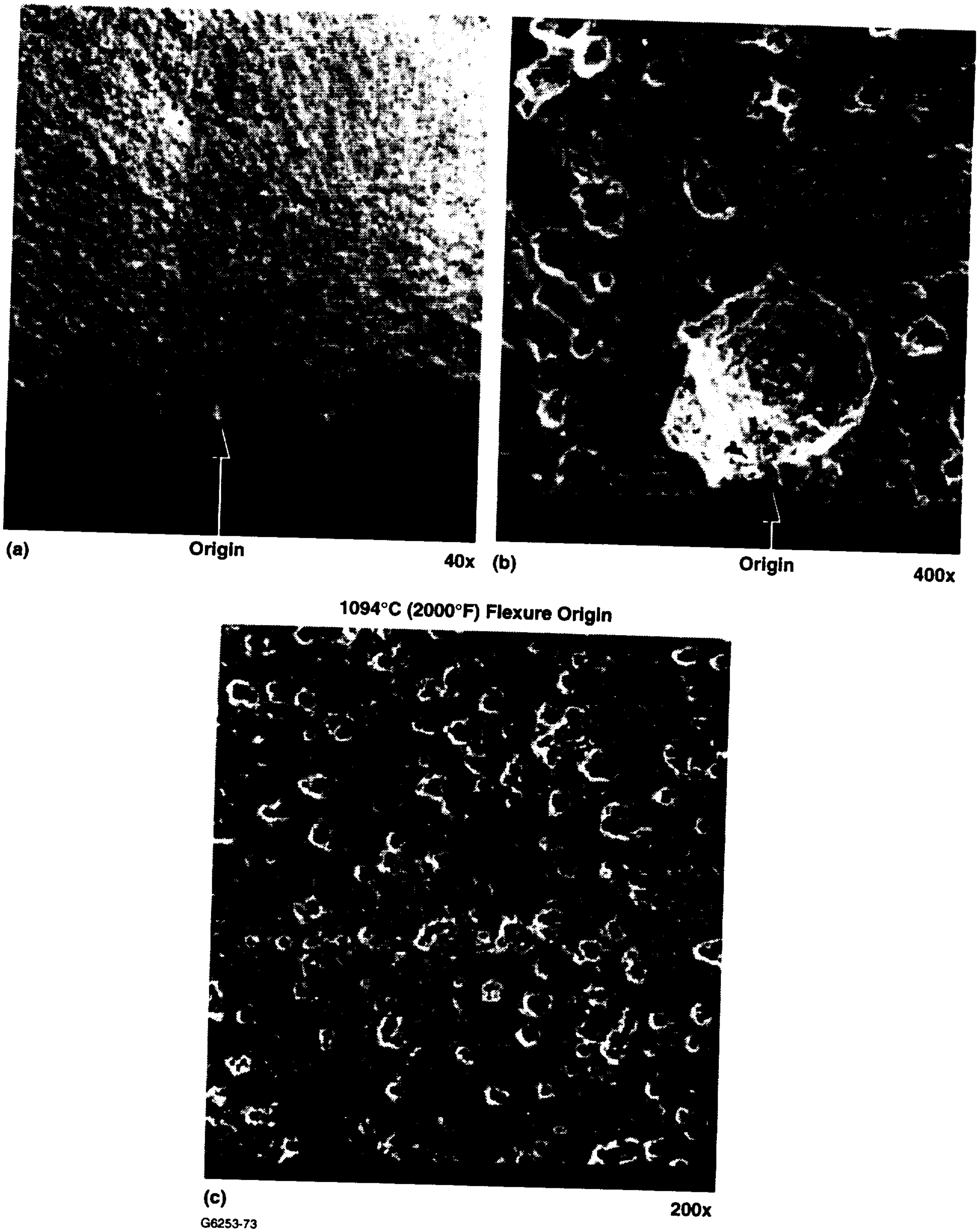


Figure 73. Typical Corning Code 9458 LAS Baseline Test Specimen Failure Originating From Pore (a) 40X Magnification; (b) 400X Magnification; and (c) From Surface Topography (200X Magnification).

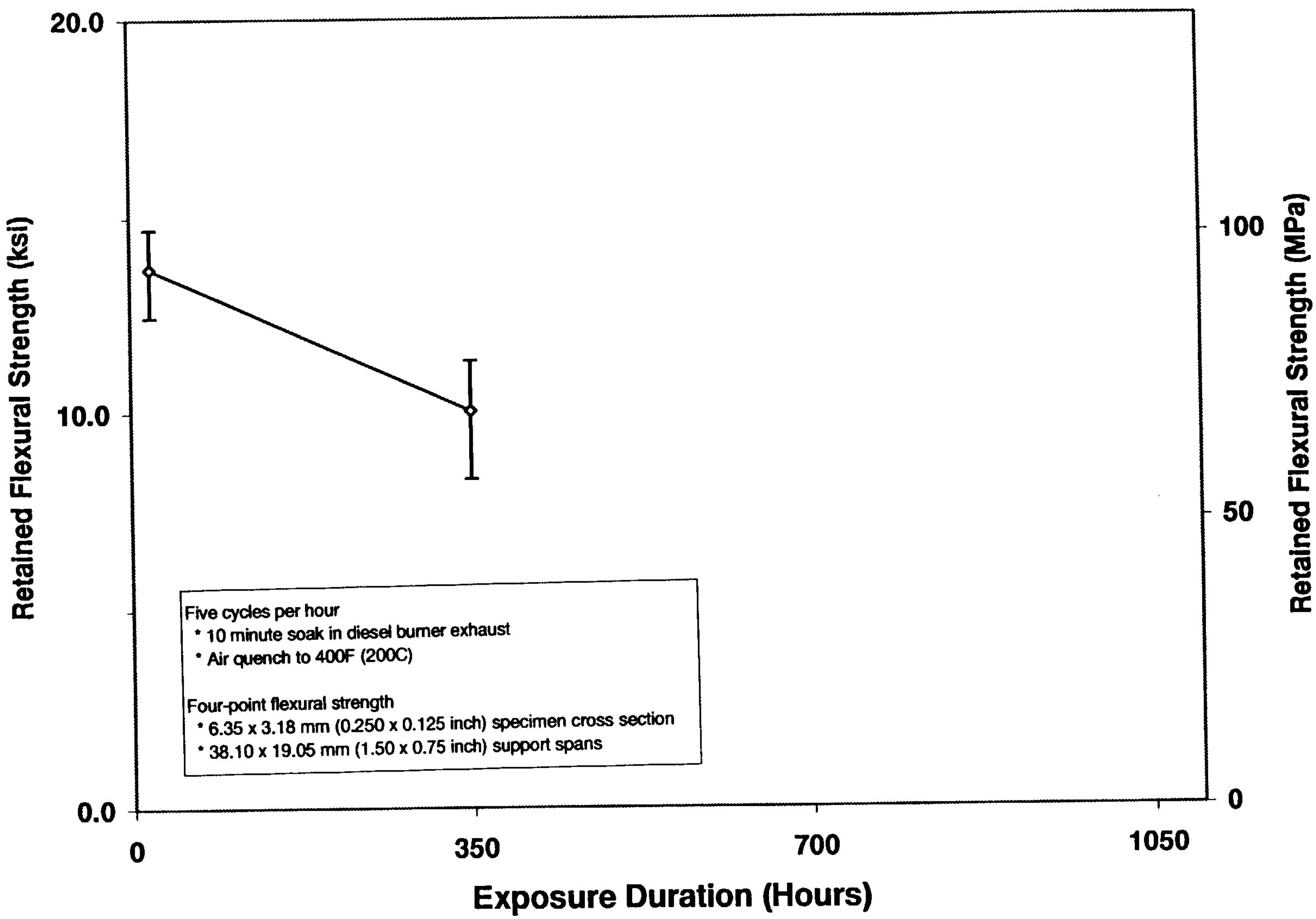


Figure 74. Corning Code 9458 LAS Post-Exposure Room-Temperature Strength Test Results Following 1093C (2000F) Cyclic Oxidation Durability Testing.

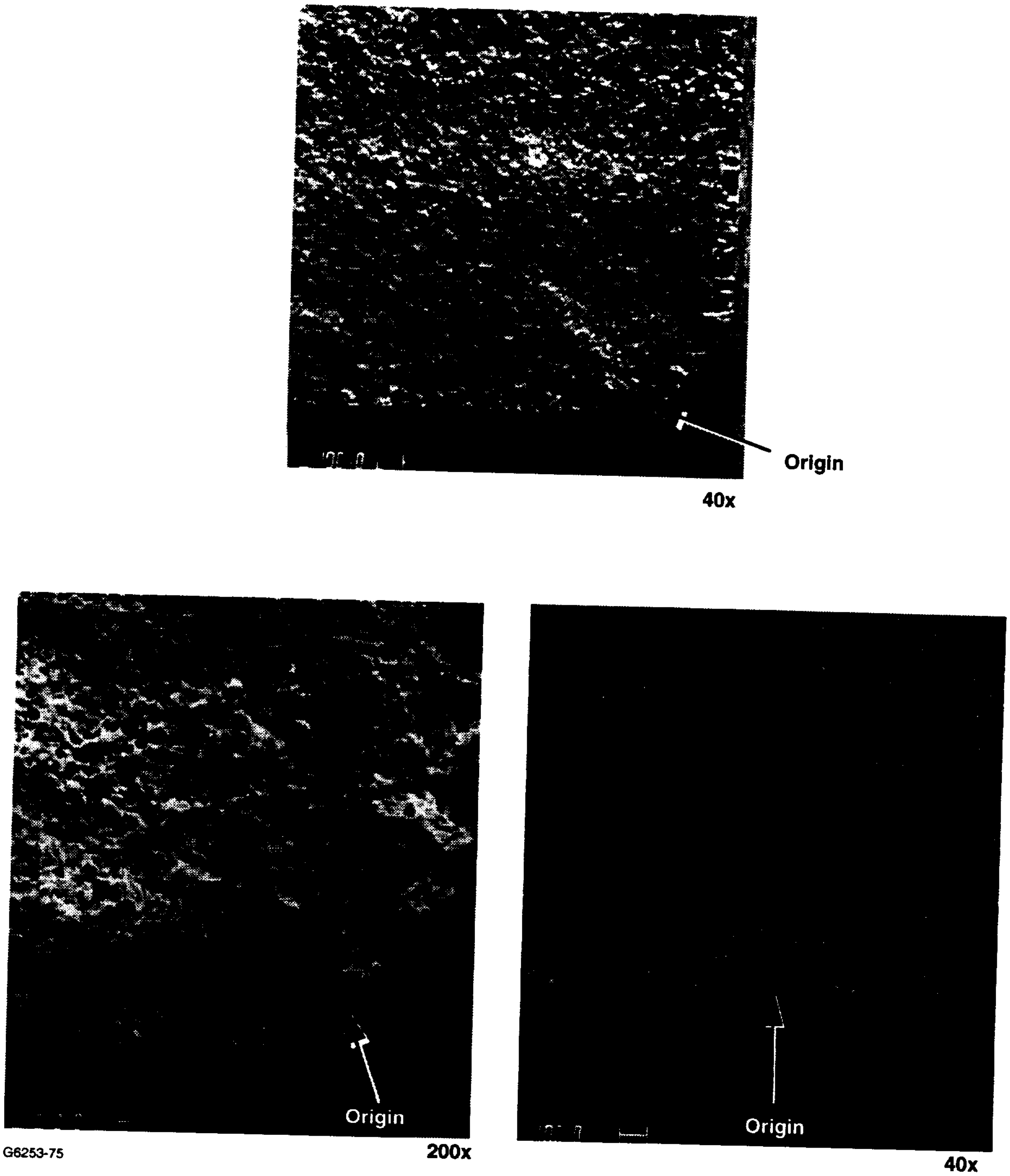
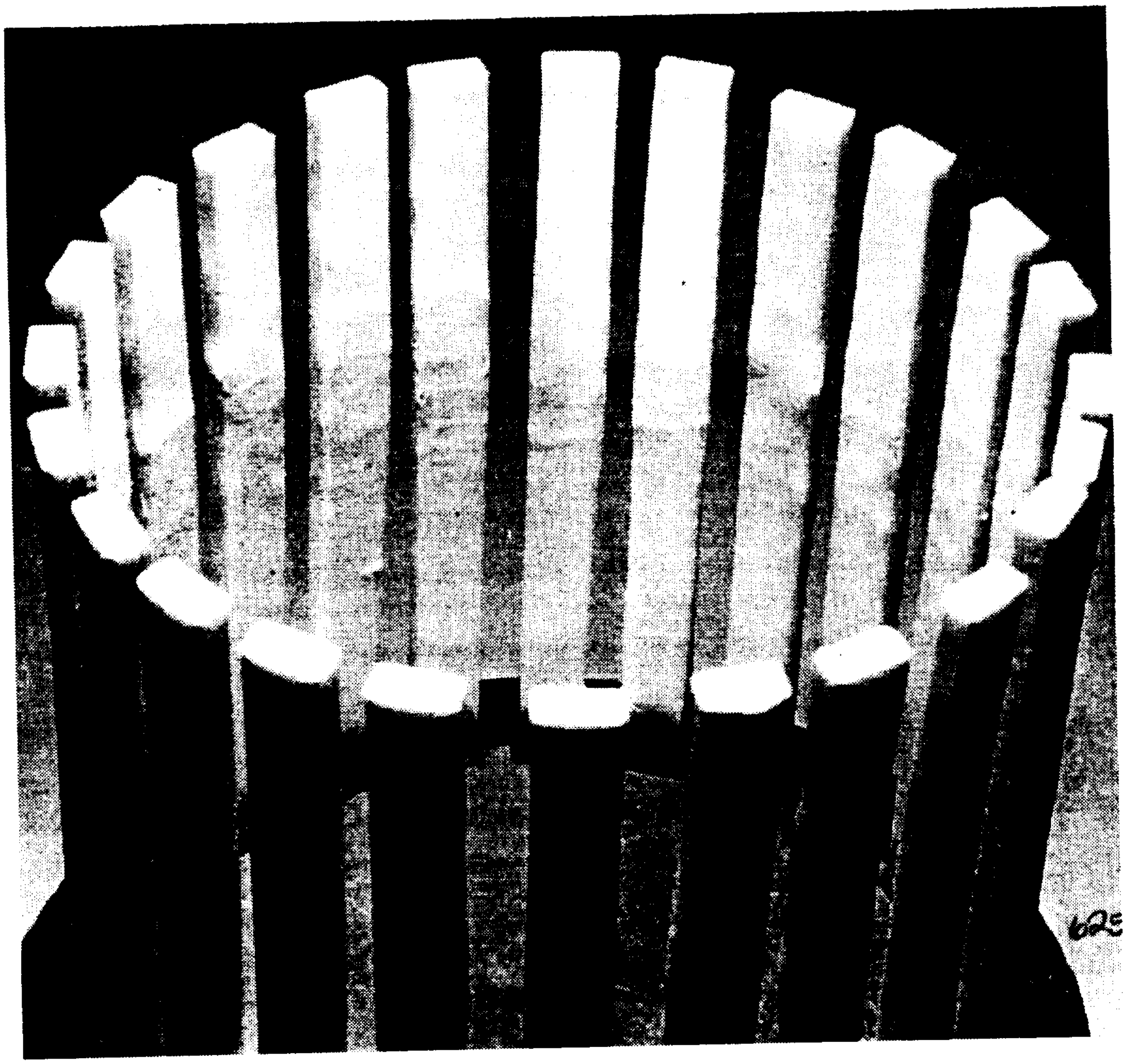


Figure 75. Representative Corning Code 9458 LAS Fracture Origins Following 350 Hours Cyclic Oxidation Durability Testing At 1093C (2000F).



G6253-76

Figure 76. Corning Code 9458 LAS Specimens Exhibited Cracking And Swelling Following Brief Overtemperature Excursion After 732 Hours Exposure.

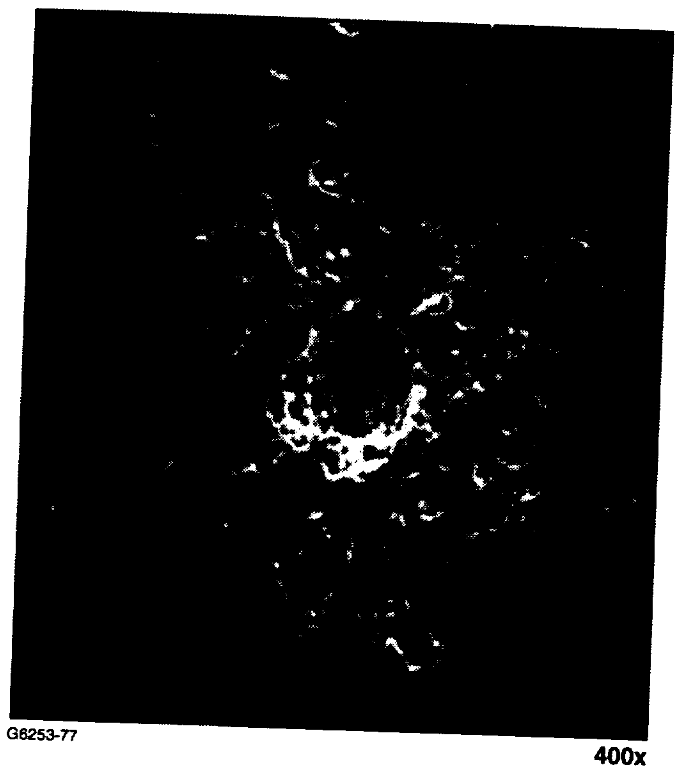


Figure 77. Typical Ford RBSN Baseline Test Specimen Failure Originating From Internal Porosity.

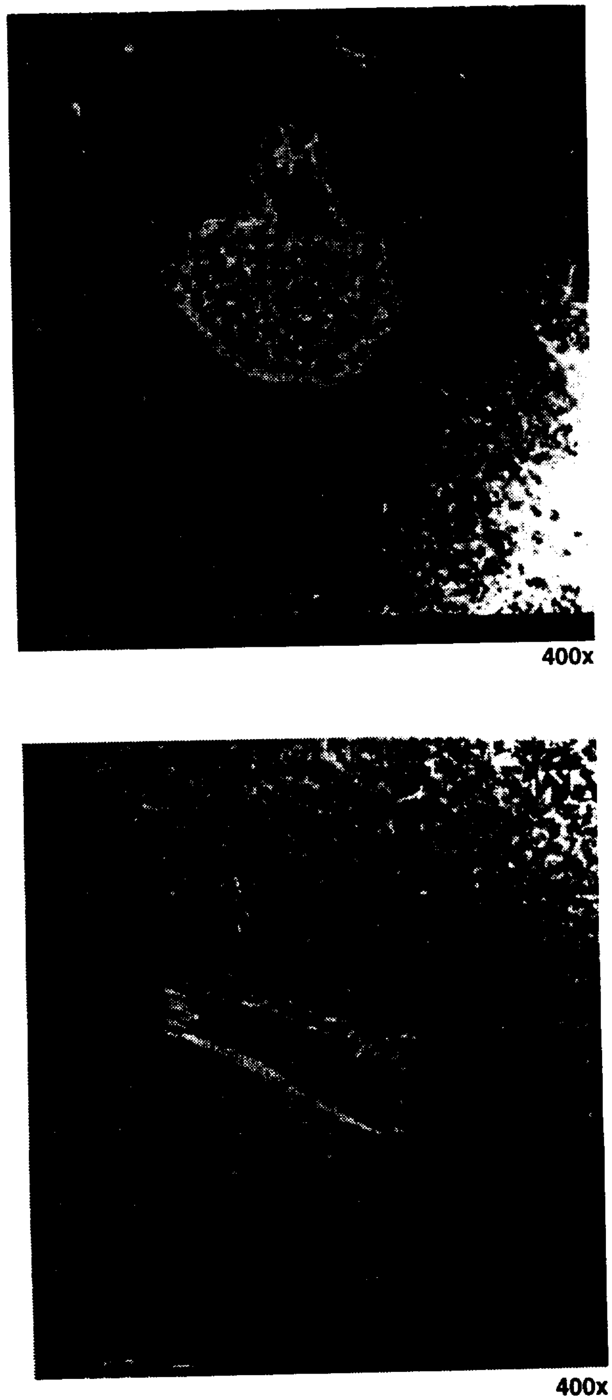


Figure 78. Typical GE Beta-SiC Baseline Test Specimen Failures Originating From Internal Pores.

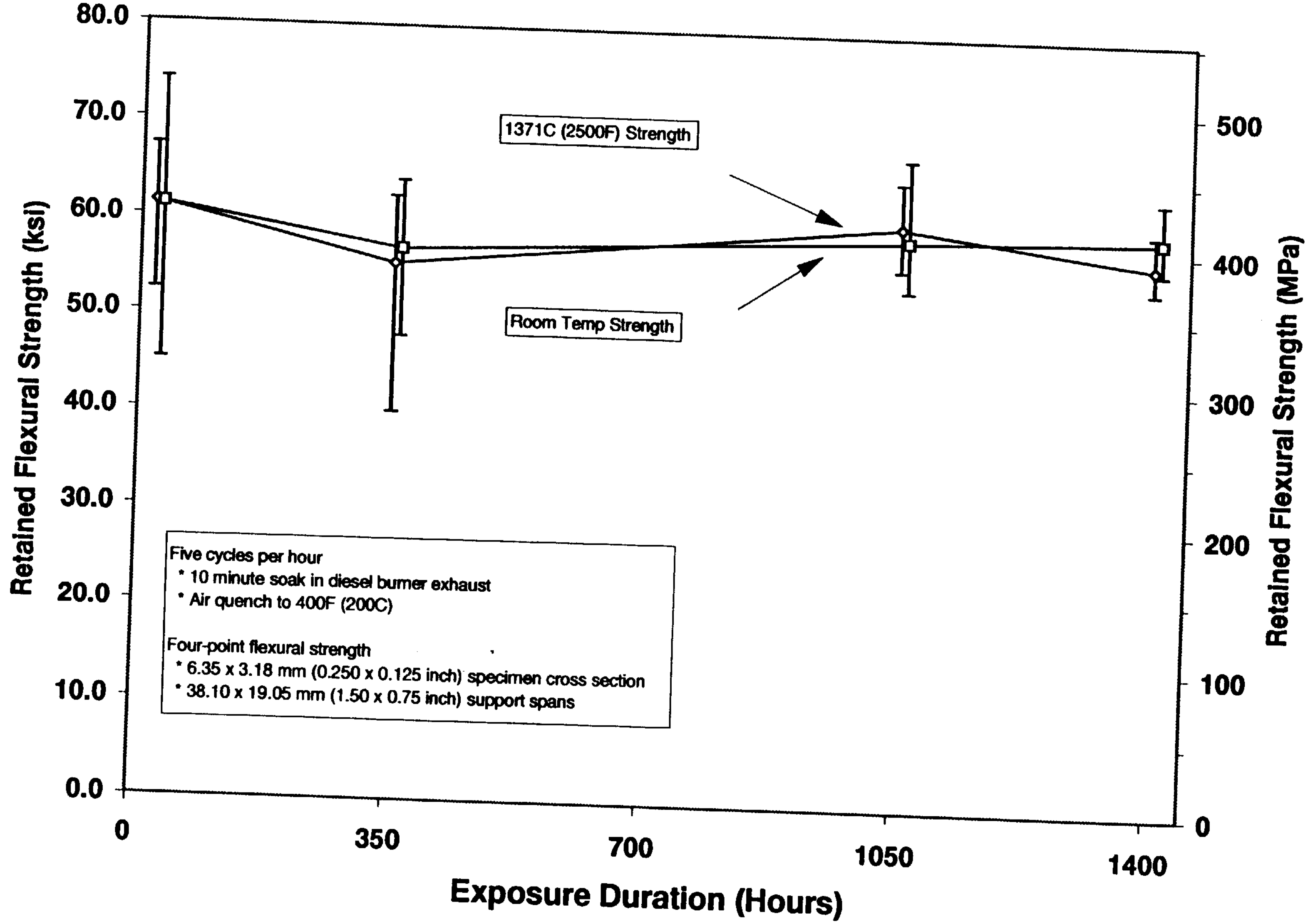
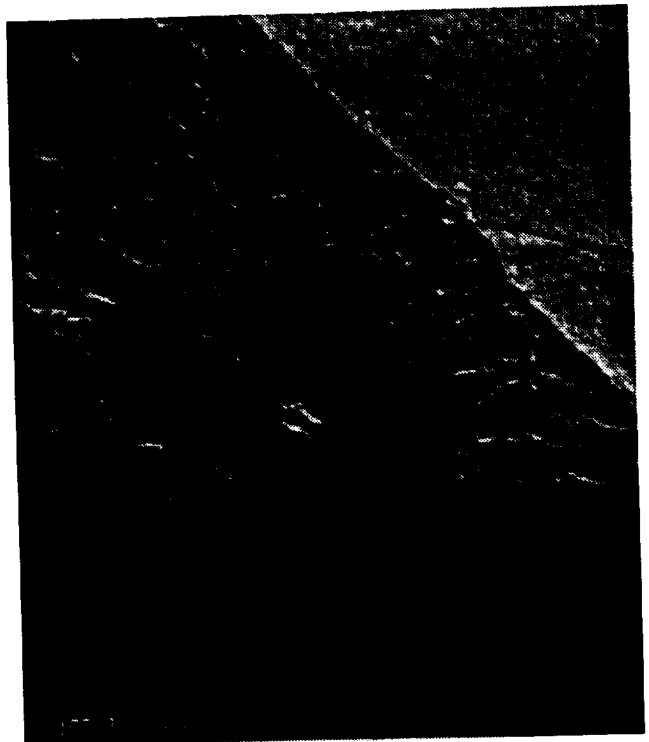


Figure 79. GE Beta-SiC Post-Exposure Room-Temperature And 1371C (2500F) Strength Test Results Following 1371C (2500F) Cyclic Oxidation Durability Testing.

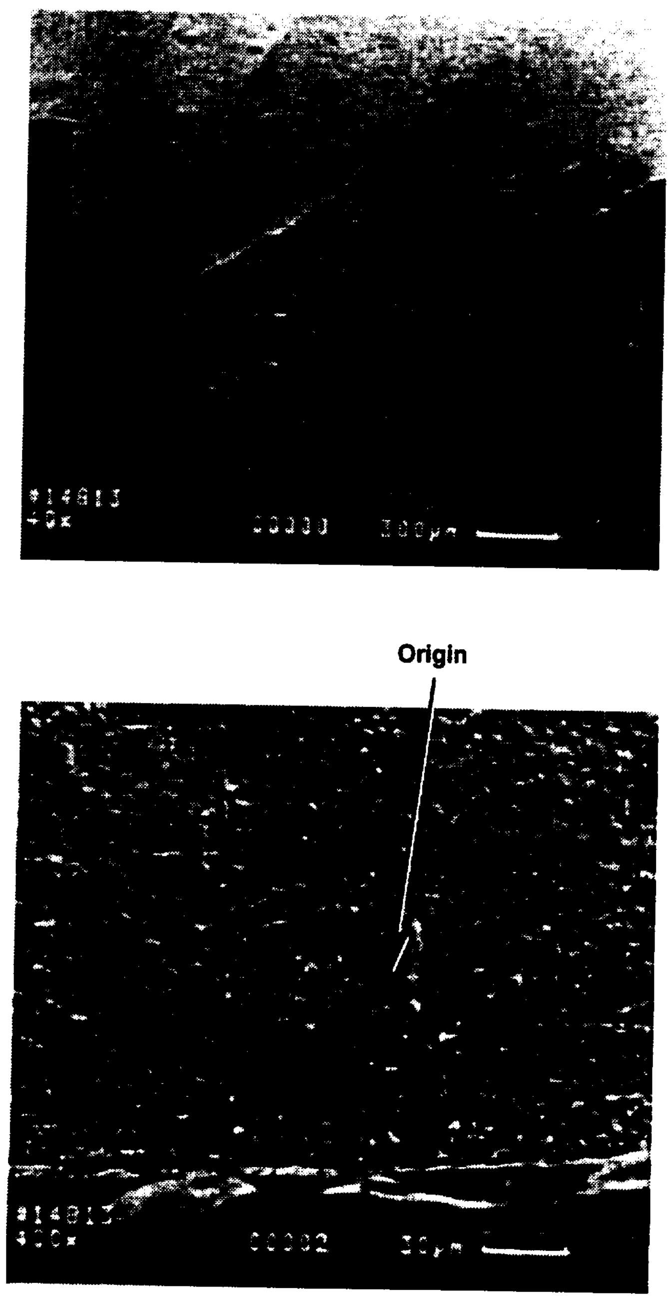


40x

G6253-80

400x

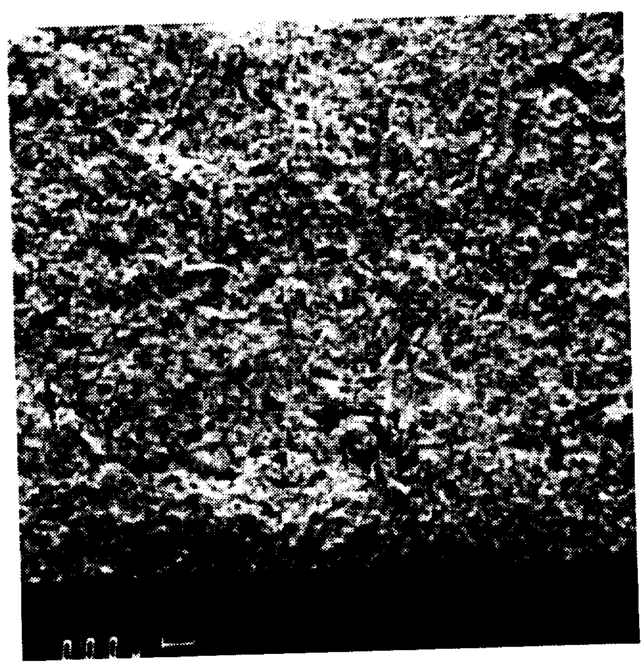
Figure 80. GE Beta-SiC Specimen Failure Originating From Internal Pore Following 350 Hours Exposure At 1371C (2500F).



G6253-81

Figure 81. GE Beta-SiC Specimen Failure Originating From Internal Porosity Following 1400 Hours Exposure At 1371C (2500F).

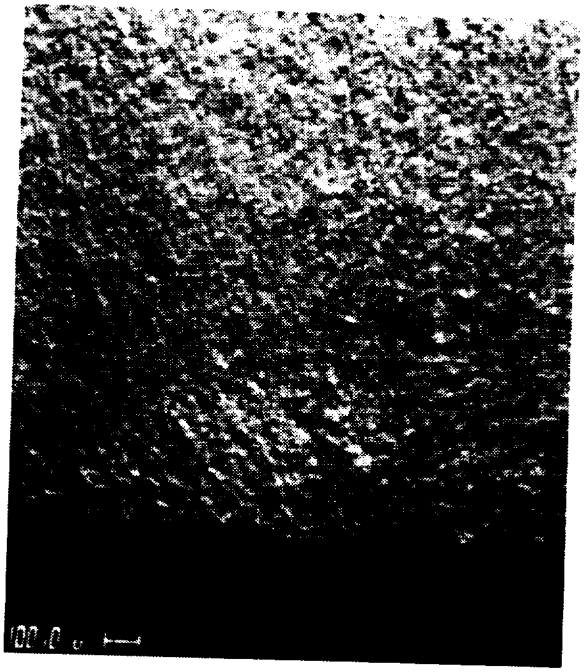
40x



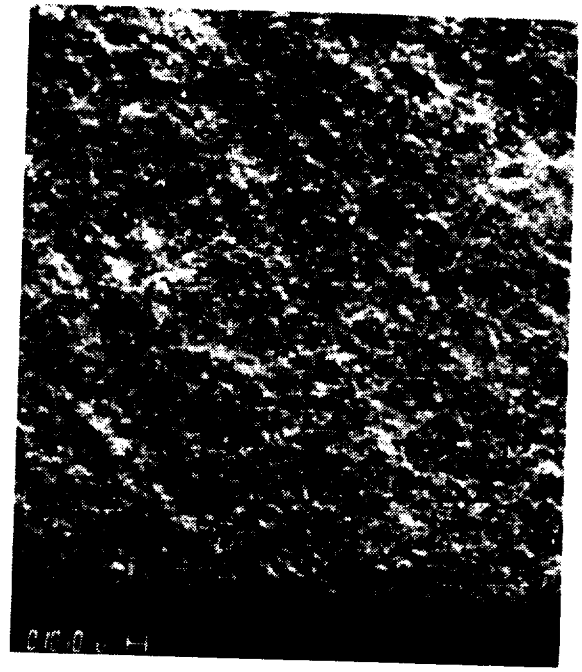
400x

G6253-82

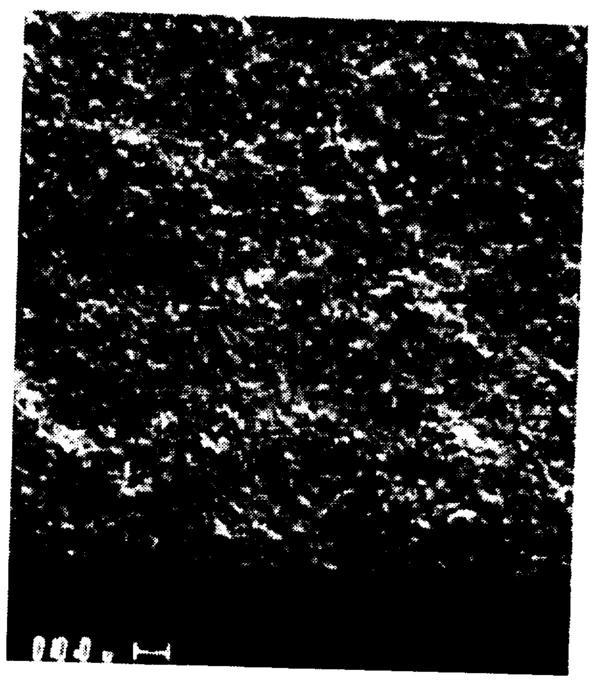
Figure 82. Typical AY6 Room-Temperature Baseline Test Specimen Failure Originating From Subsurface Porosity.



40x



200x



400x

G6253-83

Figure 83. Typical AY6 1204C (2200F) Baseline Test Specimen Failure Originating From Area Of Slow Crack Growth.

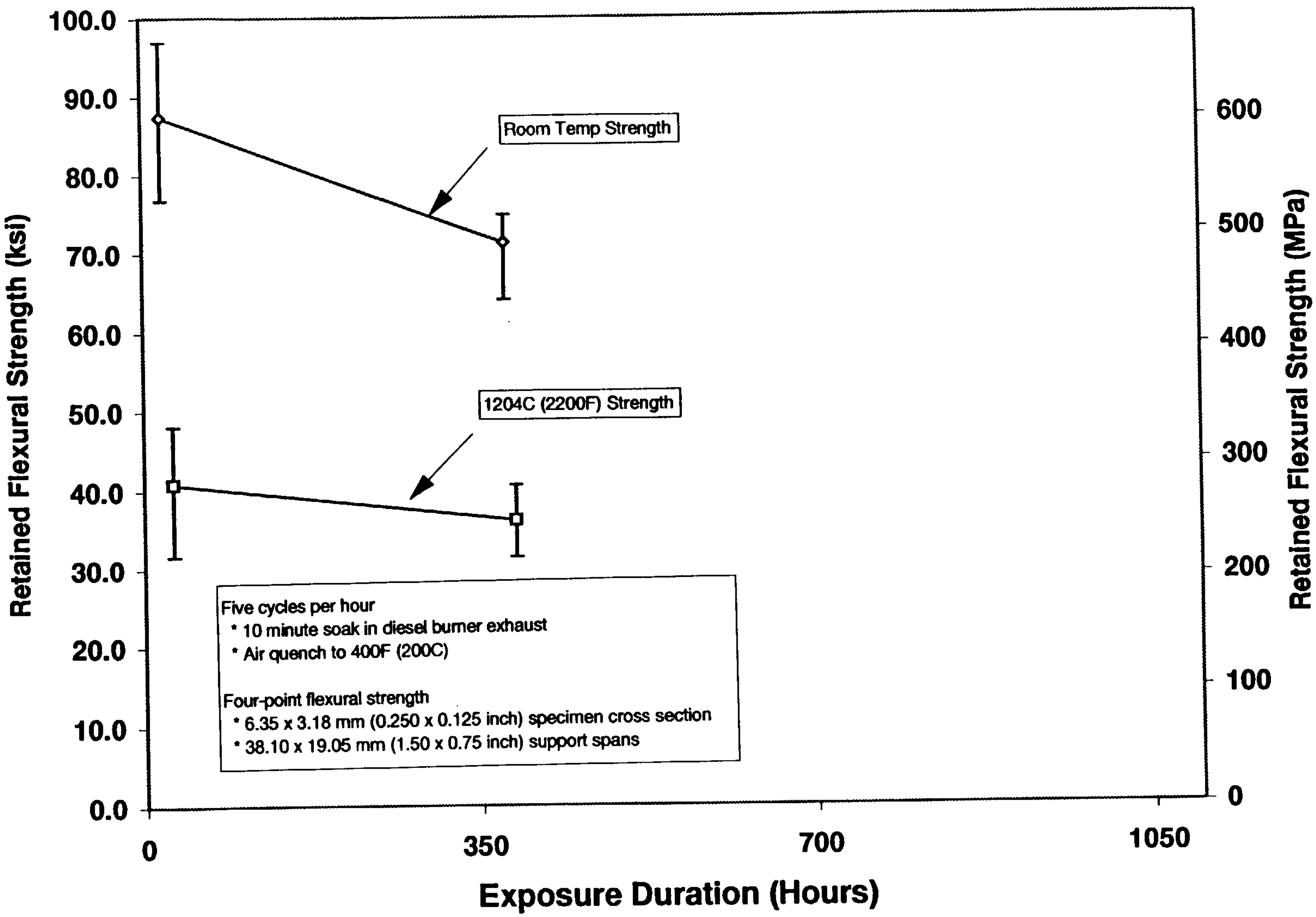
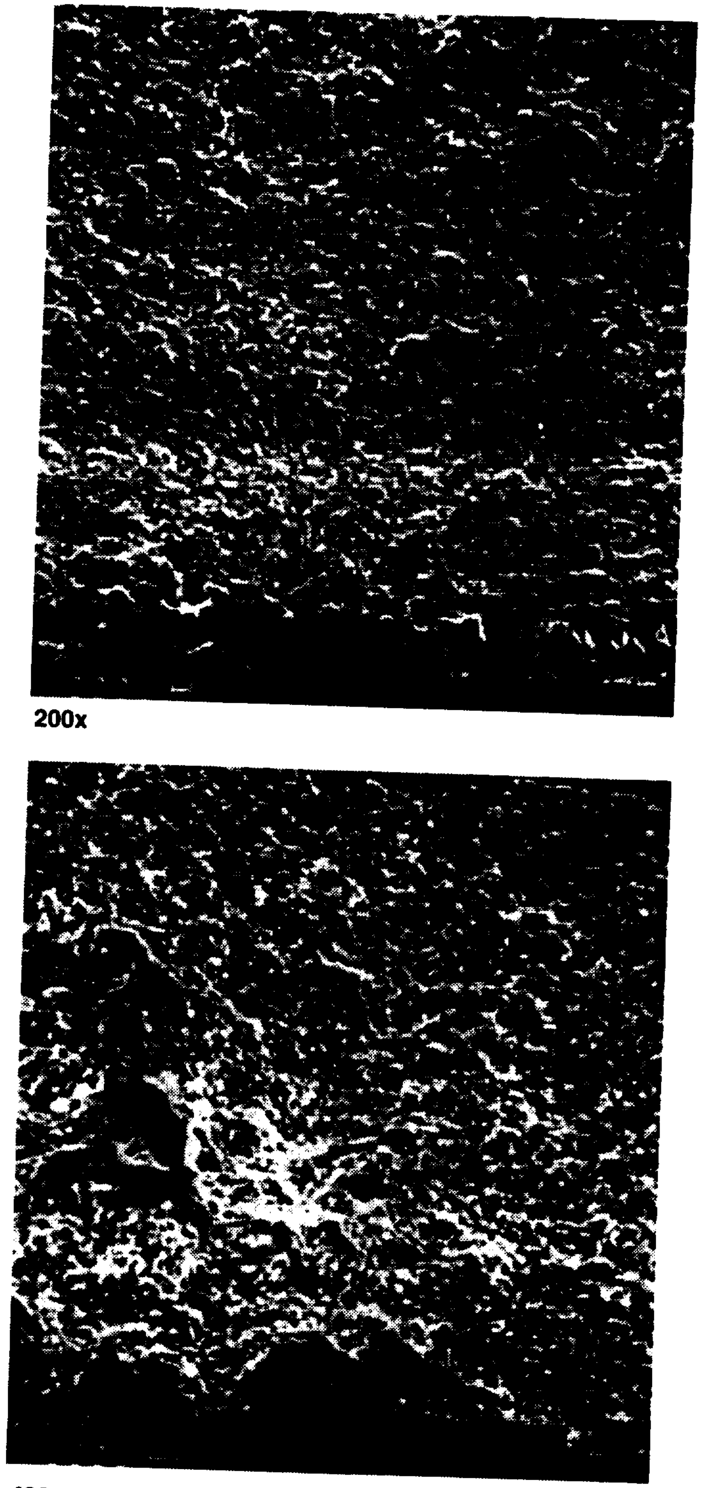


Figure 84. AY6 Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.



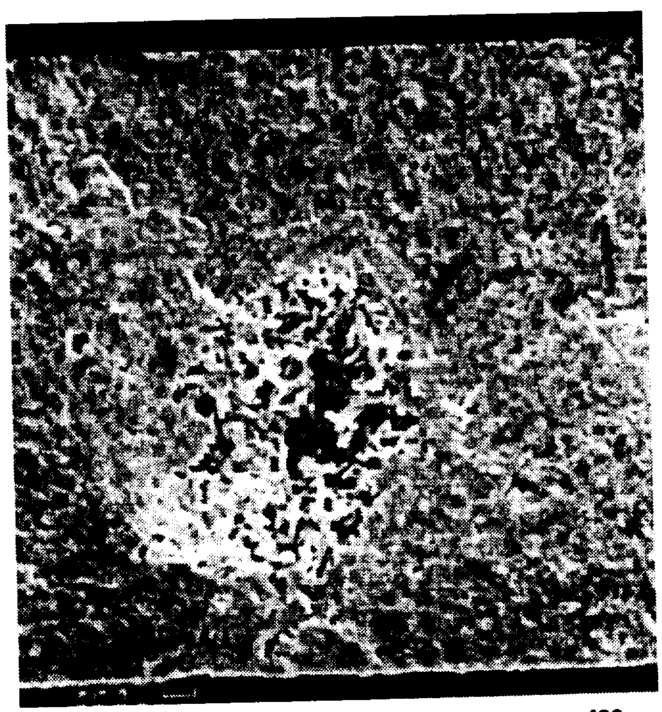
200x

400x

G6253-85

Figure 85. Typical AY6 Specimen Failures Originating From Flame-Exposed Surface Following 377 Hours Exposure At 1204C (2200F).

(a) Room-Temperature Flexure 400x



(b) 1204°C (2200°F) Flexure 400x

G6253-86

Figure 86. Typical PY6 Baseline Test Specimen Failures Originating From Surface-Connected And Subsurface Porosity.

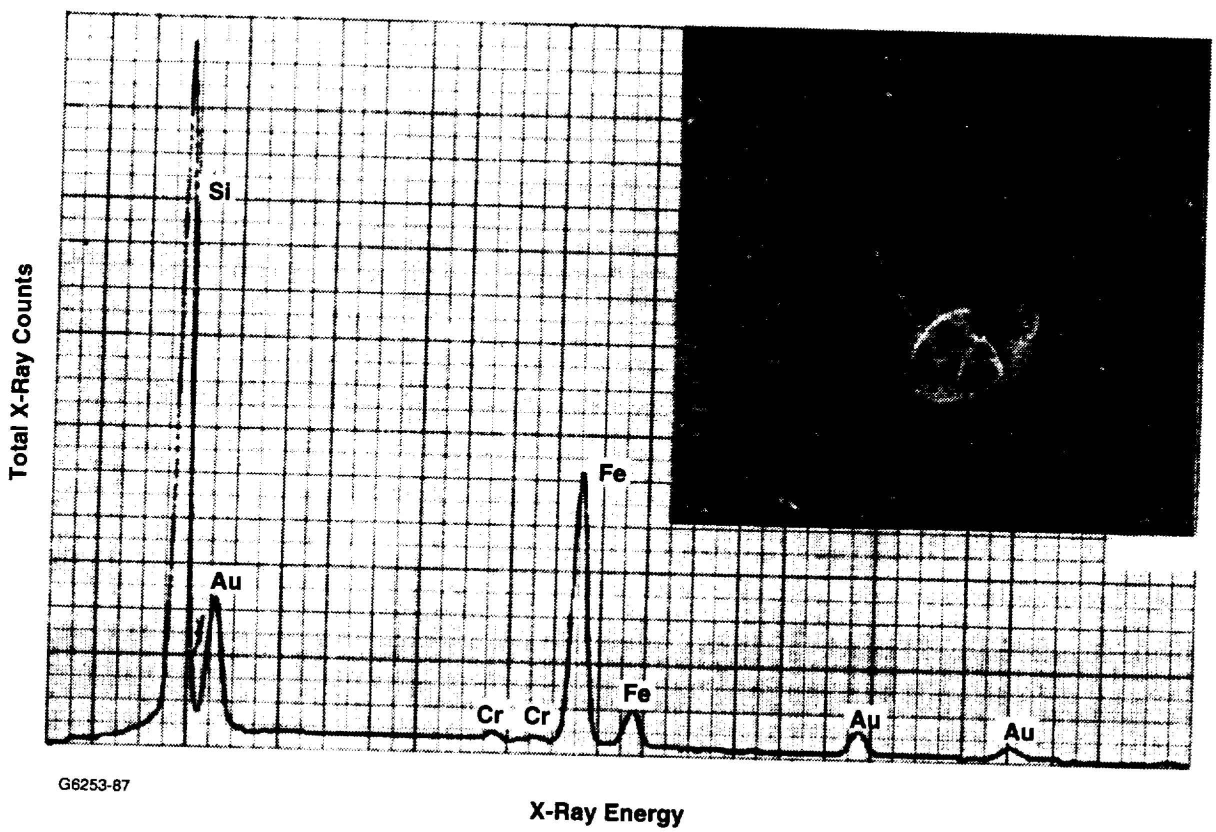


Figure 87. PY6 Baseline Test Specimen Failures Originating From Iron-Based Inclusion And Associated Porosity.

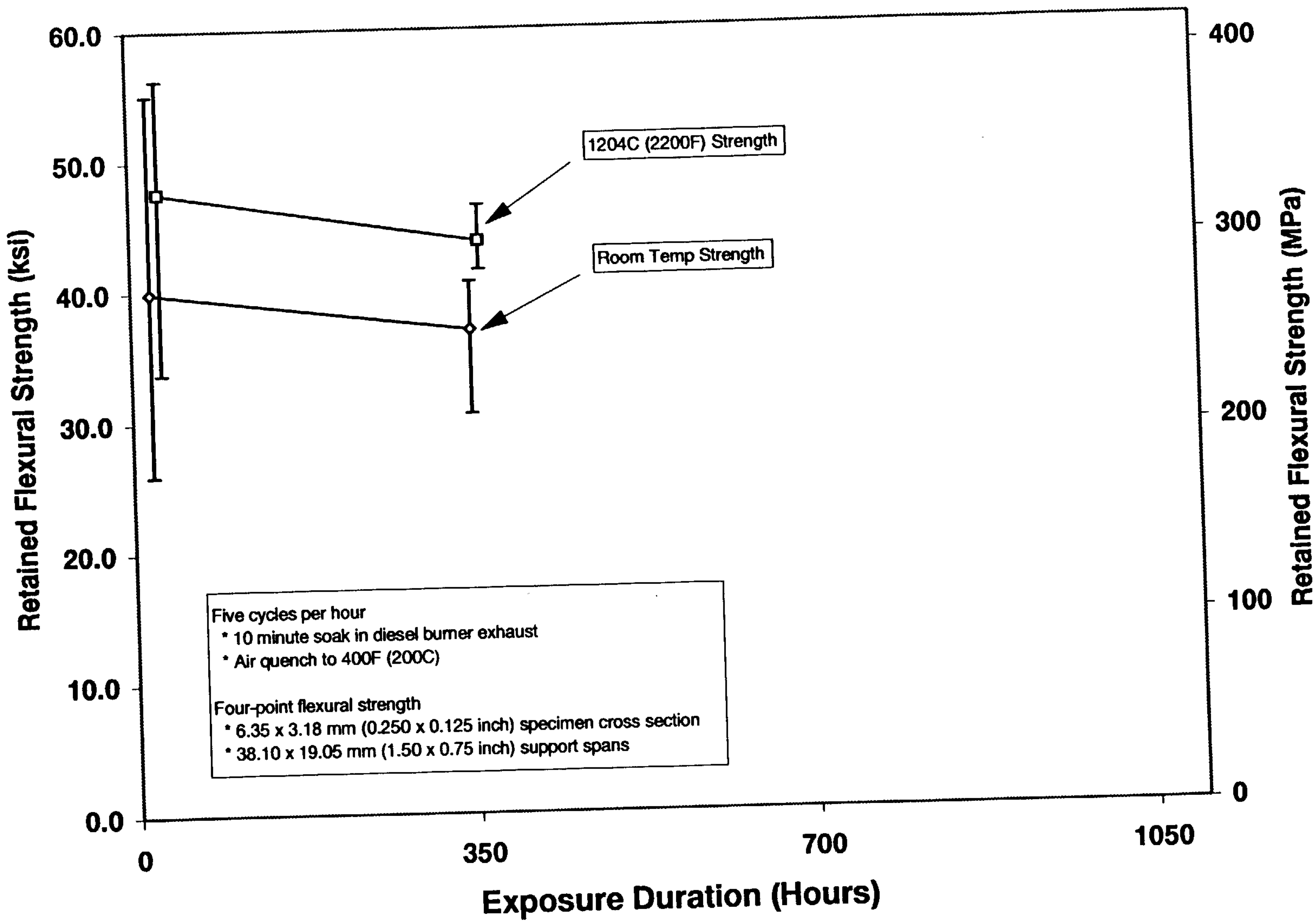
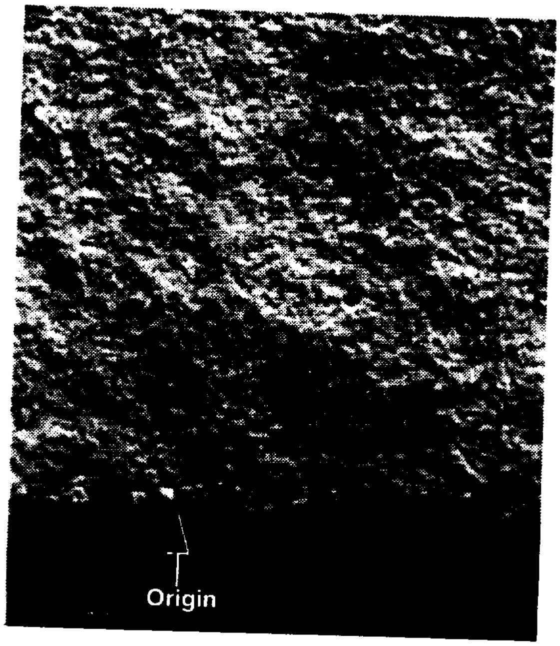
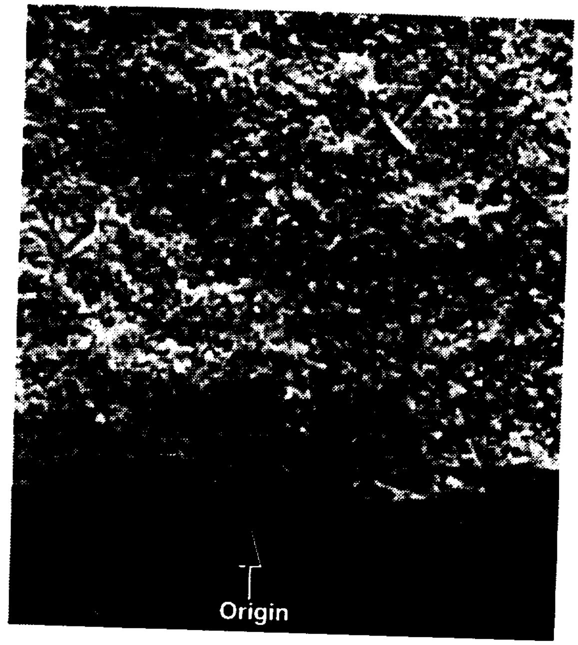


Figure 88. PY6 Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.



(a) Room-Temperature Test 200x



(b) 1204°C (1200°F) Flexure 400x

(c) As-Exposed Surface 200x

G6253-89

Figure 89. Typical PY6 Specimen Failure Origins And Surface Topography Following 350 Hours Exposure At 1204C (2200F).

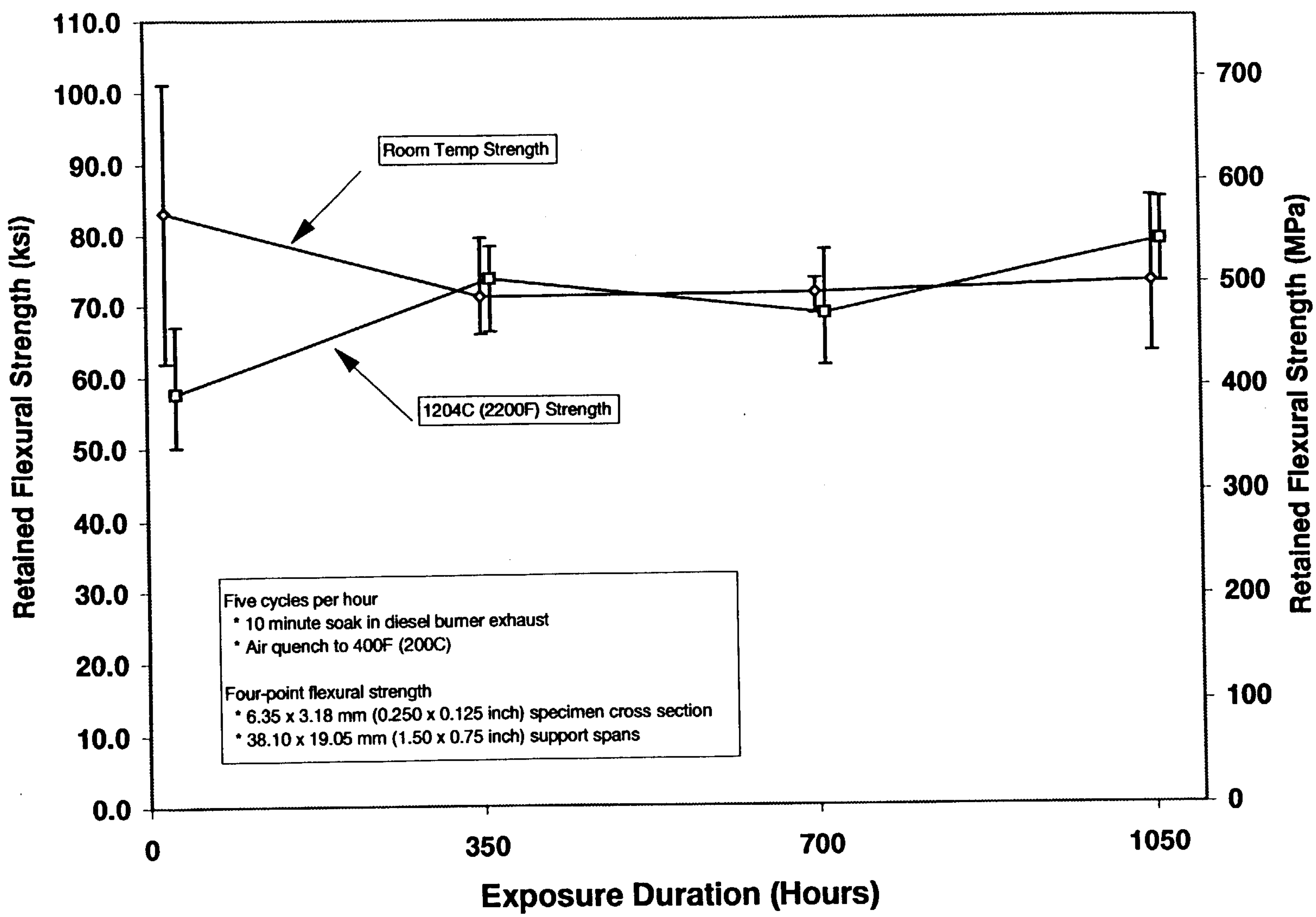
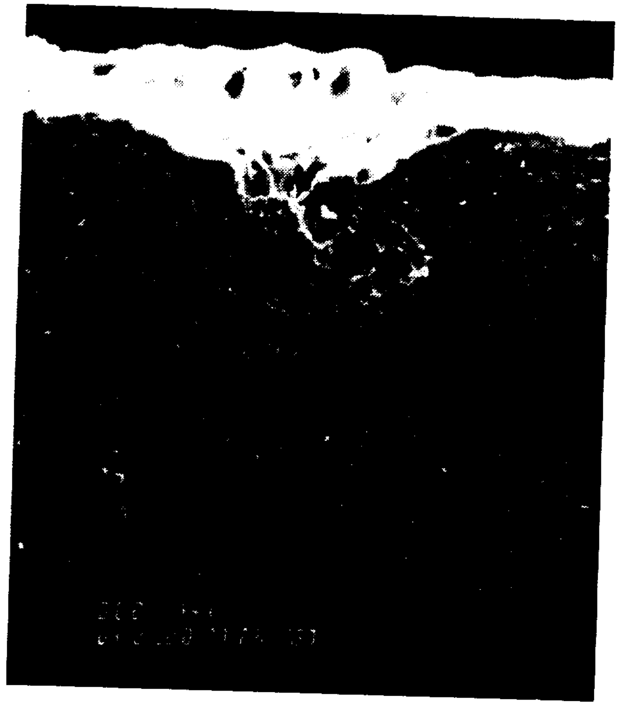
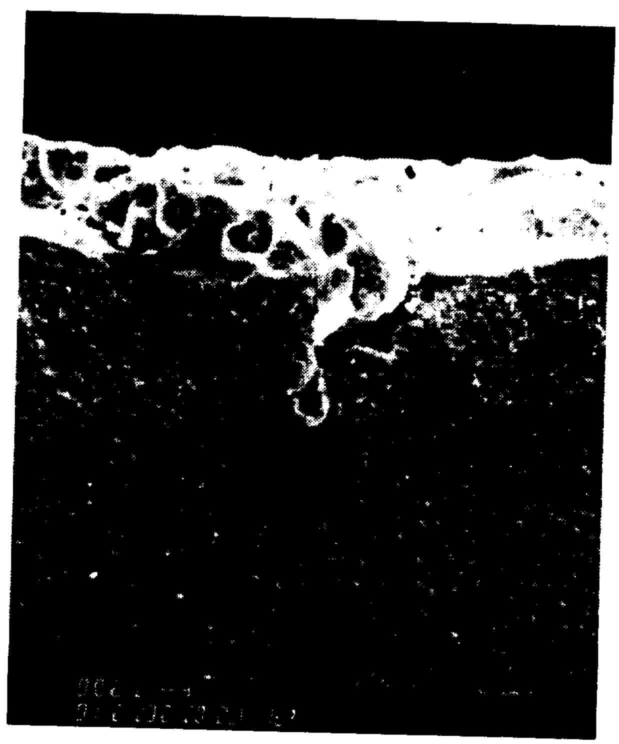


Figure 90. HIPped PY6 Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.



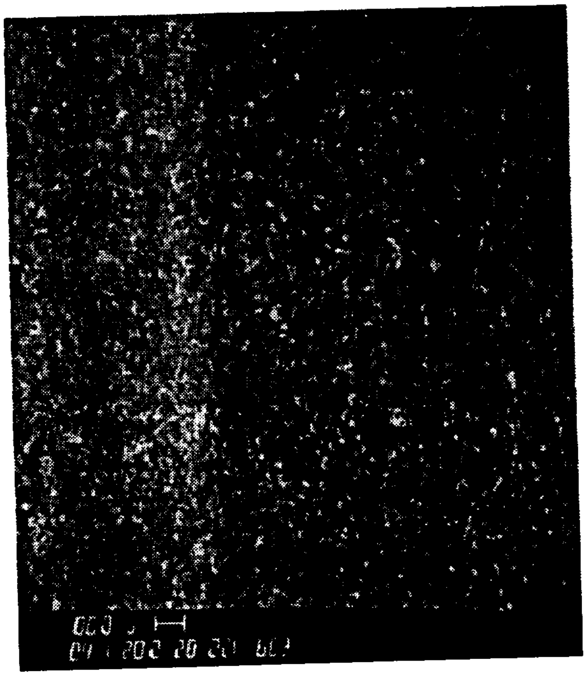
(a) 350 Hours 400x



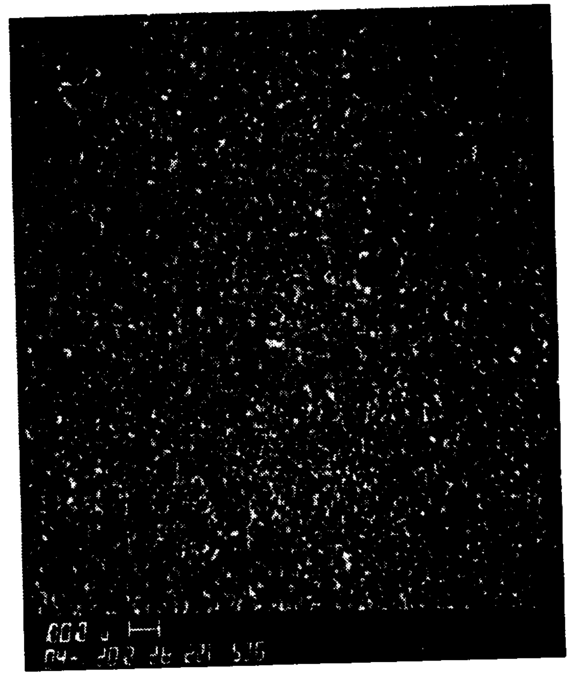
(b) 700 Hours 400x

G6253-91

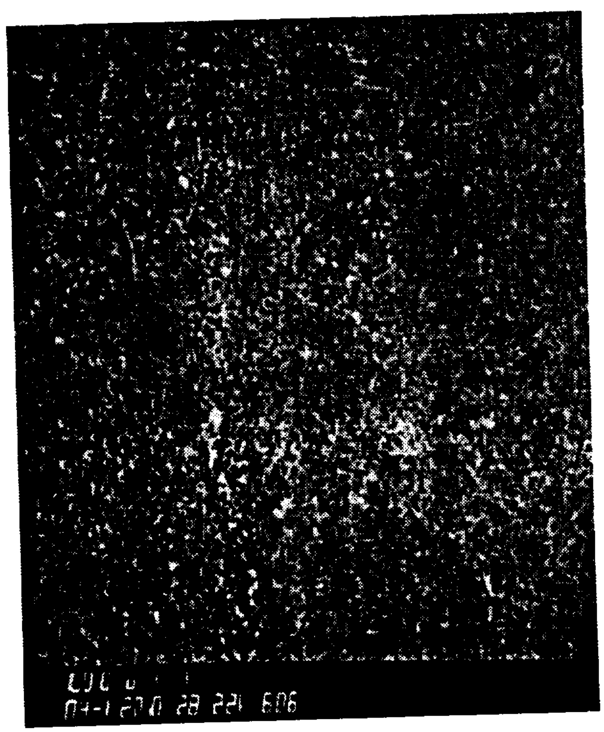
Figure 91. Typical HIPped PY6 Specimen Failures Originating From Oxidation Pits Following Exposure At 1204C (2200F).



(a) 350 Hours 40x



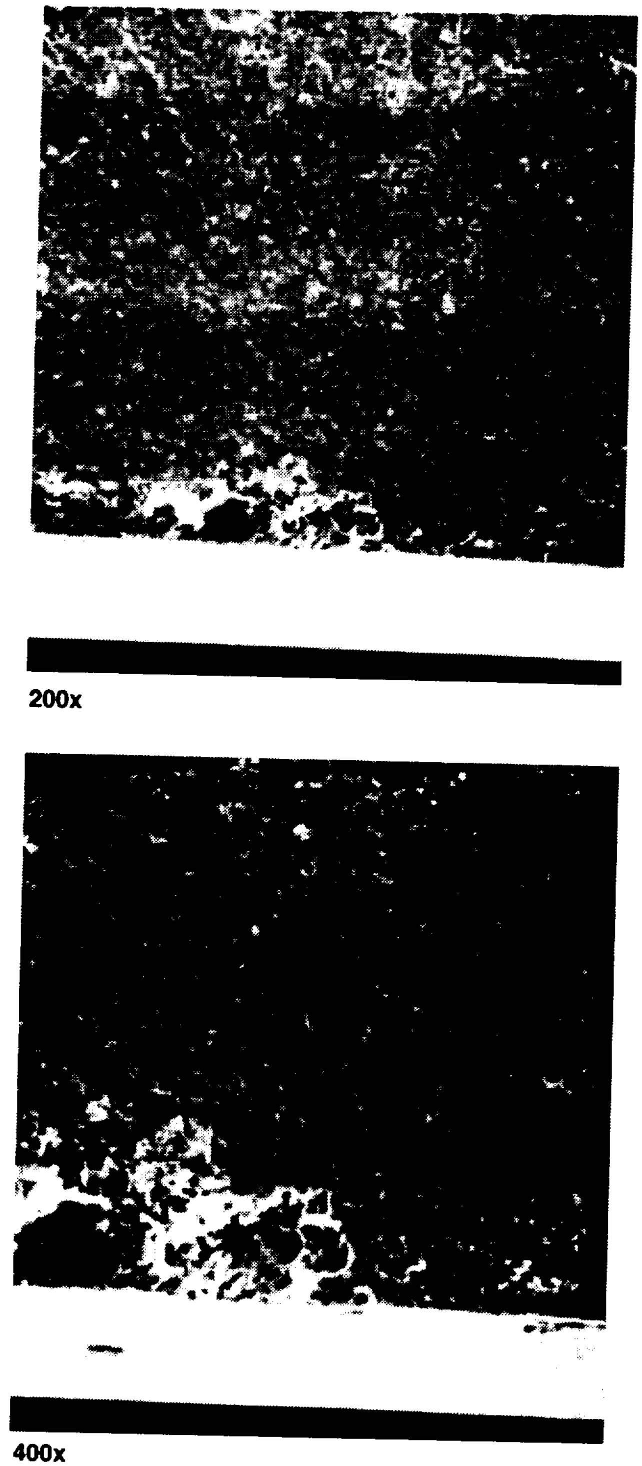
(b) 700 Hours 40x



(c) 1050 Hours 40x

G6253-92

Figure 92. HIPped PY6 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1204C (2200F): (a) 350 Hours; (b) 700 Hours; (c) 1050 Hours.



G6253-93

Figure 93. Typical SC-201 Baseline Test Specimen Failure Originating From Surface Connected Porosity.

200x

1000x

G6253-94

Figure 94. Typical SC-201 Baseline Test Specimen Failure Originating From Subsurface Porosity.

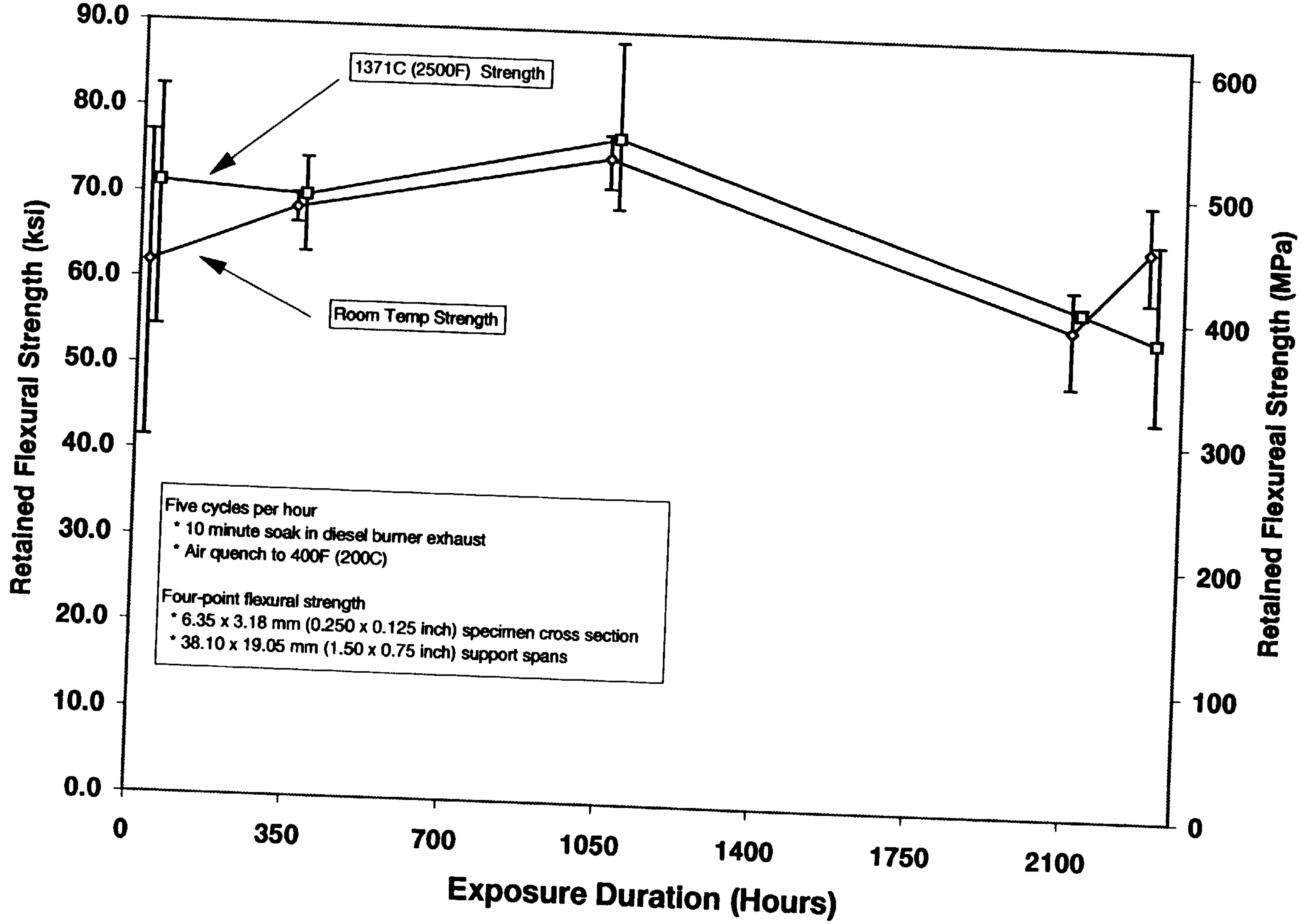
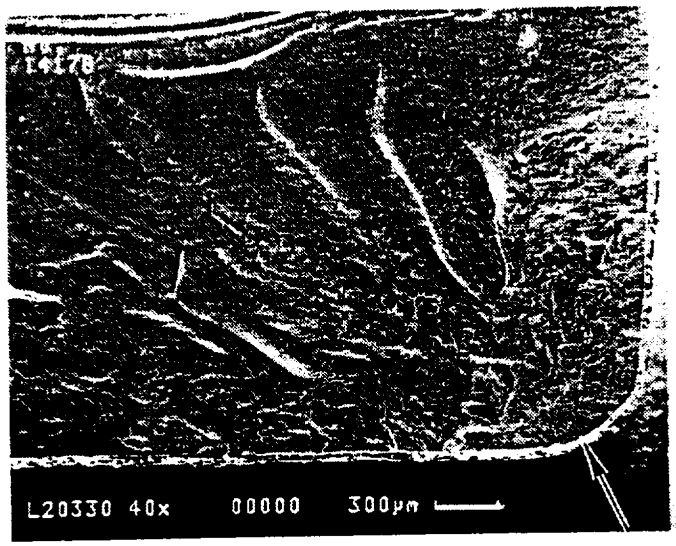
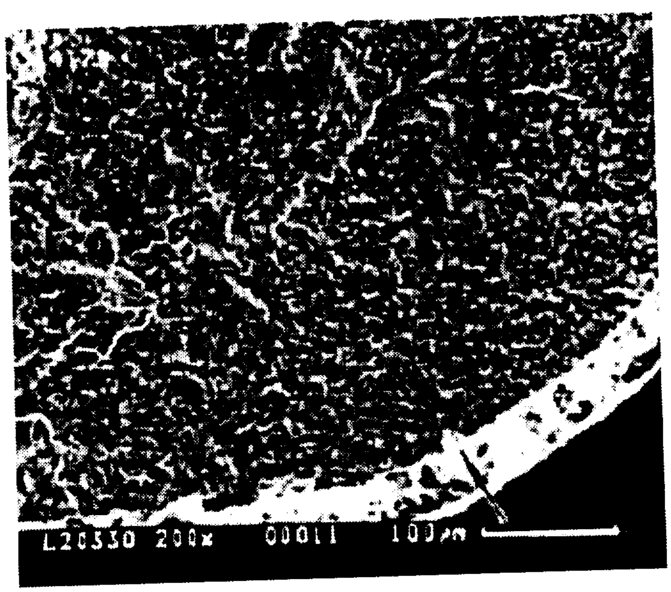


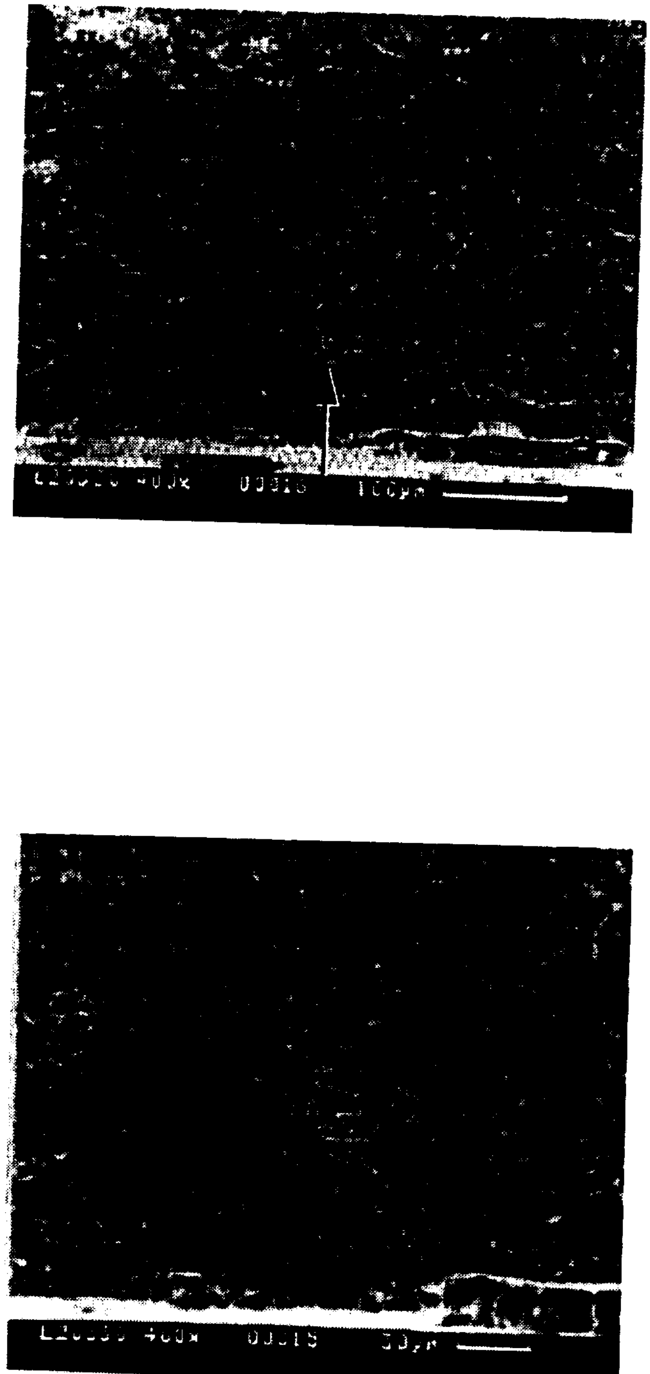
Figure 95. SC-201 Post-Exposure Room-Temperature And 1371C (2500F) Strength Test Results Following 1371C (2500F) Cyclic Oxidation Durability Testing.





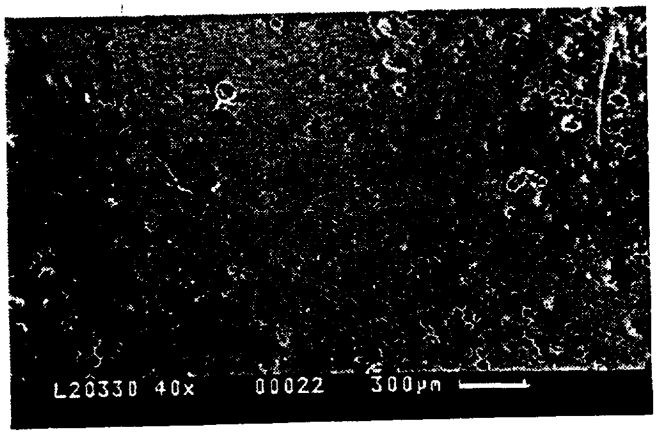
G6253-96

Figure 96. Typical SC-201 Specimen Failure Originating At Chamfer Of Flame-Exposed Surface Following 2100 Hours Exposure At 1371C (2500F).

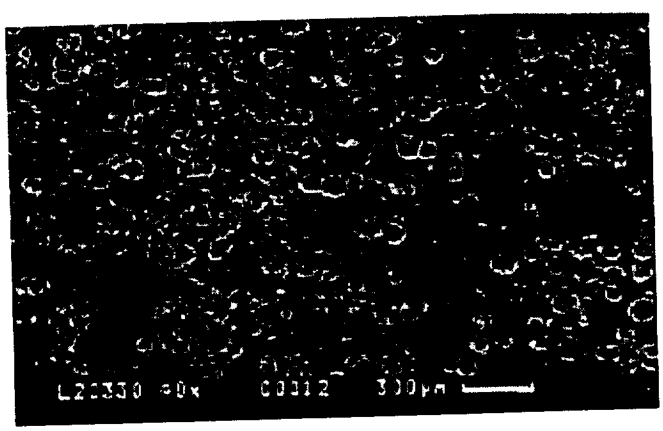


G6253-97

Figure 97. SC-201 Specimen Failure Originating From Internal Porosity Following 1050 Hours Exposure At 1371C (2500F).



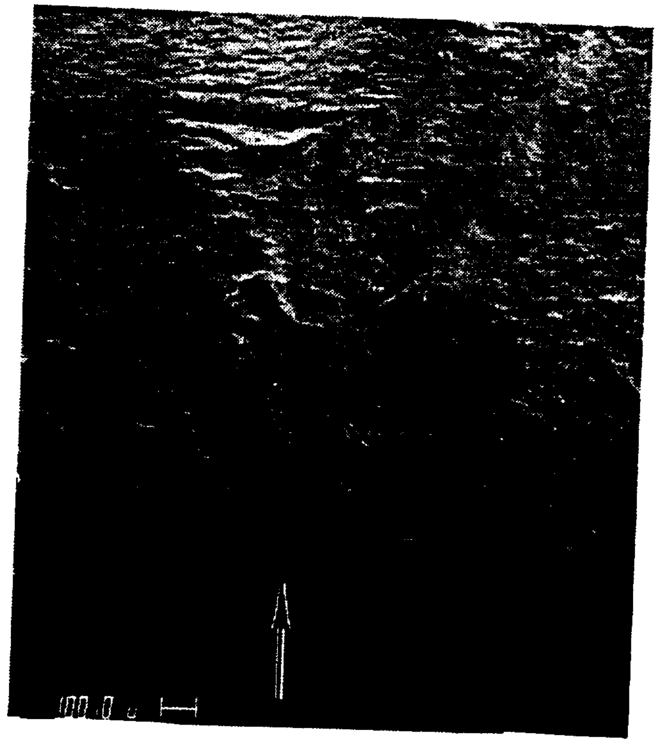
(a) 1050 Hours



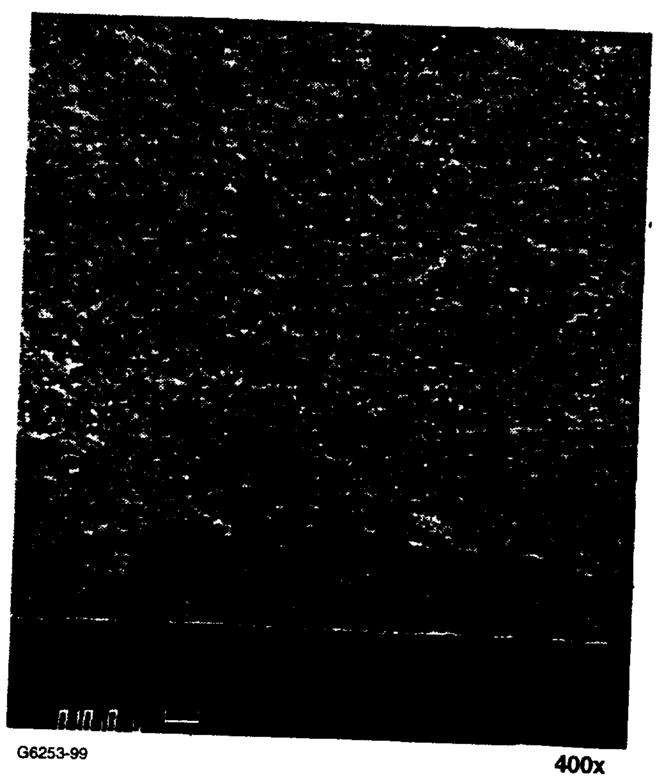
(b) 2100 Hours

G6253-98

Figure 98. SC-201 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1371C (2500F): (a) 1050 Hours; (b) 2100 Hours.



40x



G6253-99

400x

Figure 99. Typical SN-250M Baseline Test Specimen Failure Originating From Machined Surface.

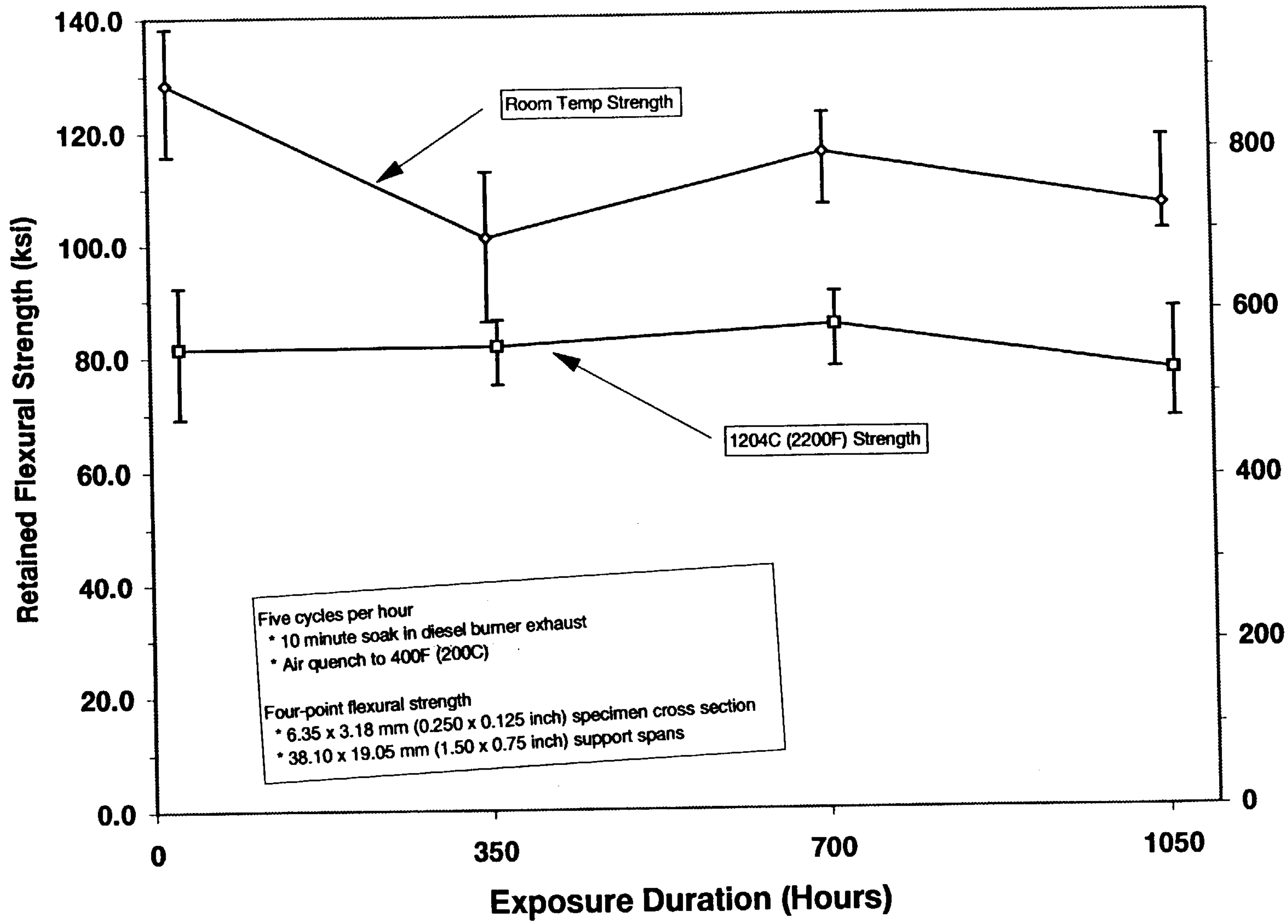
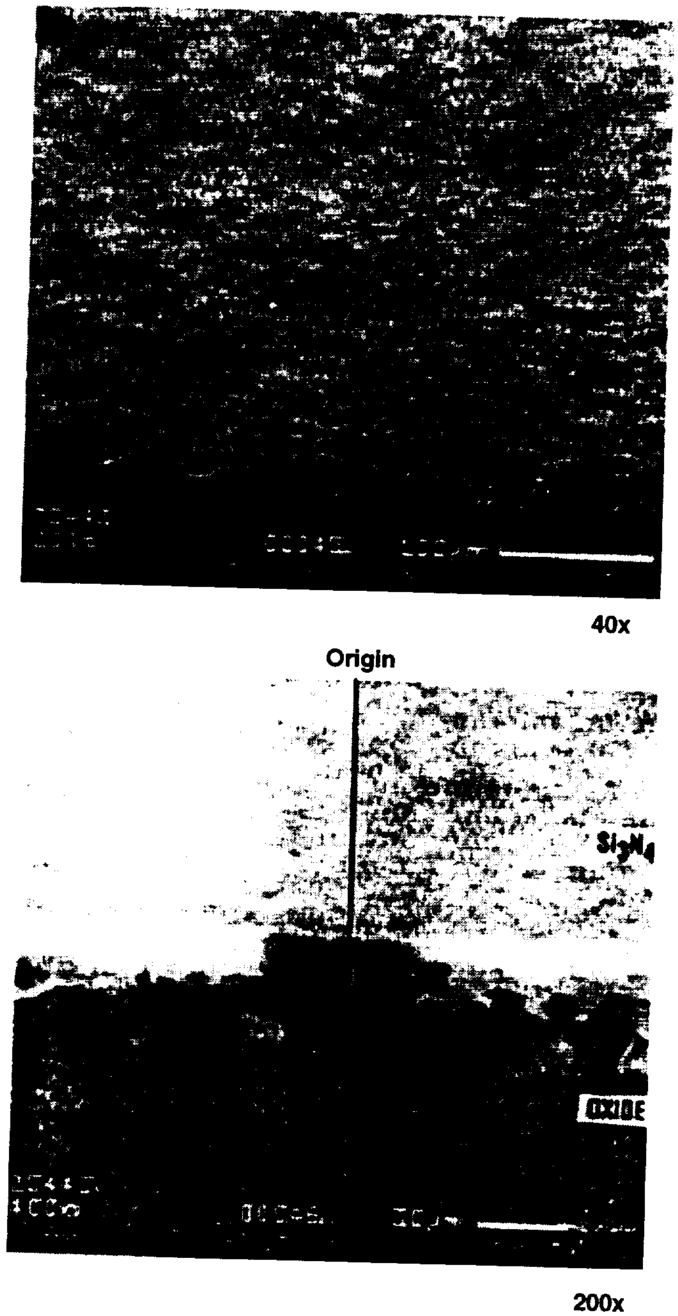
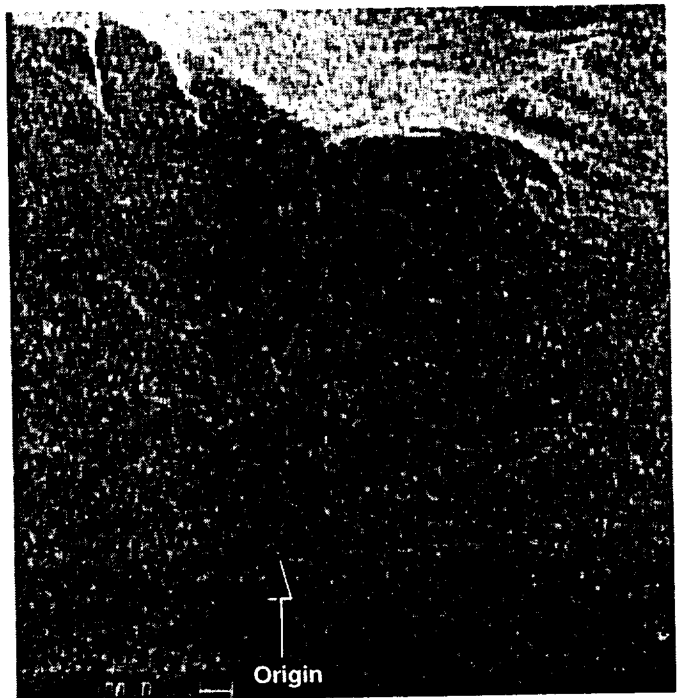


Figure 100. SN-250M Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.



G6253-101

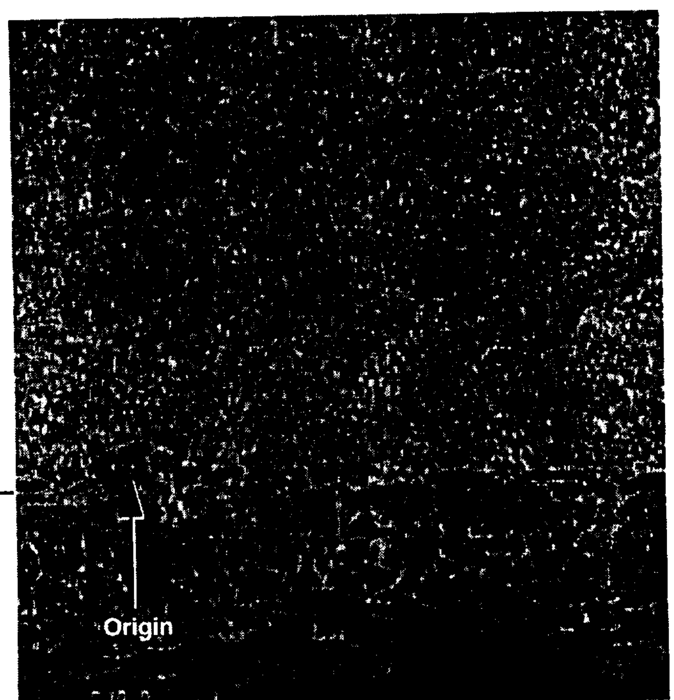
Figure 101. SN-250M Specimen Failure Originating From Oxidation Pit Following 350 Hours Exposure At 1204C (2200F).



40x

Si3N4

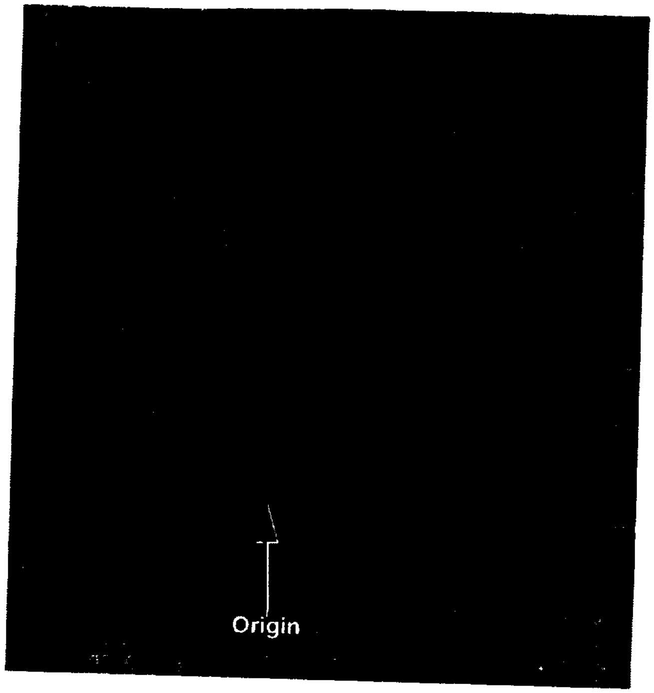
Oxide Layer



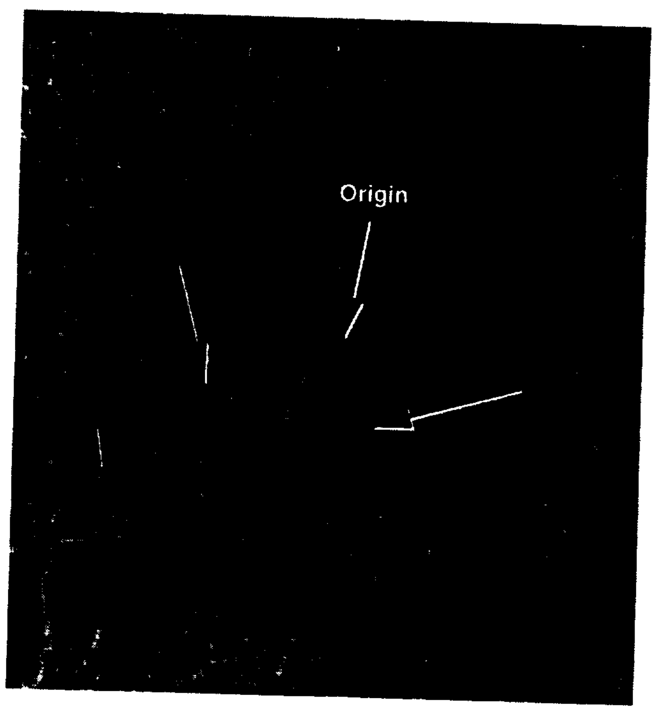
200x

G6253-102

Figure 102. SN-250M Specimen Failure Originating From Oxidation Pit Following 700 Hours Exposure At 1204C (2200F).



40x



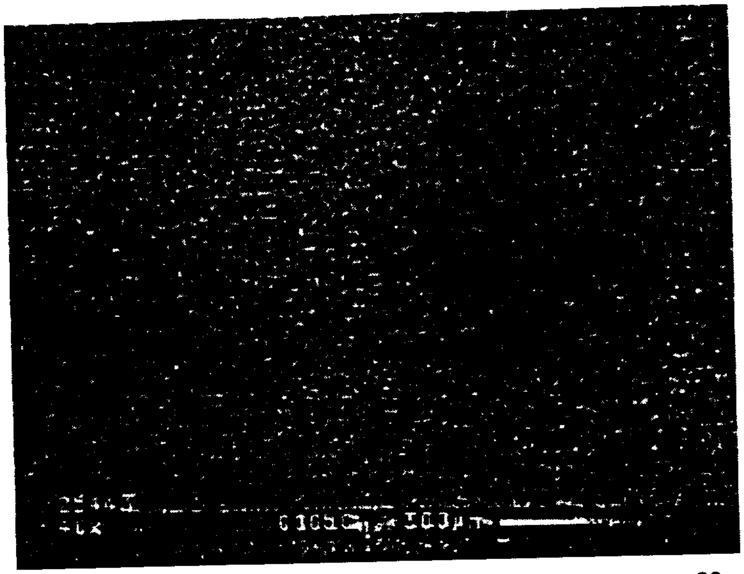
Si_3N_4

Oxide Layer

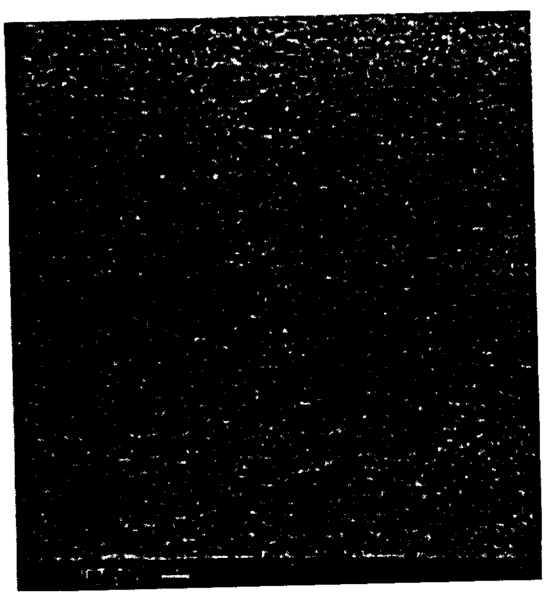
400x

G6253-103A

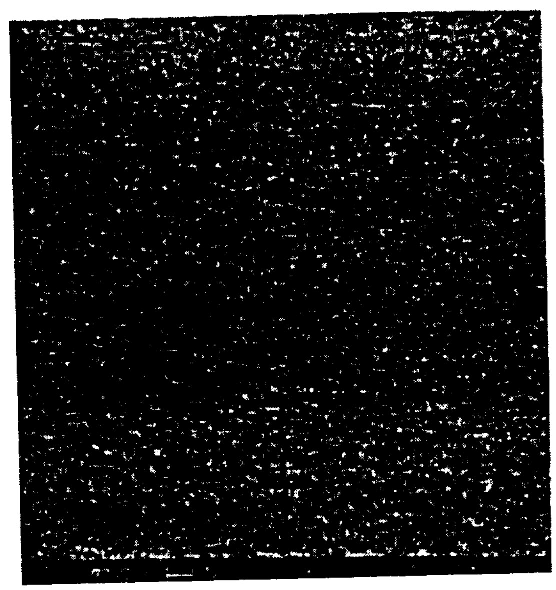
Figure 103. SN-250M Specimen Failure Originating From Oxidation Pit Following 1050 Hours Exposure At 1204C (2200F).



(a) 350 Hours 20x



(b) 700 Hours 40x



(c) 1050 Hours 40x

G6253-104

Figure 104. SN-250M Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1204C (2200F): (a) 350 Hours; (b) 700 Hours; (c) 1050 Hours.

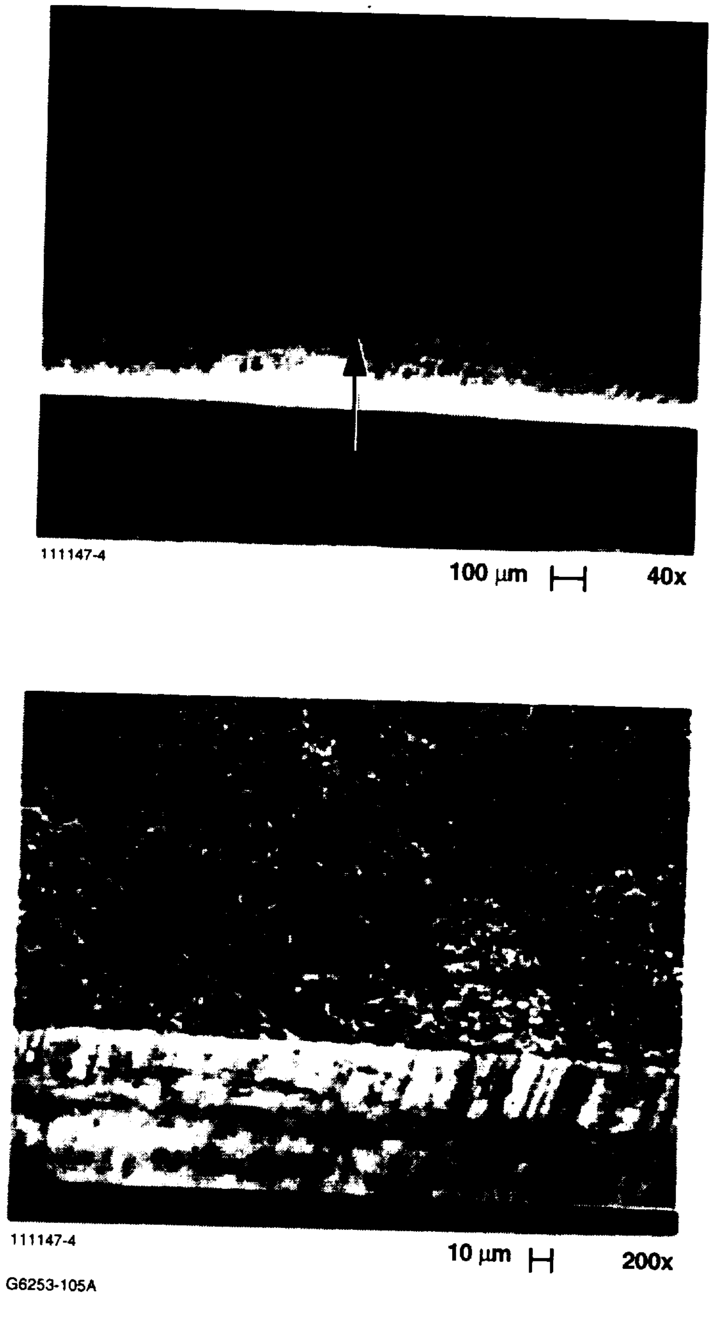


Figure 105. Typical SN-251 Baseline Test Specimen Failure Originating From Acicular Si_3N_4 Grain.

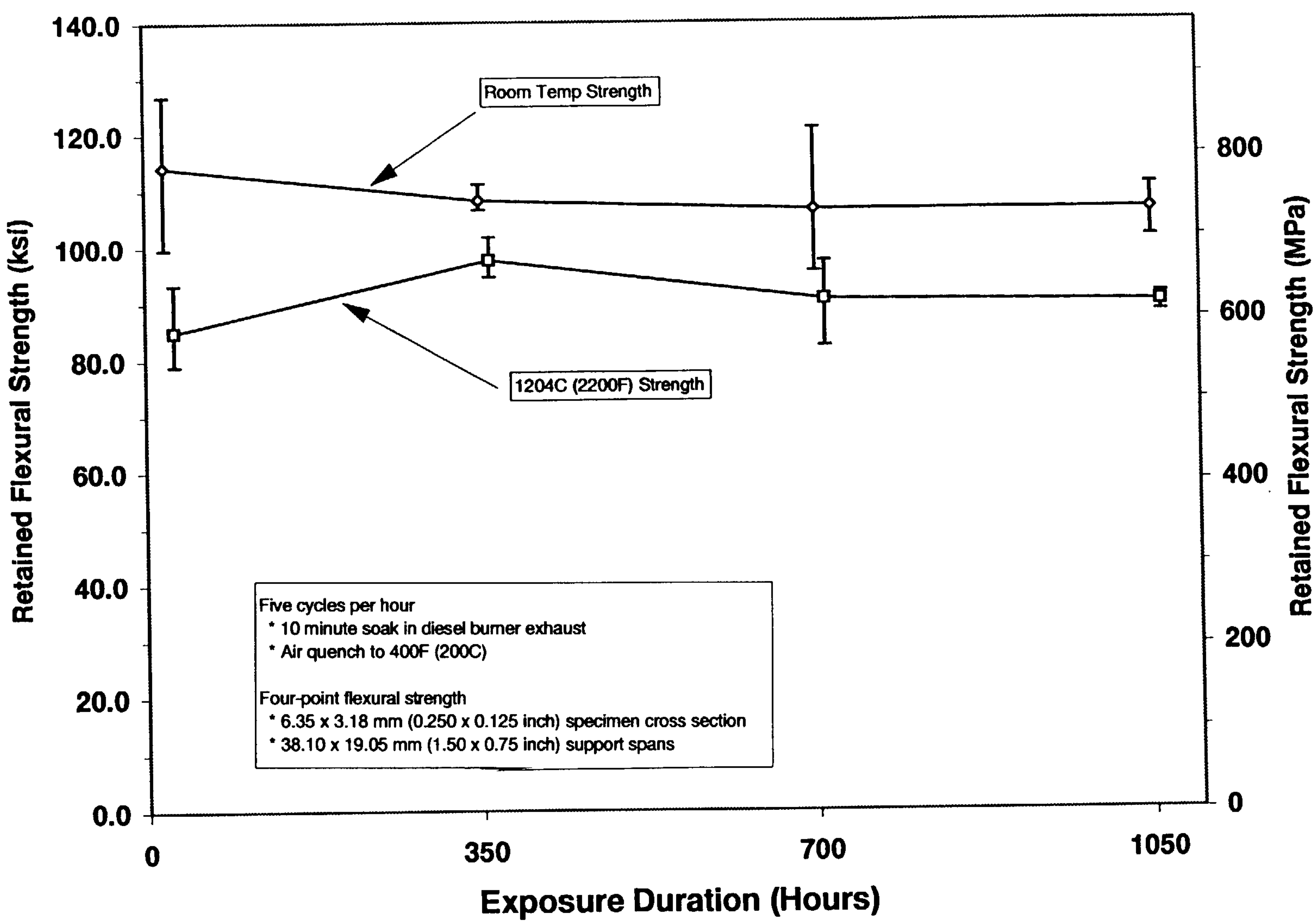
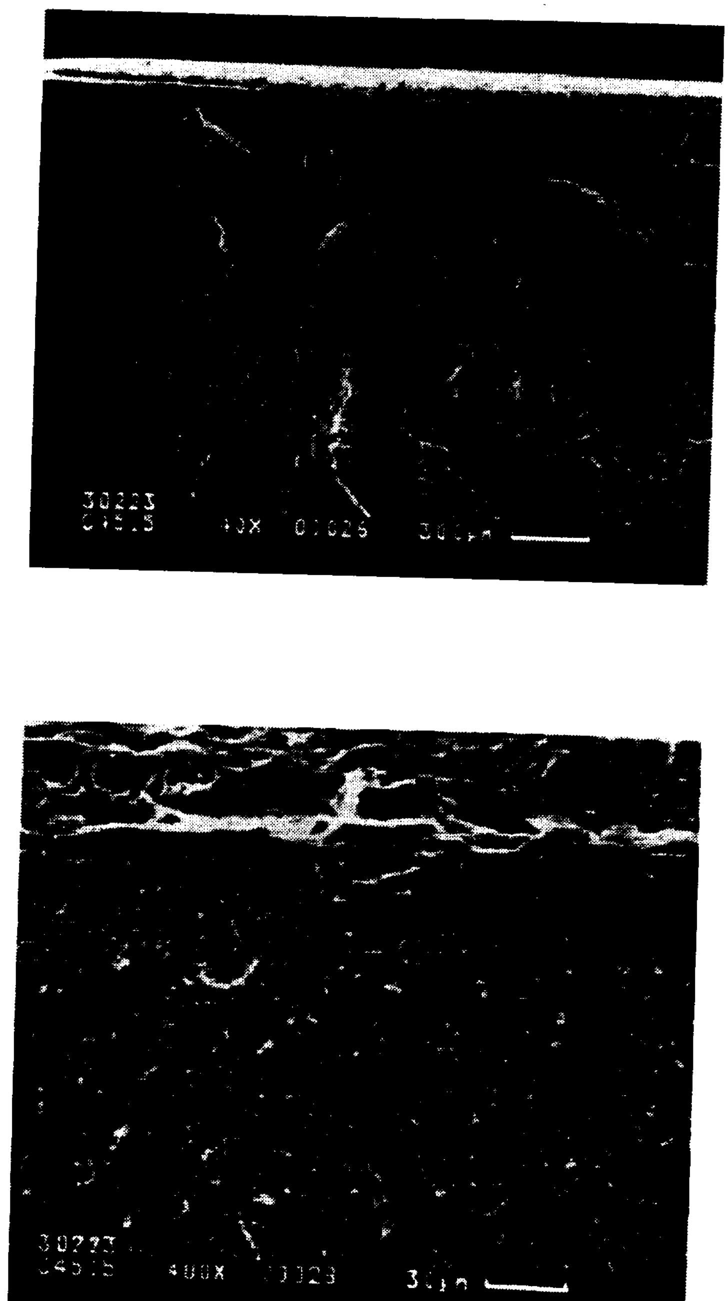
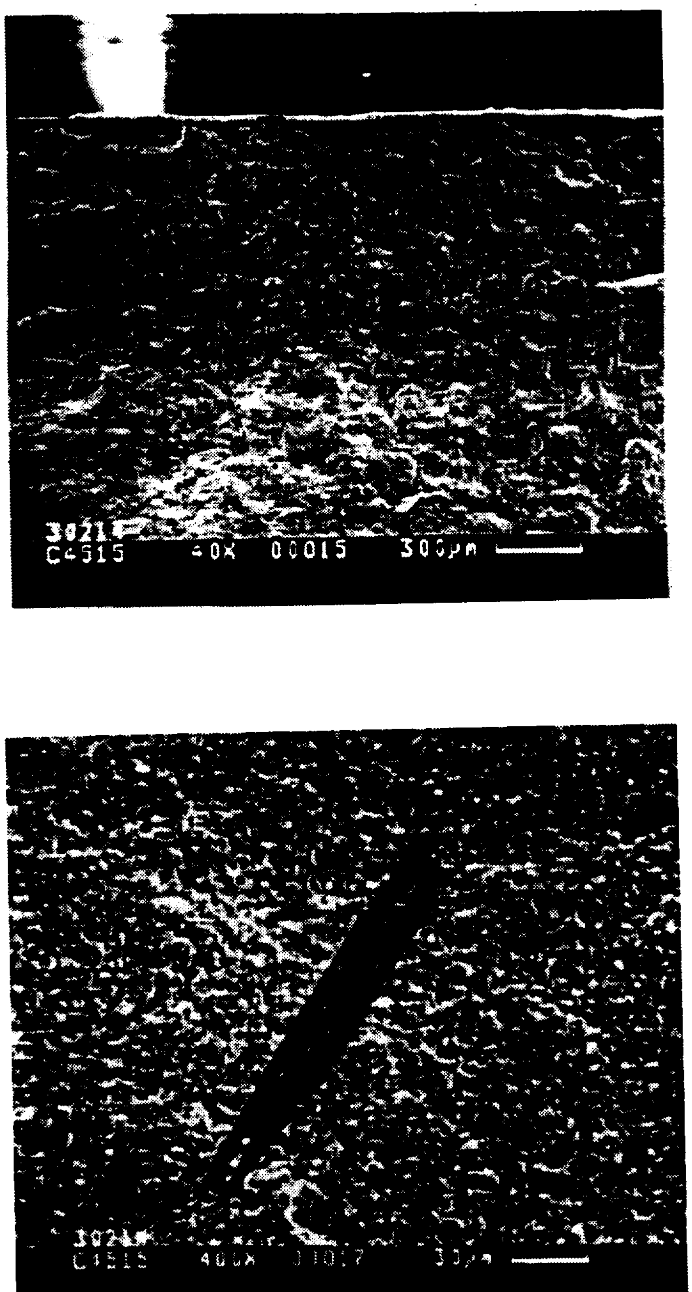


Figure 106. SN-251 Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.



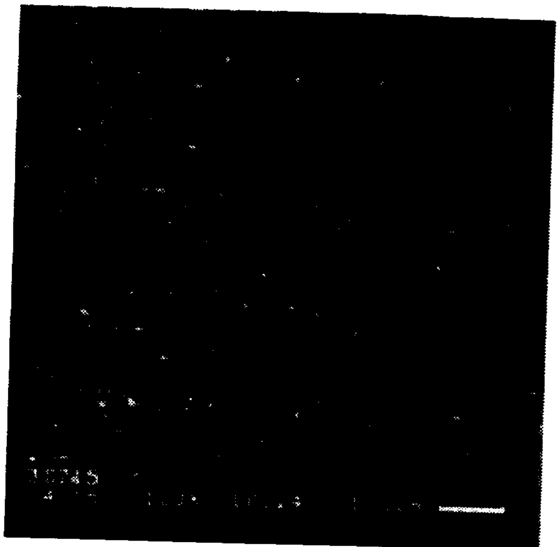
G6253-107

Figure 107. SN-251 Specimen Failure Originating From Oxidation Pit Following 700 Hours Exposure At 1204C (2200F).

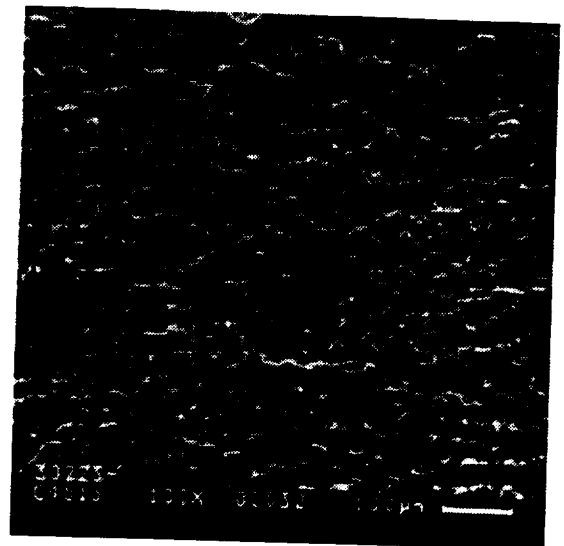


G6253-108

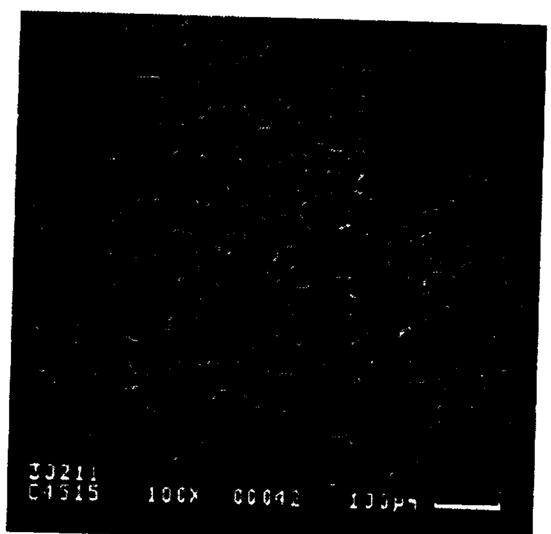
Figure 108. SN-251 Specimen Failure Originating From Large Si_3N_4 Grain Following 350 Hours Exposure At 1204C (2200F).



(a) 350 Hours



(b) 700 Hours



(c) 1050 Hours

G6253-109

Figure 109. SN-251 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1204C (2200F): (a) 350 Hours; (b) 700 Hours; (c) 1050 Hours.

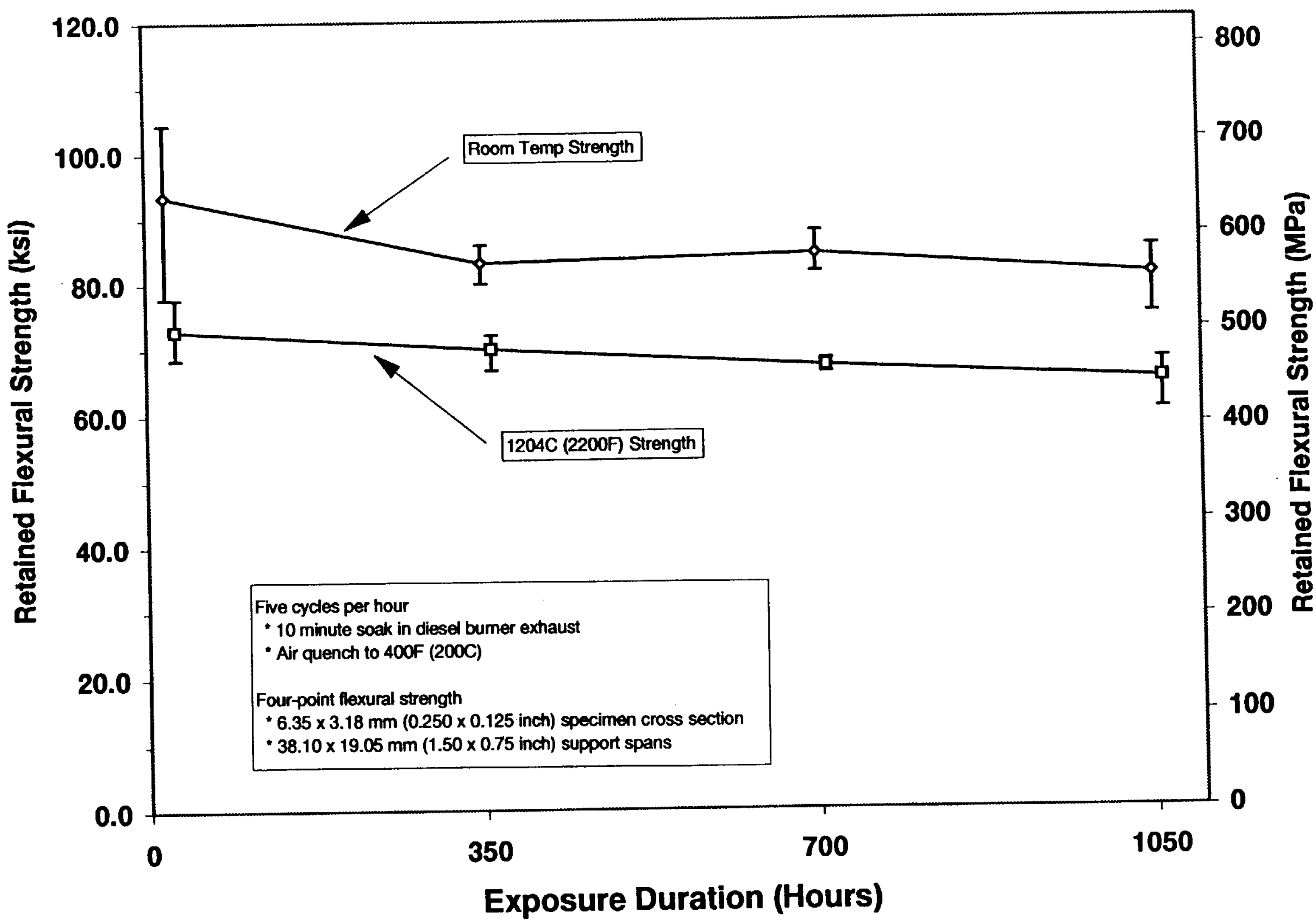
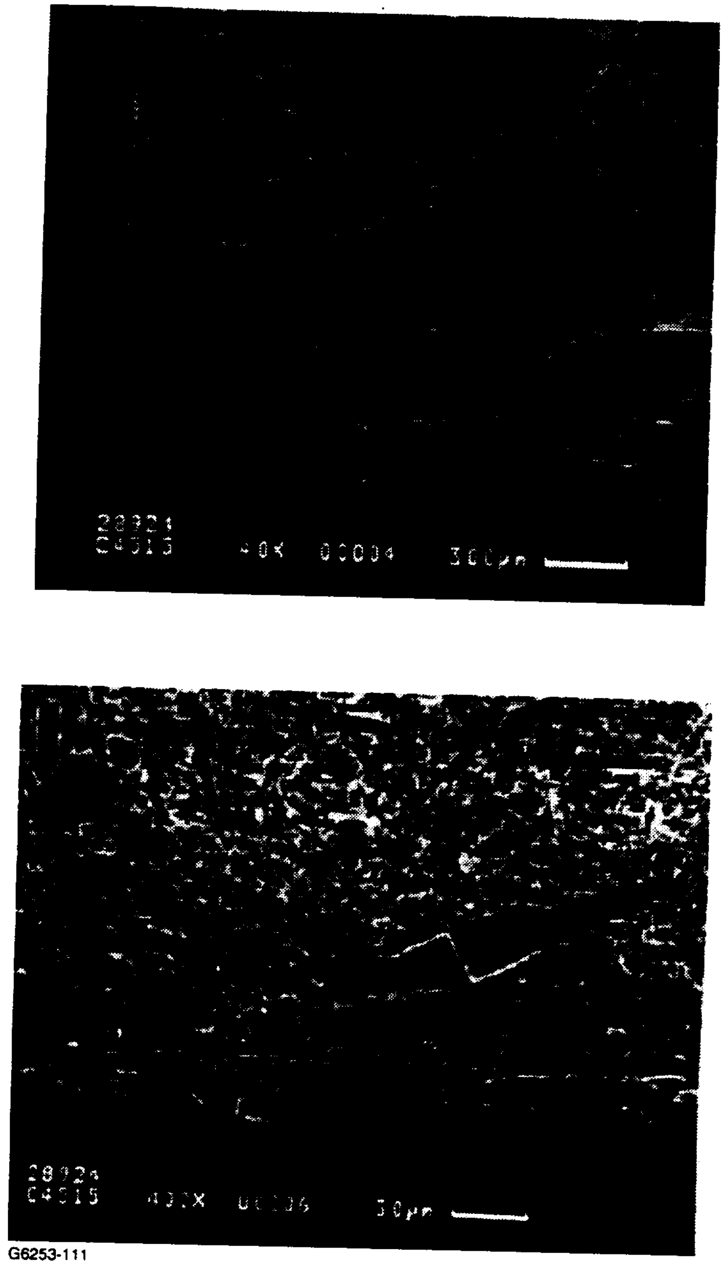
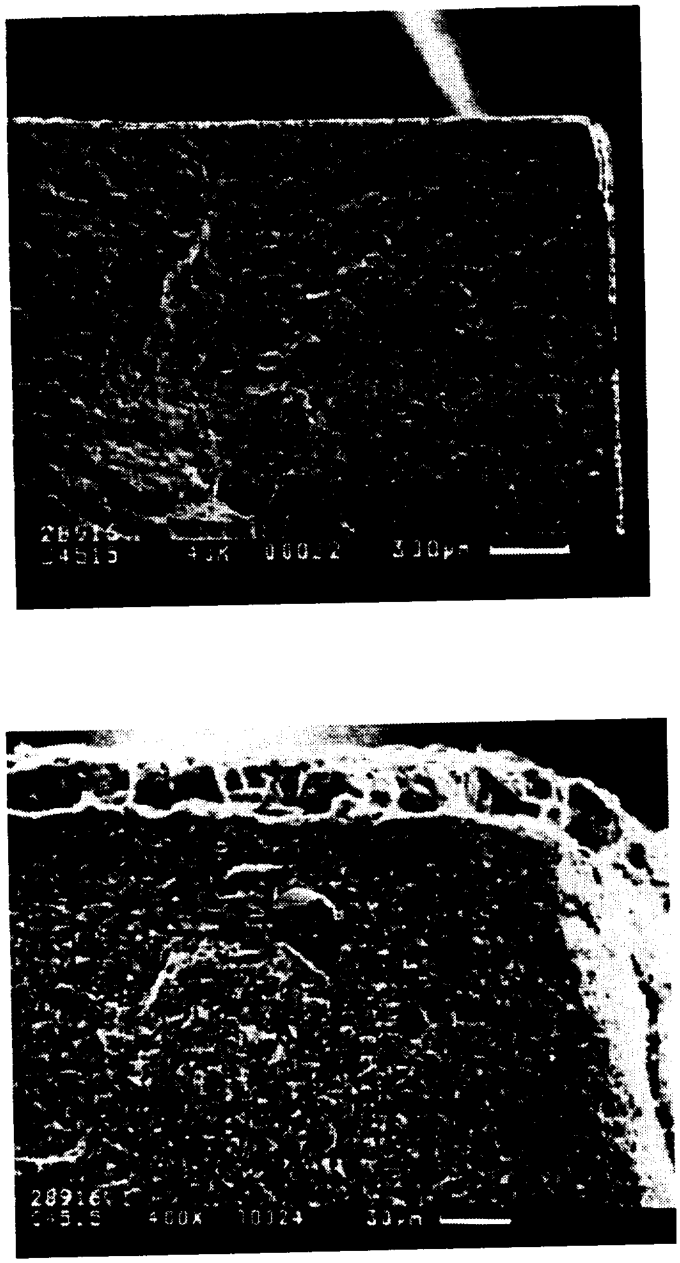


Figure 110. SN-252 Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.



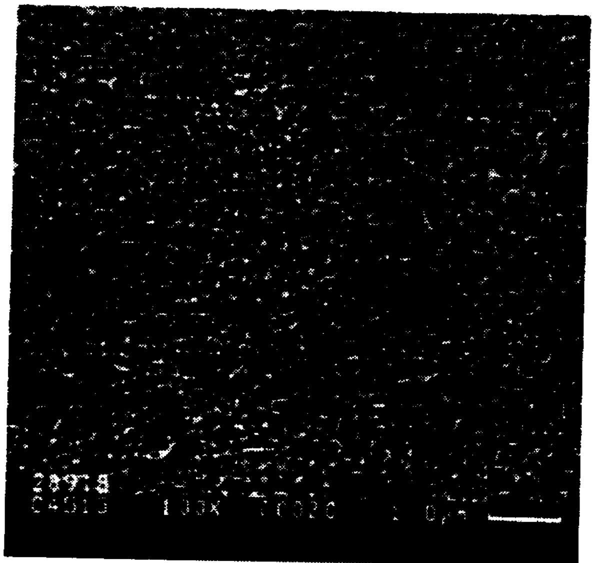
G6253-111

Figure 111. SN-252 Specimen Failure Originating From Large Si_3N_4 Grain Following 700 Hours Exposure At 1204C (2200F).

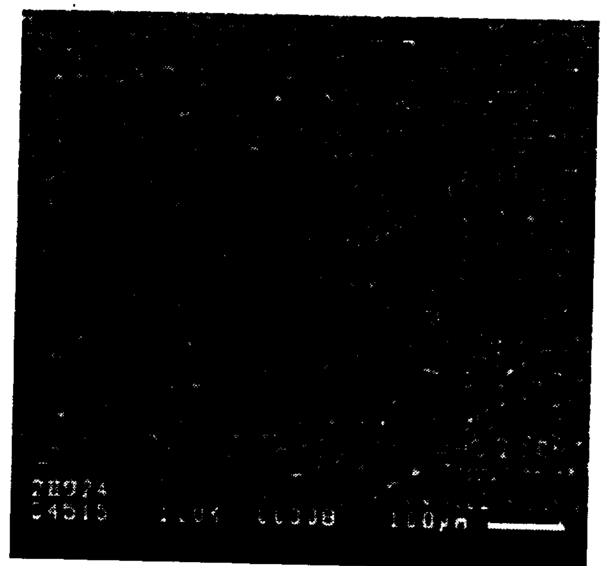


G6253-112

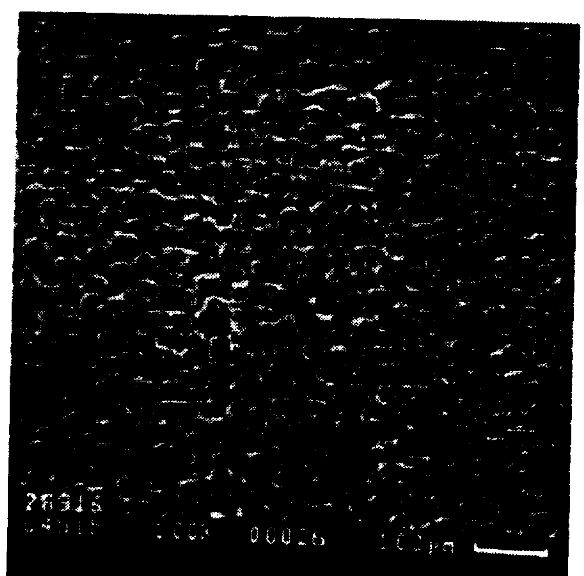
Figure 112. SN-252 Specimen Failure Originating From Large Si_3N_4 Grain Following 1050 Hours Exposure At 1204C (2200F).



(a) 350 Hours



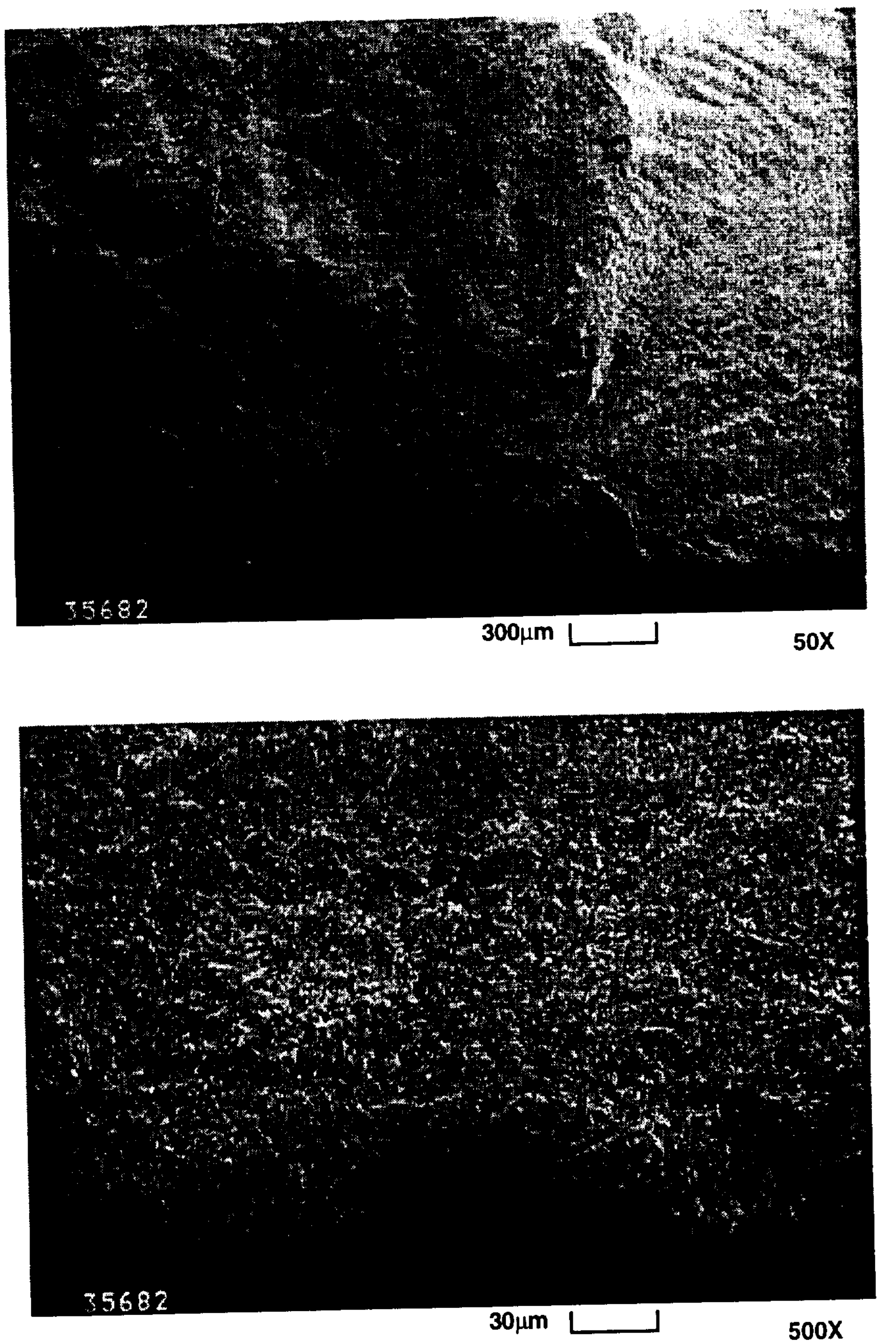
(b) 700 Hours



(c) 1050 Hours

G6253-113

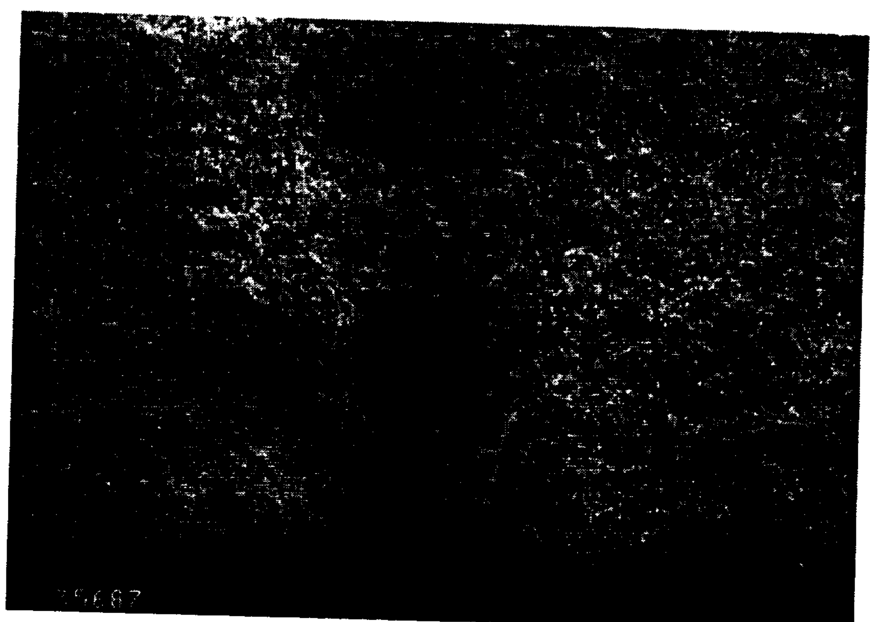
Figure 113. SN-252 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1204C (2200F): (a) 350 hours; (b) 700 Hours; (c) 1050 Hours.



G6253-114

Figure 114. SN-253 Baseline Test Specimen Failure Originating From Pit In As-Processed Surface.

300μm 50X



30μm 500X

G6253-115

Figure 115. SN-253 Baseline Specimen Failure Originating From A Pock (Partially-Enclosed Surface Cavity) In As-Processed Surface.

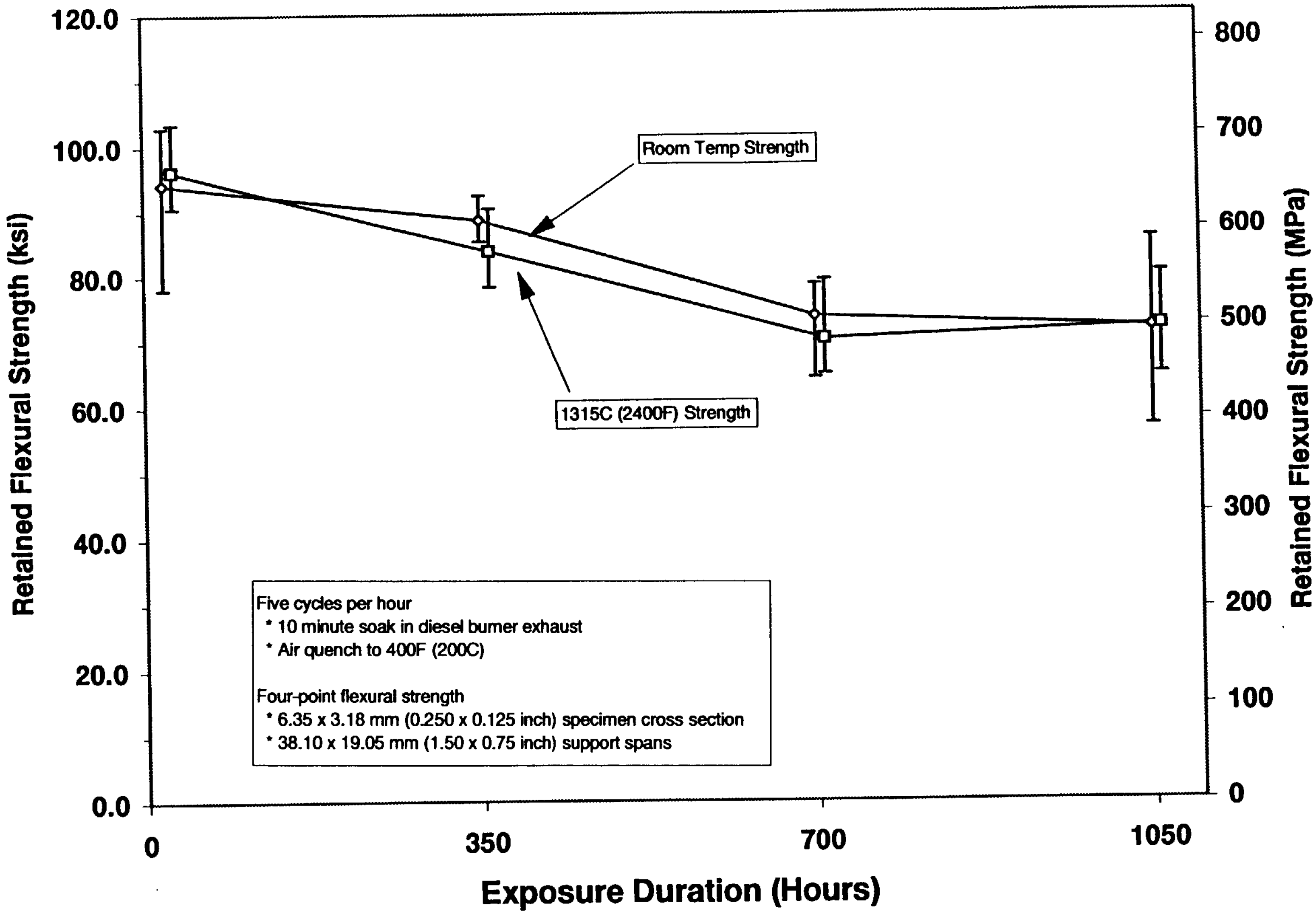
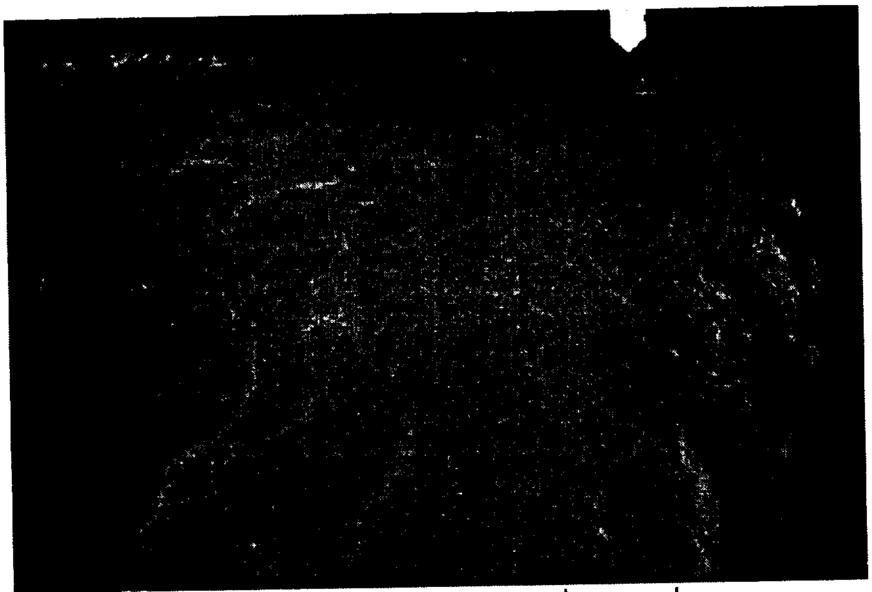
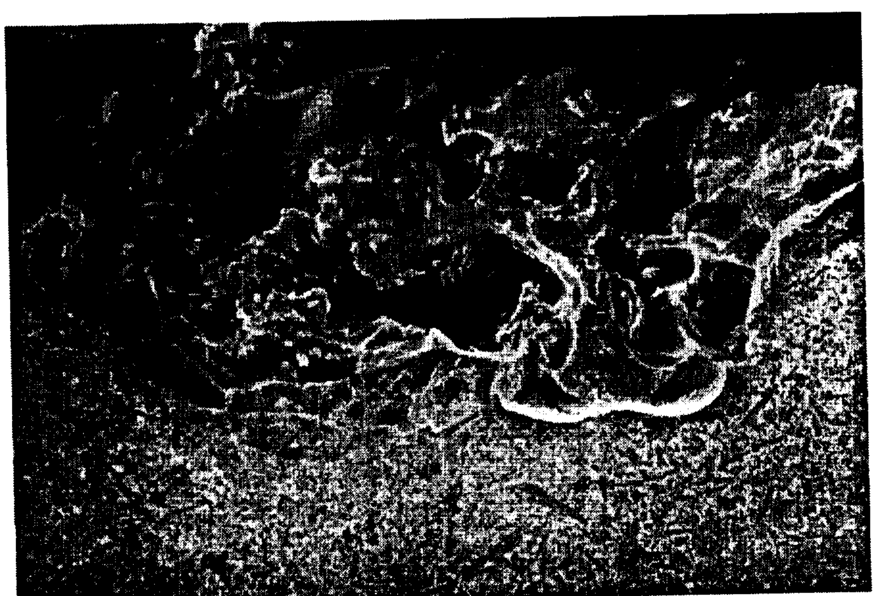


Figure 116. SN-253 Room-Temperature And 1316C (2400F) Strength Test Results Following 1316C (2400F) Cyclic Oxidation Durability Testing.

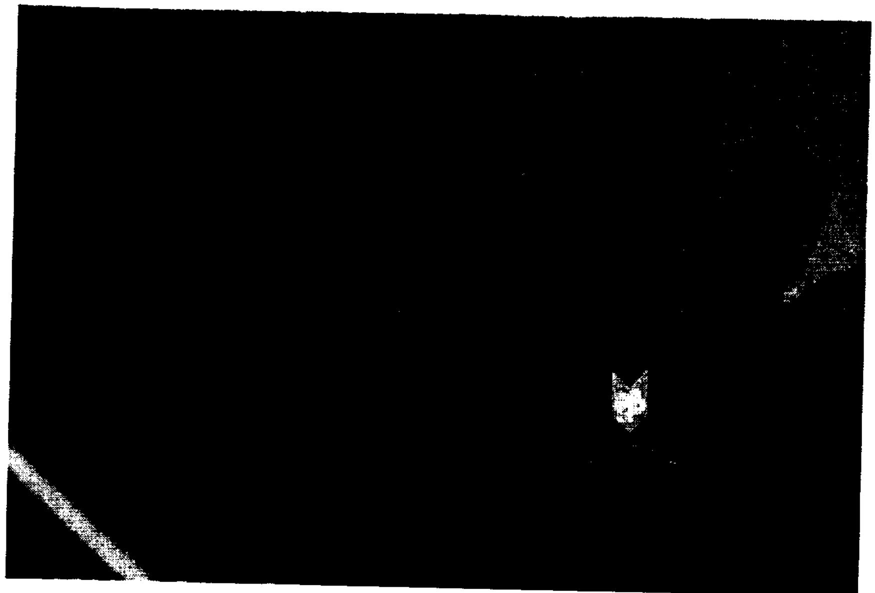
Figure 117. SN-253 Specimen Failure Originating From Oxidation Pit Following 350 Hours Exposure At 1316C (2400F).





G6253-118

Figure 118. SN-253 Specimen Failure Originating From Oxidation Pit Following 700 Hours Exposure At 1316C (2400F).



(View of Flame Exposed Surface)

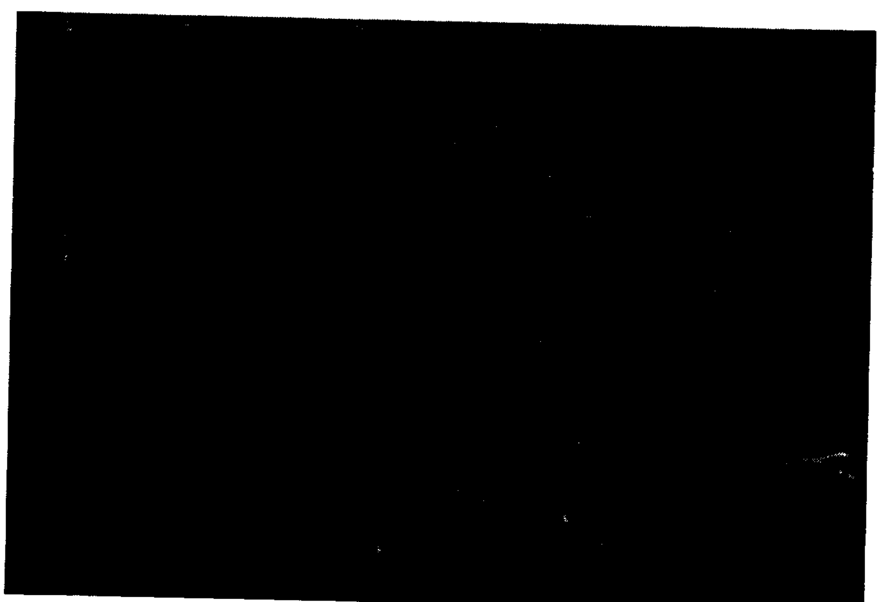


Figure 119. SN-253 Specimen Failure Originating From Large Surface Pit On Specimen Edge Following 700 Hours Exposure At 1316C (2400F).

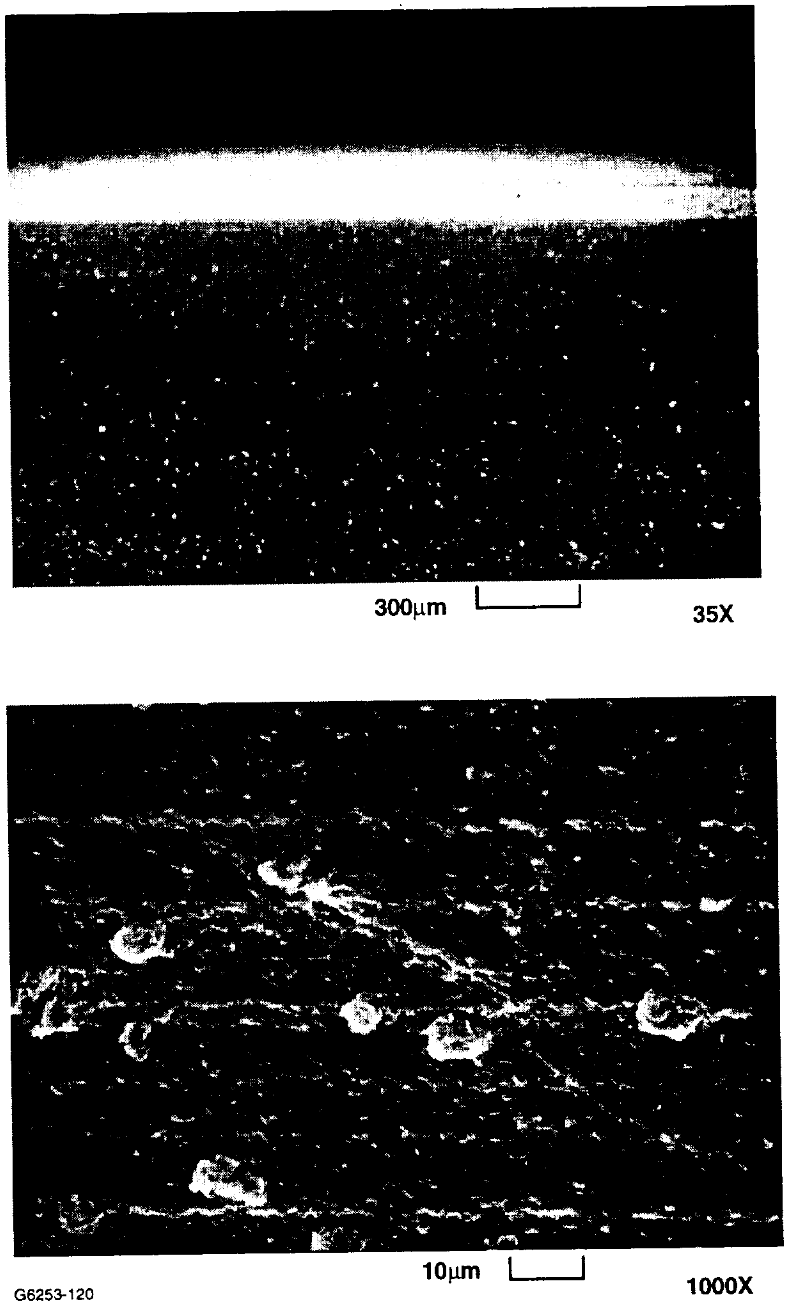
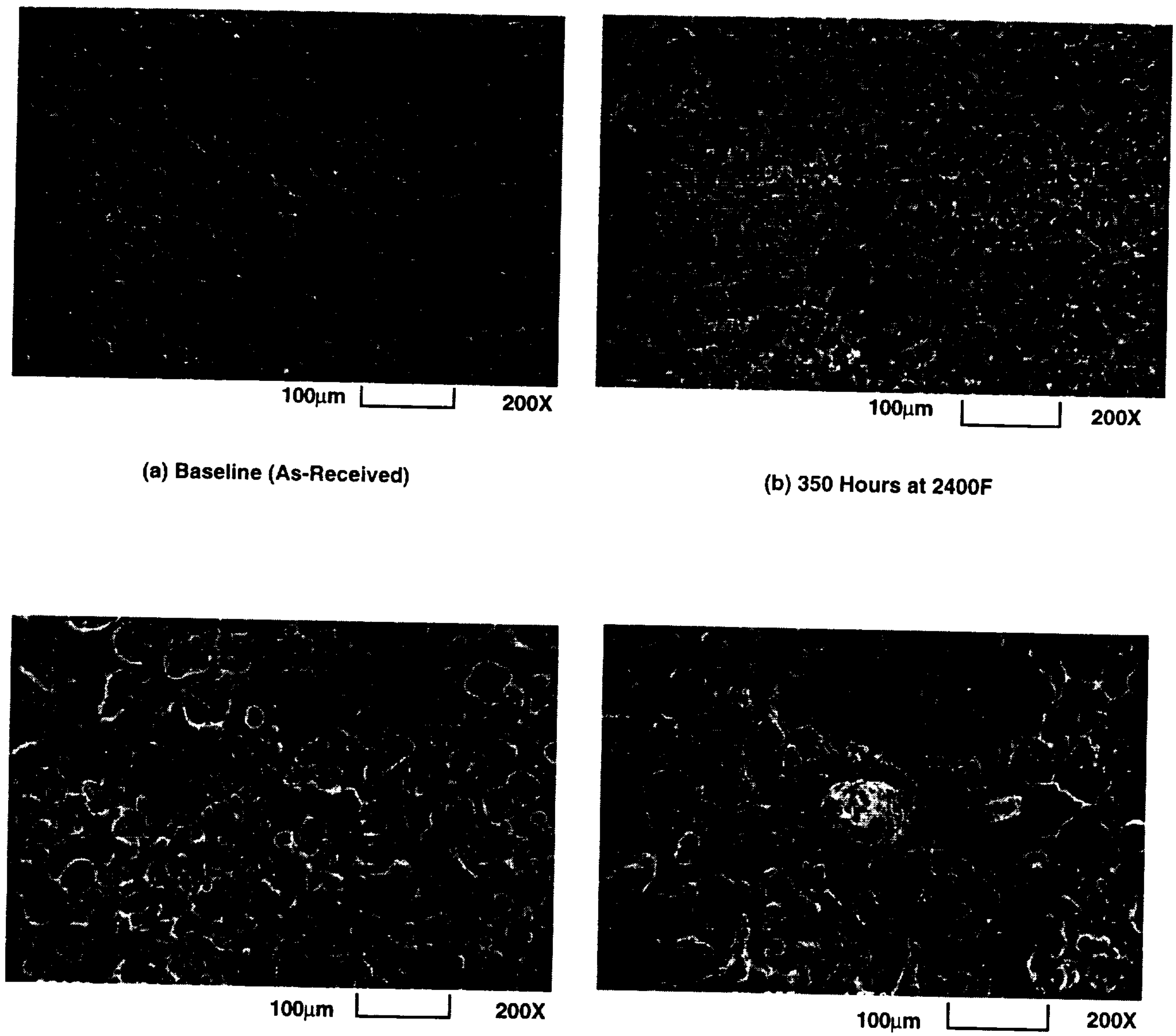


Figure 120. SN-253 Specimen Exhibiting Cracks Emanating From Local Discoloration (White Spot) In Cooler Specimen Attachment Area Following 700 Hours Exposure At 1316C (2400F).

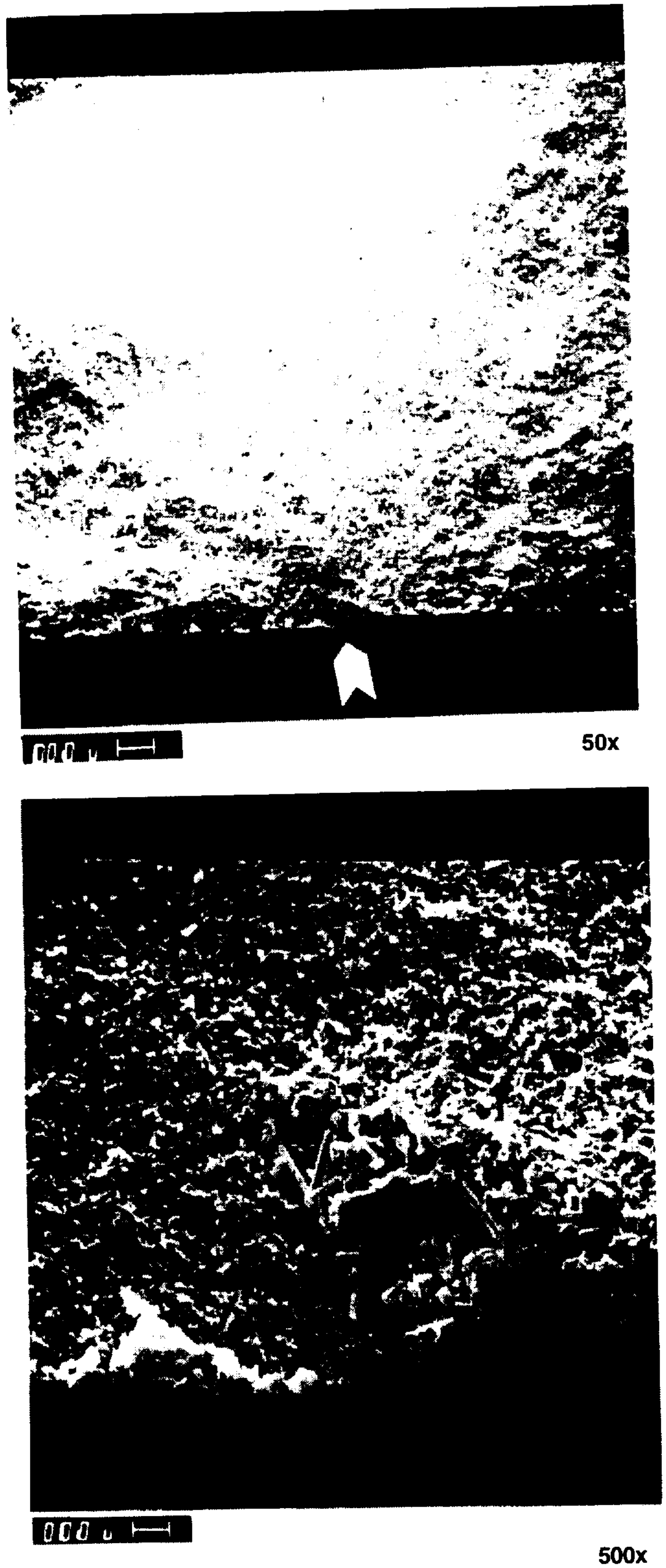


G6253-121

(c) 700 Hours at 2400F

(d) 1050 Hours at 2400F

Figure 121. SN-253 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1316C (2400F): (a) Baseline (Zero Hours); (b) 350 Hours; (c) 700 Hours; (d) 1050 Hours.



G6253-122

Figure 122. Typical SN-260 Baseline Specimen Failure Originating From Pit In As-Processed Surface.

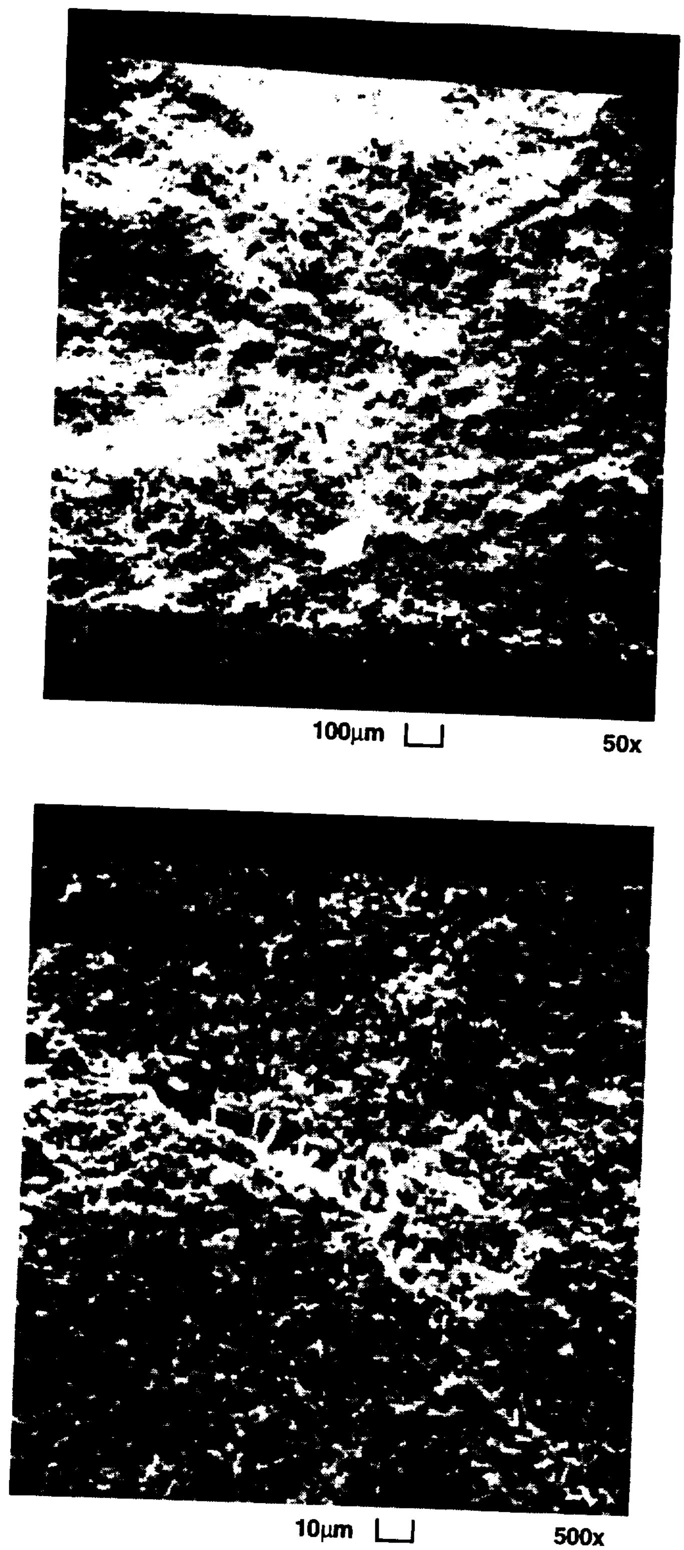


Figure 123. SN-260 Baseline Specimen Failure Originating From Internal Porosity.

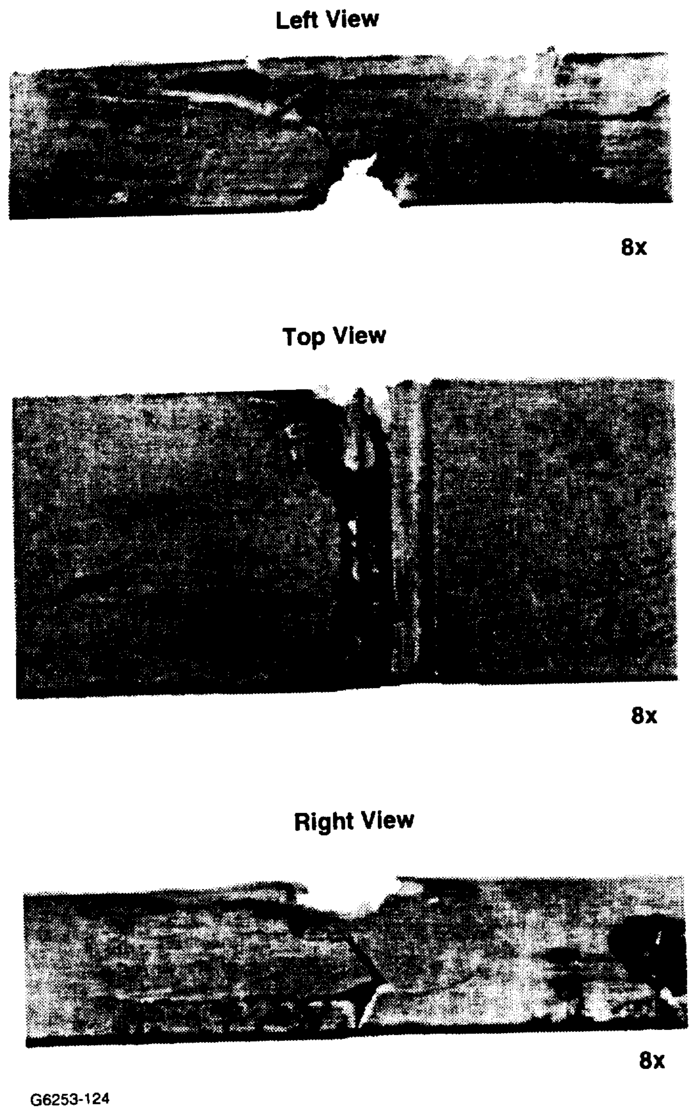


Figure 124. Cracks Observed In SN-260 Cyclic Durability Test Specimens Originating From Notch Used For Fixturing Test Bars In Durability Specimen Holder.

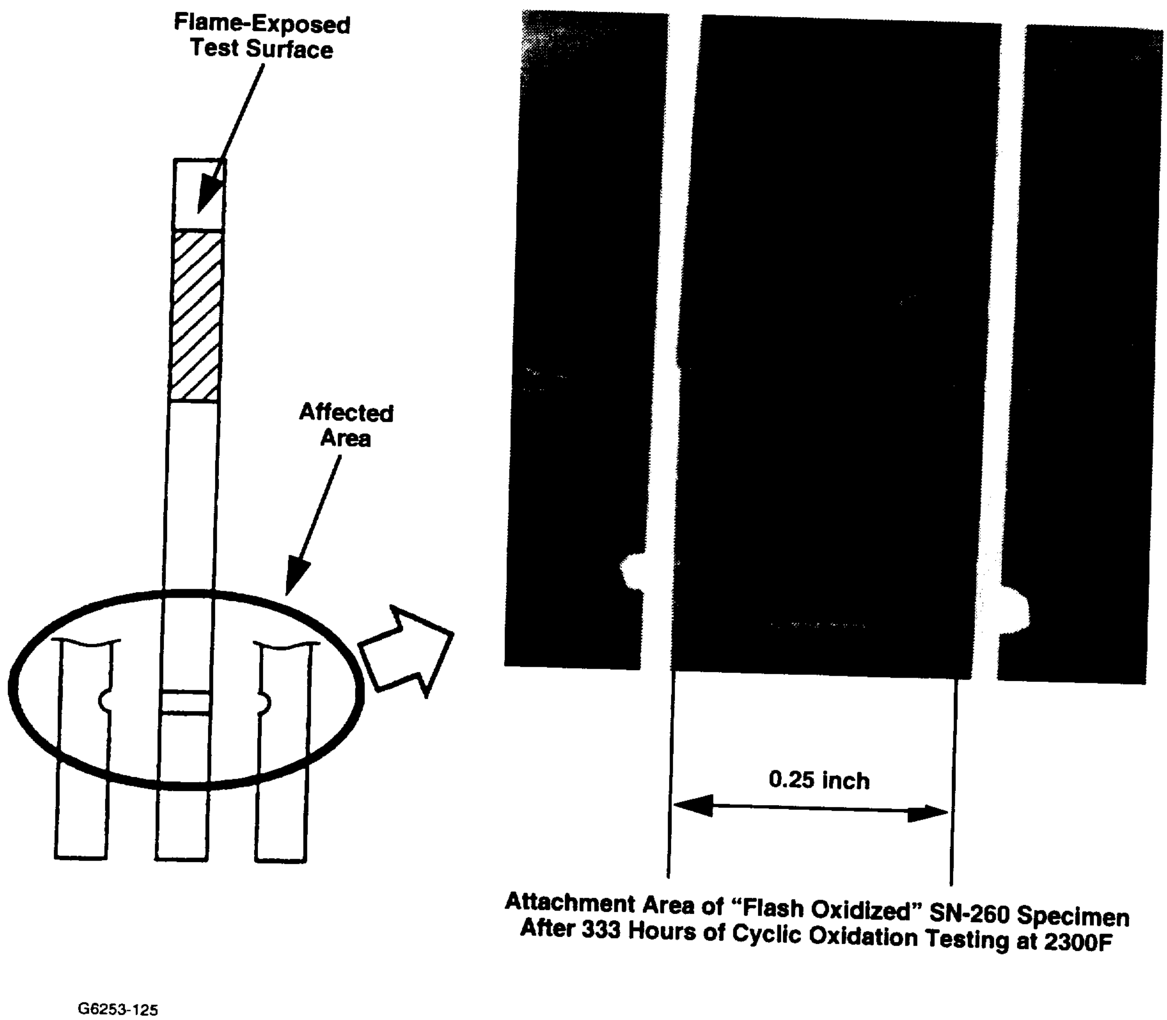


Figure 125. Cracks Observed In SN-260 Specimens From Second Cyclic Oxidation Test Originated Approximately 0.25 inch (0.6 cm) Above Notch In Attachment Area.

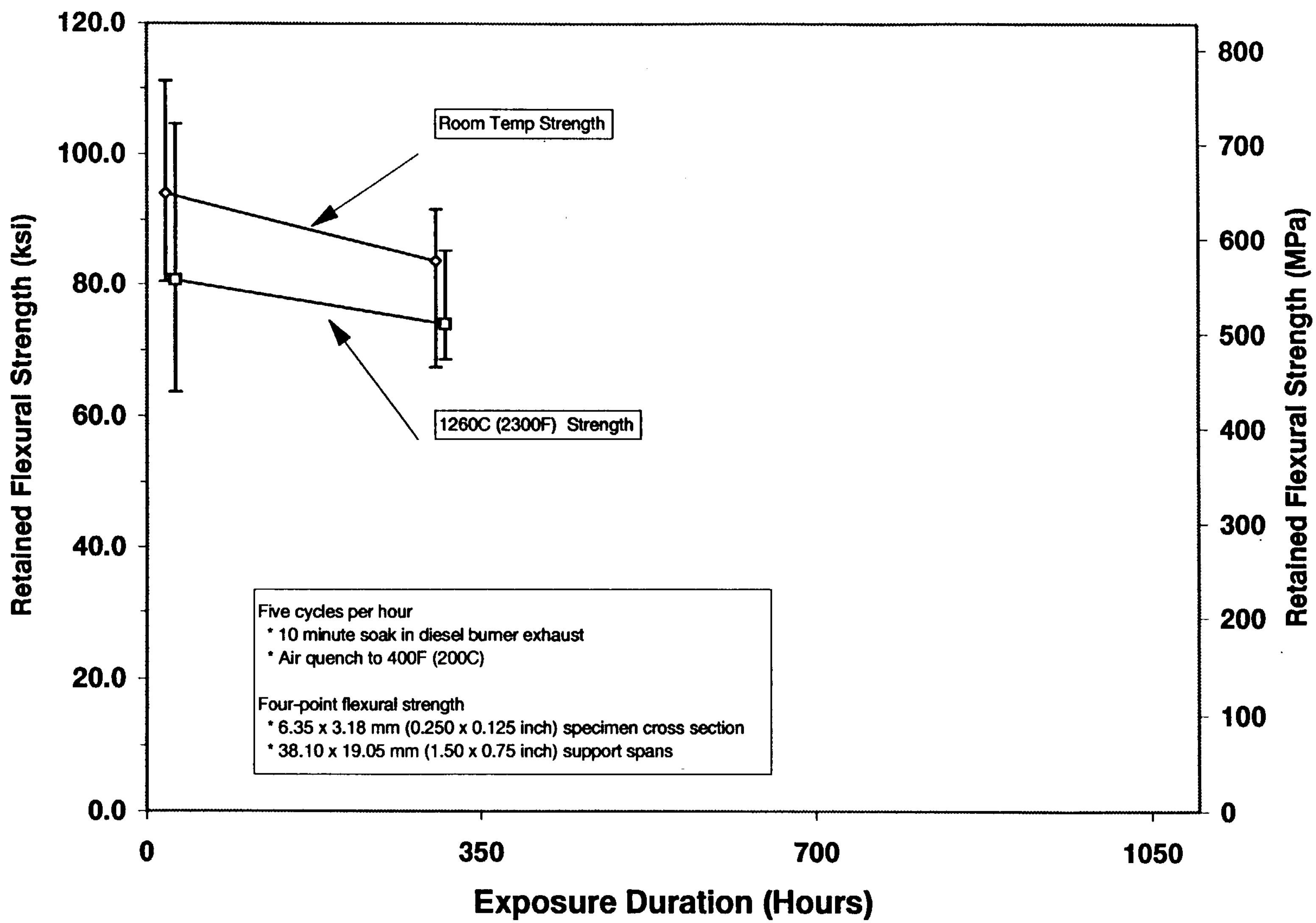


Figure 126. SN-260 Post-Exposure Room-Temperature And 1260C (2300F) Strength Test Results Following 1260C (2300F) Cyclic Oxidation Durability Testing.

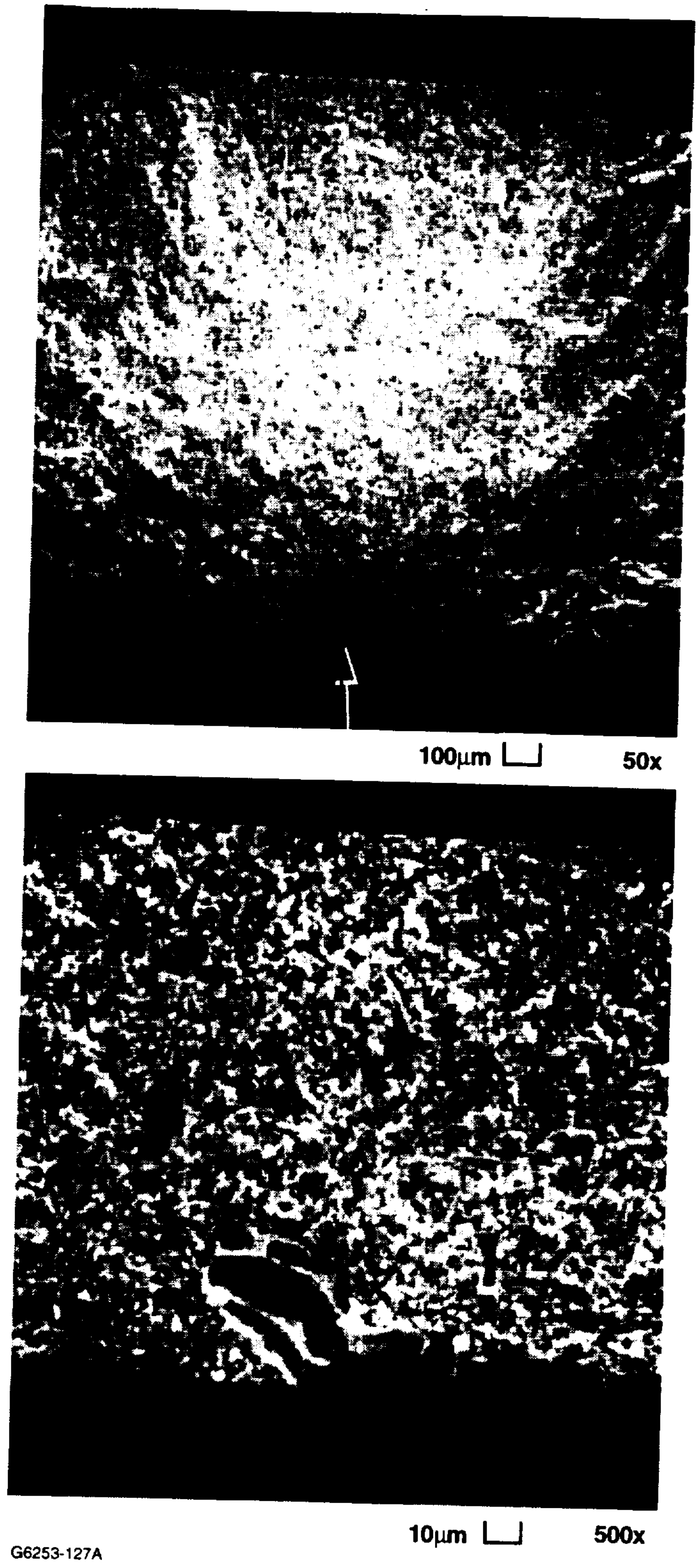


Figure 127. SN-260 Specimen Failure Originating From Oxidation Pit Following 303 Hours Exposure At 1260C (2300F).

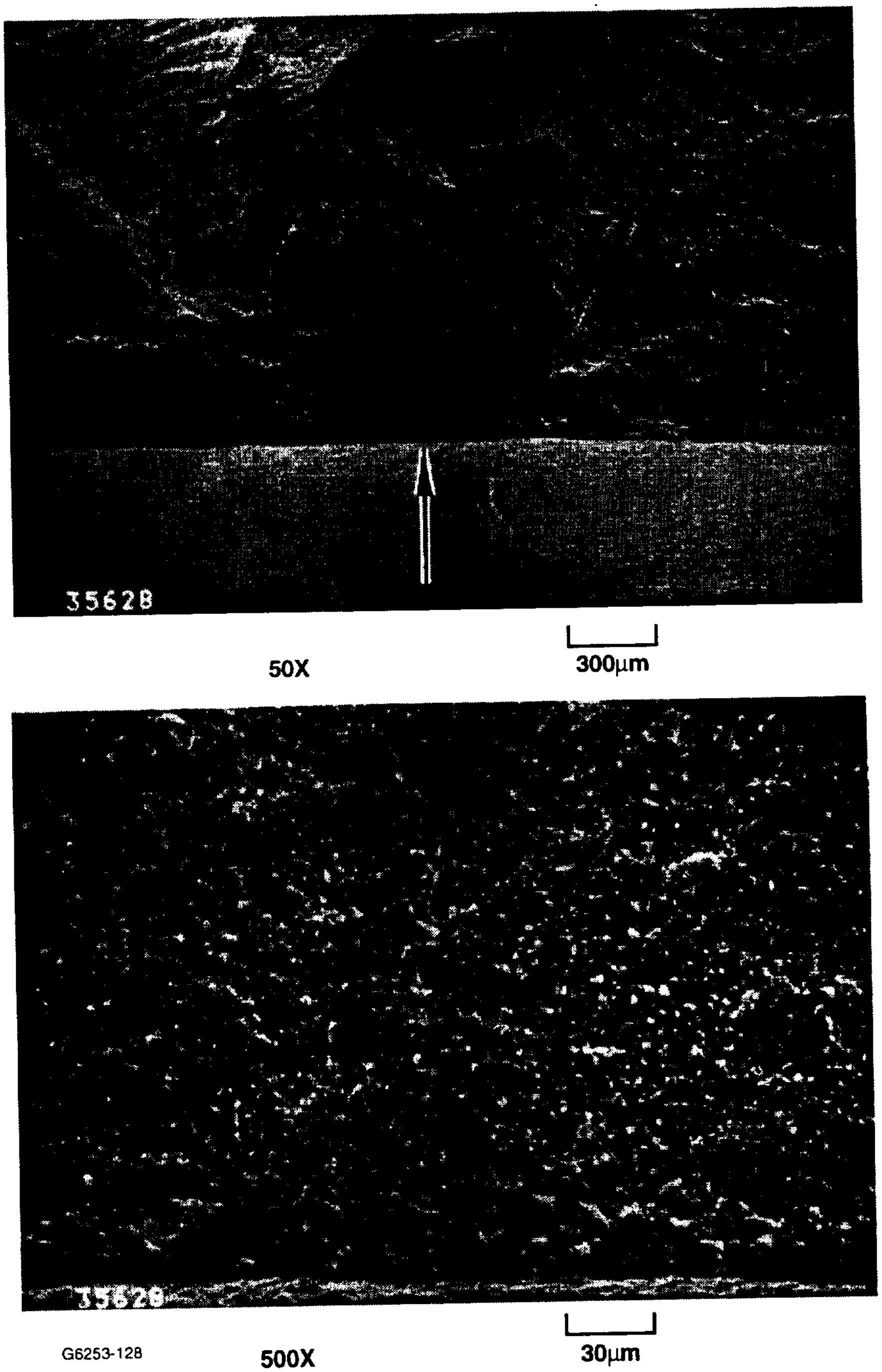
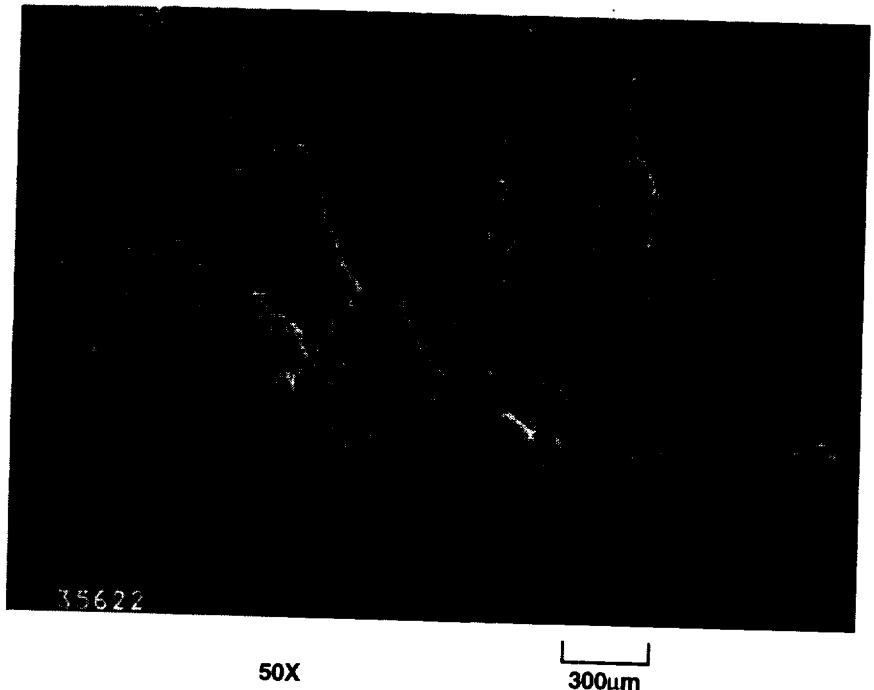
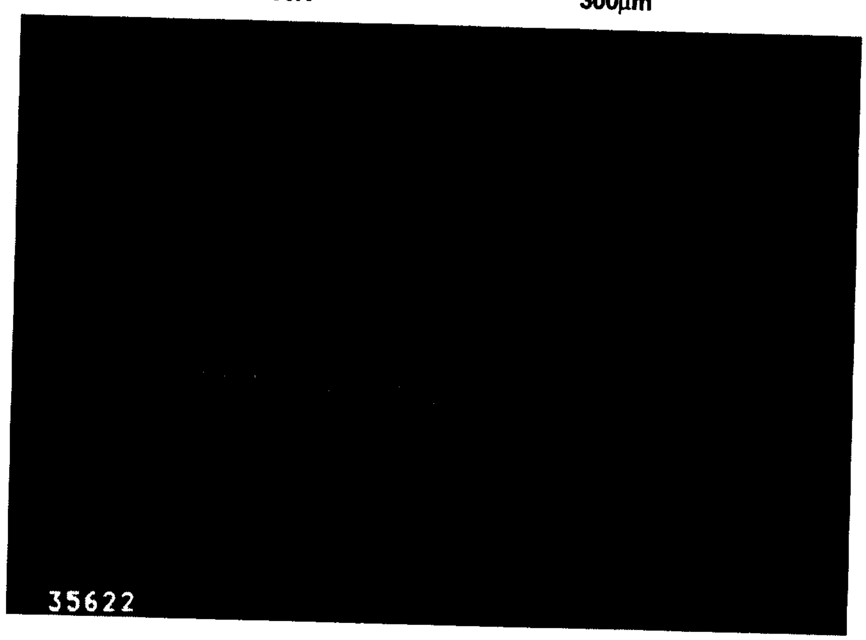


Figure 128. SN-281 Baseline Test Specimen Failure Originating From As-Processed Surface.

(a) SEM Photomicrograph (50x Magnification)





G6253-129 (b) WDX Element Map for Sintering Additive Constituent

Figure 129. SN-281 Baseline Test Specimen Exhibited A Stringer-Like Concentration Of Sintering Additive.

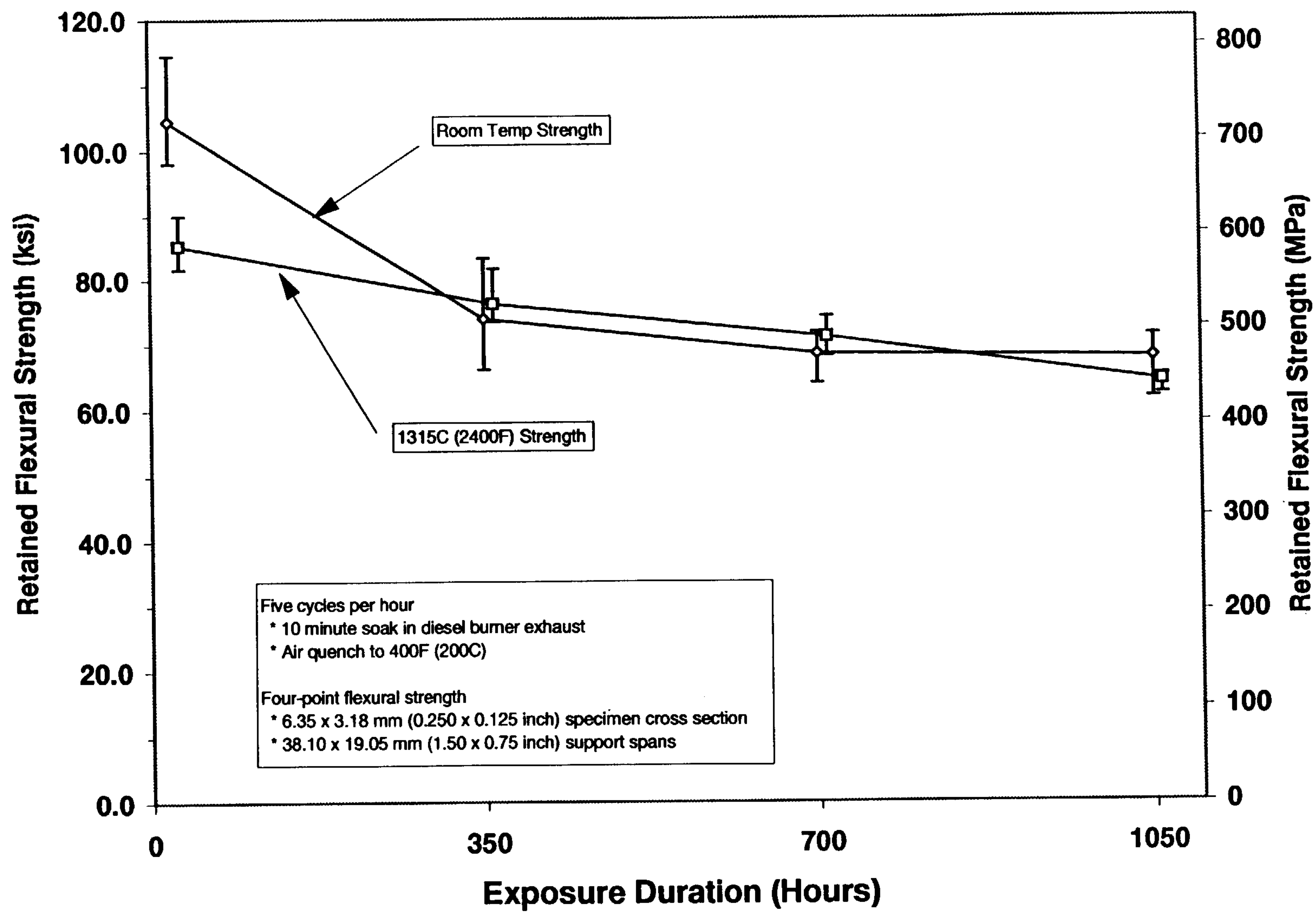
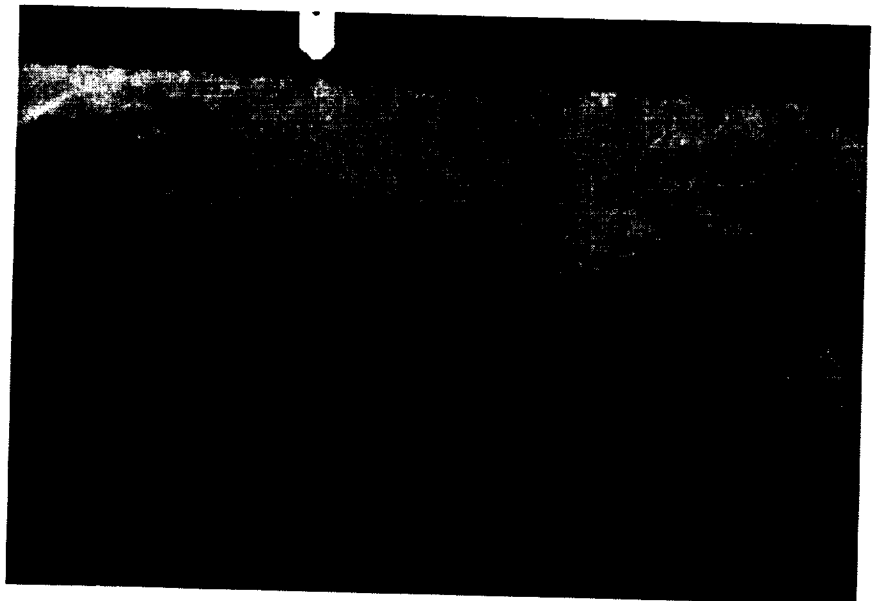


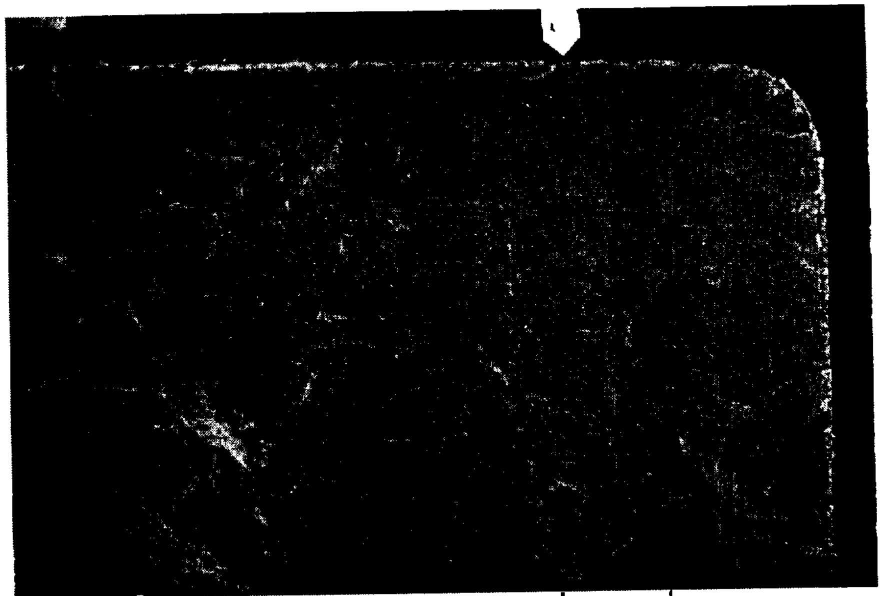
Figure 130. SN-281 Post-Exposure Room-Temperature And 1316C (2400F) Strength Test Results Following 1316C (2400F) Cyclic Oxidation Durability Testing.



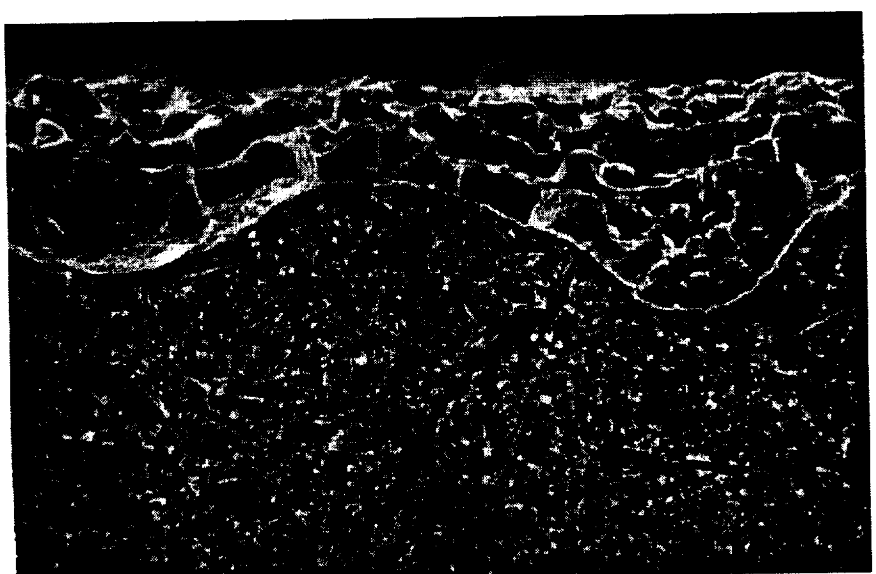
50X 300μm

G6253-131 500X 30μm

Figure 131. SN-281 Specimen Failure Originating From Oxidation Pit Following 700 Hours Exposure At 1316C (2400F.



50X 300μm



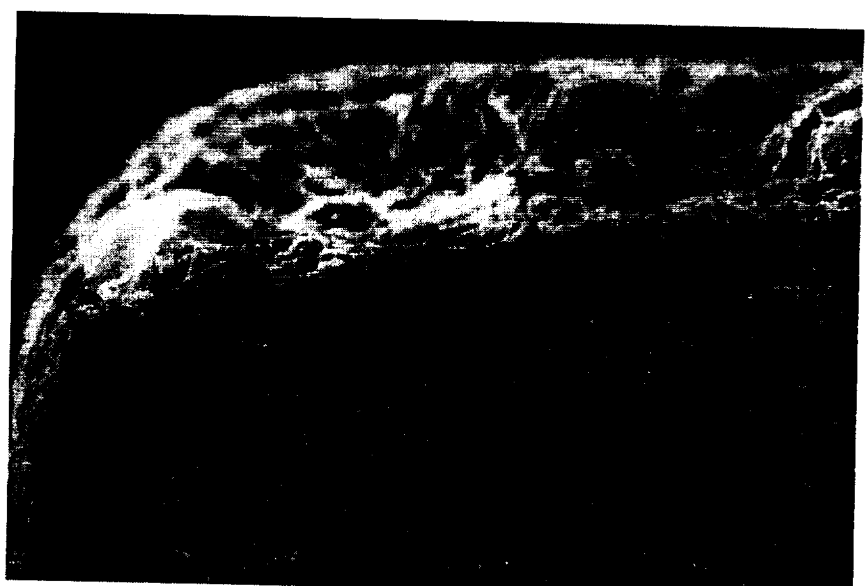
500X 30μm

G6253-132

Figure 132. SN-281 Specimen Failure Originating From Oxidation Pit Following 1050 Hours Exposure At 1316C (2400F).

19X 1000μm

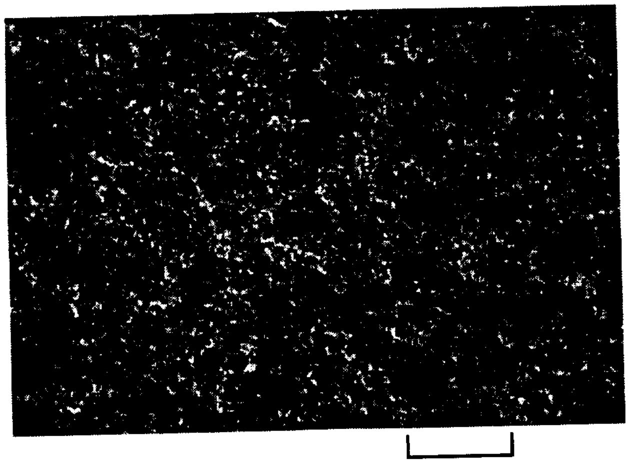
(View of Flame Exposed Surface)



G6253-133

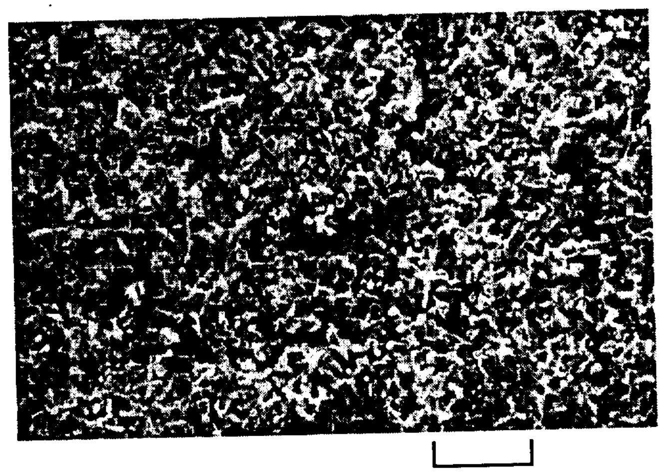
200X 100μm

Figure 133. SN-281 Specimen Failure Originating From Large Surface Pit On Specimen Edge Following 1050 Hours Exposure At 1316C (2400F).



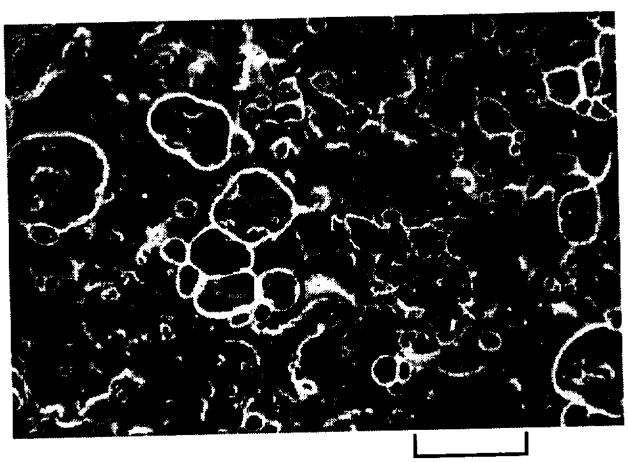
200X 100μm

(a) Baseline (As-Received)



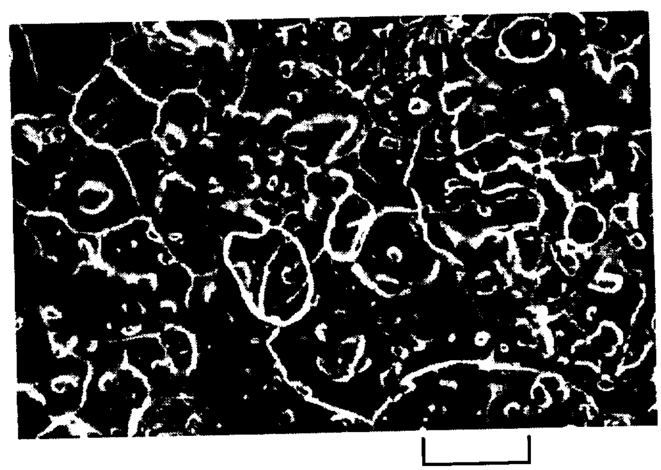
200X 100μm

(b) 350 Hours at 2400F



200X 100μm

(c) 700 Hours at 2400F

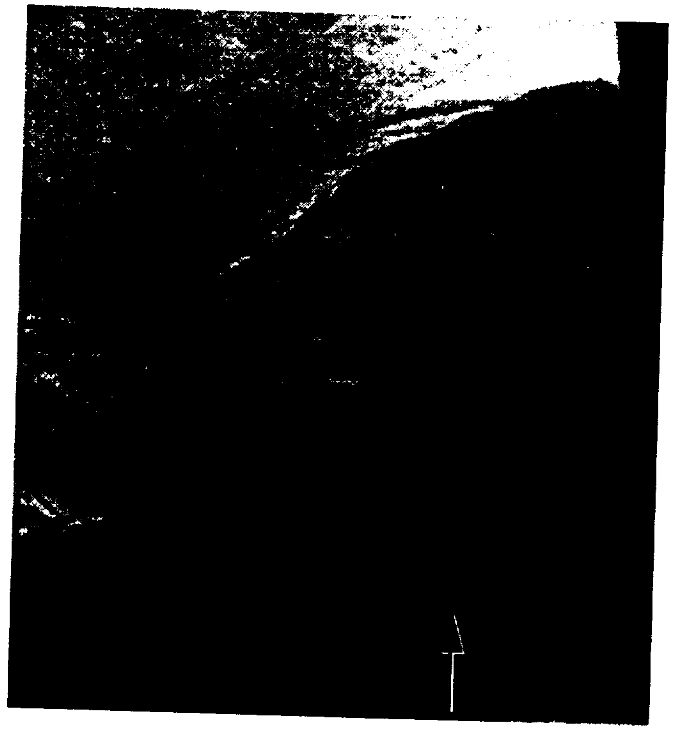


200X 100μm

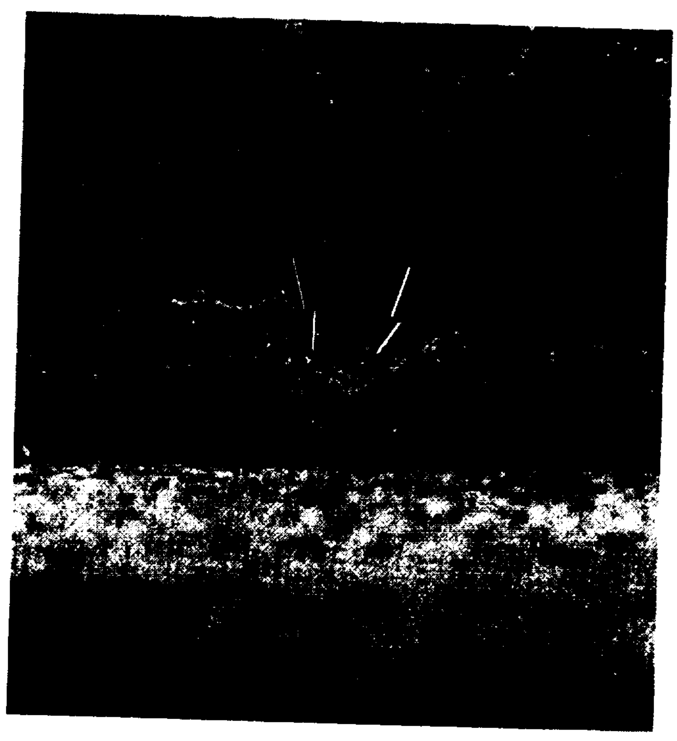
(d) 1050 Hours at 2400F

G6253-134

Figure 134. SN-281 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1316C (2400F): (a) Baseline (Zero Hours); (b) 350 hours; (c) 700 Hours; (d) 1050 Hours.



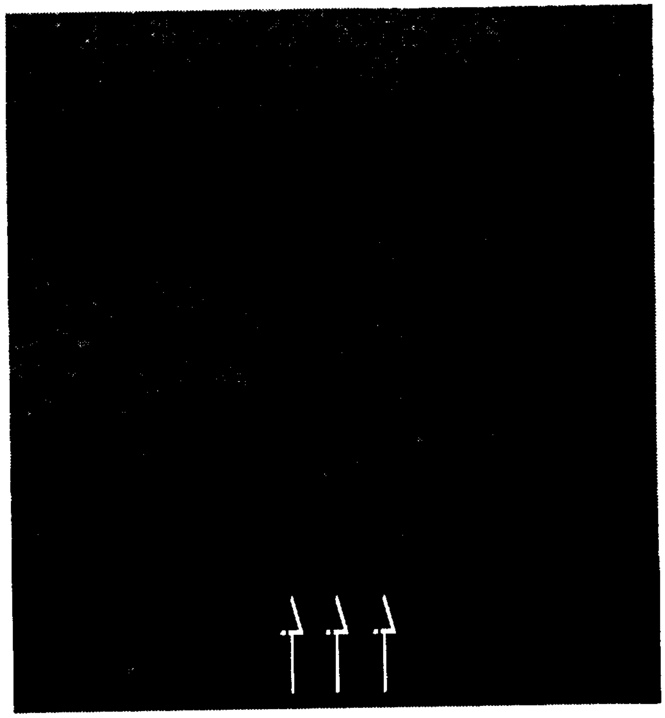
40x



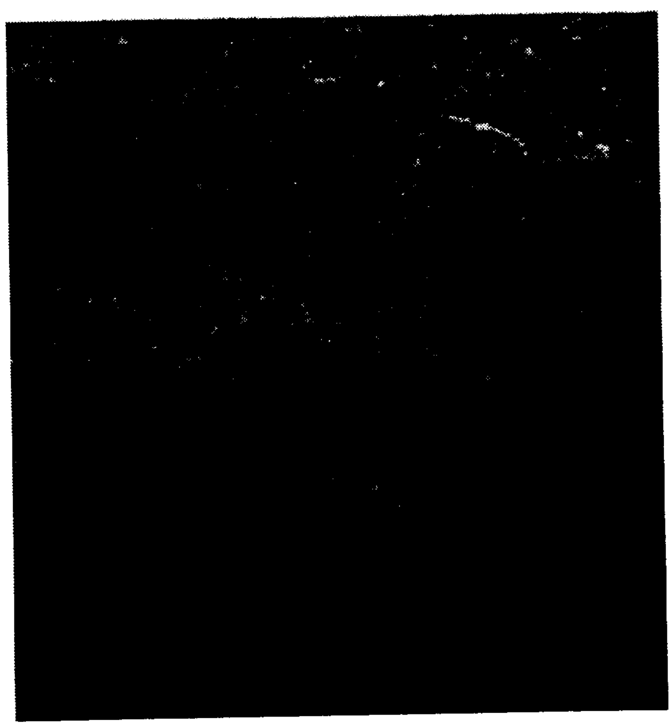
G6253-135

400x

Figure 135. SN-50 Room-Temperature Baseline Test Specimen Failure Originating From Subsurface Porosity.



40x



400x

G6253-136

Figure 136. SN-50 1204C (2200F) Baseline Test Specimen Failure Originating From Area Of Slow Crack Growth.

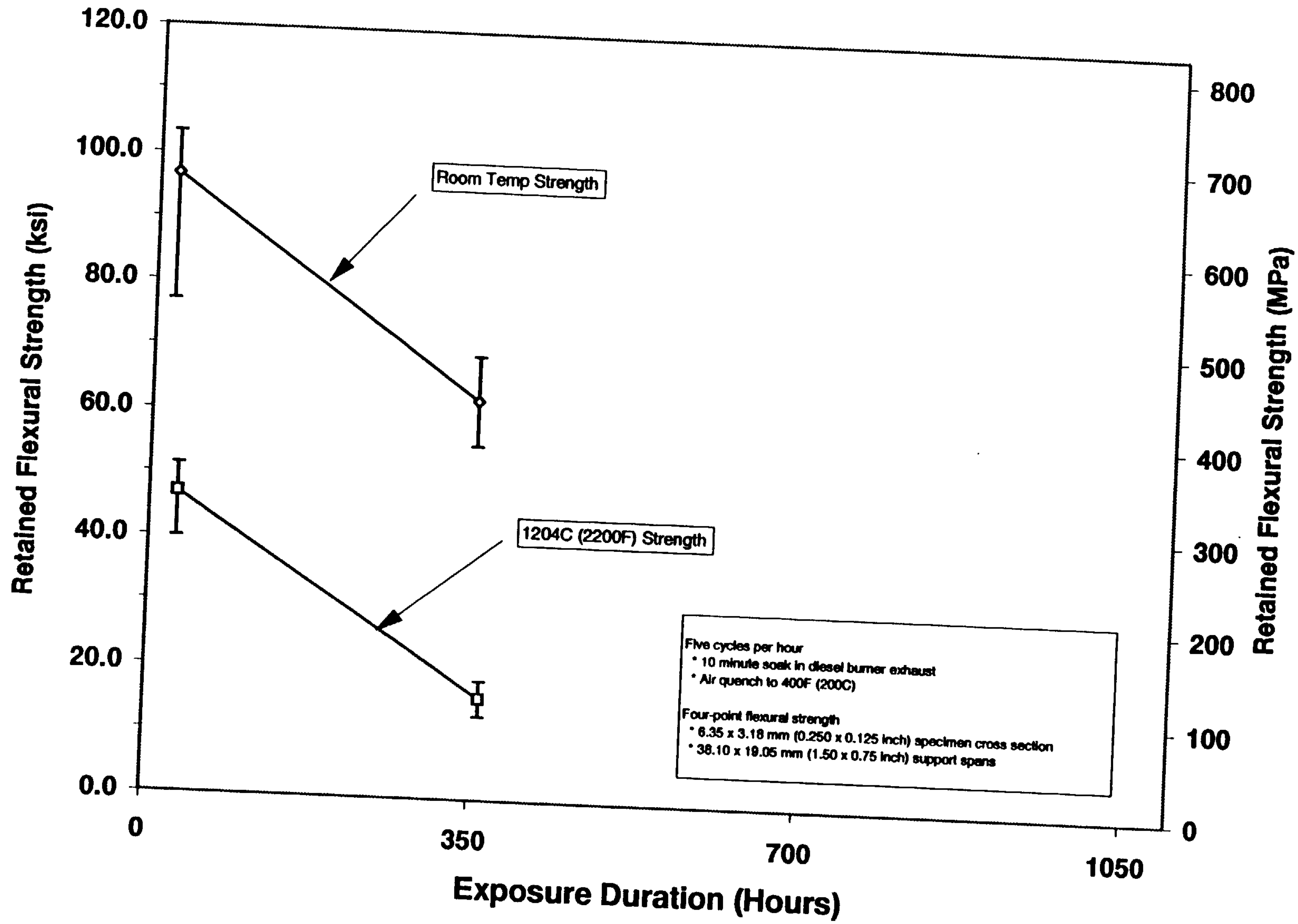
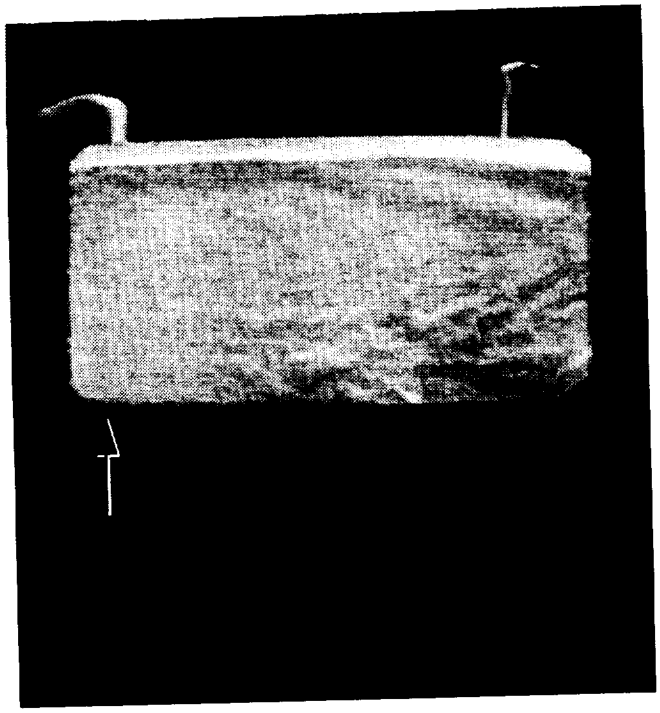
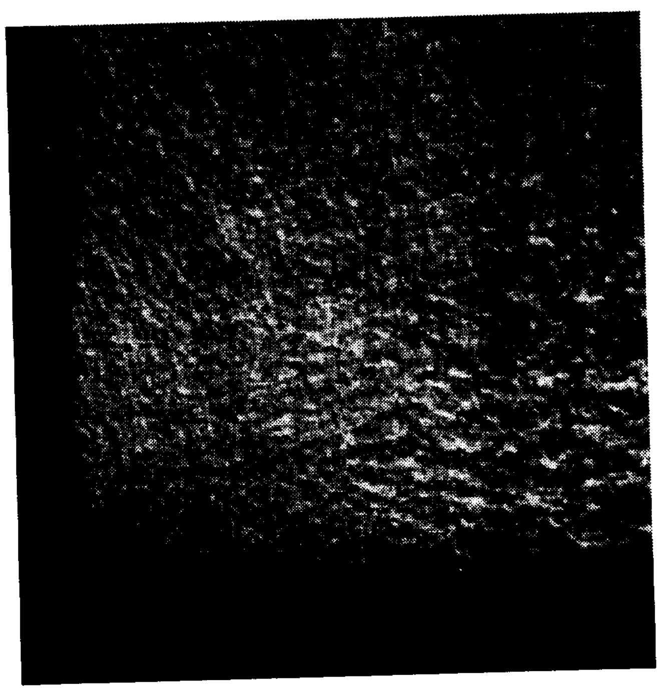


Figure 137. SN-50 Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.



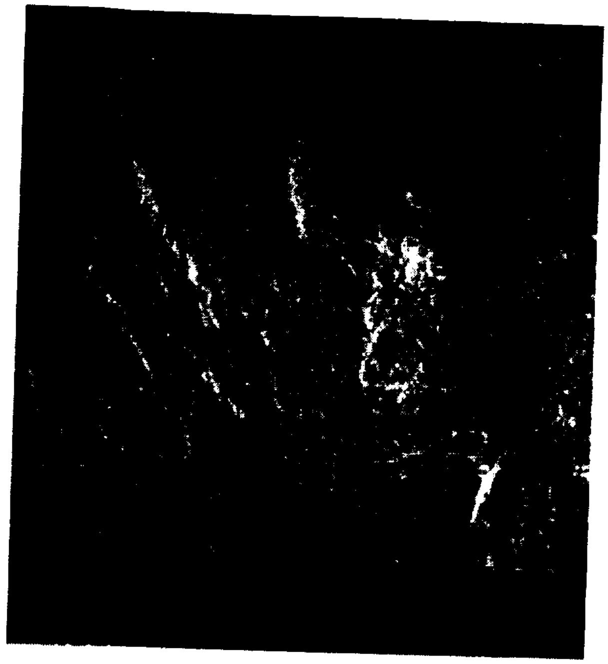
10x



40x

G6253-138

Figure 138. Typical SN-50 Room-Temperature Specimen Failure Originating From Flame-Exposed Surface Following 350 Hours Exposure At 1204C (2200F).



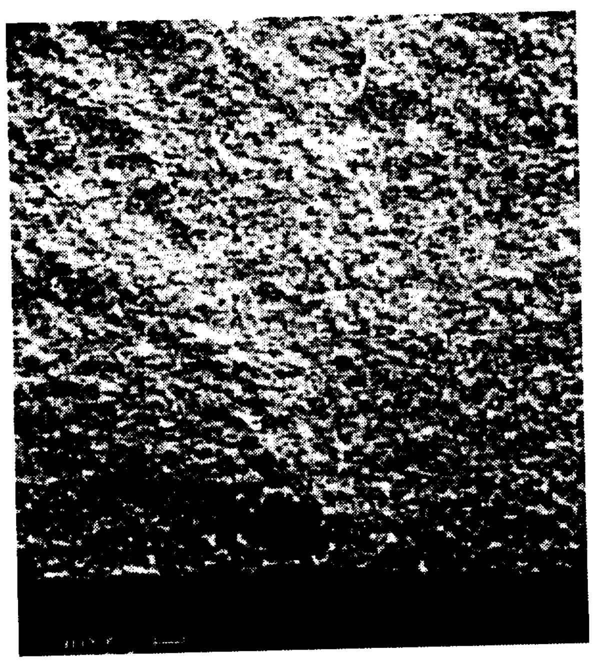
40x

G6253-139

200x

Figure 139. Typical SN-82 Baseline Test Specimen Failure Originating From As-Processed Surface.

200x



400x

G6253-140

Figure 140. Typical SN-82 Baseline Test Specimen Failure Originating From Porosity.

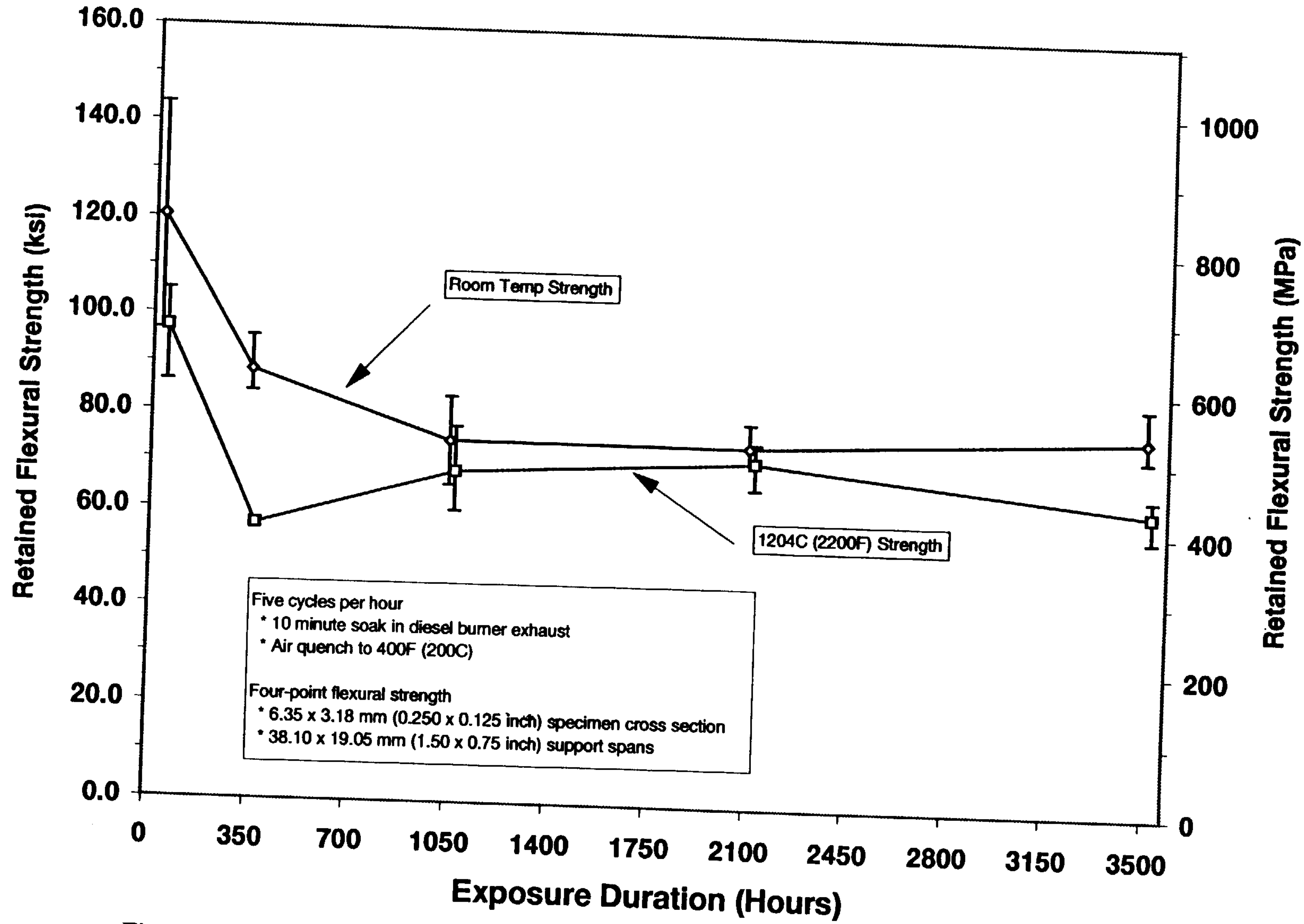
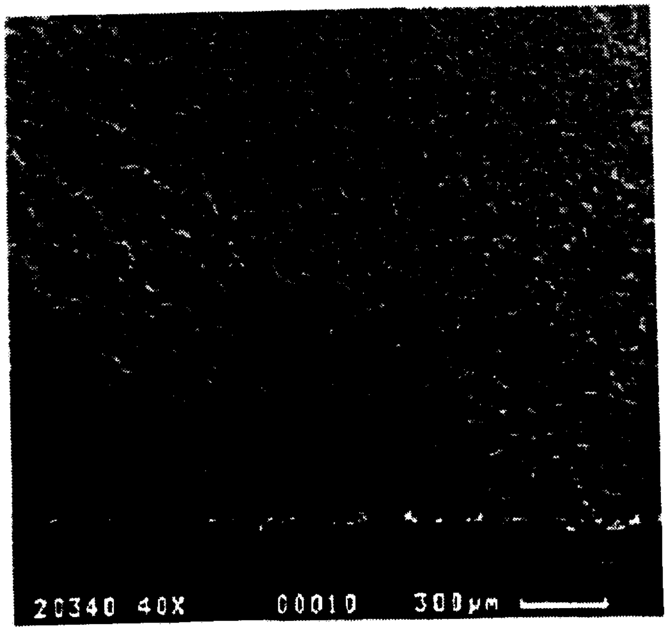
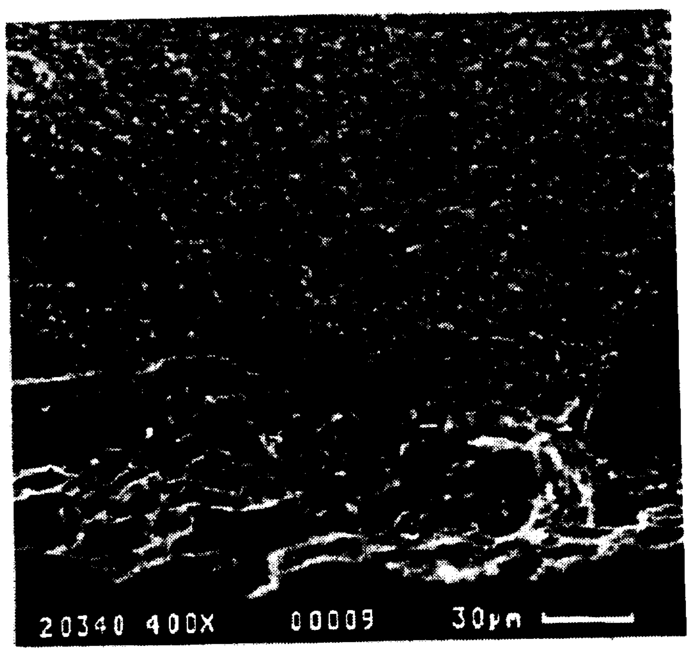


Figure 141. SN-82 Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.



40x



400x

G6253-142

Figure 142. SN-82 Specimen Failure Originating From Oxidation Pit Following 2100 Hours Exposure At 1204C (2200F).

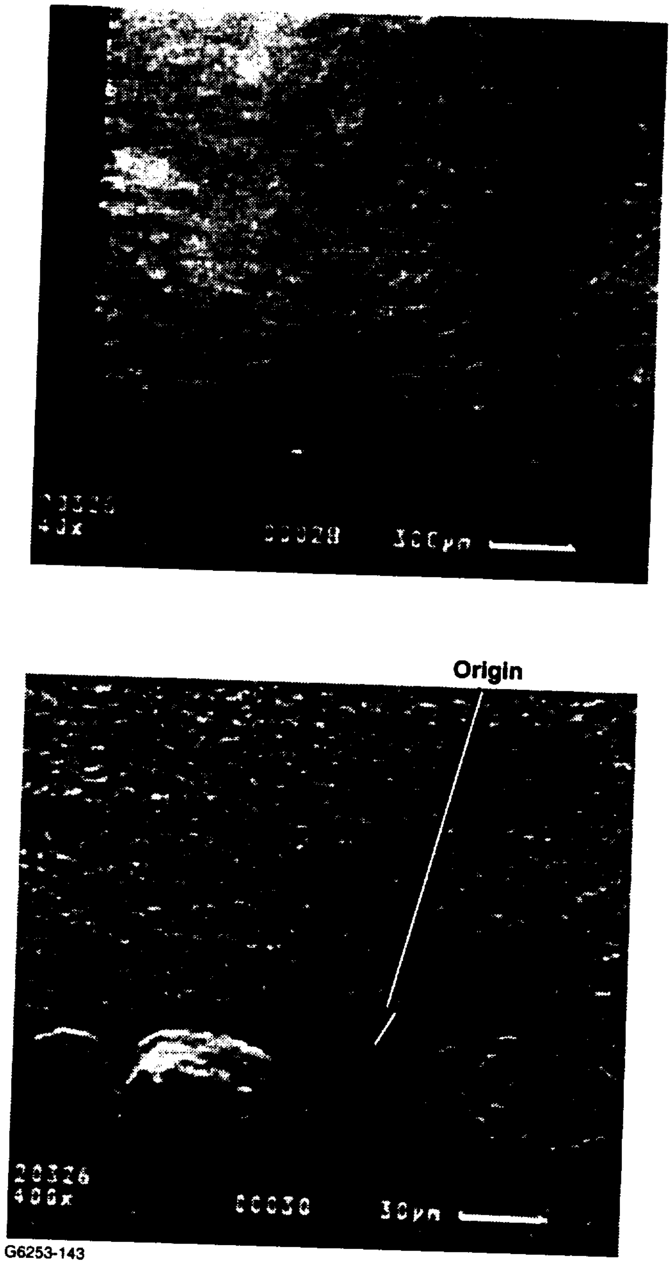
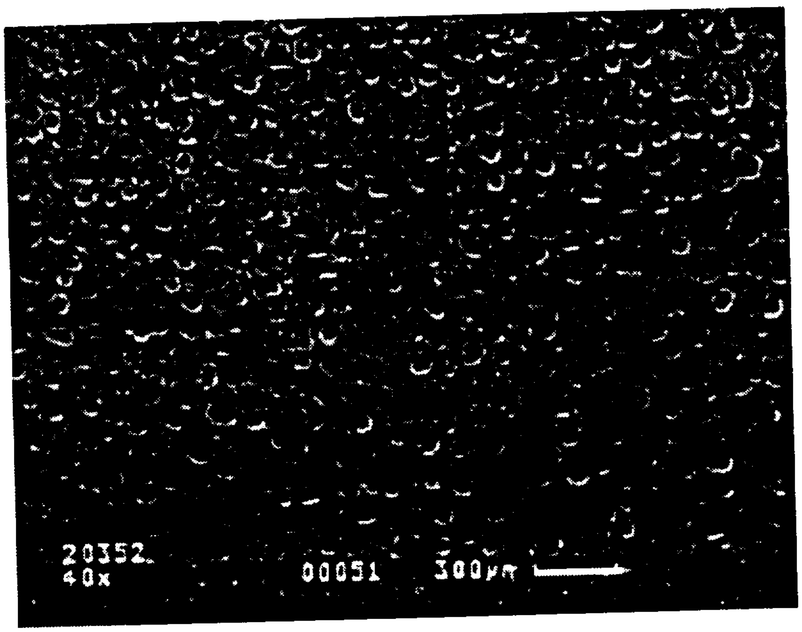
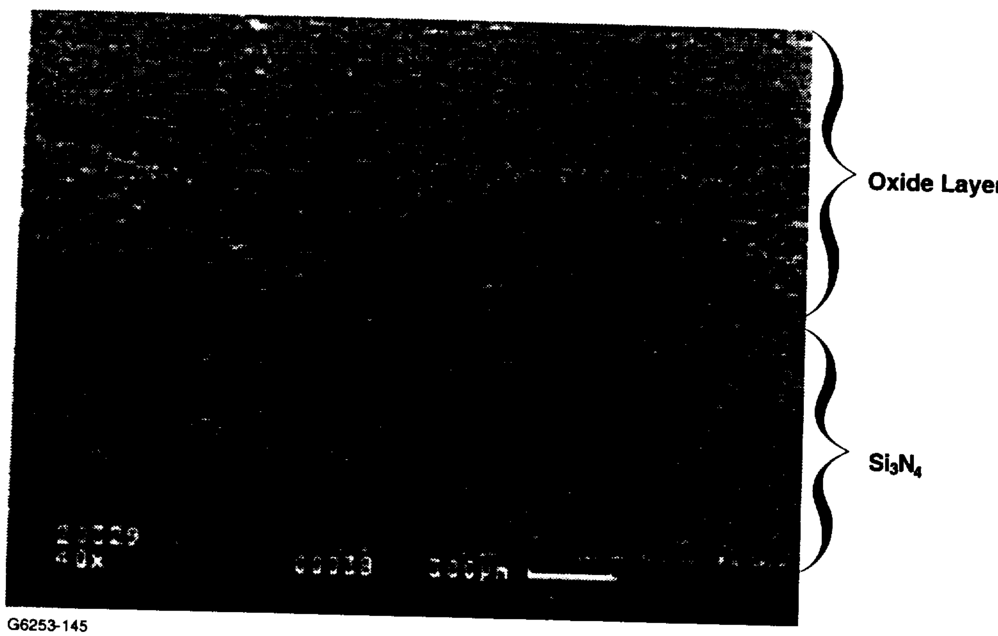


Figure 143. SN-82 Specimen Failure Originating From Oxidation Pit Following 3500 Hours Exposure At 1204C (2200F).



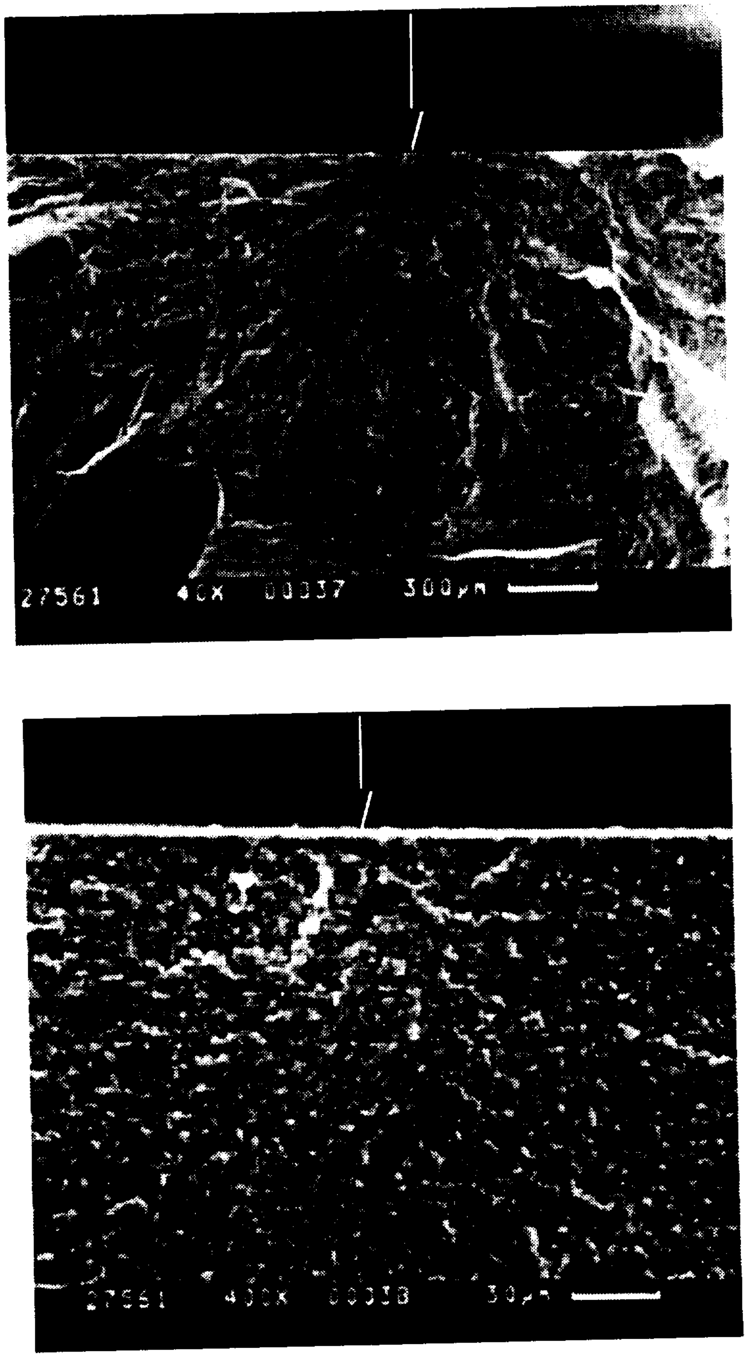
G6253-144

Figure 144. SN-82 Specimen Surface Topography Following 2100 Hours Cyclic Oxidation Durability Exposure At 1316C (2400F).



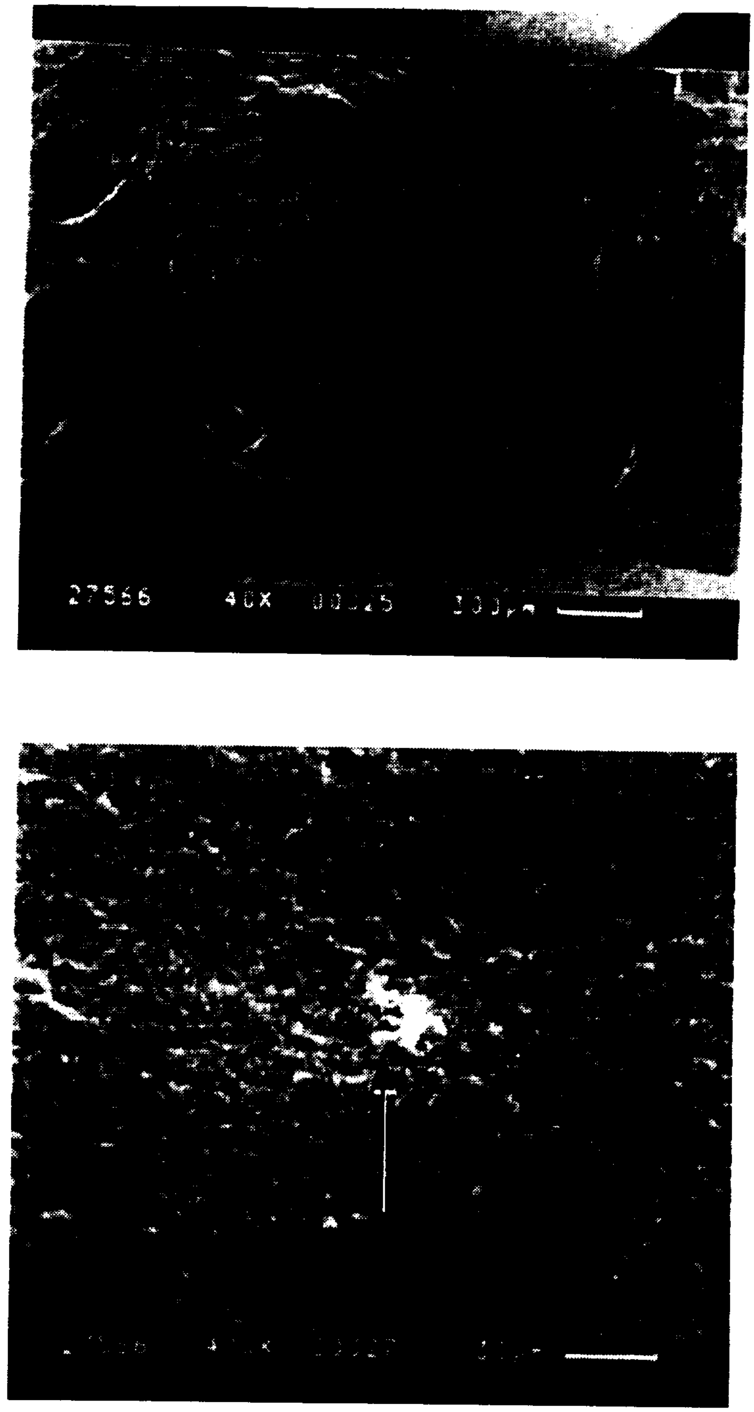
G6253-145

Figure 145. Local Areas Of Oxide Spalling On SN-82 Specimen Following 3500 Hours Cyclic Oxidation Durability Exposure At 1316C (2400F).



G6253-146

Figure 146. Typical SN-84 Baseline Test Specimen Failure Originating From Machined Surface.



G6253-147

Figure 147. SN-84 Baseline Test Specimen Failure Originating From Internal Inclusion Composed Of Iron, Chromium, And Nickel.

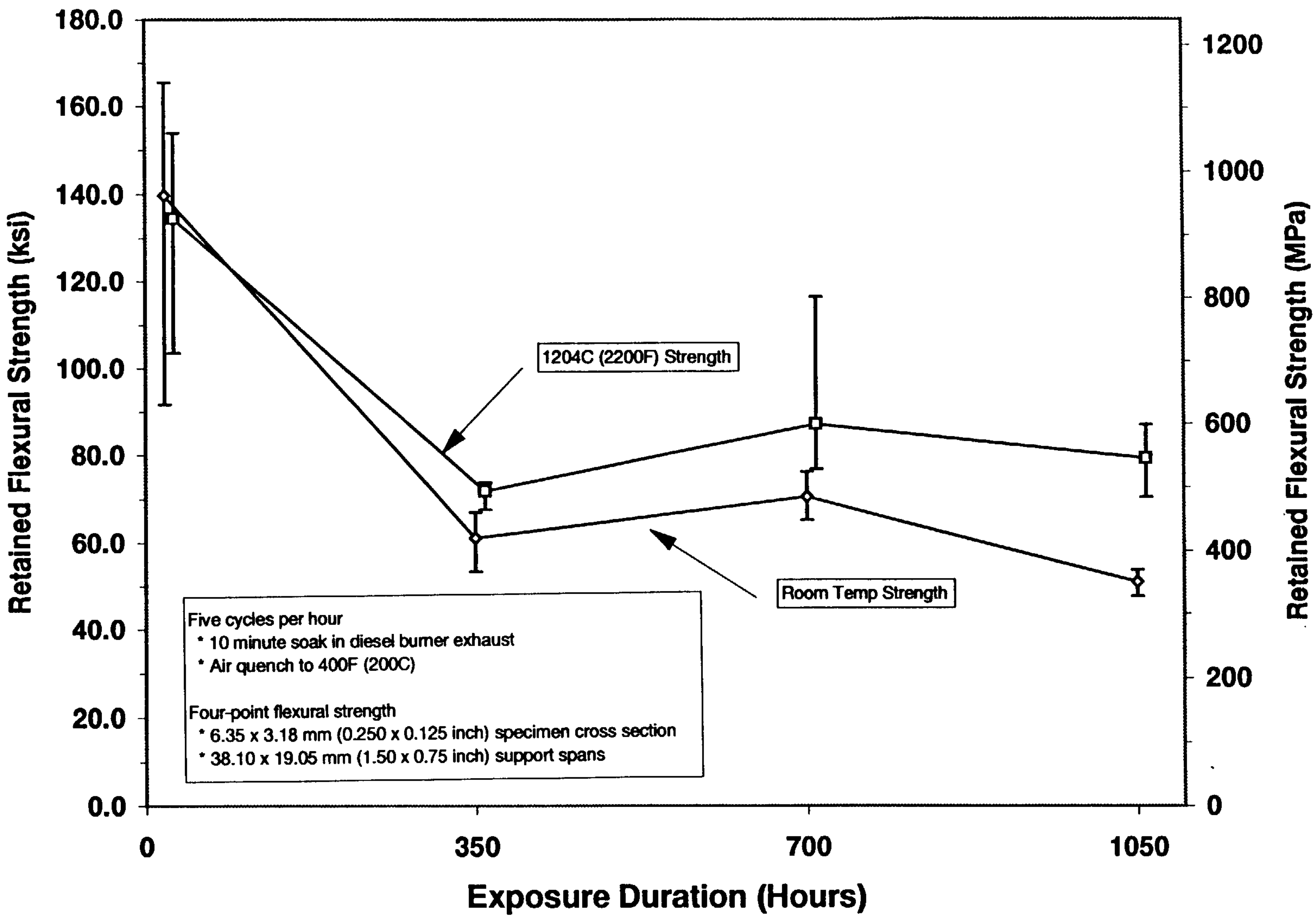
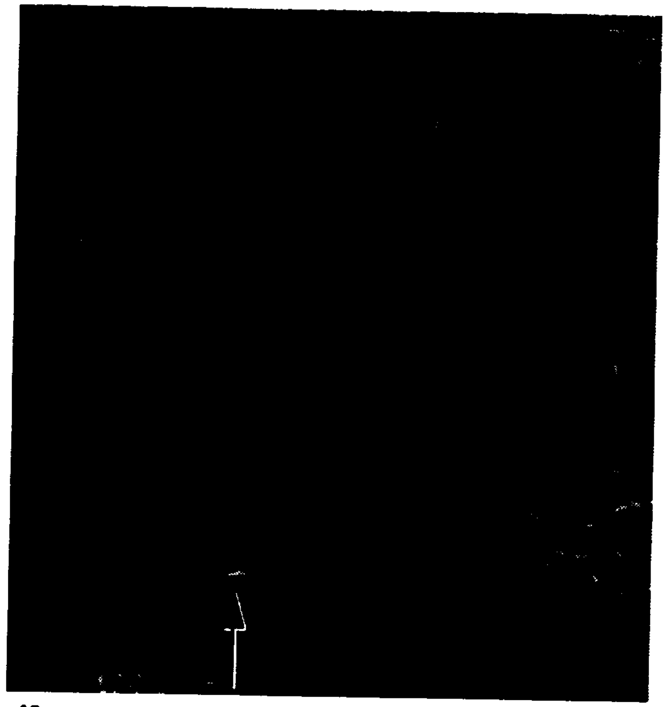
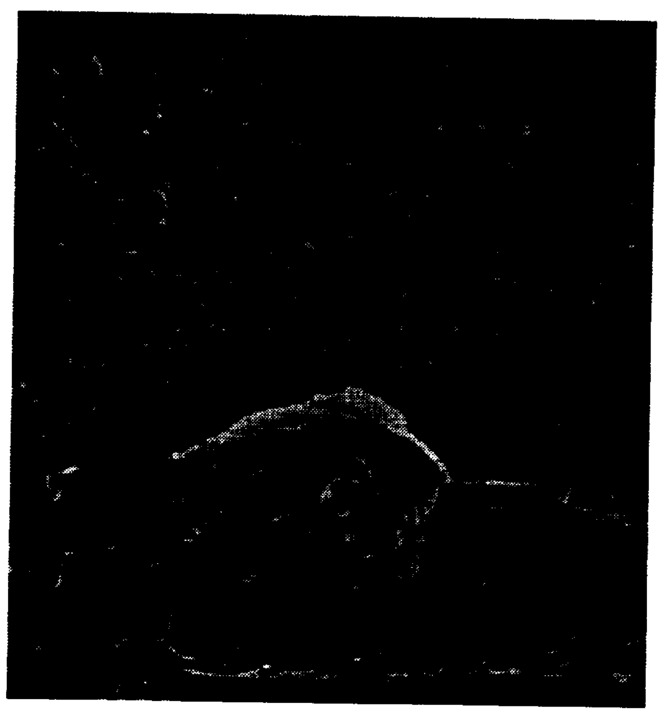


Figure 148. SN-84 Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.



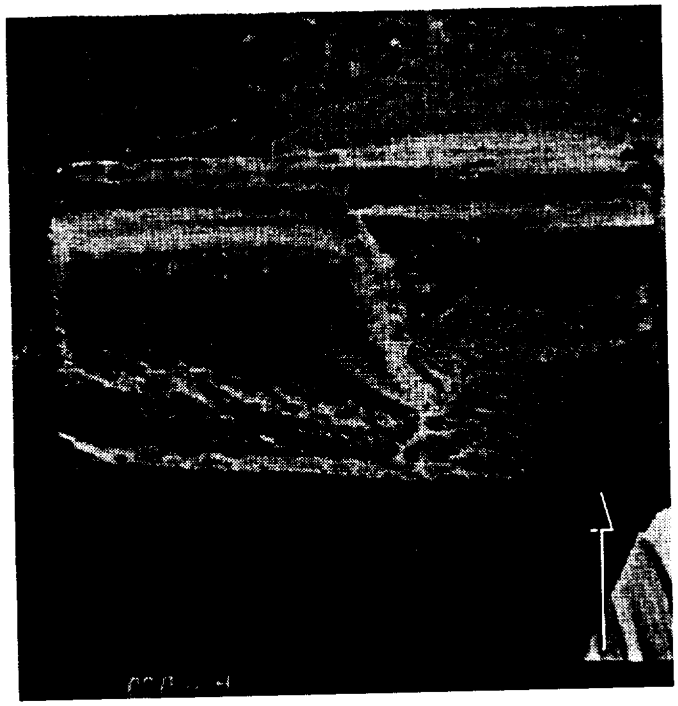
40x



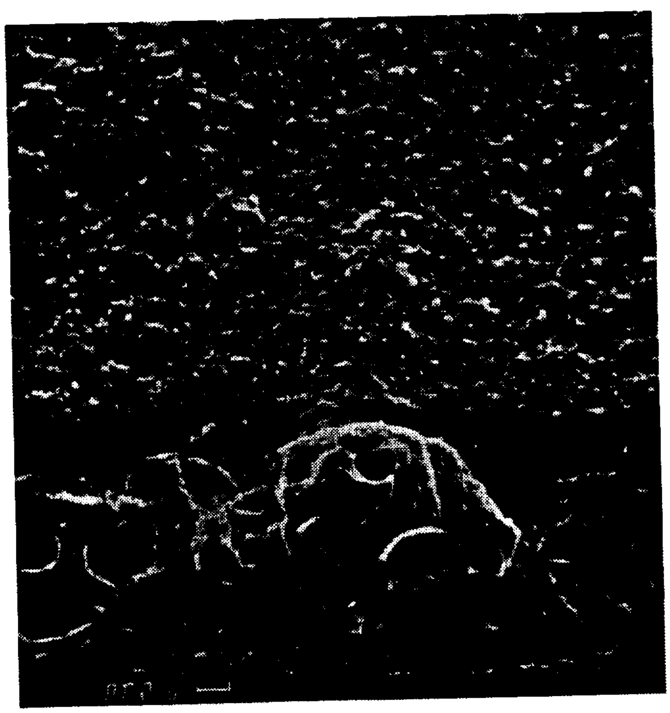
400x

G6253-149

Figure 149. SN-84 Specimen Failure Originating From Oxidation Pit Following 700 Hours Exposure At 1204C (2200F).



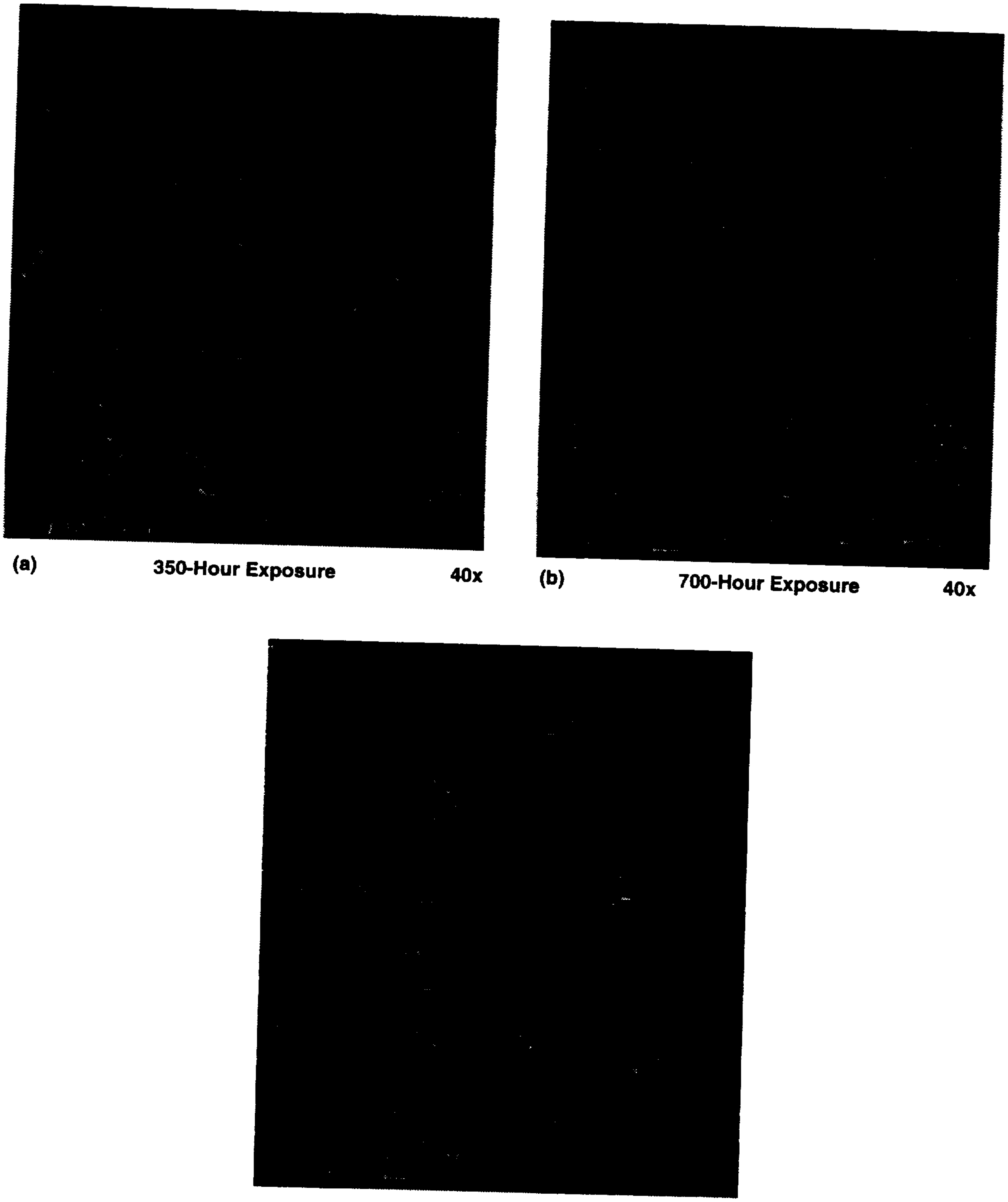
9x



400x

G6253-150

Figure 150. SN-84 Specimen Failure Originating From Oxidation Pit Following 1050 Hours Exposure At 1204C (2200F).



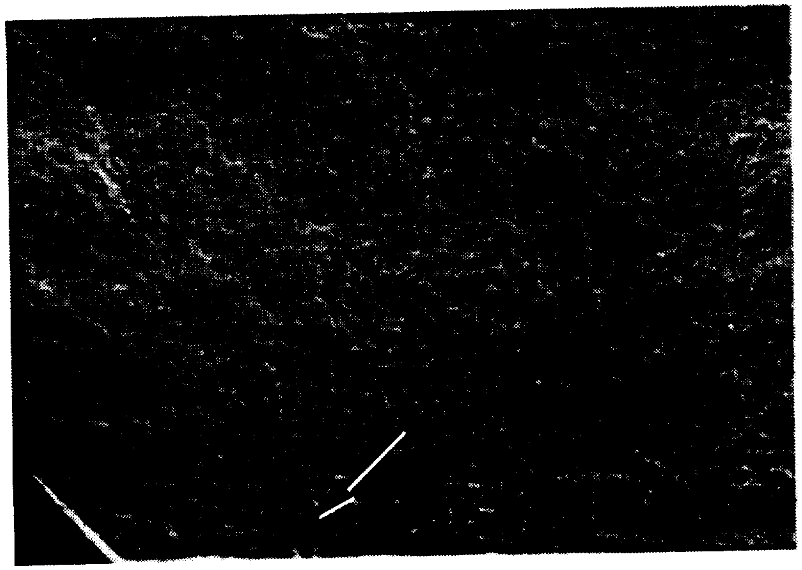
(a) 350-Hour Exposure 40x

(b) 700-Hour Exposure 40x

(c) 1050-Hour Exposure 40x

G6253-151

Figure 151. SN-84 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1204C (2200F): (a) 350 Hours; (b) 700 Hours; (c) 1050 Hours.



50x 300μm

500x 30μm

G6253-152

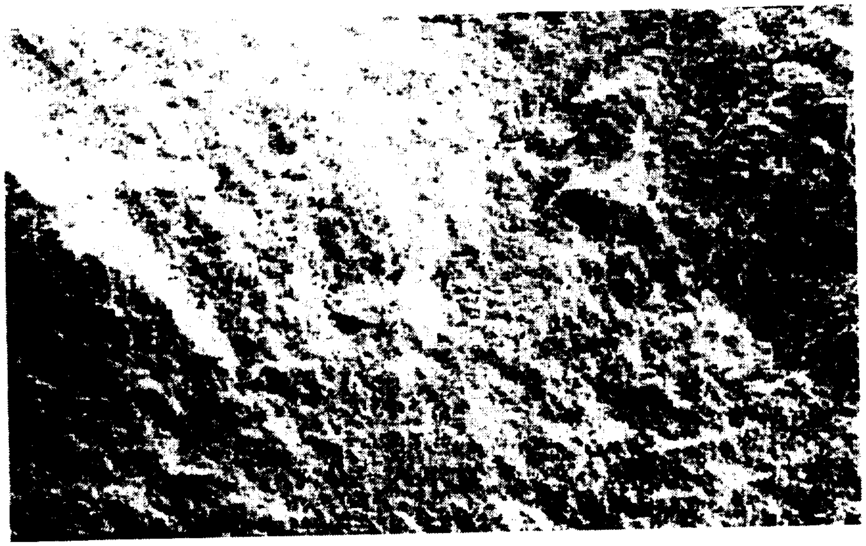
Figure 152. Typical SN-88 Room-Temperature Baseline Test Specimen Failure Originating From Surface Pit.

50x   300μm

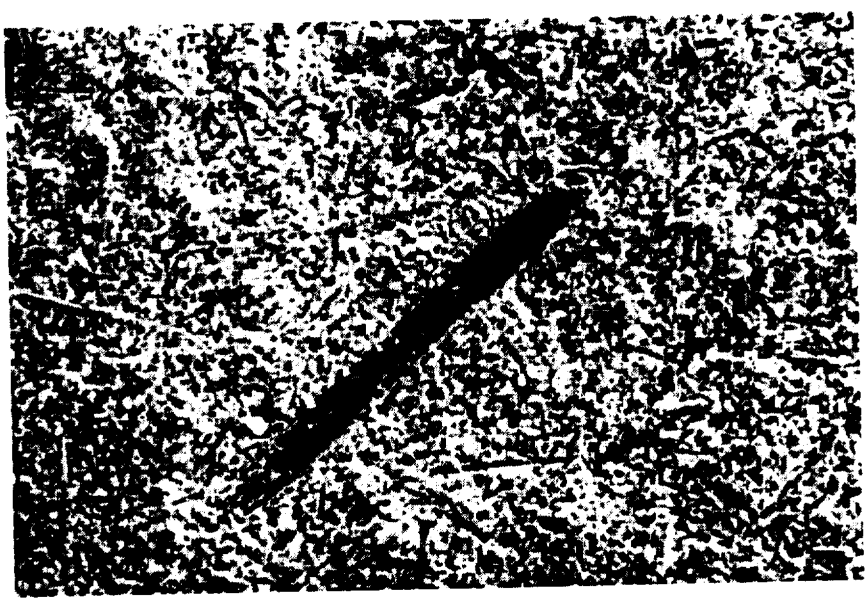
500x   30μm

G6253-153

Figure 153. Typical SN-88 1260C (2300F) Baseline Test Specimen Failure Originating From Large Si_3N_4 Grain Intersecting The As-Processed Surface.



300μm 50x



30μm 500x

G6253-154A

Figure 154. SN-88 1260C (2300F) Baseline Test Specimen Failure Originating From Large Internal Si_3N_4 Grain.

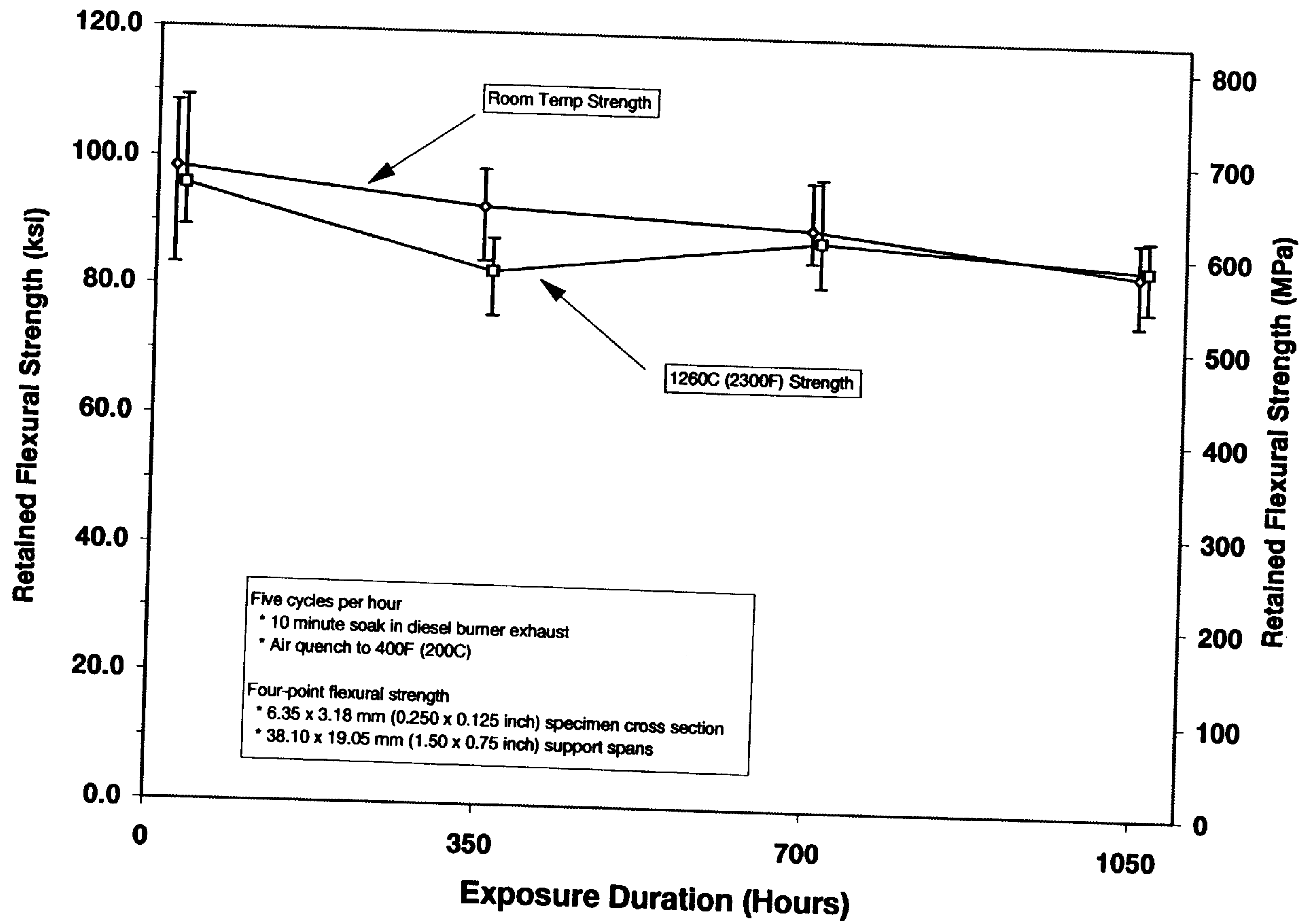
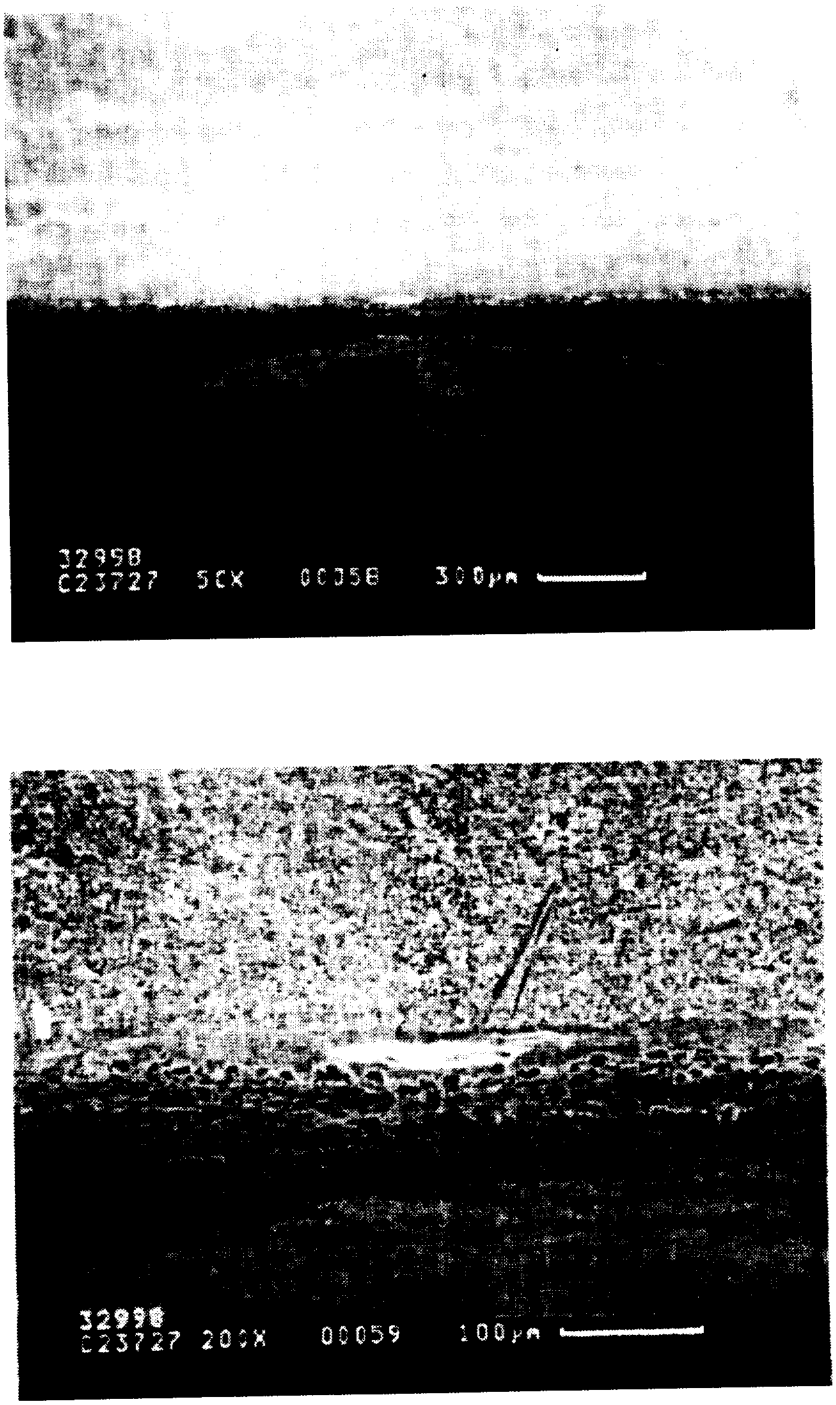
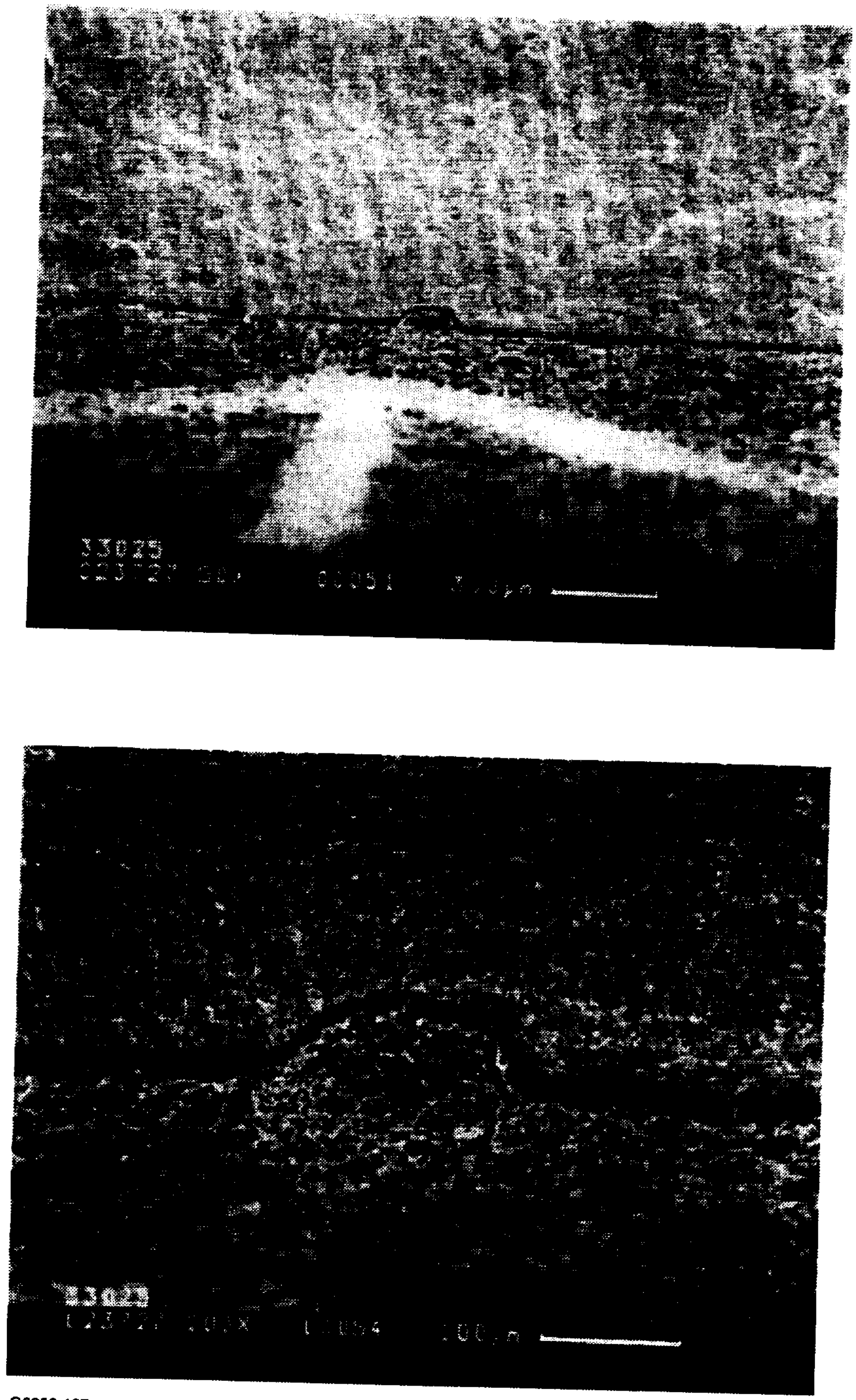


Figure 155. SN-88 Post-Exposure Room-Temperature And 1260C (2300F) Strength Test Results Following 1260C (2300F) Cyclic Oxidation Durability Testing.



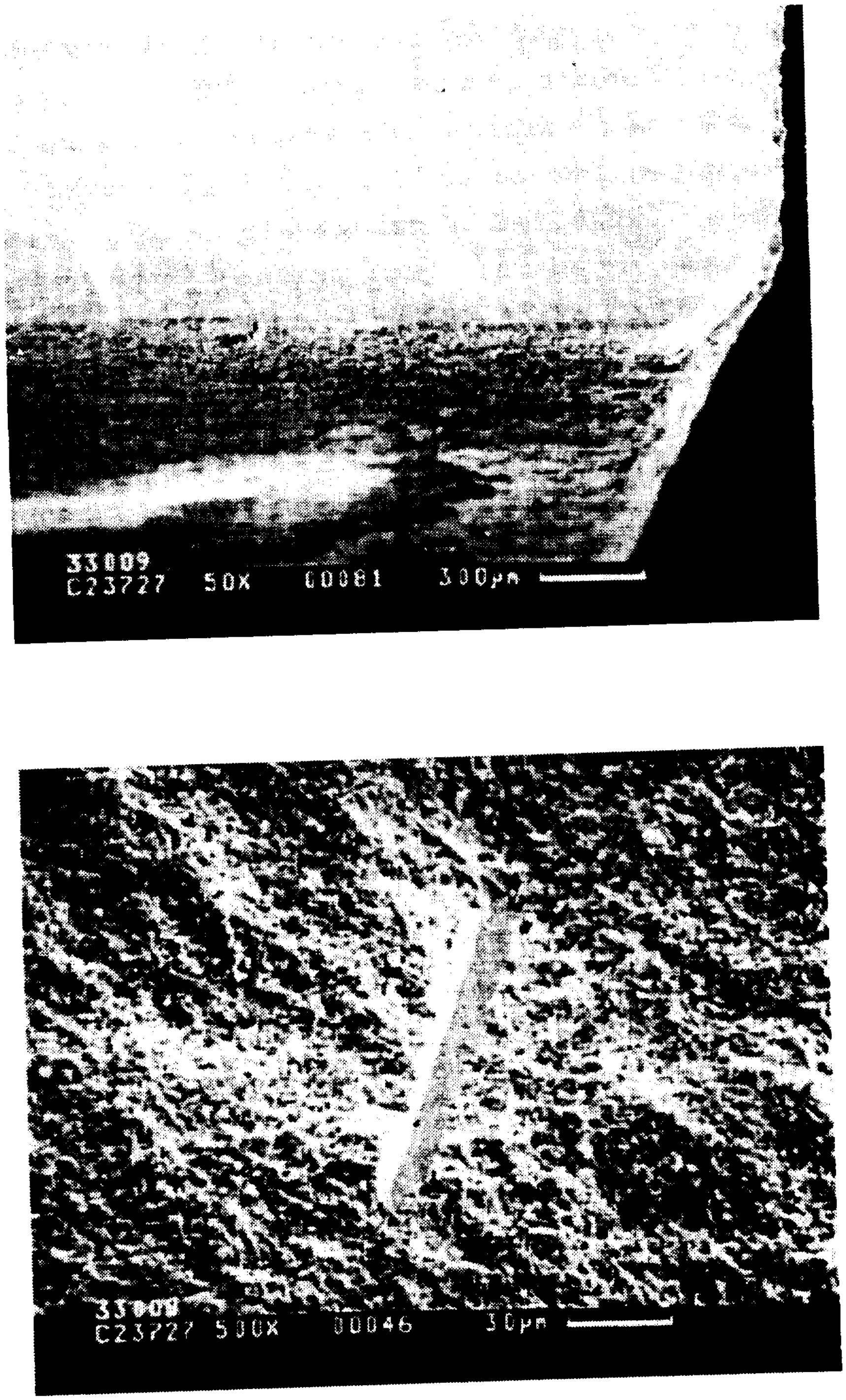
G6253-156

Figure 156. SN-88 Fracture Origin At Acicular Si_3N_4 Grain Intersecting The Surface Following 350 Hours Exposure At 1260C (2300F).



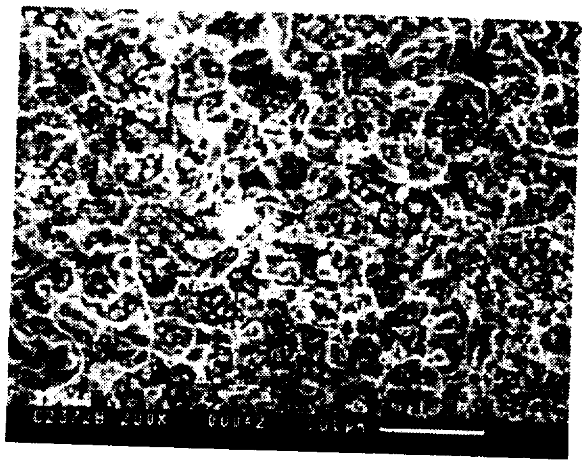
G6253-157

Figure 157. SN-88 Fracture Origin At Pit Following 700 Hours Exposure At 1260C (2300F).

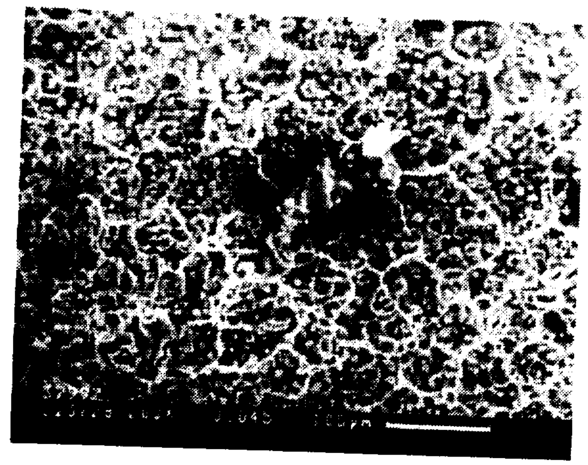


G6253-158

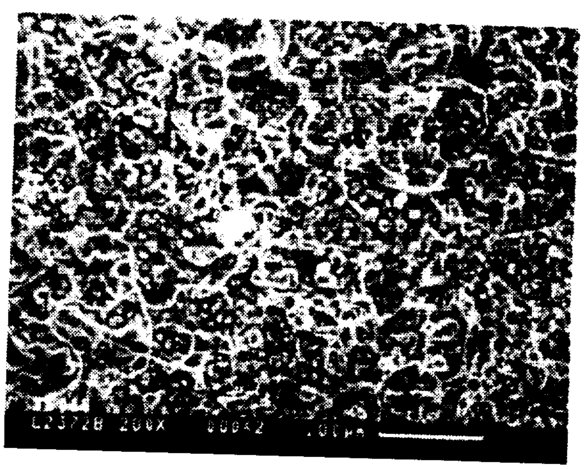
Figure 158. SN-88 Fracture Origin At Internal Silicon Nitride Grain Following 1050 Hours Exposure At 1260C (2300F).



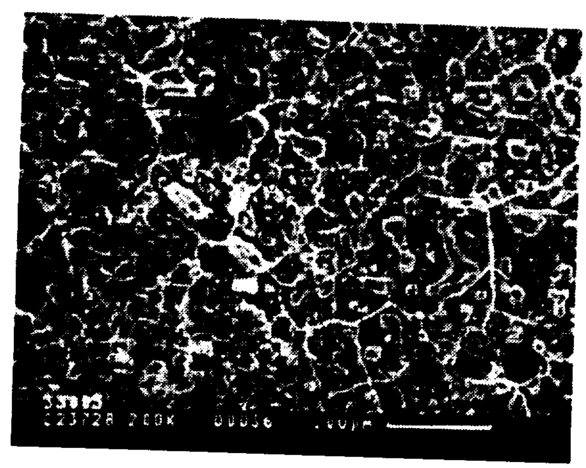
(a) Baseline (As-Received)



(b) 350 Hours at 2300F



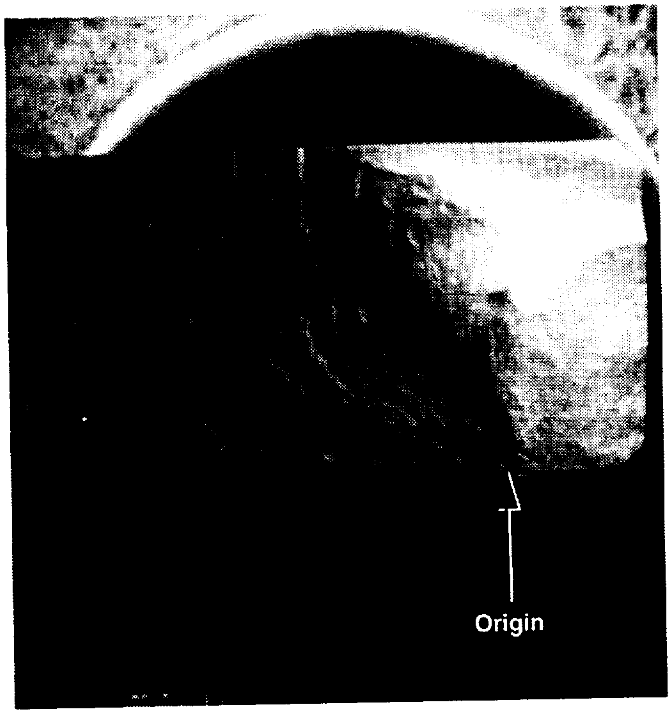
(c) 700 Hours at 2300F



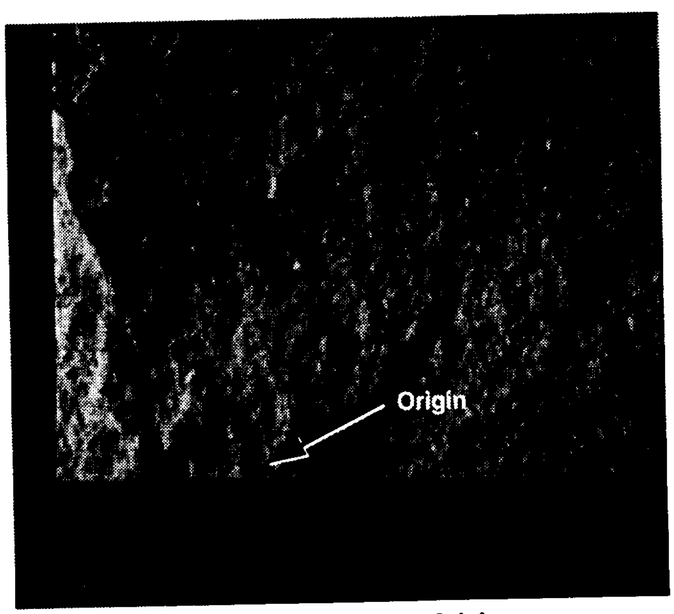
(d) 1050 Hours at 2300F

G6253-159

Figure 159. SN-88 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1260C (2300F): (a) Baseline (Zero Hours); (b) 350 Hours; (c) 700 Hours; (d) 1050 Hours.



20x



400x Machining Groove Origin

G6253-160

Figure 160. Typical NCX-34 Baseline Test Specimen Failure Originating From Machined Surface.

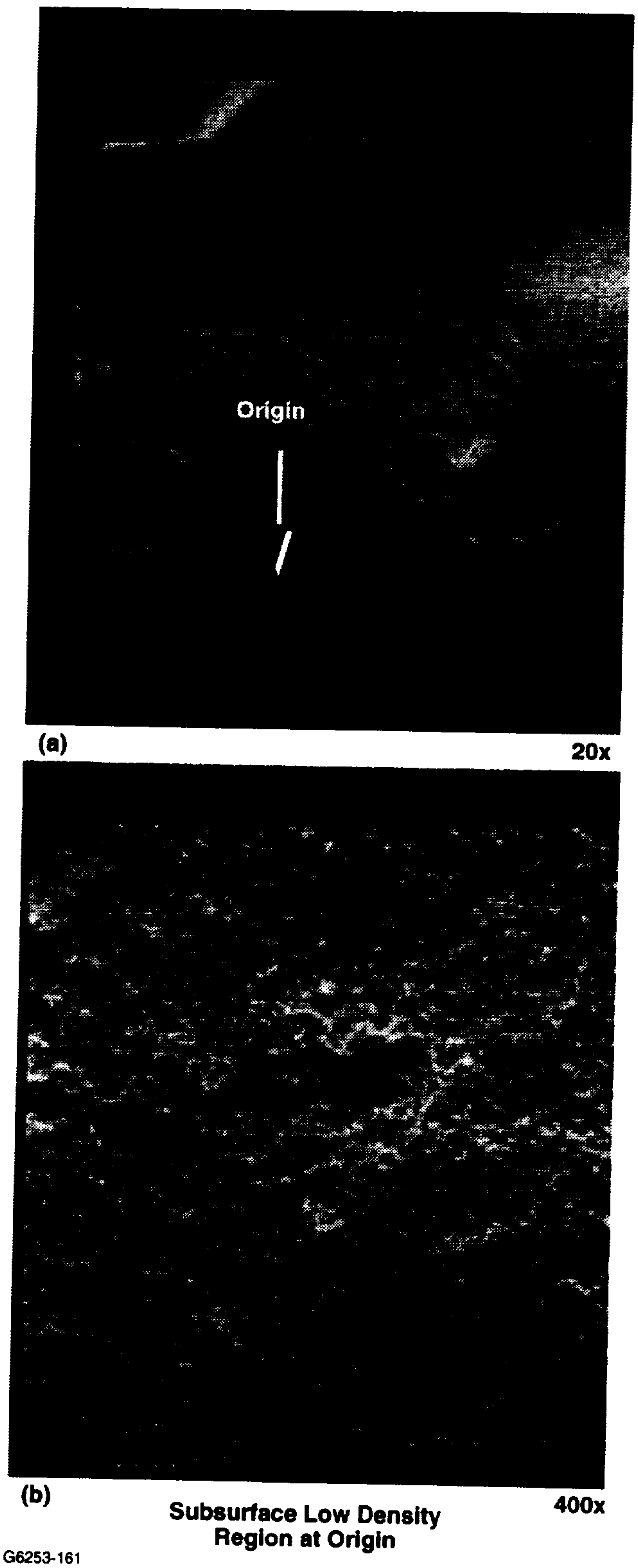
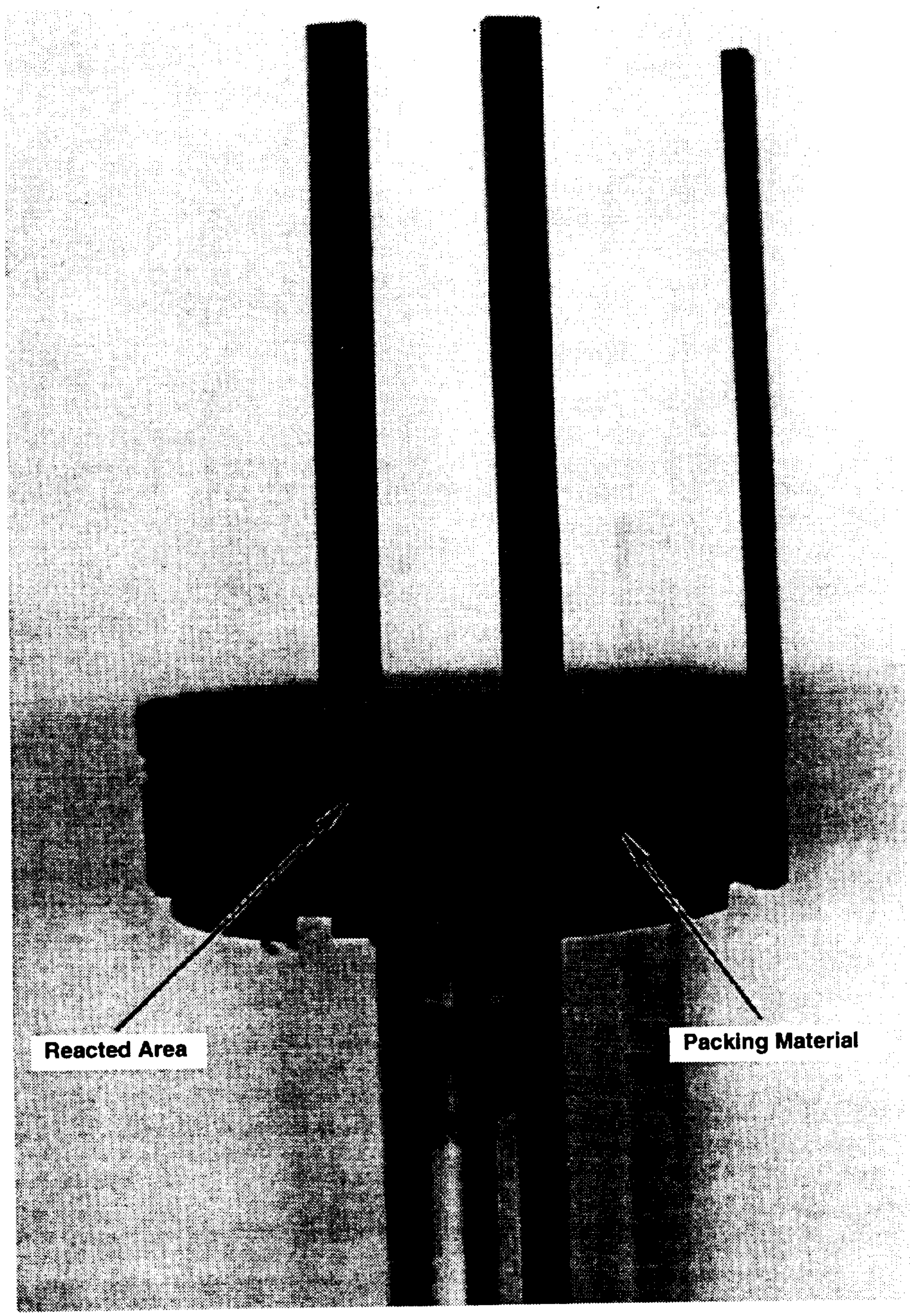


Figure 161. NCX-34 Baseline Test Specimen Failure Originating From Subsurface Porosity.



G6253-162

Figure 162. NCX-34 Specimens Exhibited Severe Cracking Following 47.1 Hours Cyclic Exposure At 1371C (2500F).

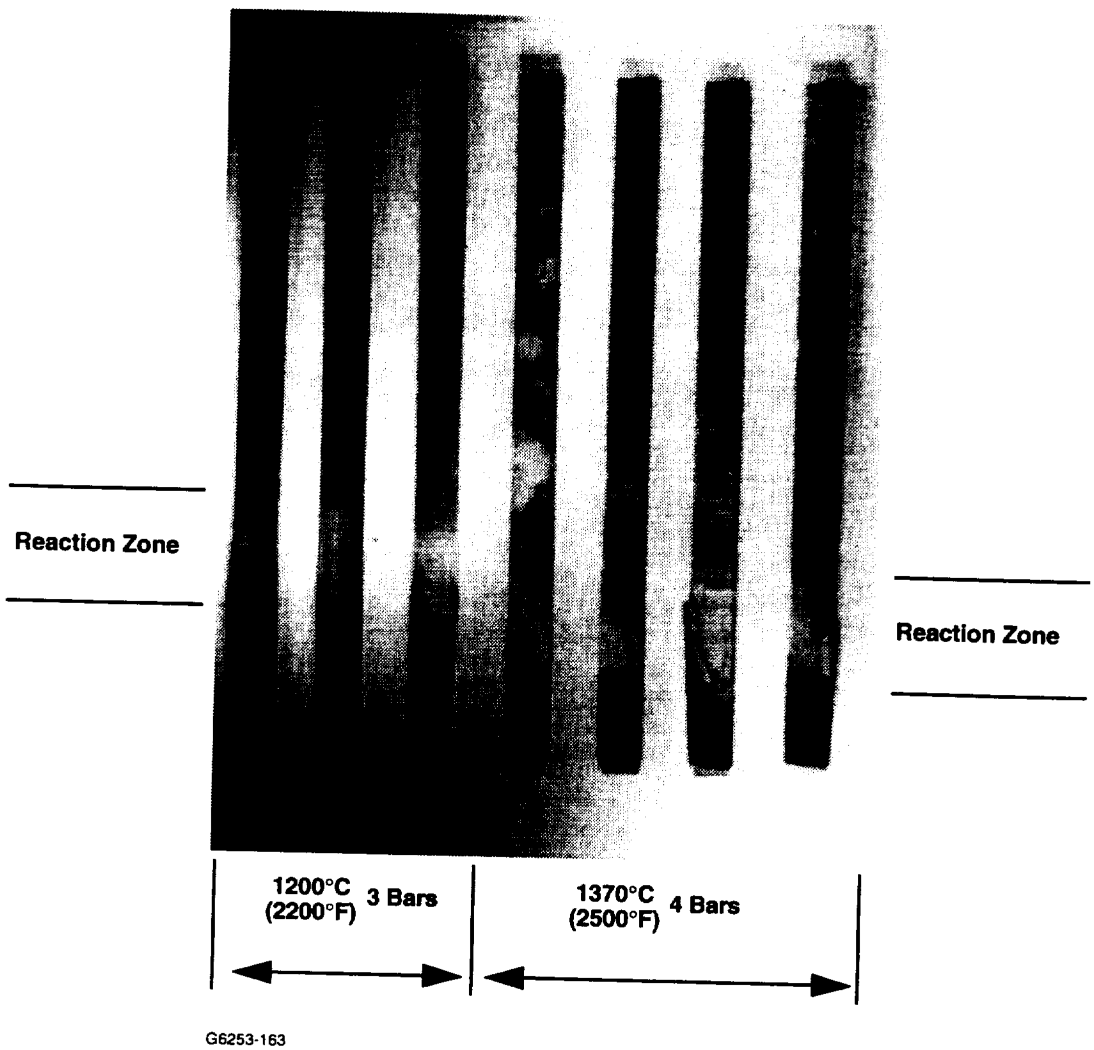


Figure 163. Cracking In NCX-34 Specimens Exposed At 1204C (2200F) Occurred Closer To Middle Of Bars Than In Specimens Exposed At 1371C (2500F).

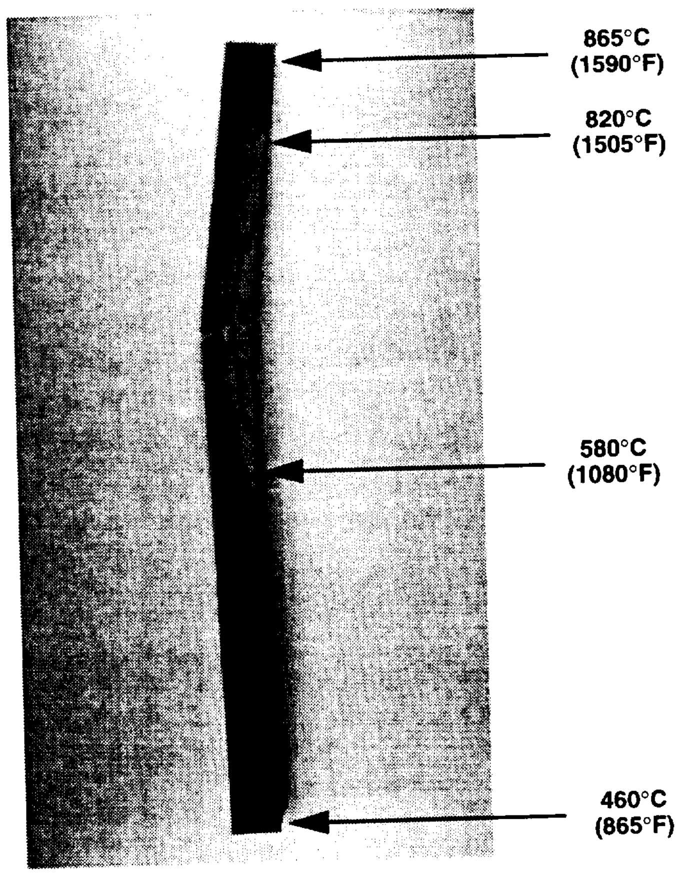
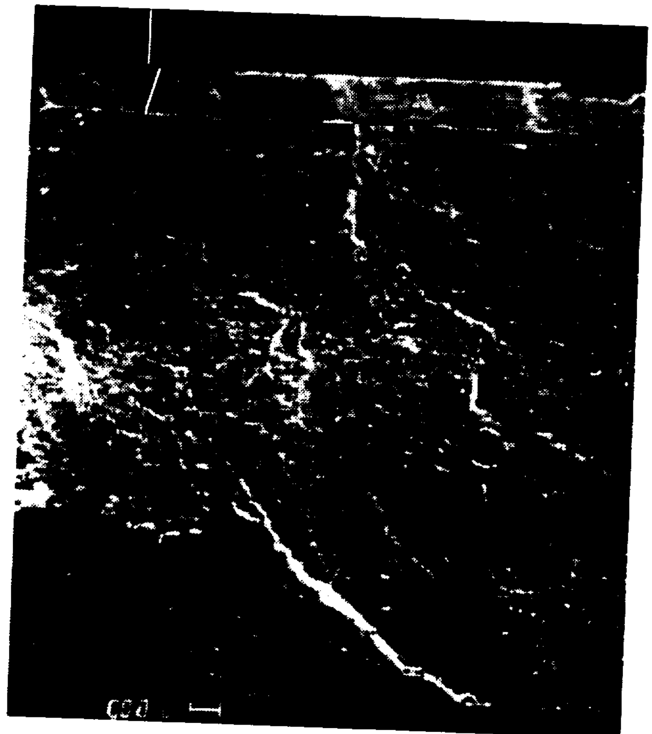
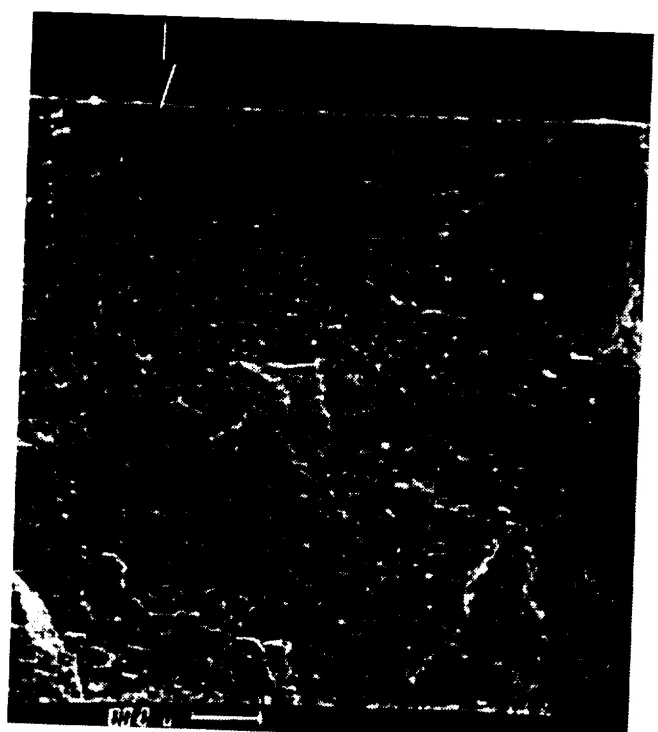


Figure 164. NCX-34 Test Bar Following 29 Hours Gradient Furnace Exposure.



40x



100x

G6253-165

Figure 165. Typical NT-154 Baseline Test Specimen Failure Originating From Machined Surface.

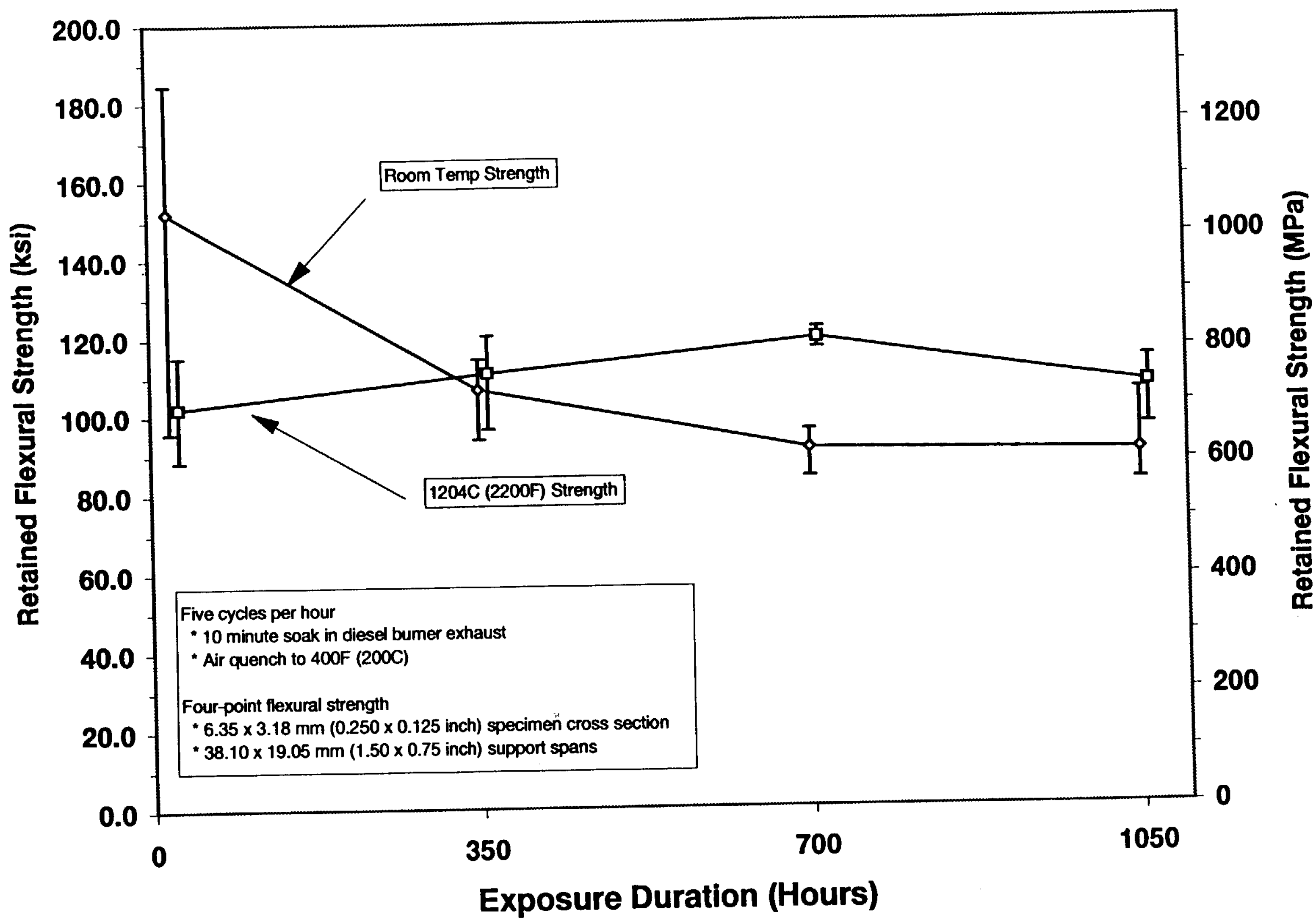


Figure 166. NT-154 Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.

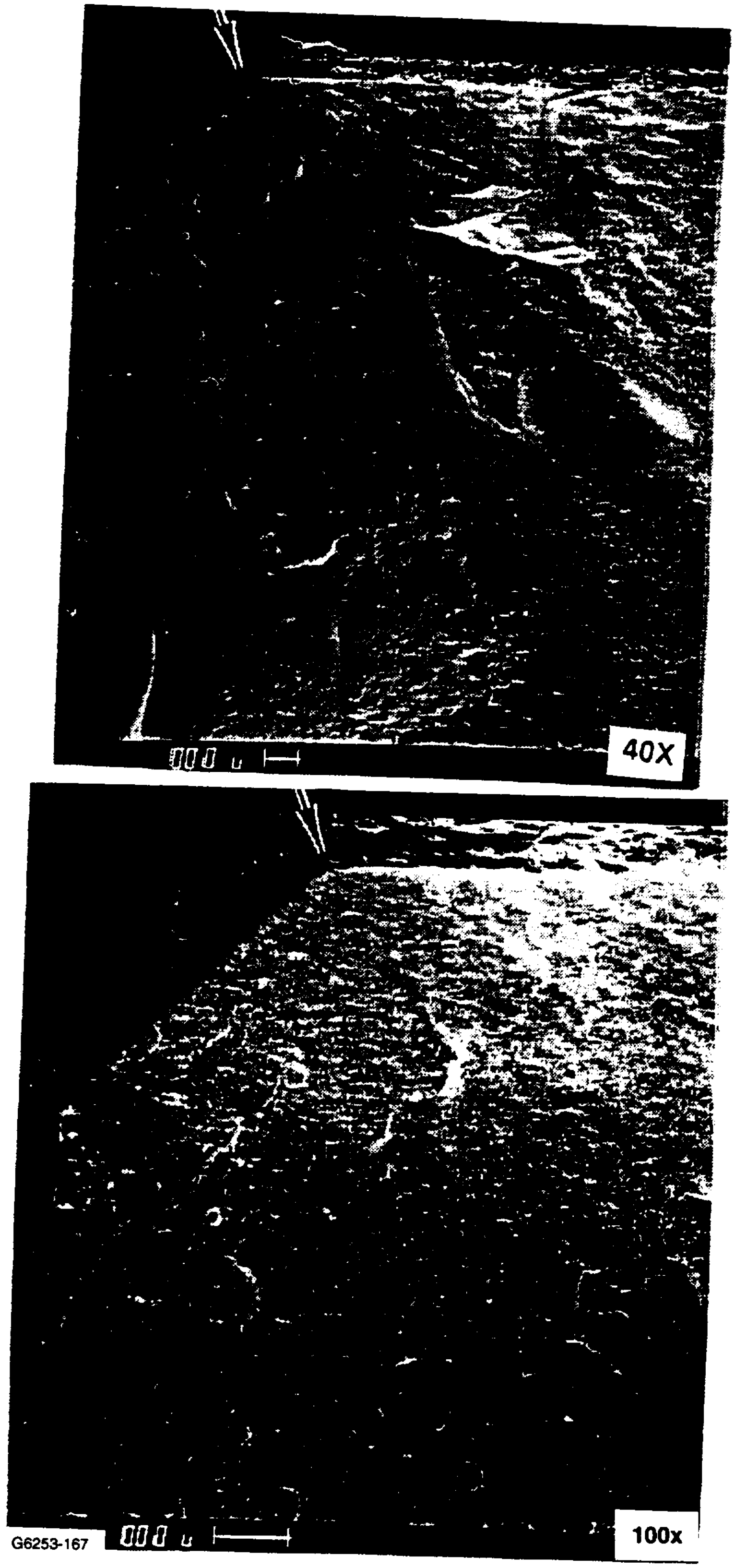


Figure 167. NT-154 Specimen Failure Originating From Chamfer Following 700 Hours Exposure At 1204C (2200F).

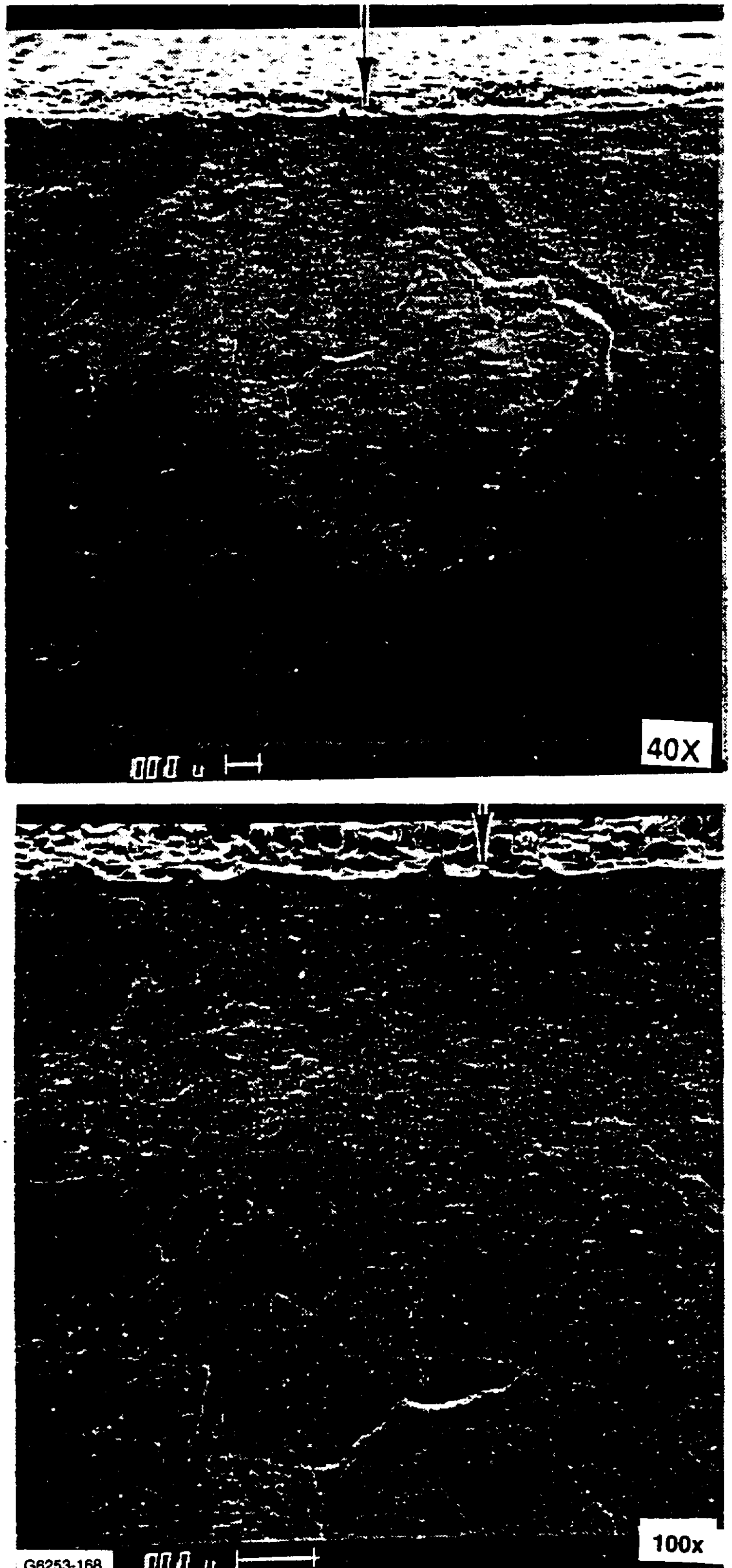


Figure 168. NT-154 Specimen Failure Originating From Exposed Surface Following 1050 Hours Exposure At 1204C (2200F).

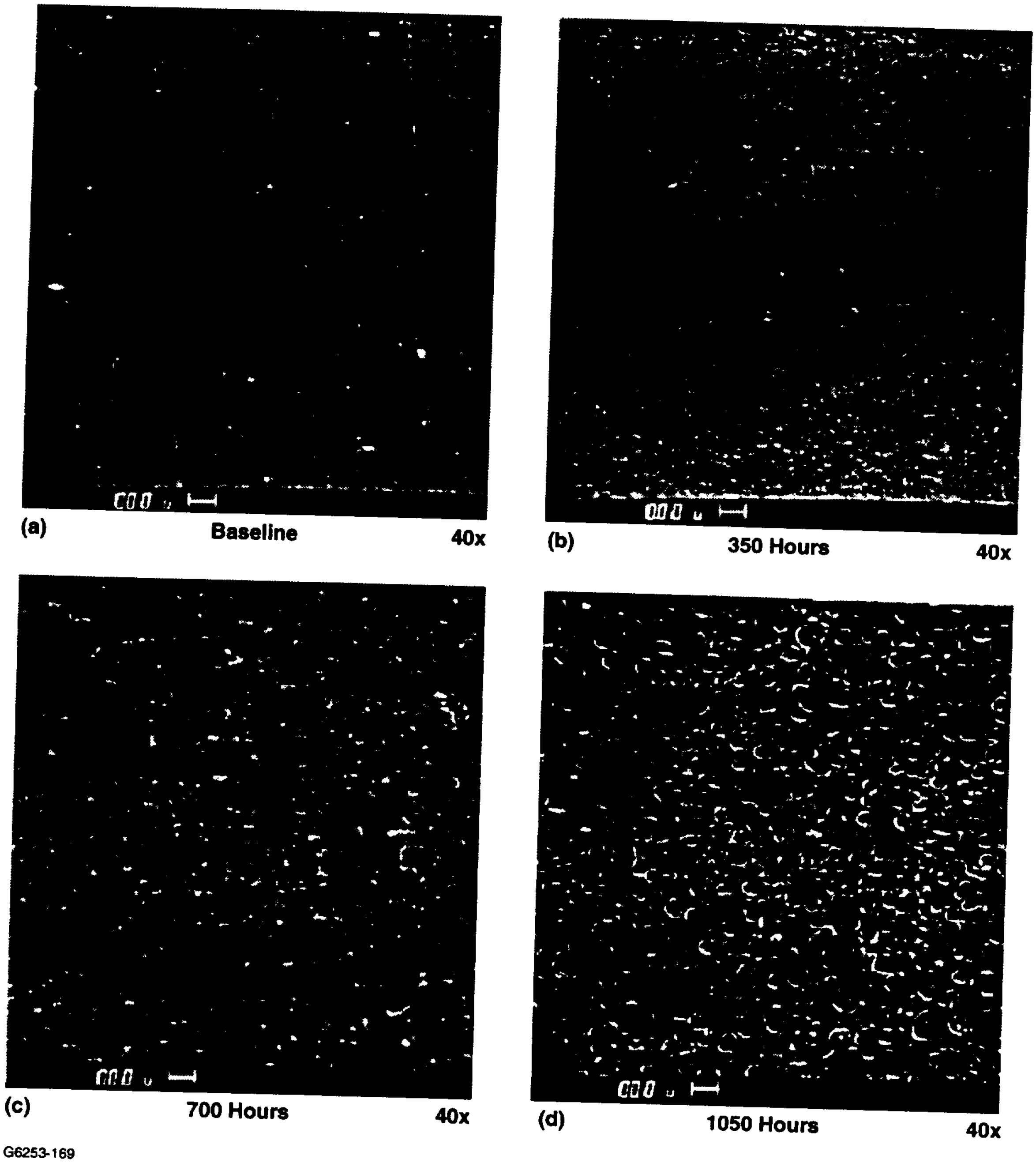
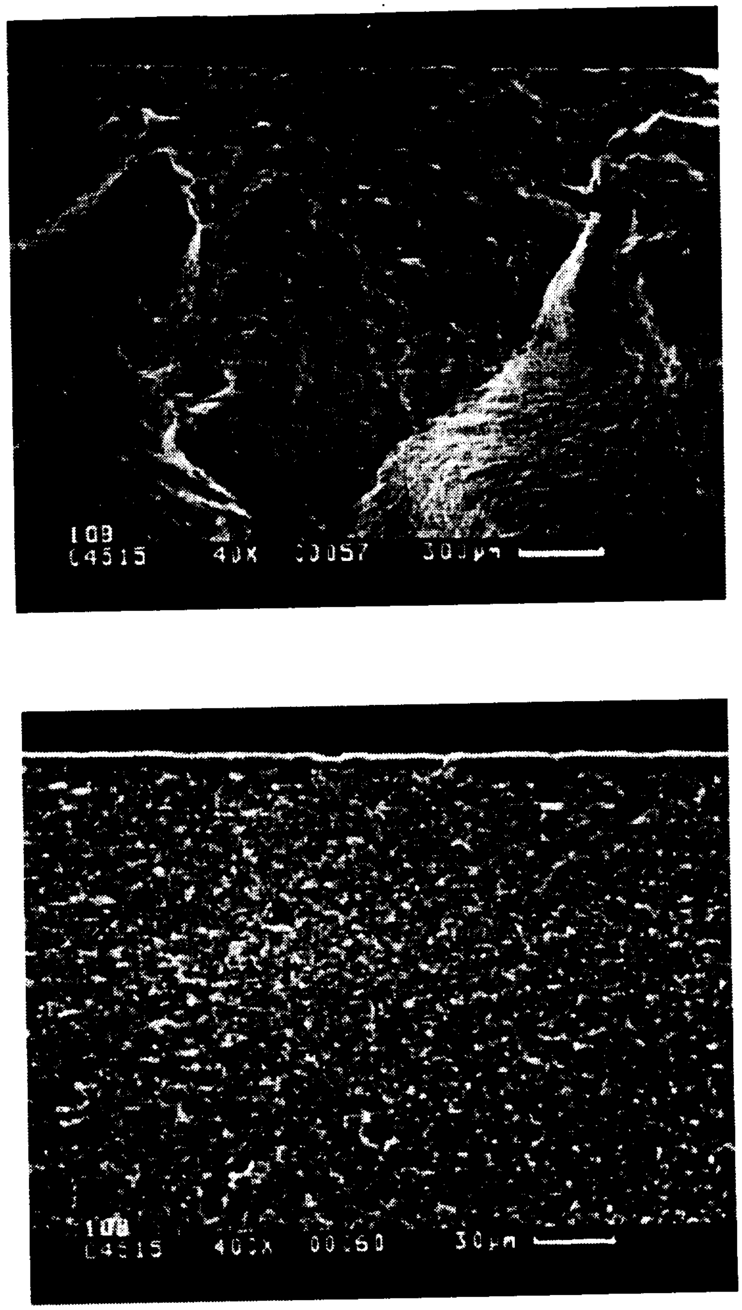


Figure 169. NT-154 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1204C (2200F): (a) Baseline (Zero Hours); (b) 350 Hours; (c) 700 Hours; (d) 1050 Hours.



G6253-170

Figure 170. Typical NT-154 Baseline Test Specimen Failure Originating From Machined Surface.

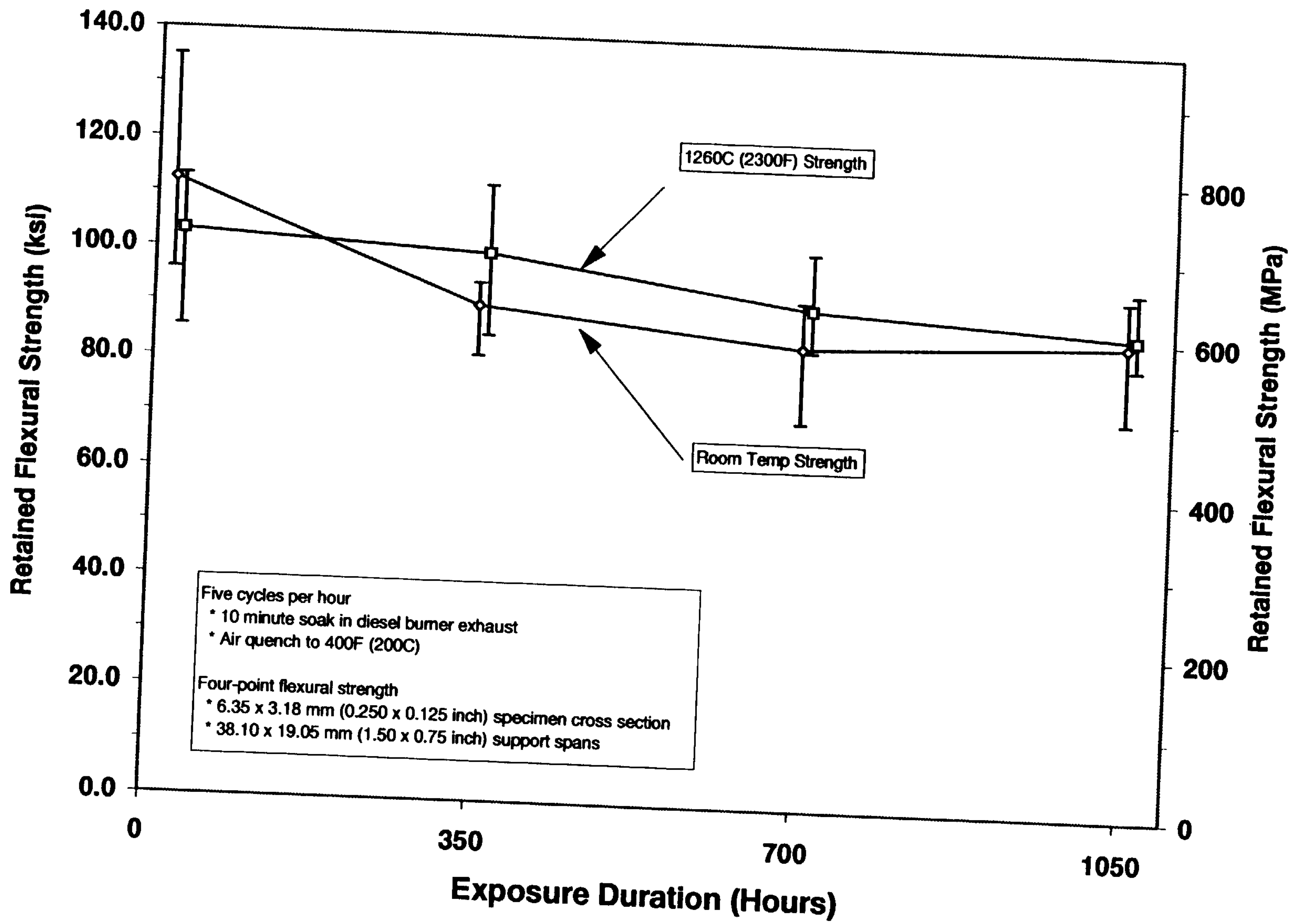
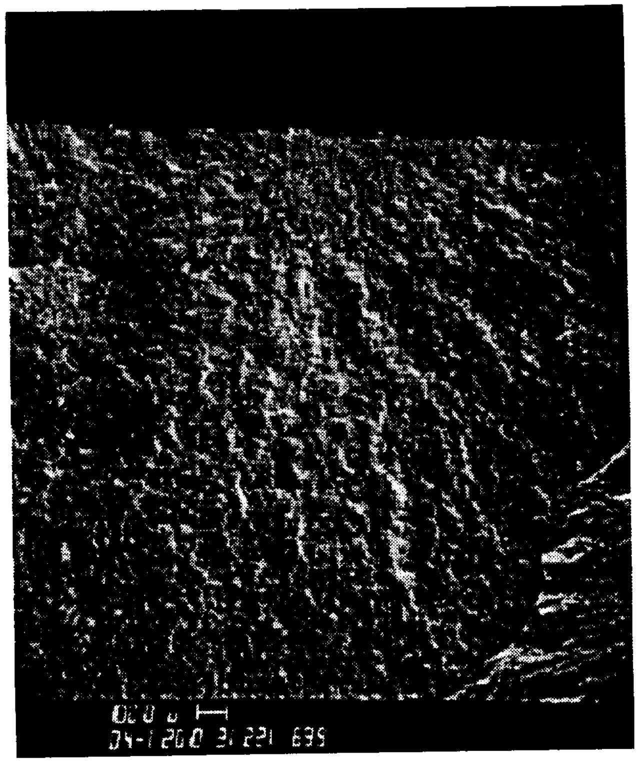
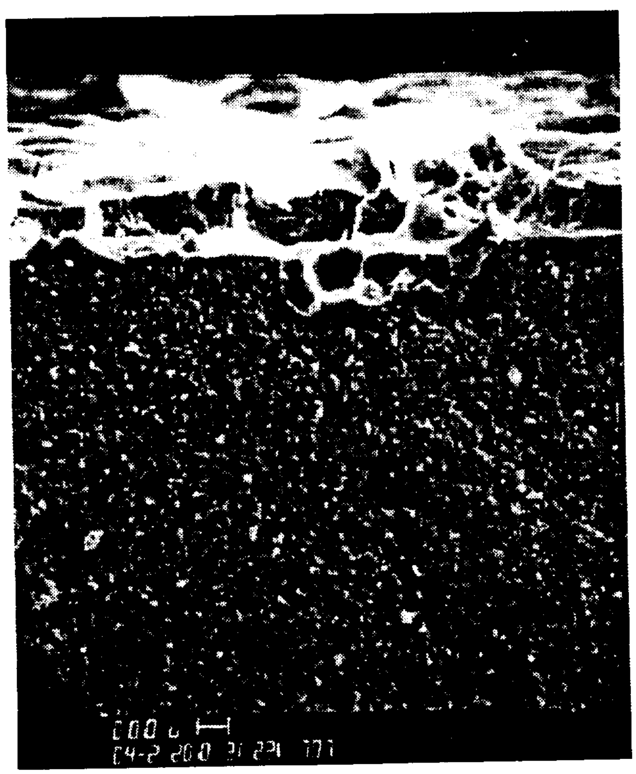


Figure 171. NT-154 Post-Exposure Room-Temperature And 1260C (2300F) Strength Test Results Following 1260C (2300F) Cyclic Oxidation Durability Testing.



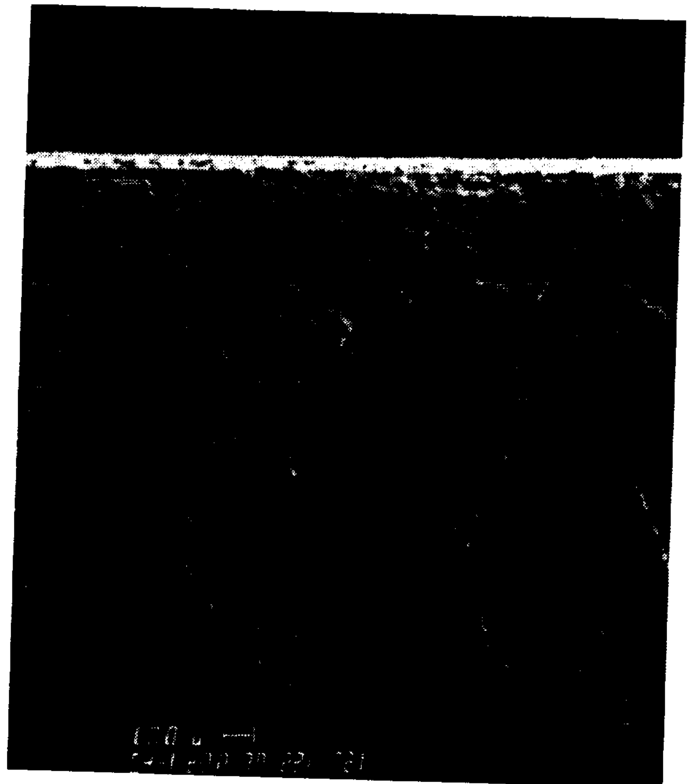
700 Hours - 40x



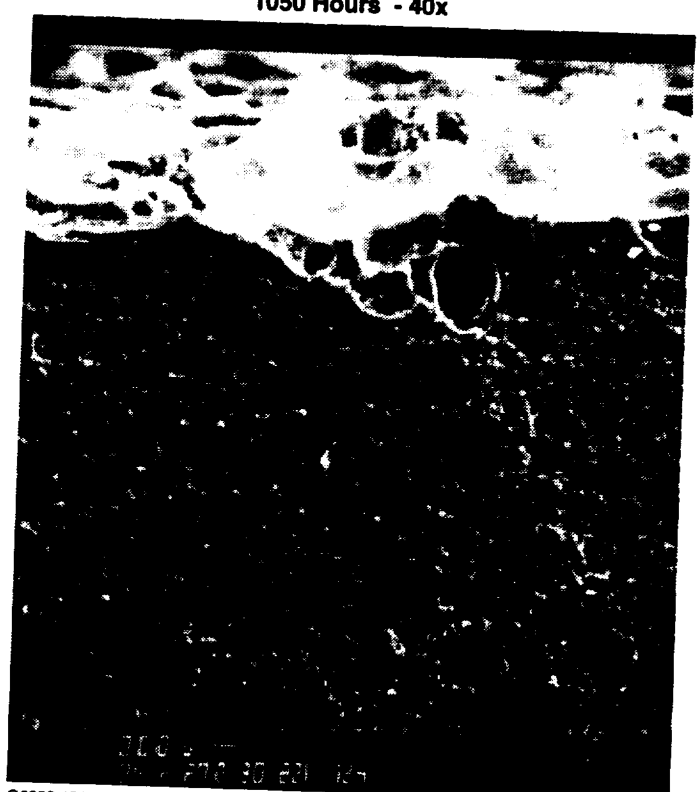
700 Hours - 400x

G6253-172

Figure 172. NT-154 Specimen Failure Originating From Oxidation Pit Following 700 Hours Exposure At 1260C (2300F).



1050 Hours - 40x



G6253-173

1050 Hours - 400x

Figure 173. NT-154 Specimen Failure Originating From Oxidation Pit Following 1050 Hours Exposure At 1260C (2300F).

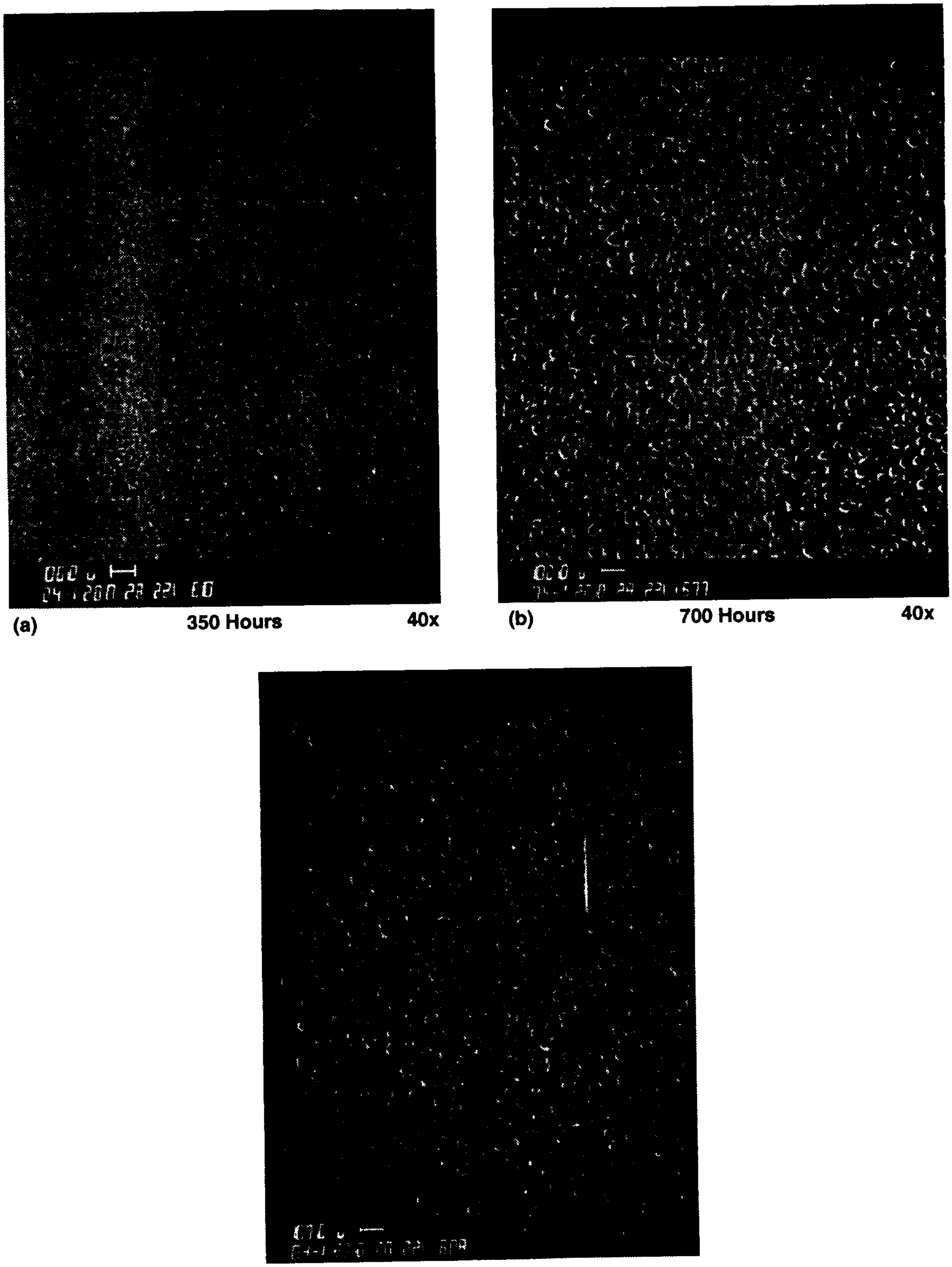


Figure 174. NT-154 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1260C (2300F): (a) 350 Hours; (b) 700 Hours; (c) 1050 Hours.

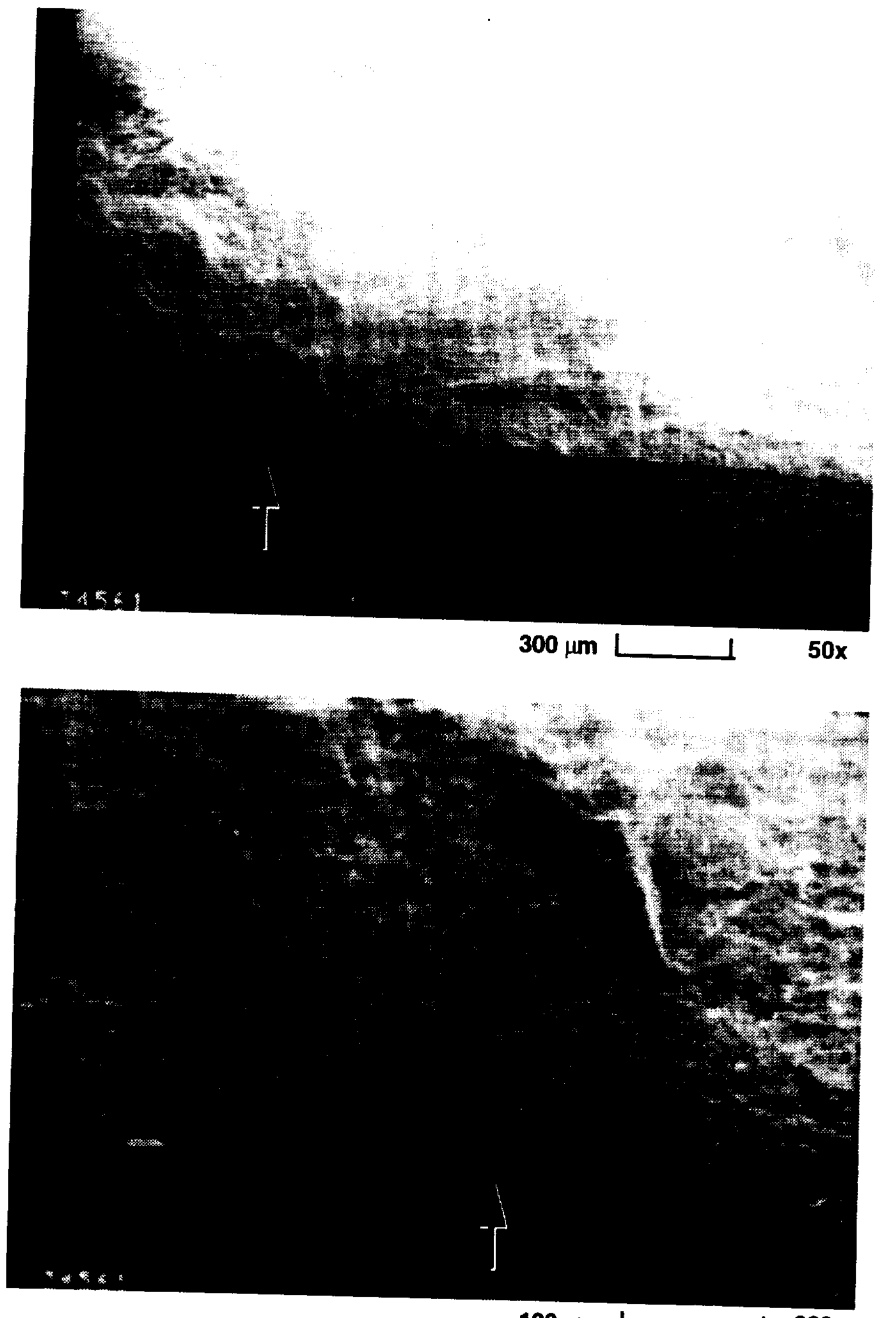


Figure 175. Typical NT-154 Baseline Test Specimen Failure Originating From As-Processed Surface.

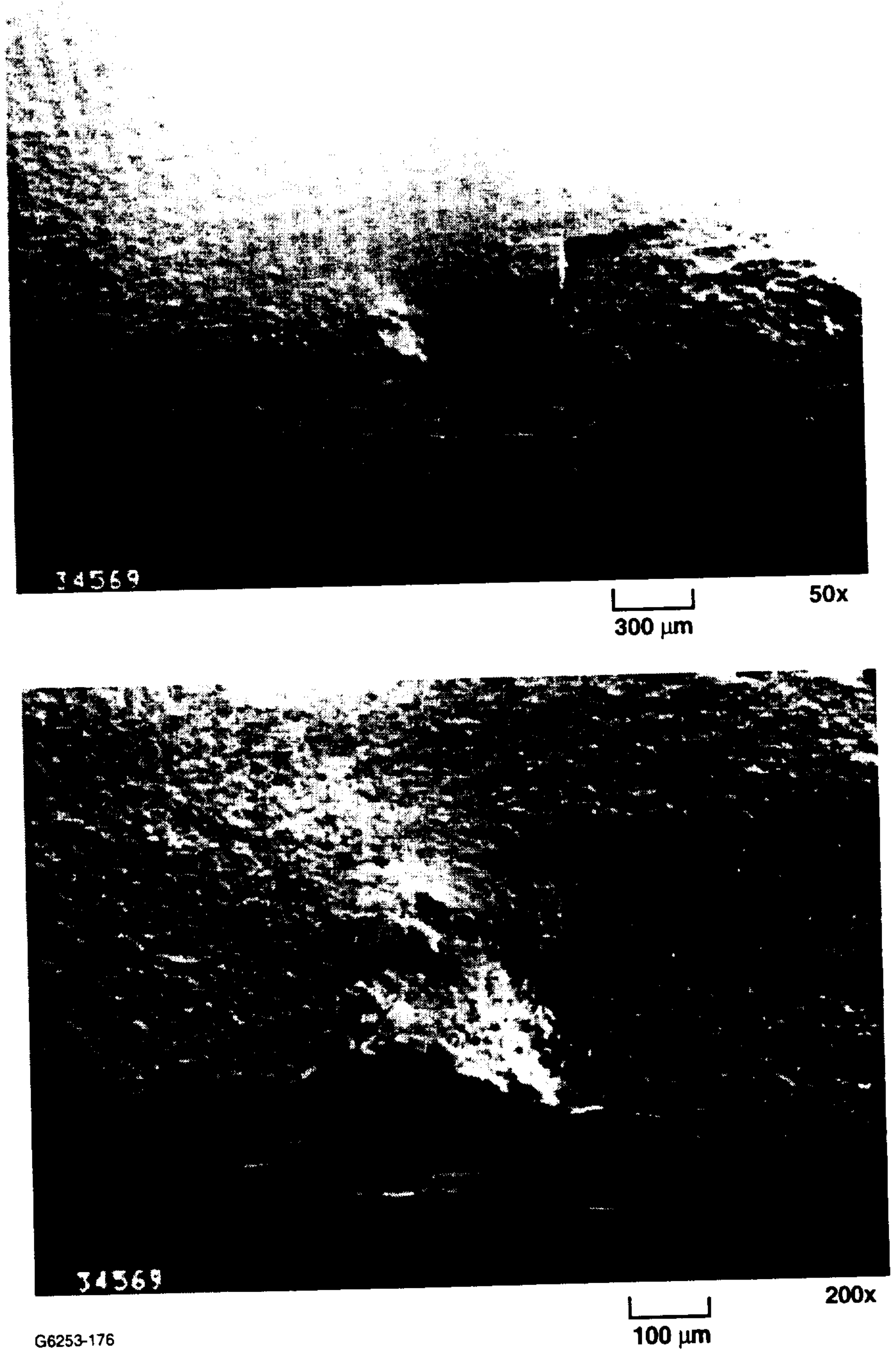
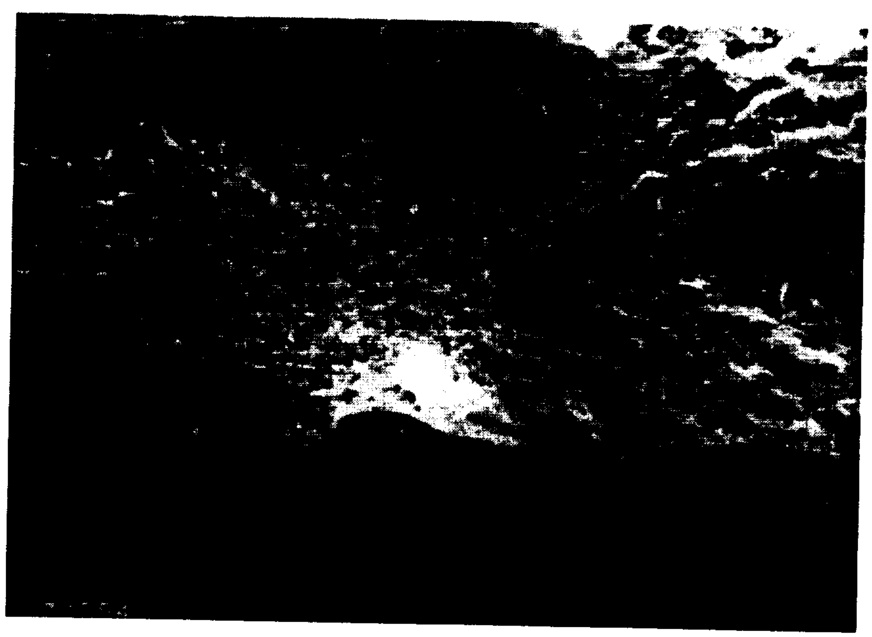


Figure 176. NT-154 Baseline Test Specimen Failure Originating From Surface-Connected Porosity.

300 µm 70x



100 µm 200x

G6253-177

Figure 177. NT-154 Baseline Test Specimen Failure Originating From An Iron-Carbon Inclusion.

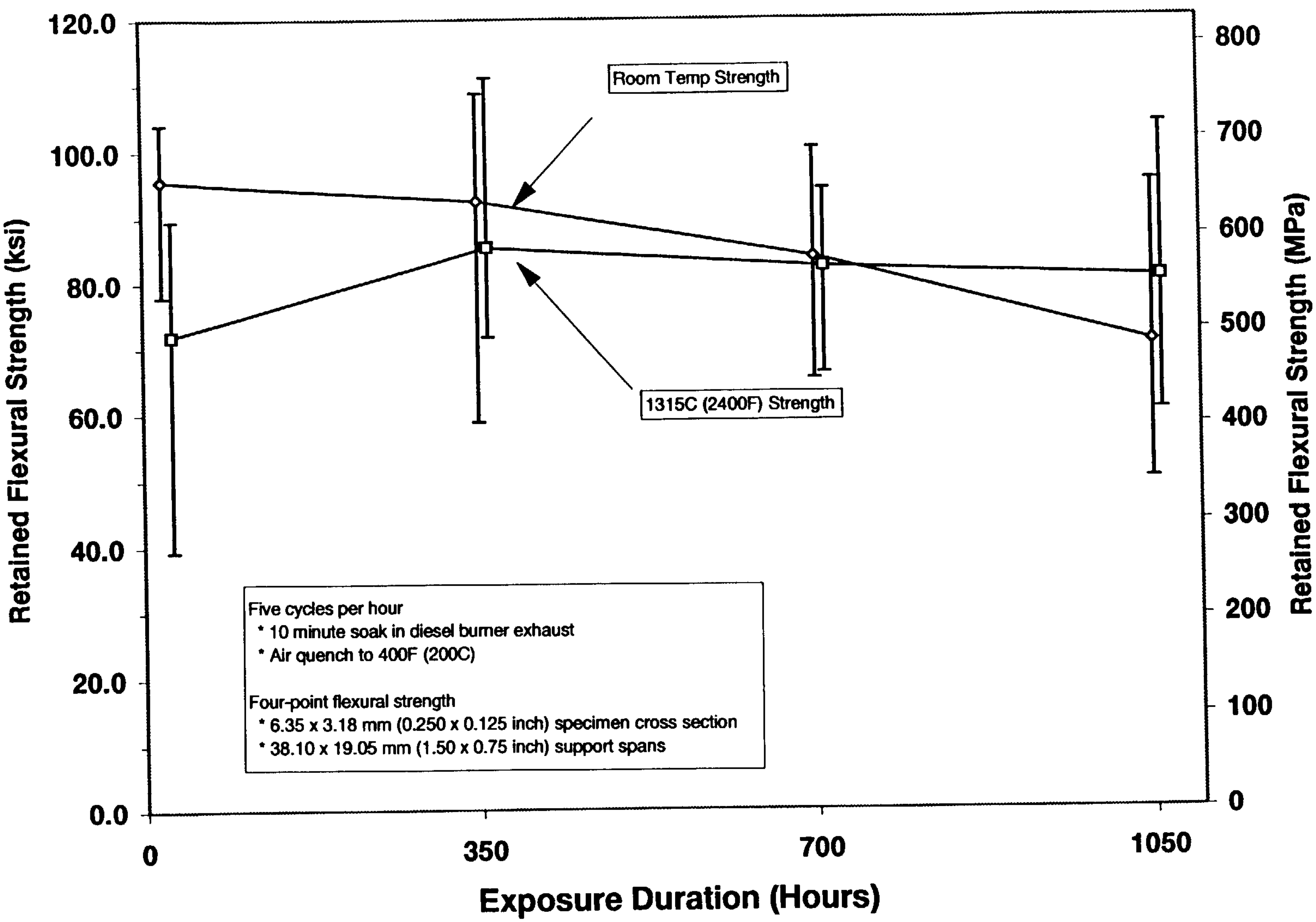
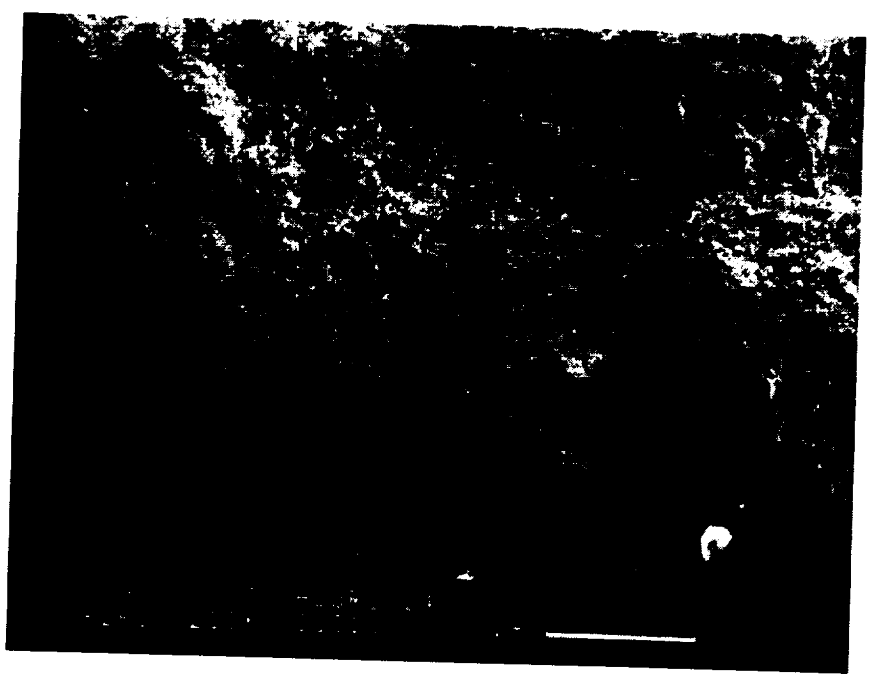


Figure 178. NT-154 Post-Exposure Room-Temperature And 1316C (2400F) Strength Test Results Following 1316C (2400F) Cyclic Oxidation Durability Testing.

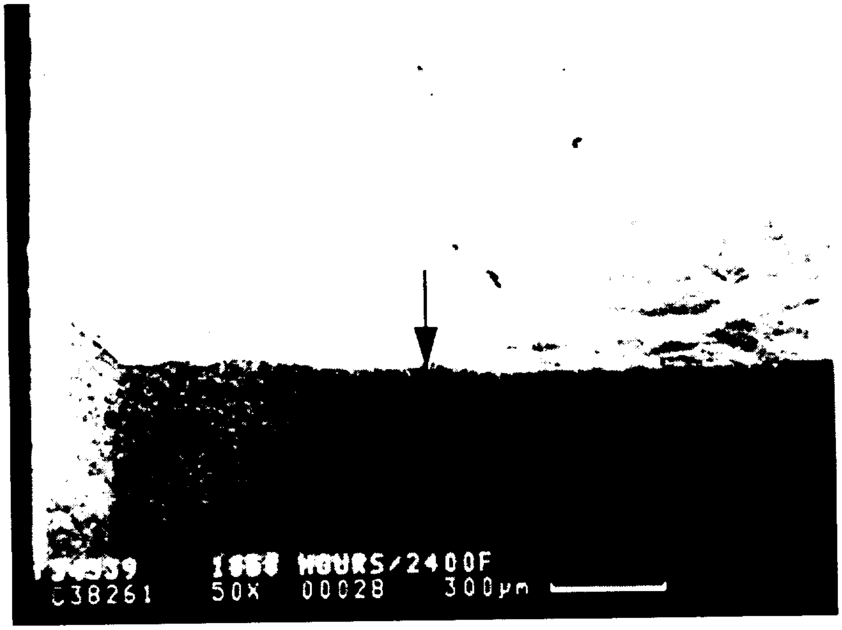
300 μm 50x



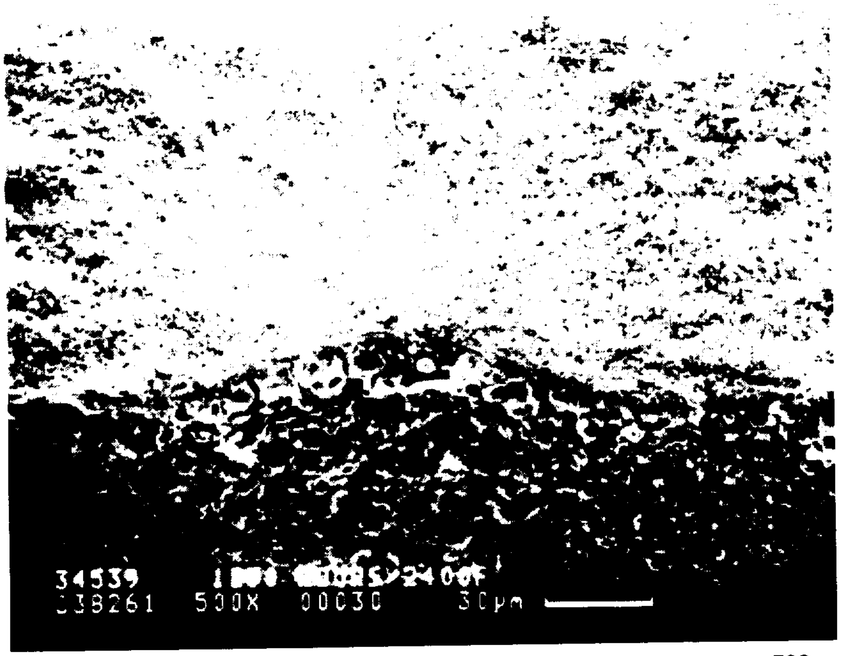
100 μm 200x

G6253-179

Figure 179. NT-154 Specimen Failure Originating From Chamfer Following 700 Hours Exposure At 1316C (2400F).



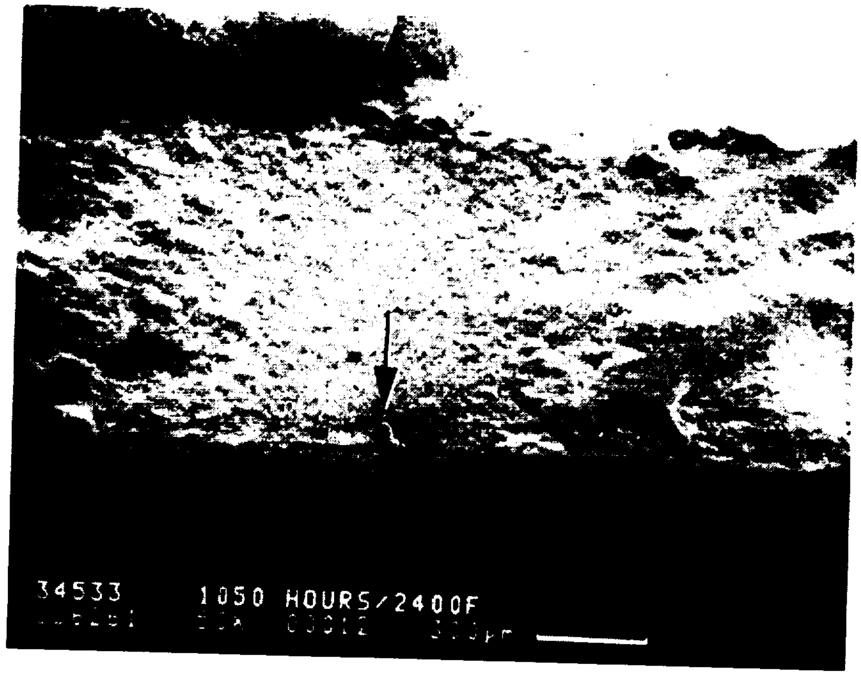
300 µm 50x



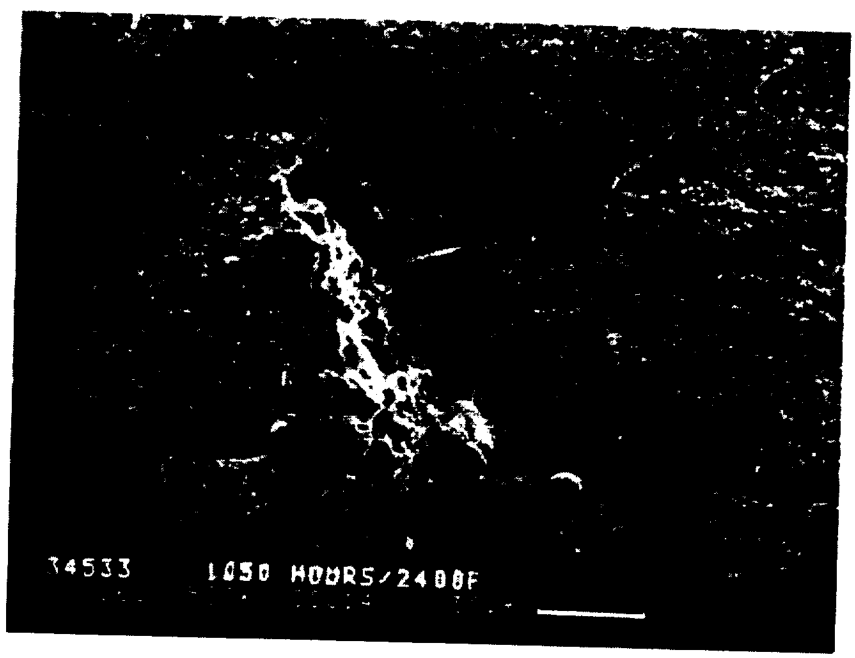
300 µm 500x

G6253-180

Figure 180. NT-154 Specimen Failure Originating From Shallow Pit Following 1050 Hours Exposure At 1316C (2400F).

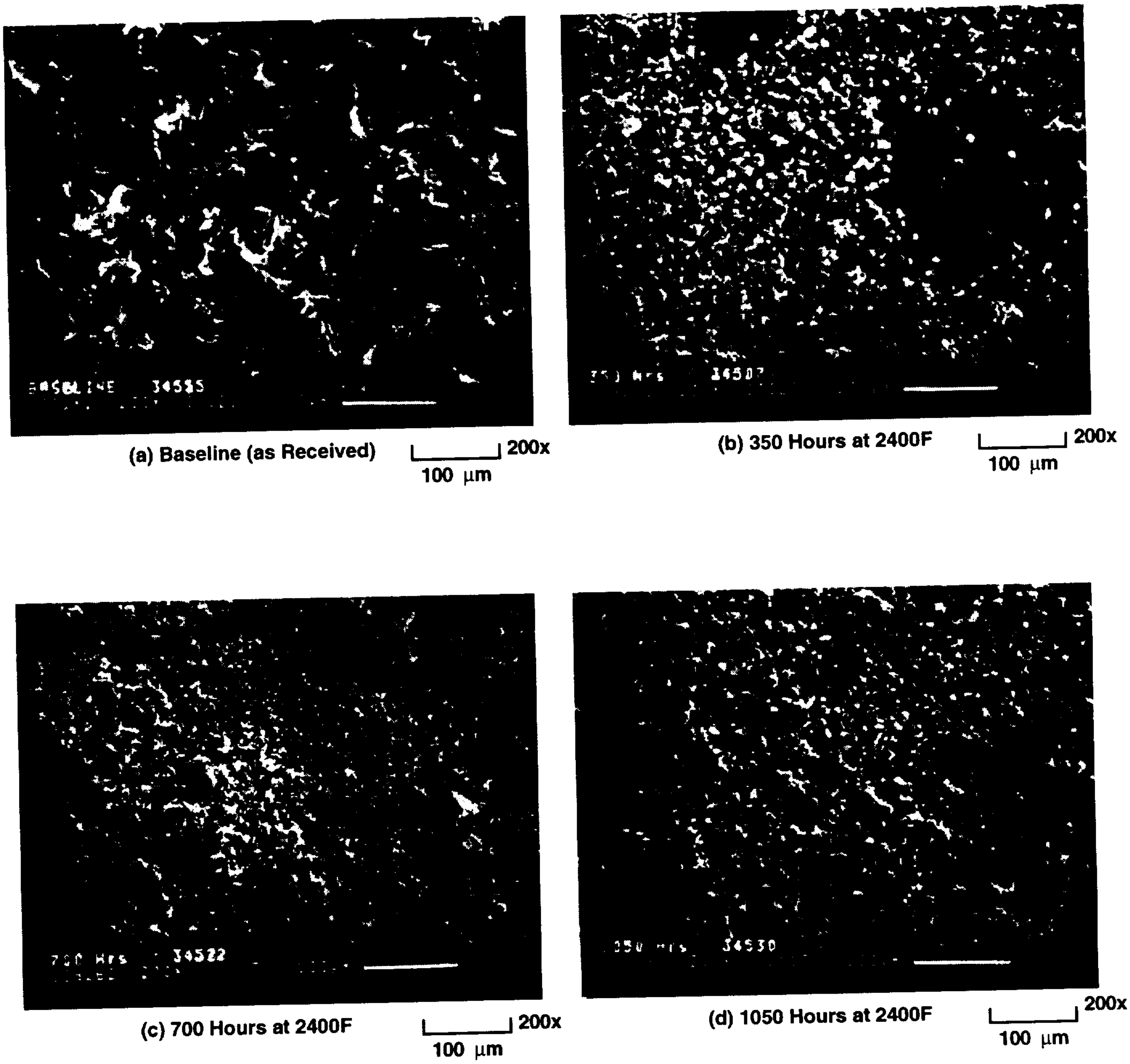


300 μm 50x



G6253-181 300 μm 500x

Figure 181. NT-154 Specimen Failure Originating From Deep Pit/Hole Following 1050 Hours Exposure At 1316C (2400F).



(a) Baseline (as Received) 200x 100 μm

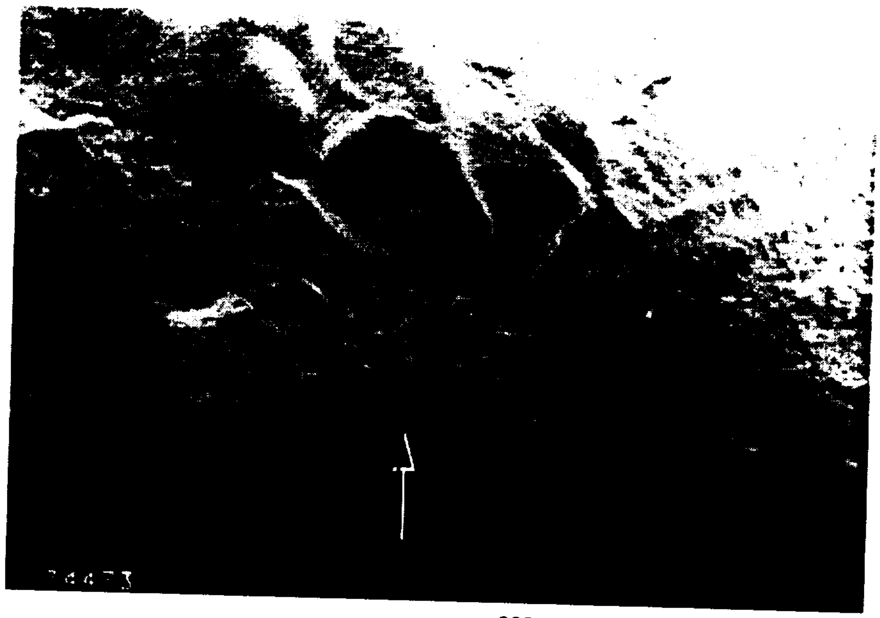
(b) 350 Hours at 2400F 200x 100 μm

(c) 700 Hours at 2400F 200x 100 μm

(d) 1050 Hours at 2400F 200x 100 μm

G6253-182

Figure 182. NT-154 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1316C (2400F): (a) Baseline (Zero Hours); (b) 350 Hours; (c) 700 Hours; (d) 1050 Hours.



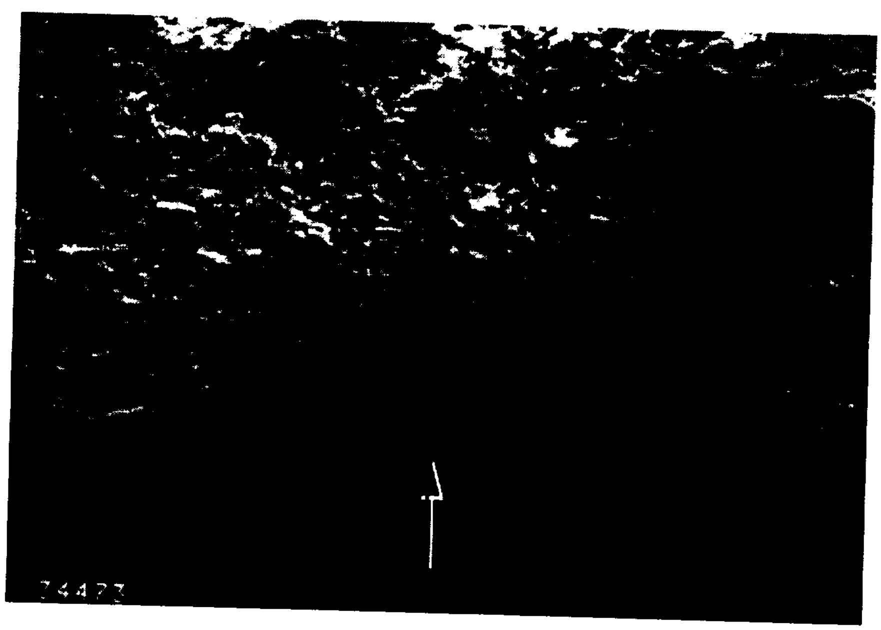
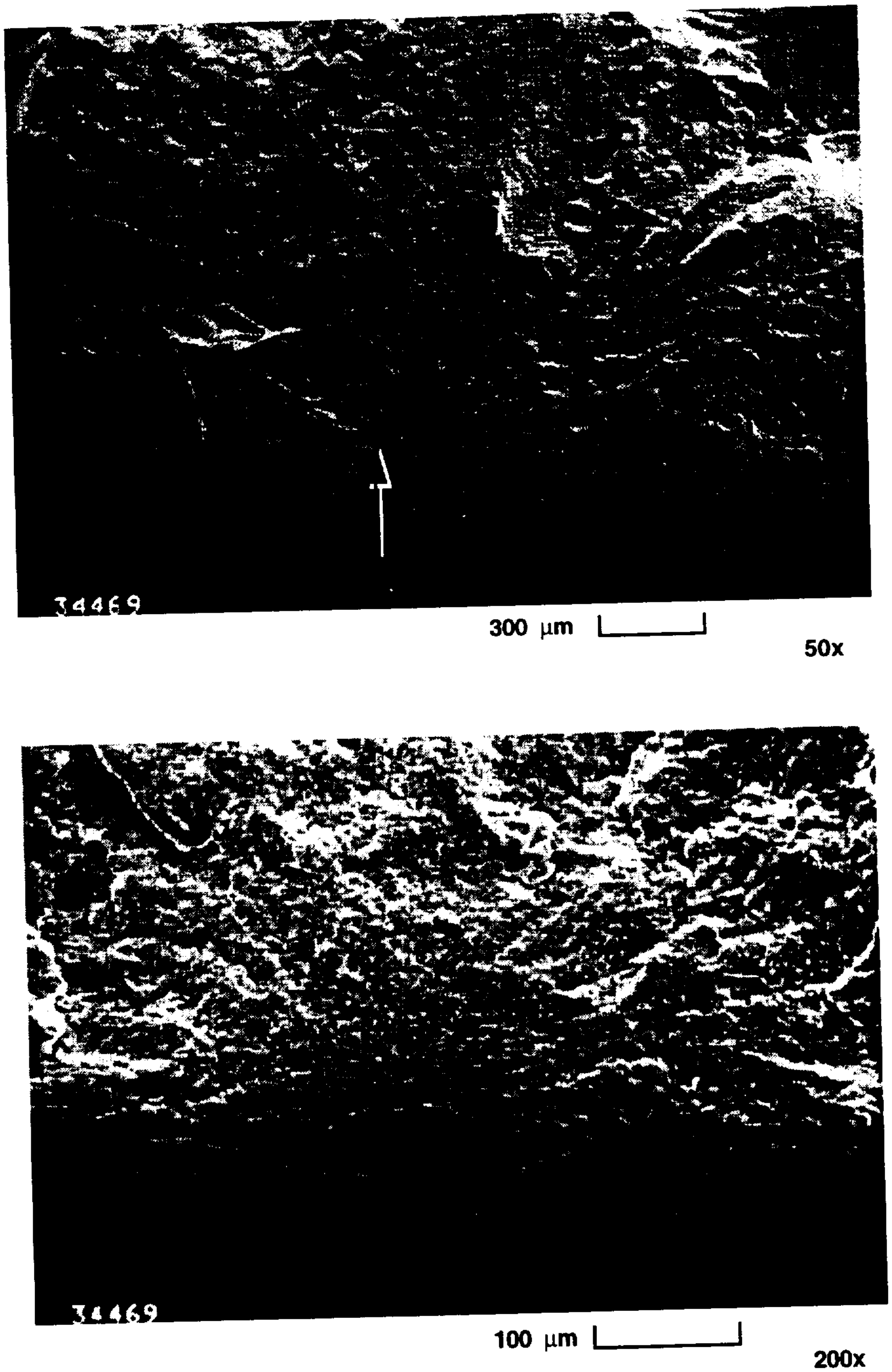


Figure 183. Typical NT-164 Baseline Test Specimen Failure Originating From As-Processed Surface.



G6253-184A

Figure 184. NT-164 Baseline Test Specimen Failure Originating From Shallow Pit In As-Processed Surface.

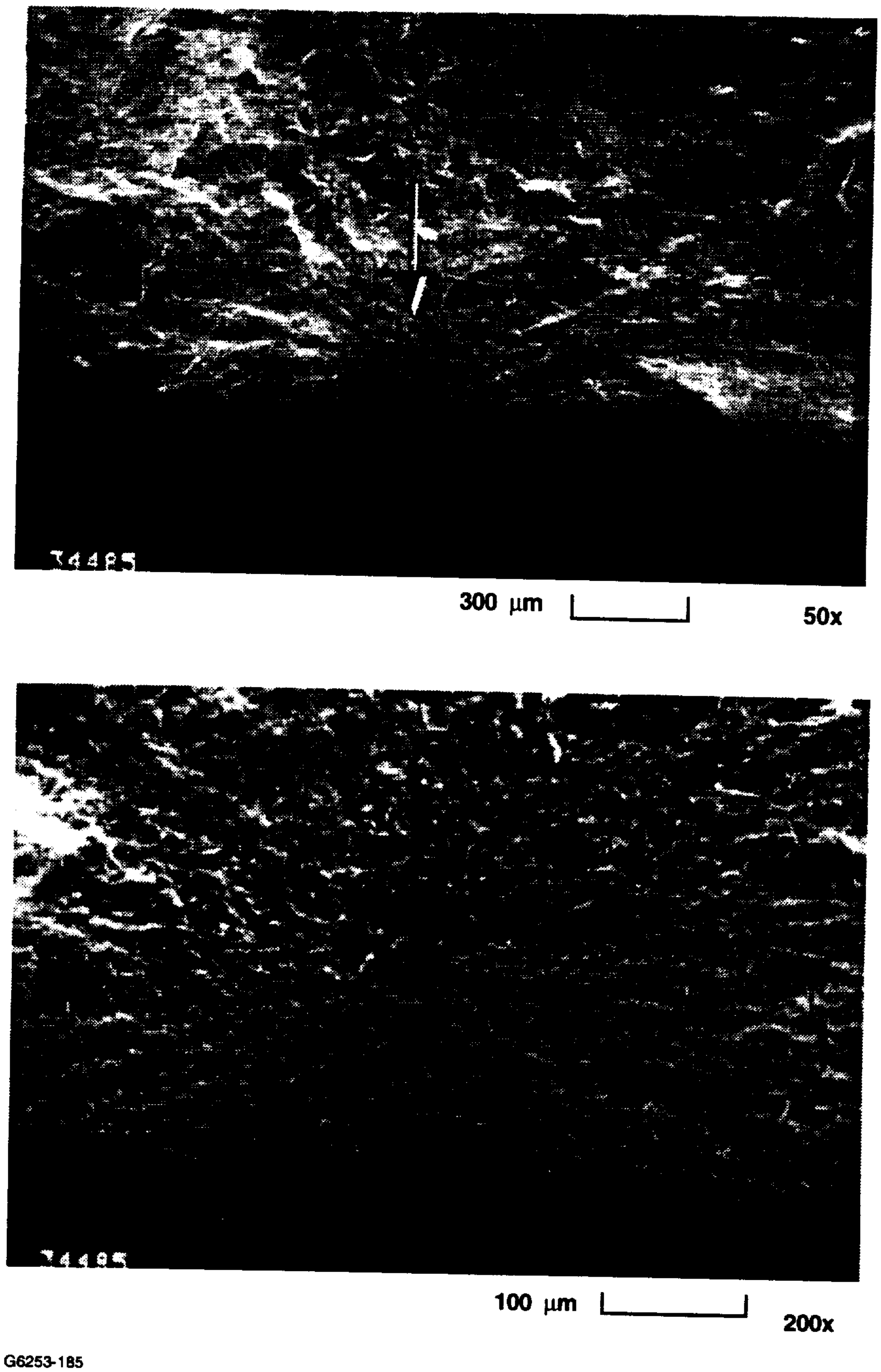


Figure 185. NT-164 Baseline Test Specimen Failure Originating From Internal Inclusion Containing Iron, Carbon, And Nickel.

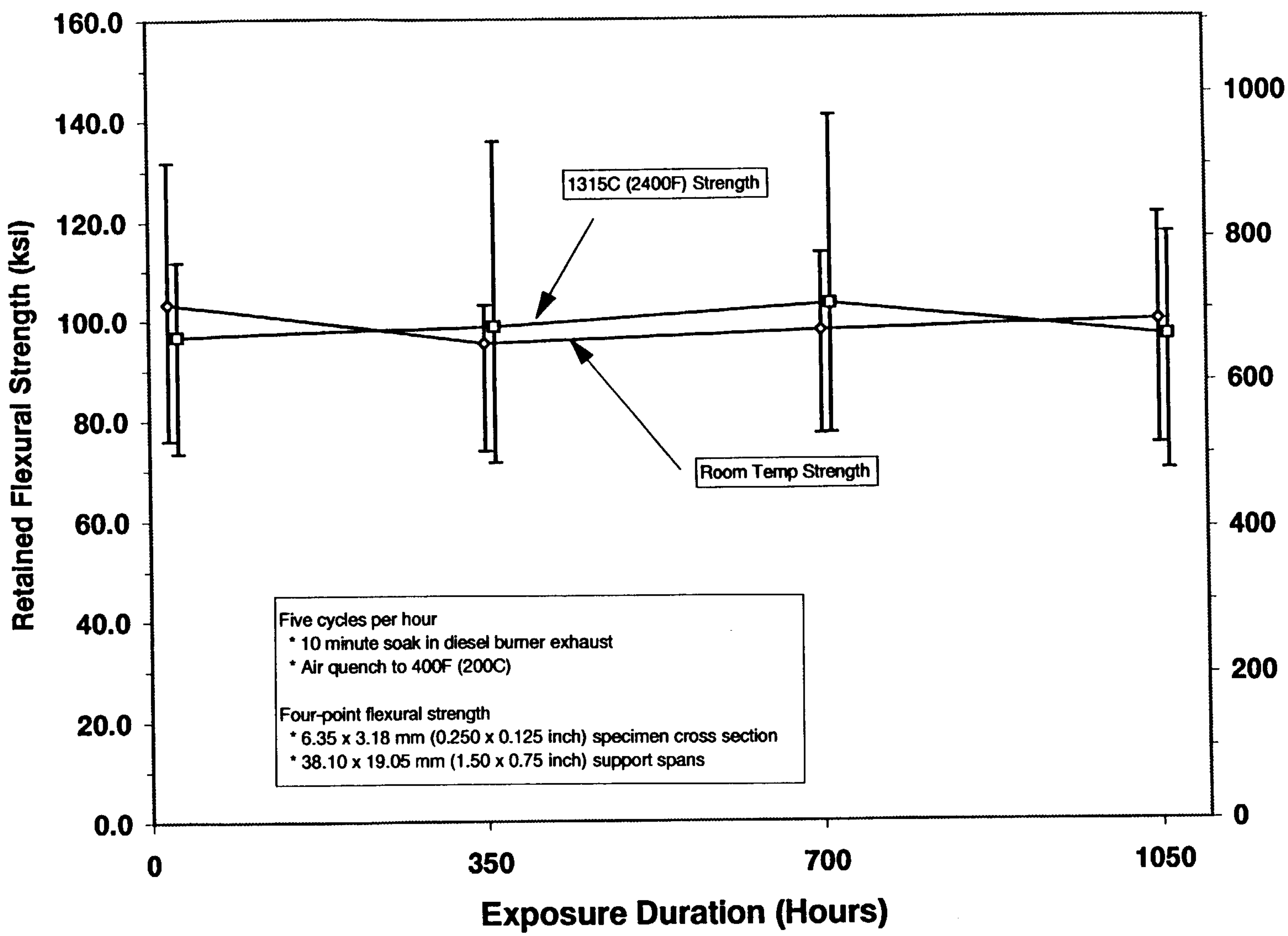


Figure 186. NT-164 Post-Exposure Room-Temperature And 1316C (2400F) Strength Test Results Following 1316C (2400F) Cyclic Oxidation Durability Testing.

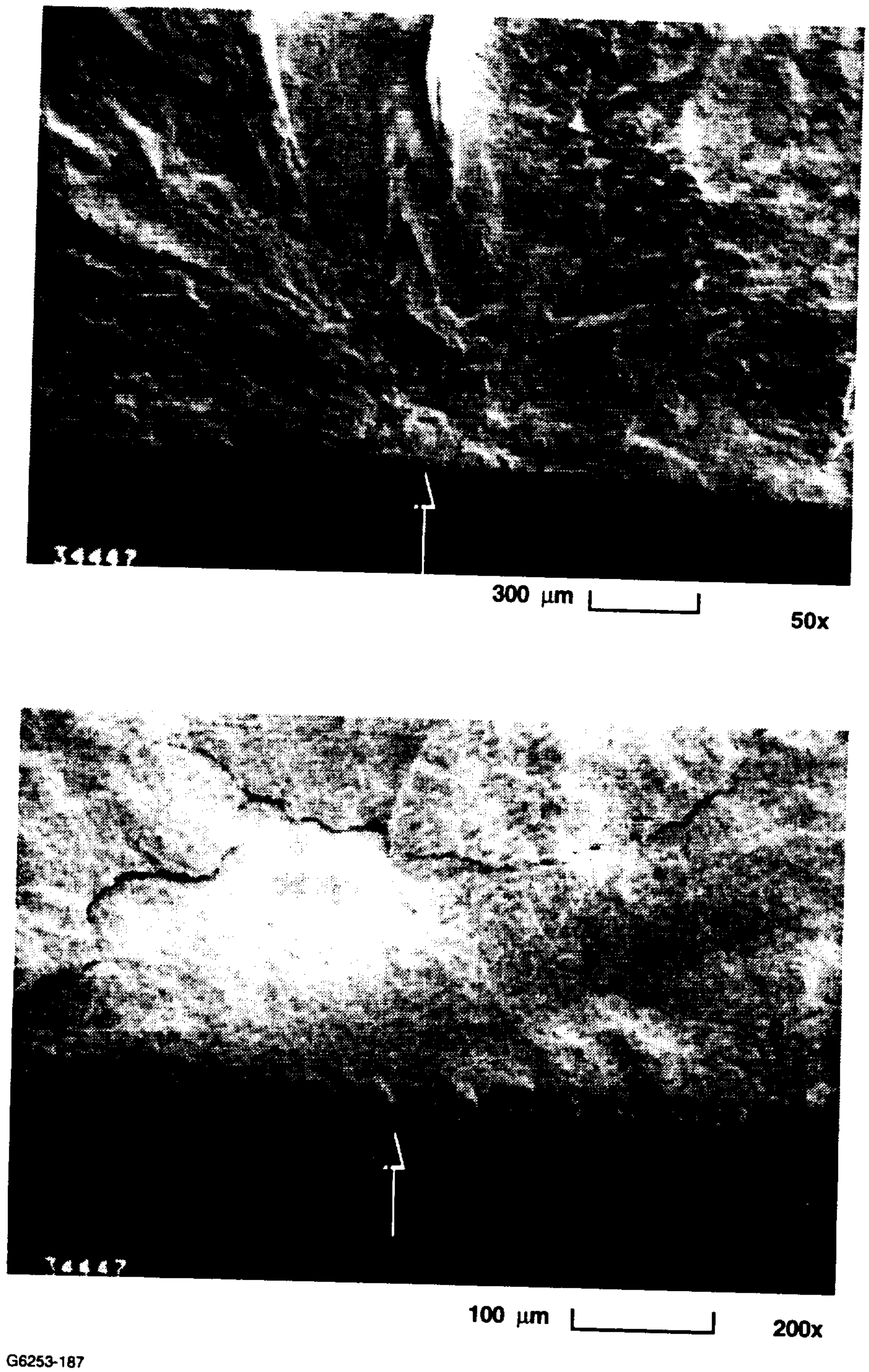


Figure 187. NT-164 Room-Temperature Test Specimen Failure Originating From Flame-Exposed Surface Following 700 Hours Exposure At 1316C (2400F).

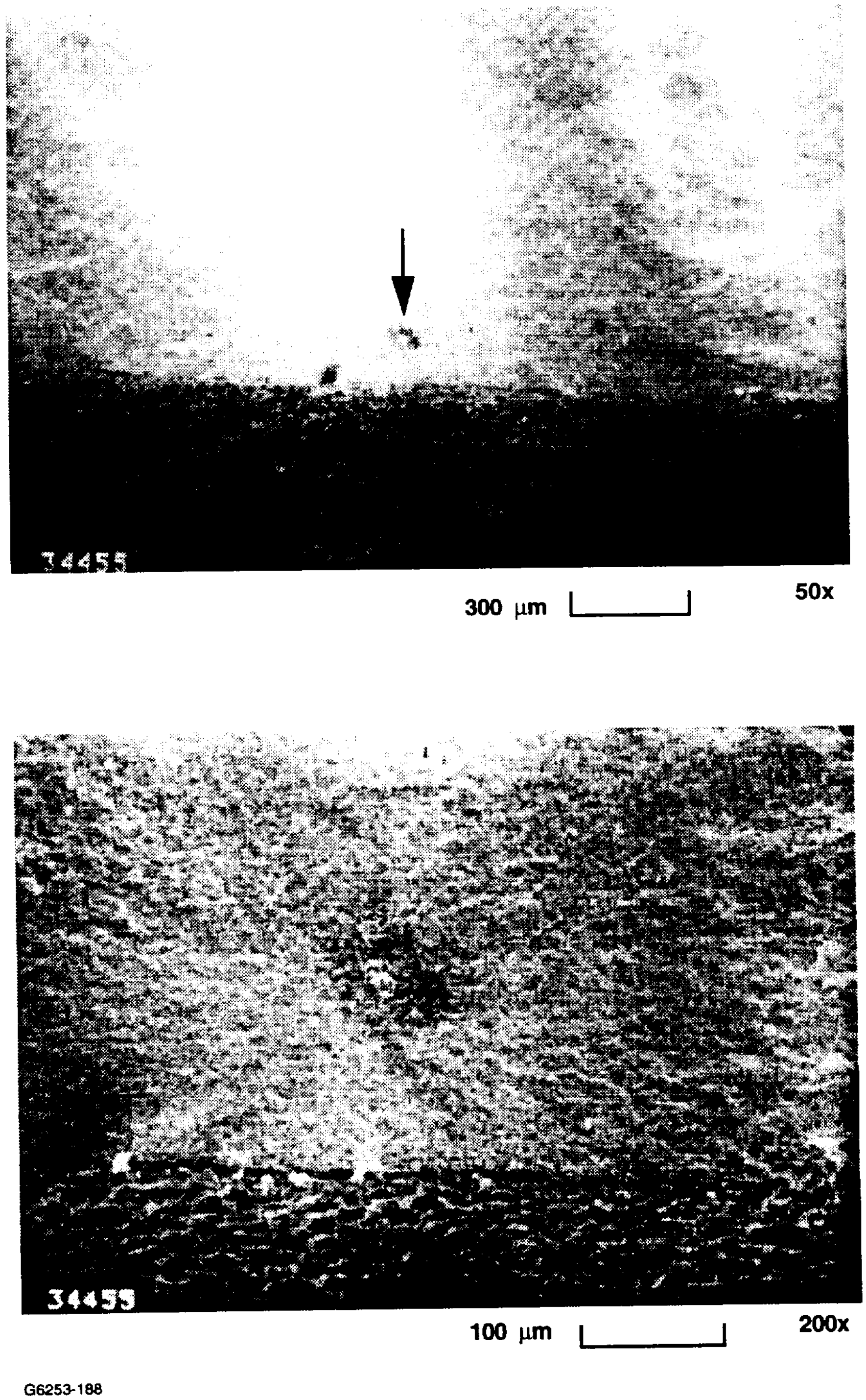
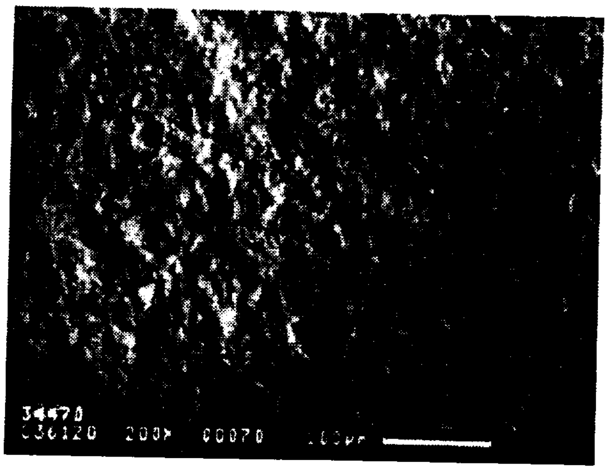
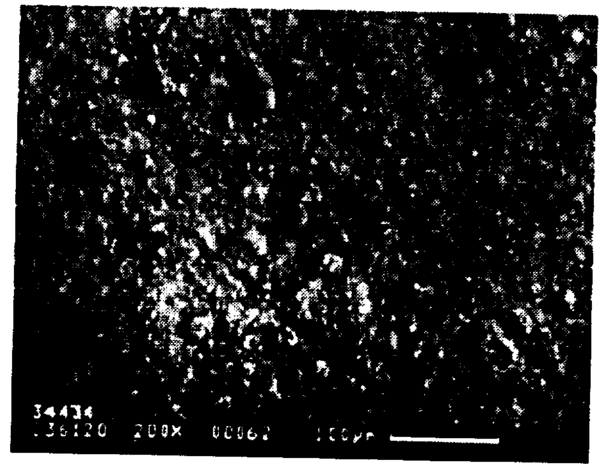


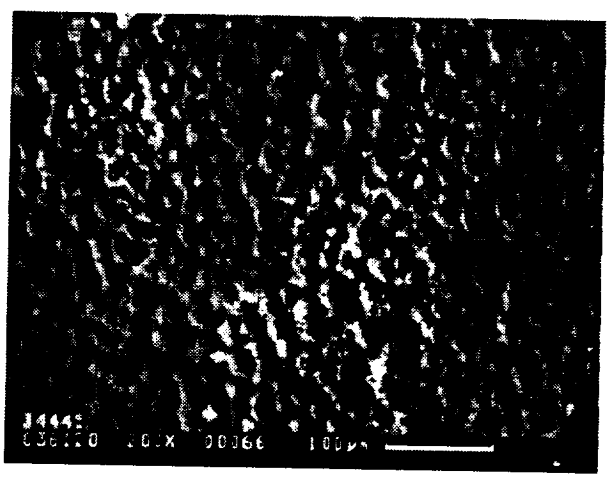
Figure 188. NT-164 1316C (2400F) Test Specimen Failure Originating From Internal Inclusion Containing Iron, Carbon, And Nickel Following 700 Hours Exposure At 1316C (2400F).



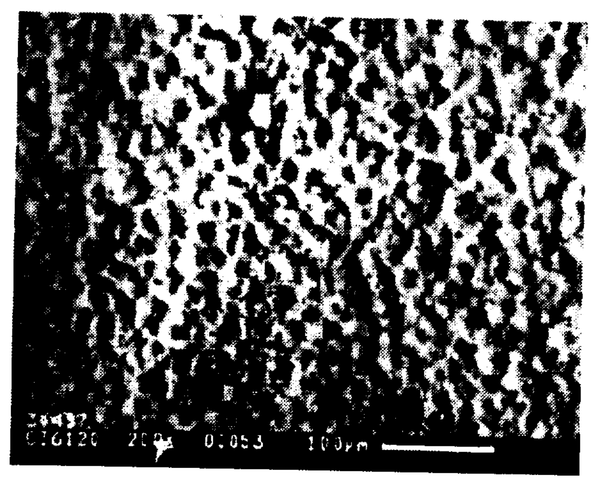
(a) Baseline (As-Received)



(b) 350 Hours at 2400F



(c) 700 Hours at 2400F



(d) 1050 Hours at 2400F

G6253-189

Figure 189. NT-164 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1316C (2400F): (a) Baseline (Zero hours); (b) 350 Hours; (c) 700 Hours; (d) 1050 Hours.

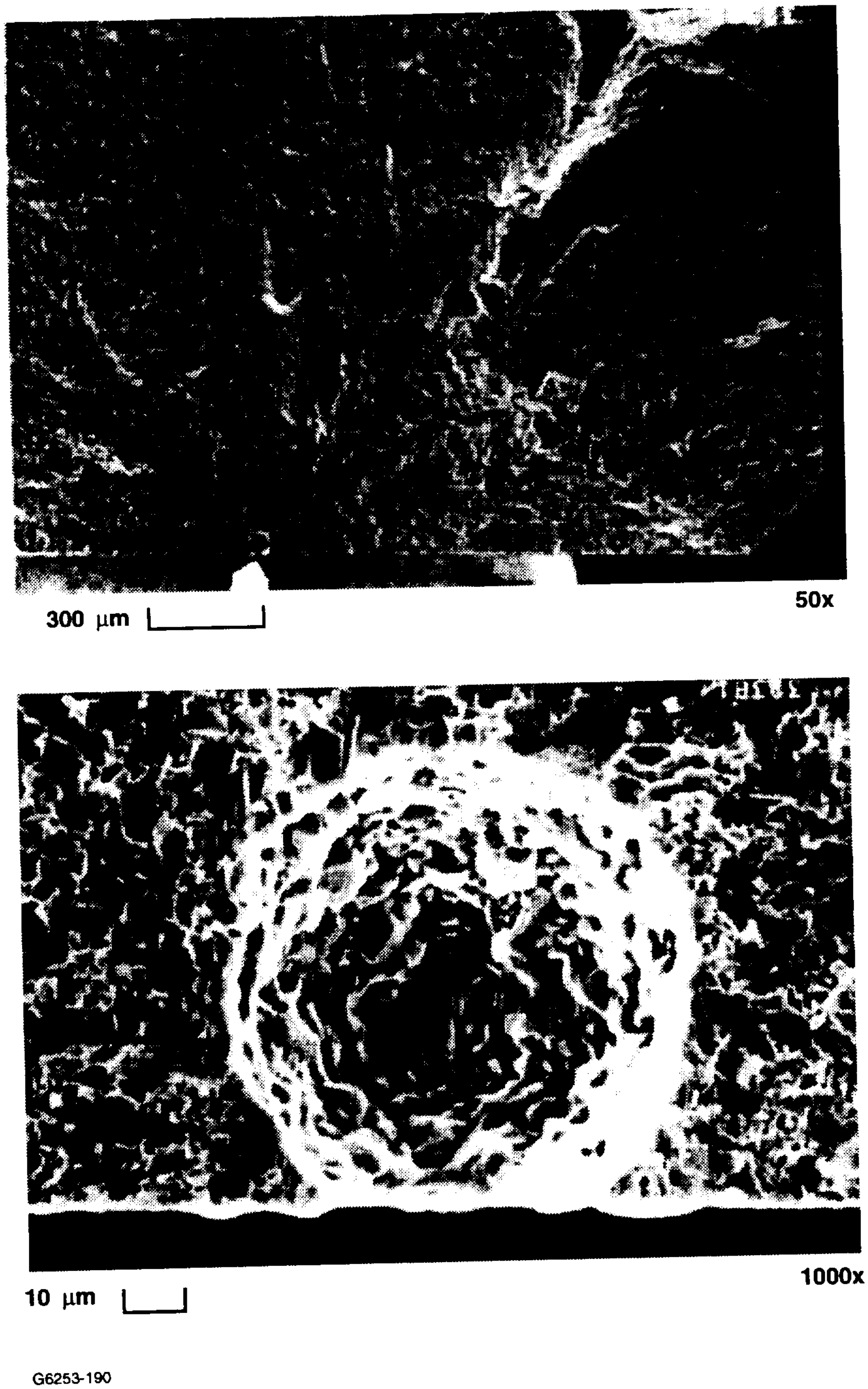
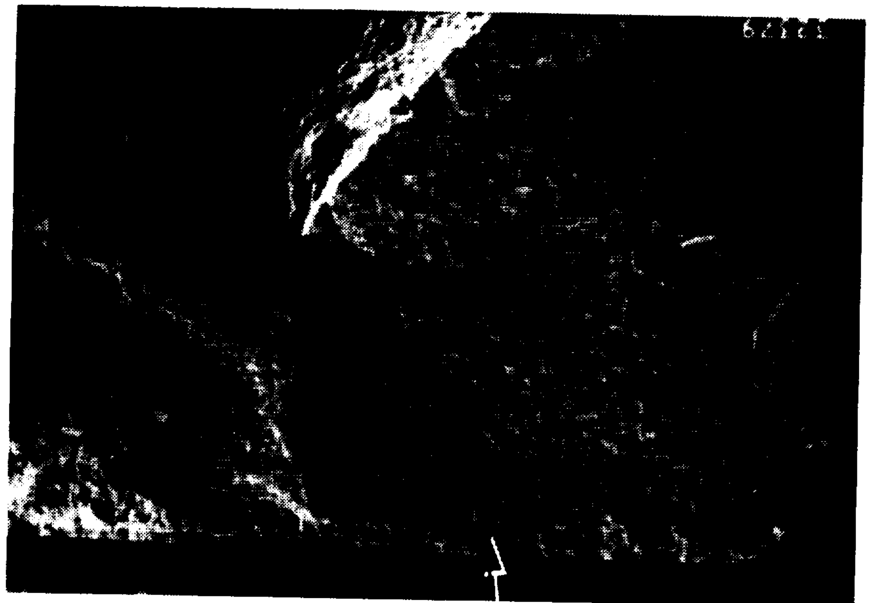


Figure 190. NT-230 Baseline Test Specimen Failure Originating From Surface-Connected Pore.



G6253-191

Figure 191. NT-230 Baseline Test Specimen Failure Originating From Internal Pore.

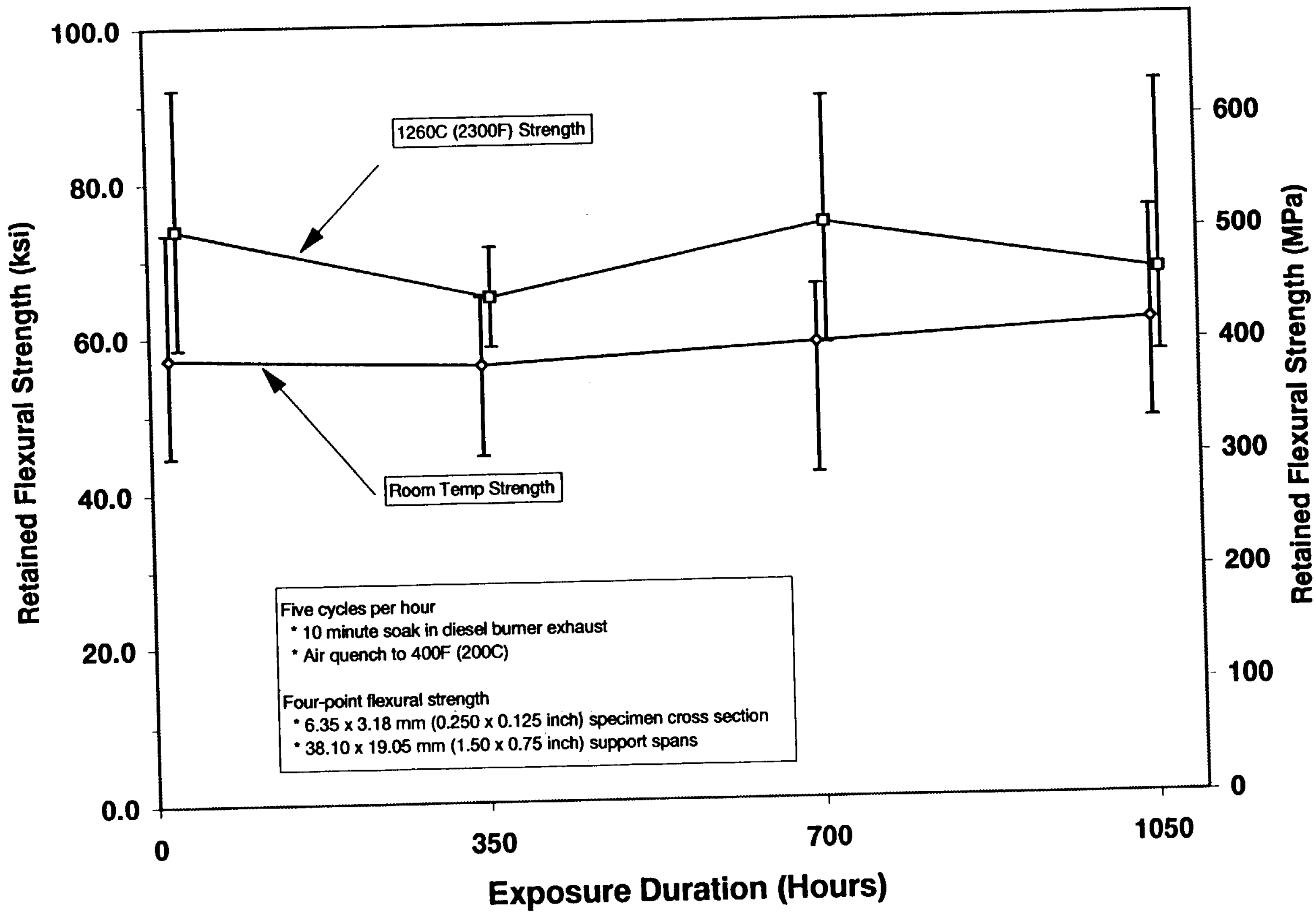


Figure 192. NT-230 Post-Exposure Room-Temperature And 1260C (2300F) Strength Test Results Following 1260C (2300F) Cyclic Oxidation Durability Testing.

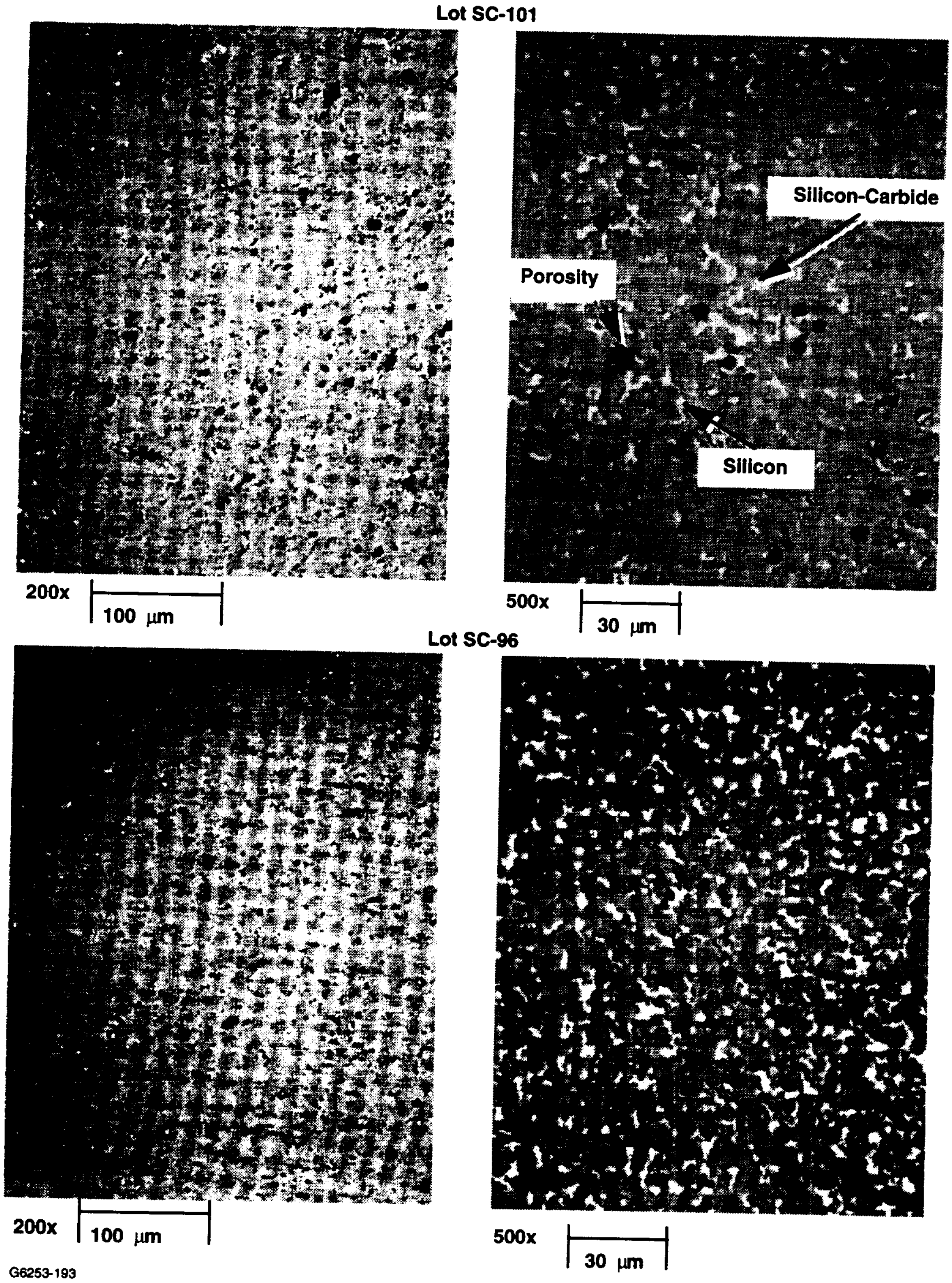
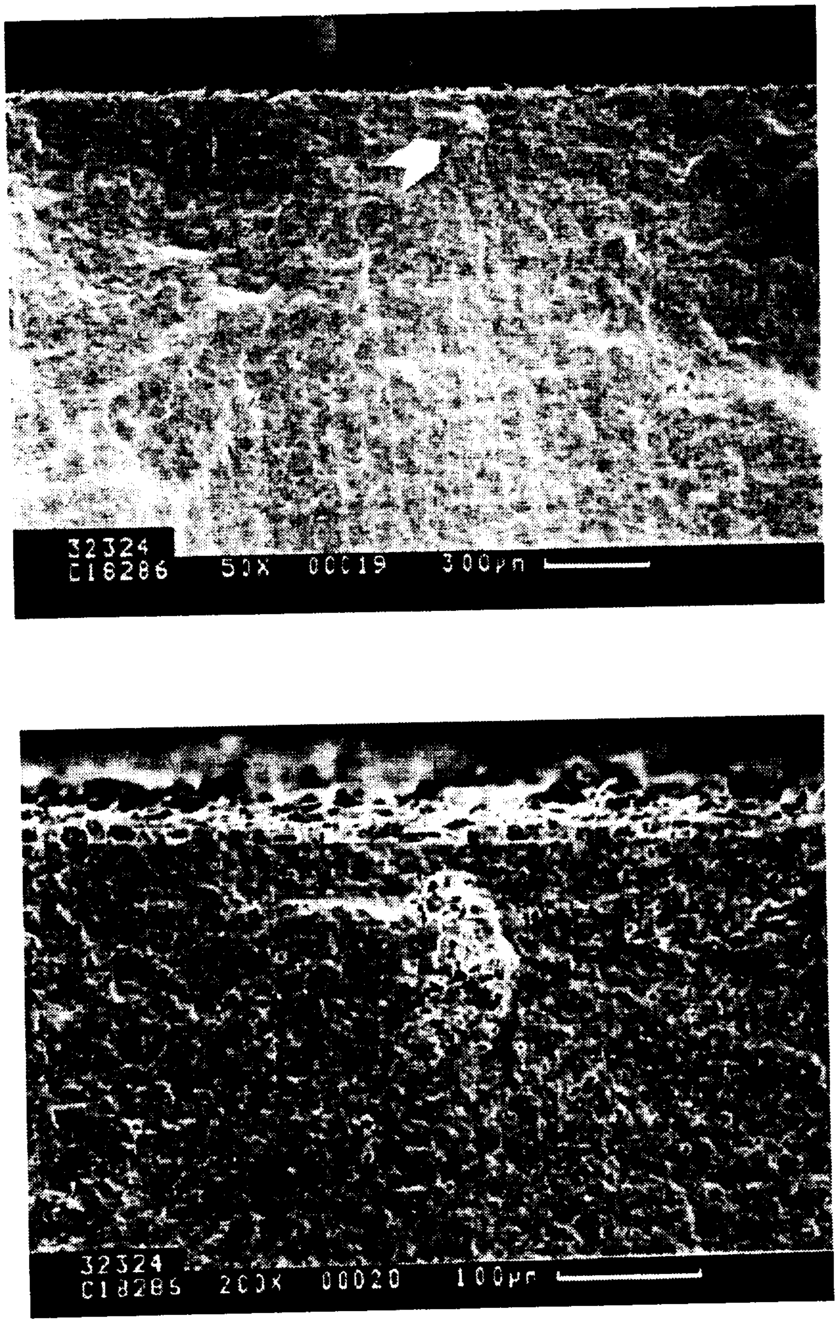
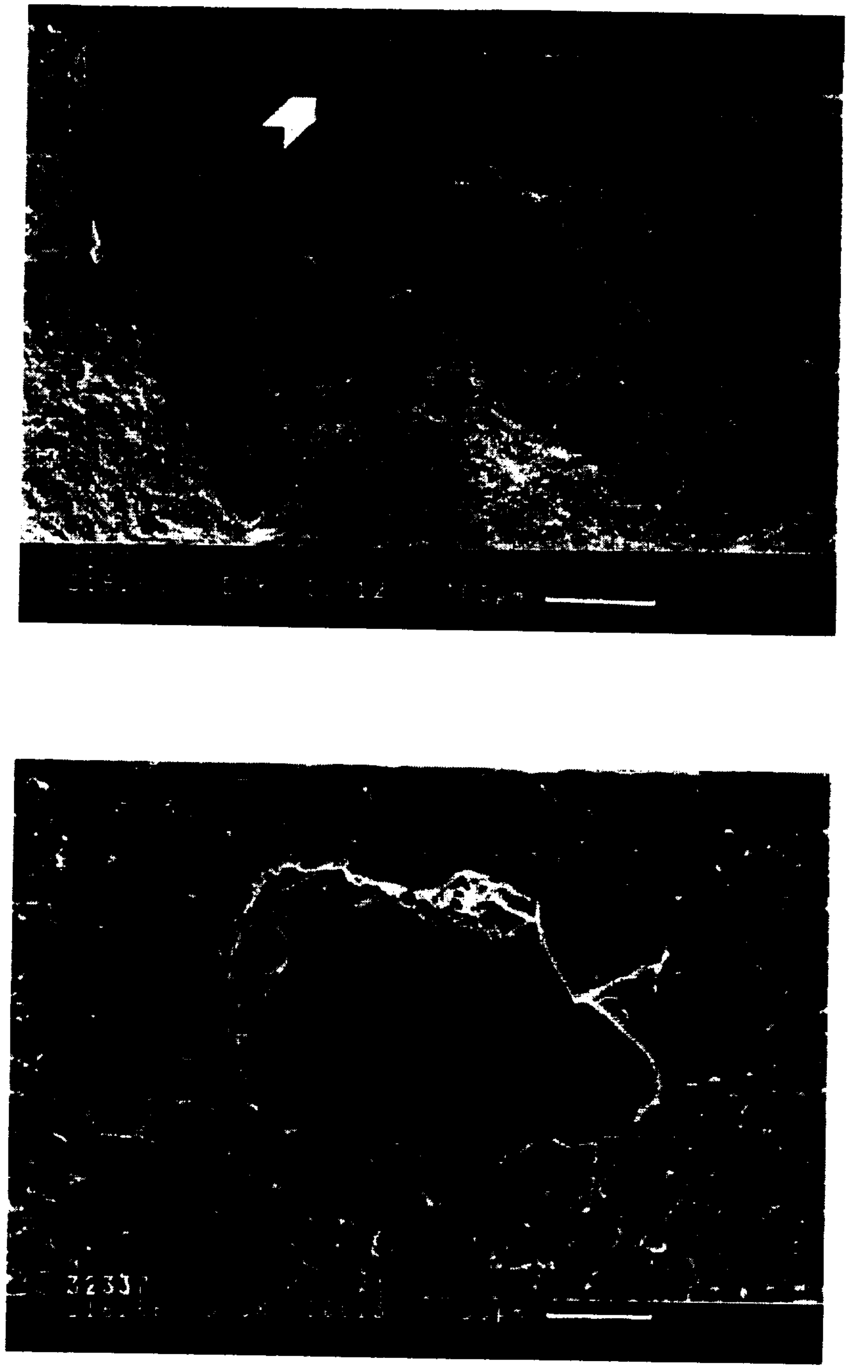


Figure 193. NT-230 Test Material From Lot No. SC-101 (Top) Exhibited Coarser Porosity Than Material From Lot No. SC-96 (Bottom).



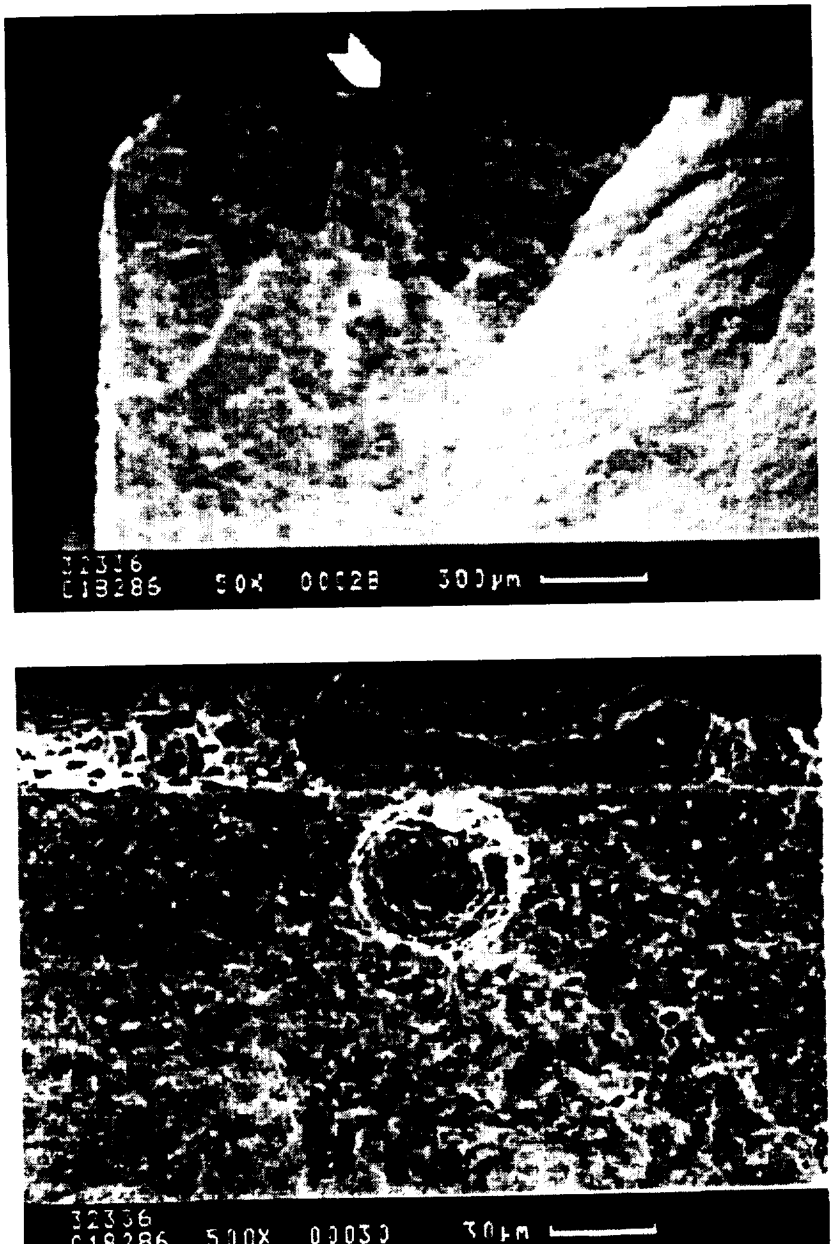
G6253-194

Figure 194. NT-230 Specimen Failure Originating From Subsurface Porosity Following 350 Hours Exposure At 1260C (2300F).



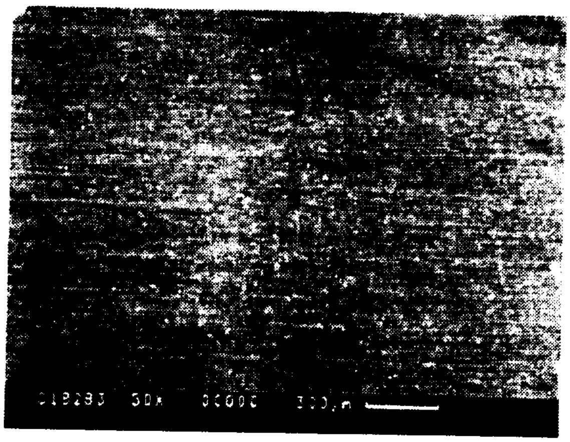
G6253-195A

Figure 195. NT-230 Specimen Failure Originating From Large Internal Pore Following 1050 Hours Exposure At 1260C (2300F).

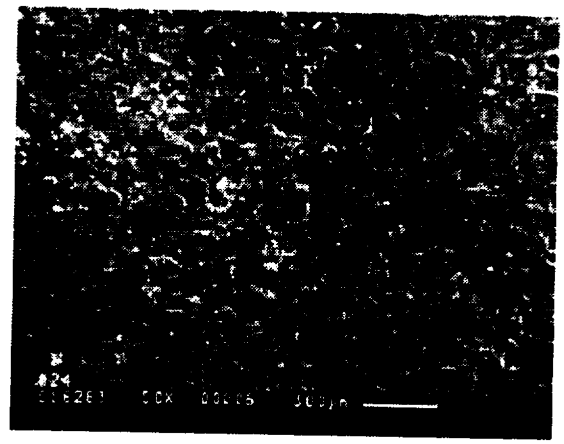


G6253-196

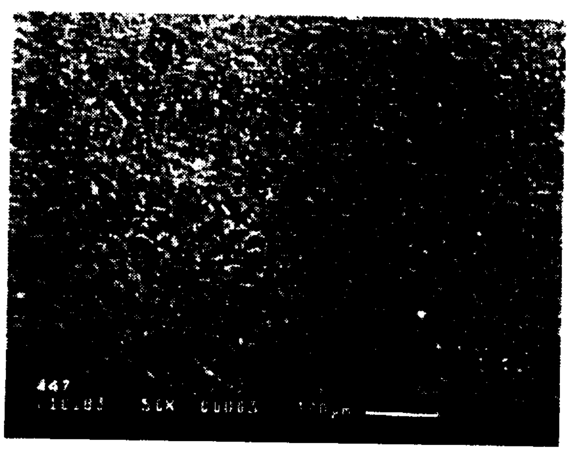
Figure 196. NT-230 Specimen Failure Originating From Subsurface Pore Following 1050 Hours Exposure At 1260C (2300F).



(a) Baseline (0 Hours)



(b) 350 Hours



(c) 700 Hours

(d) 1050 Hours

G6253-197

Figure 197. NT-230 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1260C (2300F): (a) Baseline (Zero Hours); (b) 350 Hours; (c) 700 Hours; (d) 1050 Hours.

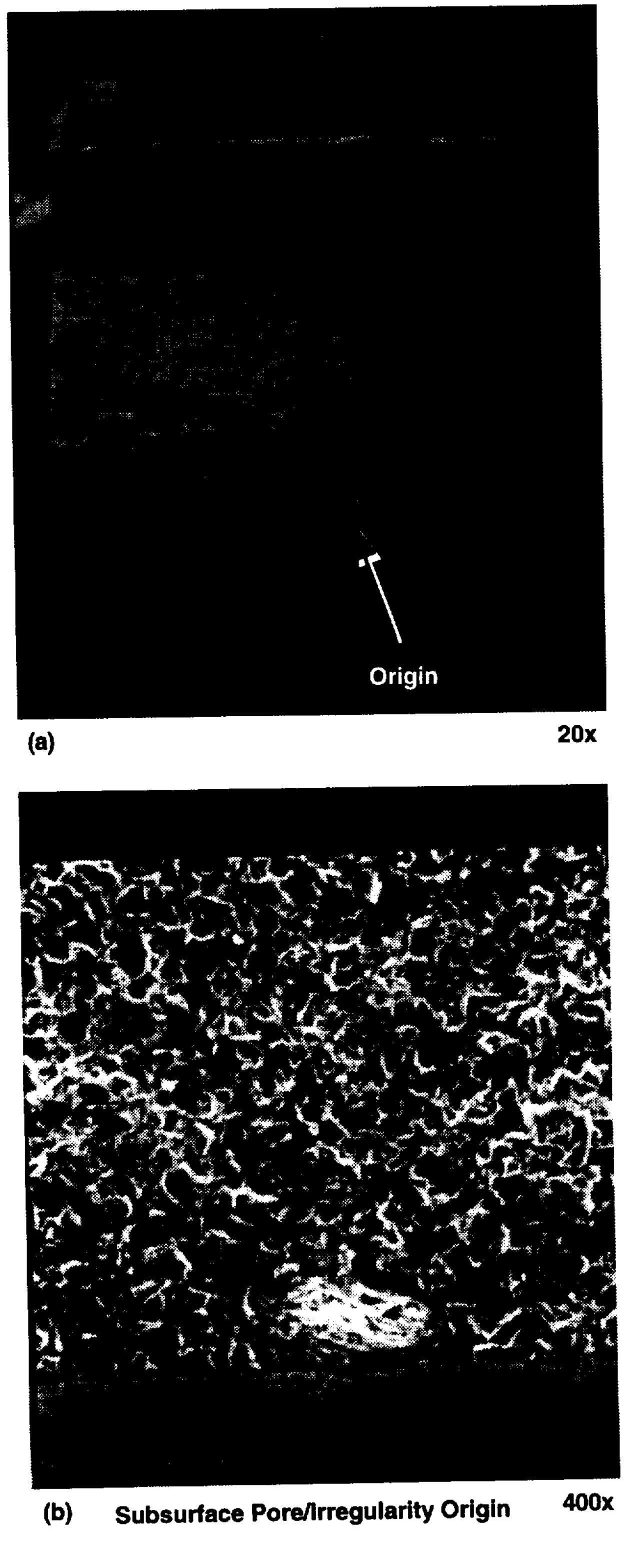
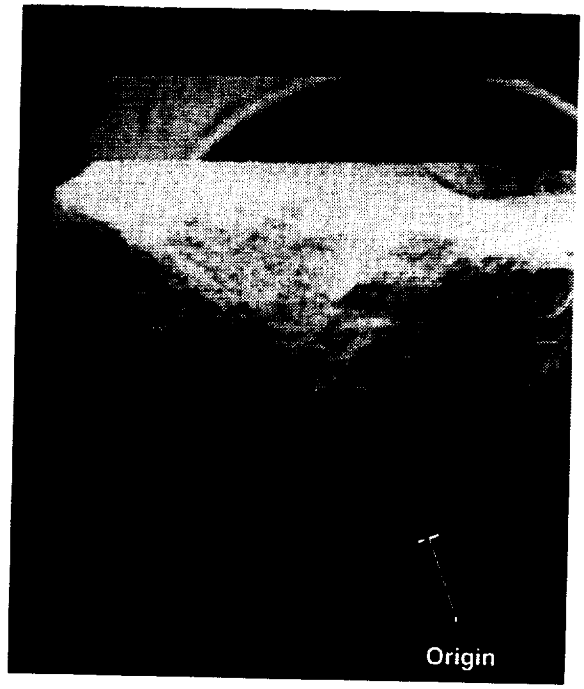
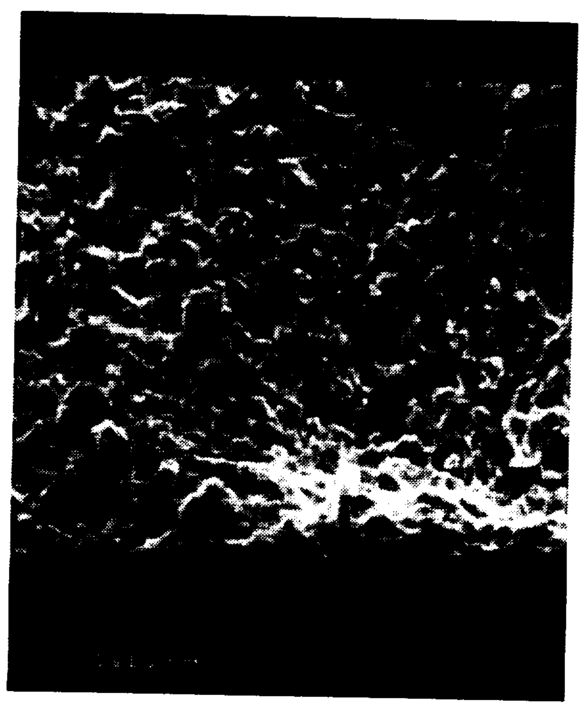


Figure 198. Typical Refel Si-SiC Room-Temperature Baseline Test Specimen Failure Originating From Subsurface Porosity.



(a) 20x



(b) Origin at Tensile Surface 400x

G6253-199

Figure 199. Typical Fracture Surface Of Refel Si-SiC 1204C (2200F) Baseline Test Specimen.

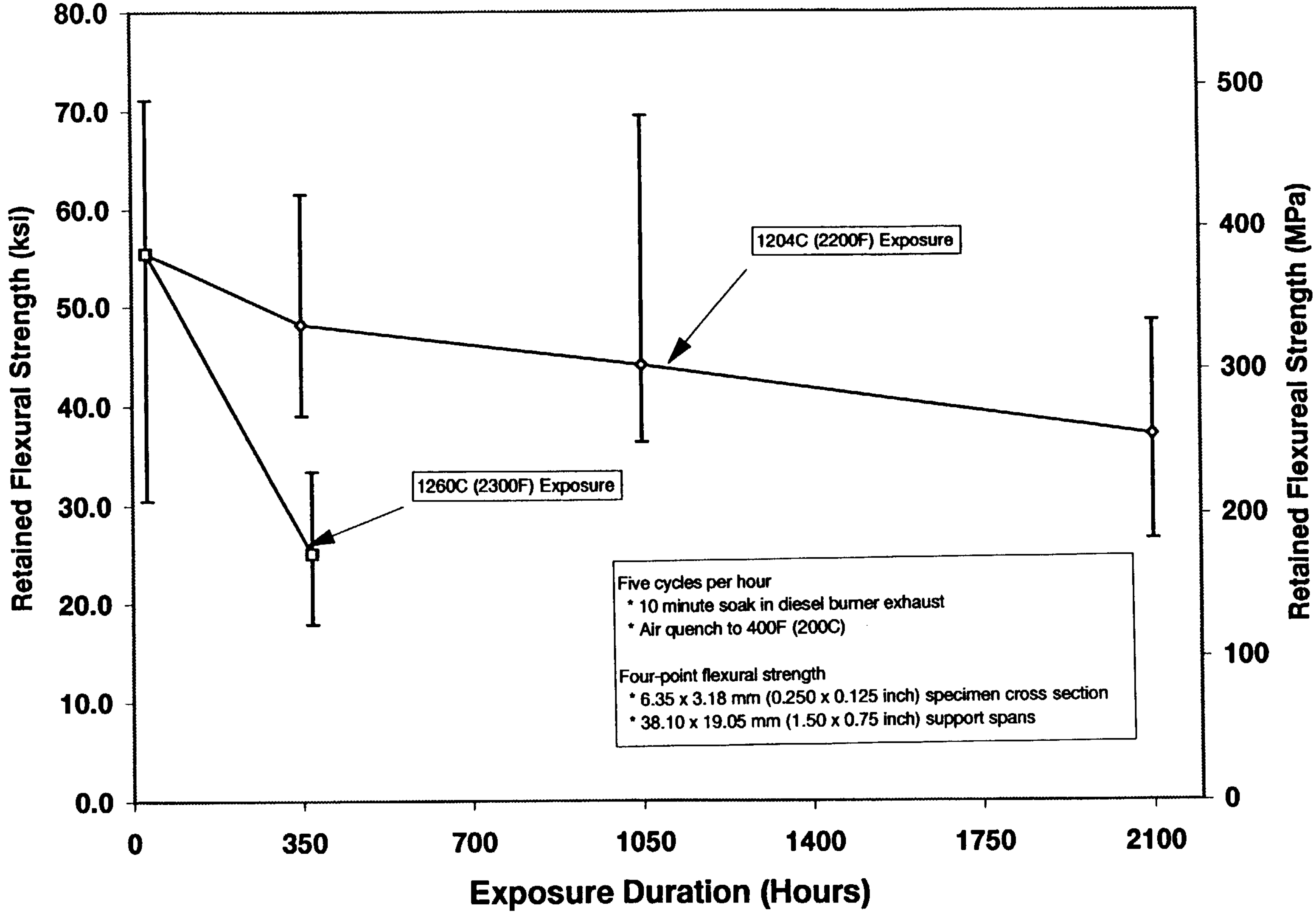
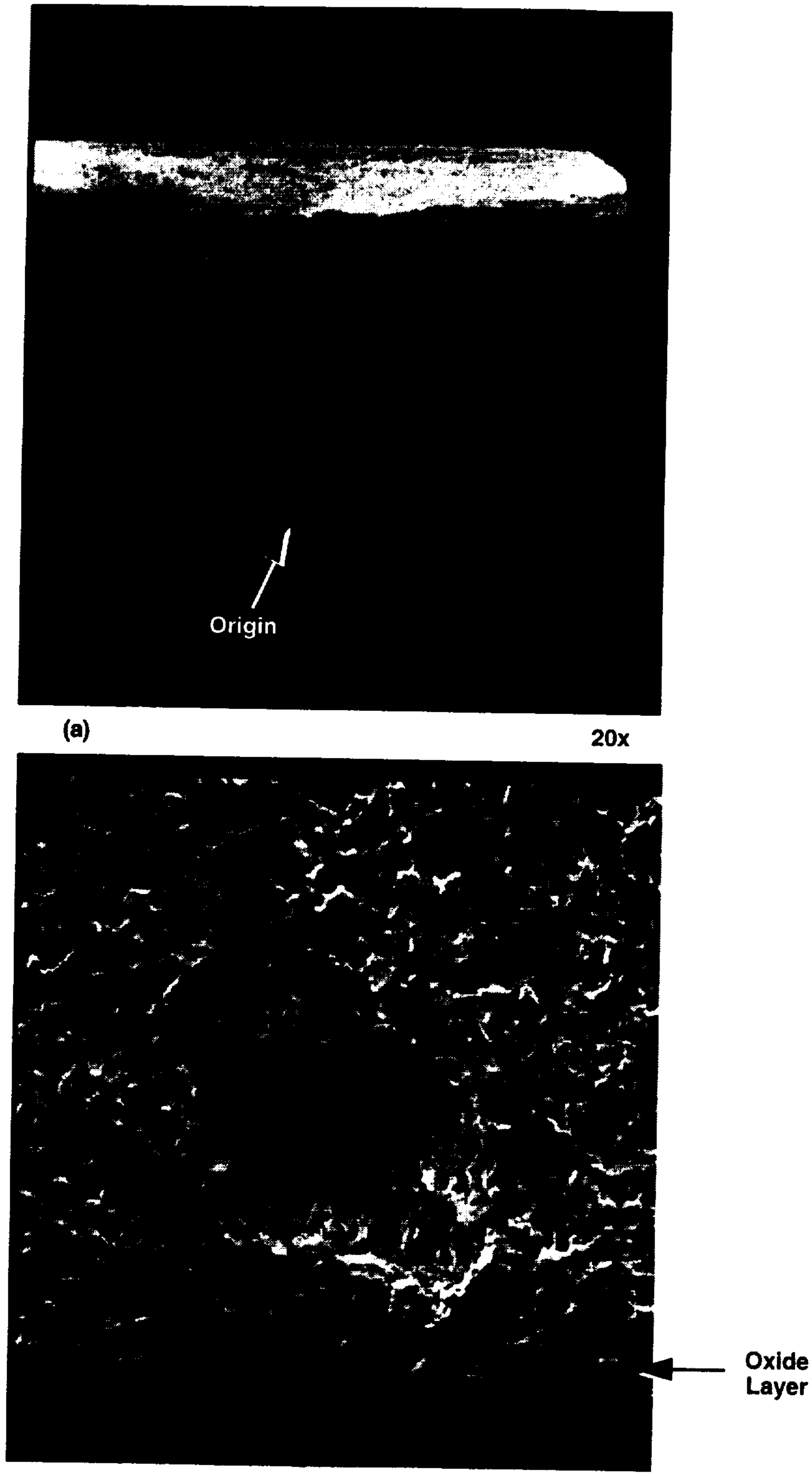


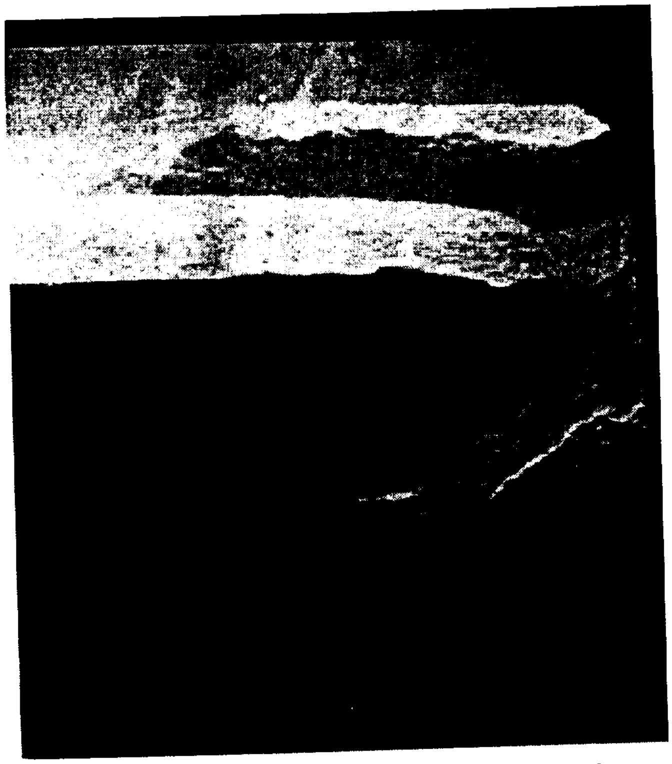
Figure 200. Refel Si-SiC Post-Exposure Room-Temperature Strength Test Results After Cyclic Oxidation Durability Testing At 1204C (2200F) And 1260C (2300F).



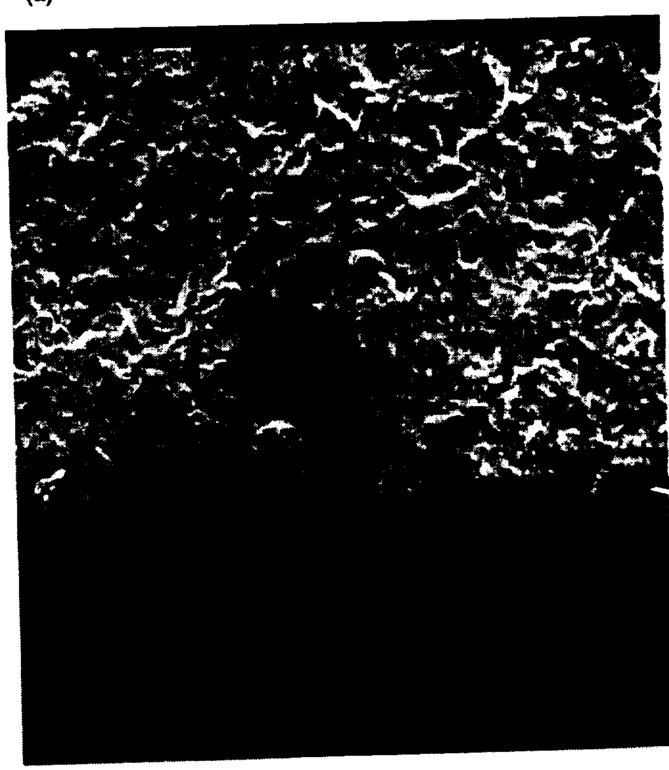
(b) Subsurface/Surface Porosity Origin 400x

G6253-201

Figure 201. Refel Si-SiC Specimen Failure Originating From Subsurface Pore Following 350 Hours Exposure At 1204C (2200F).



(a) 20x

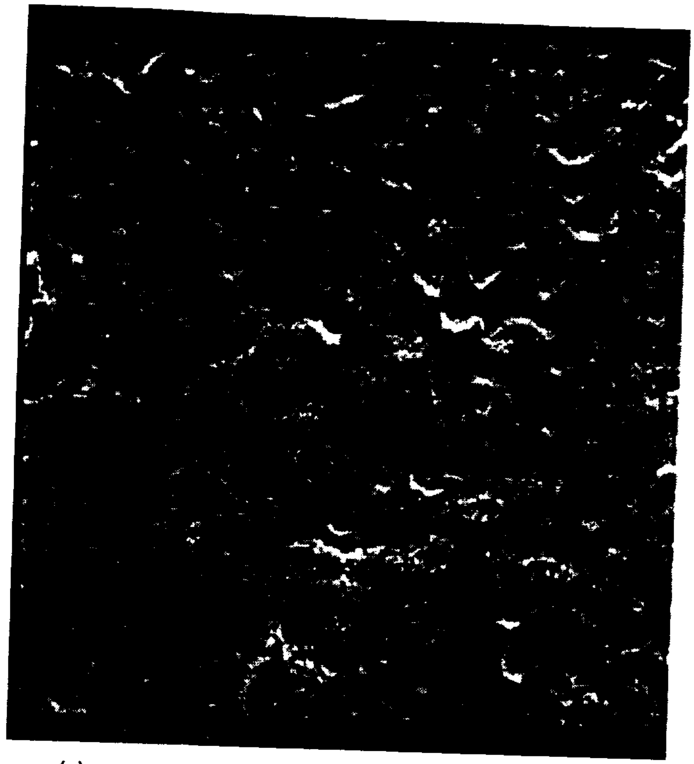


Oxide Layer

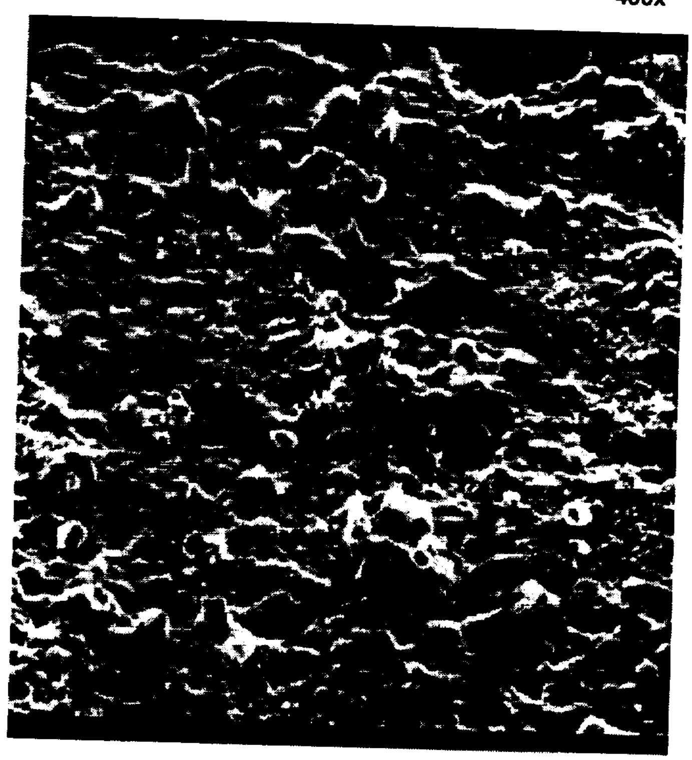
(b) Surface Pore/Oxide Reaction Origin 400x

G6253-202

Figure 202. Refel Si-SiC Specimen Failure Originating From Surface-Connected Pore Following 1050 Hours Exposure At 1204C (2200F).



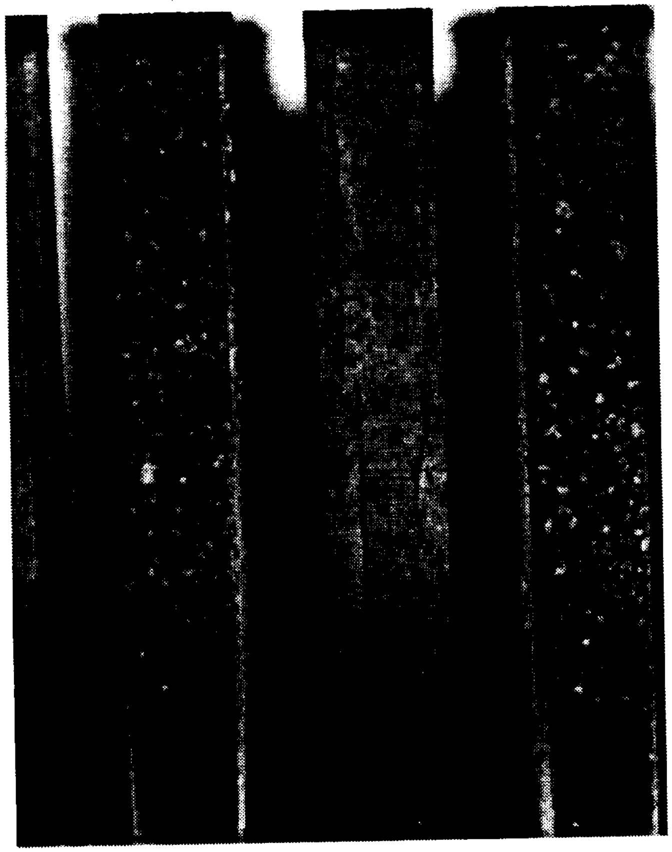
(a) 350 Hours 400x



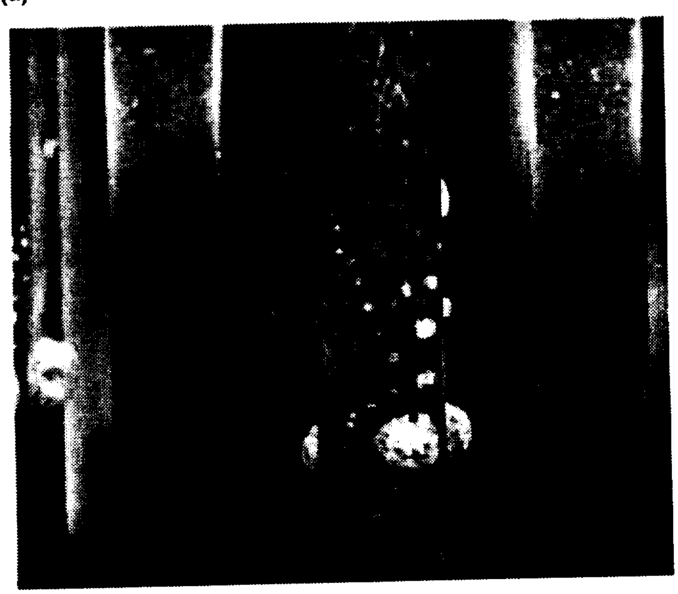
(b) 1050 Hours 400x

G6253-203

Figure 203. Refel Si-SiC Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1204C (2200F): (a) 350 Hours; (b) 1050 Hours.



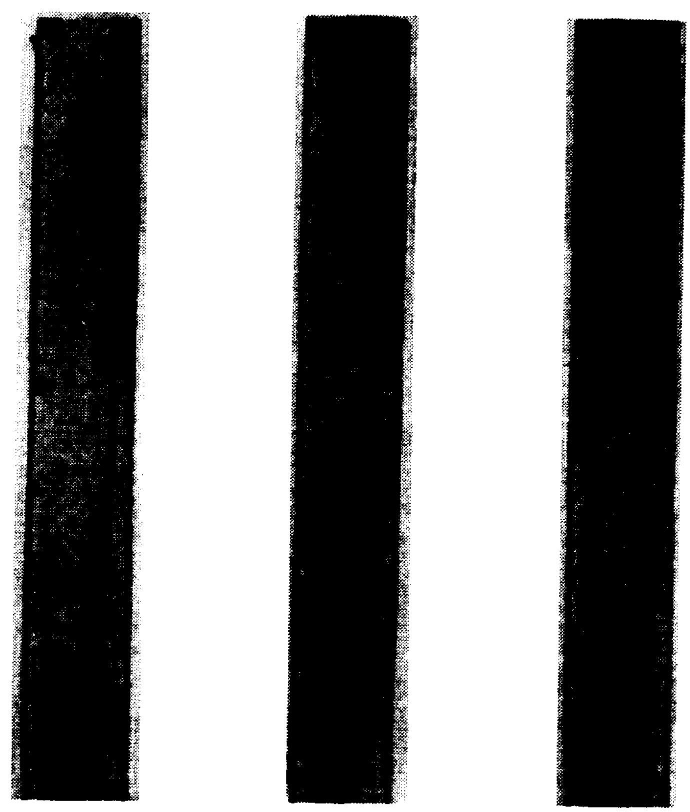
(a) Cracking



(b) Si Exudation and Oxidation

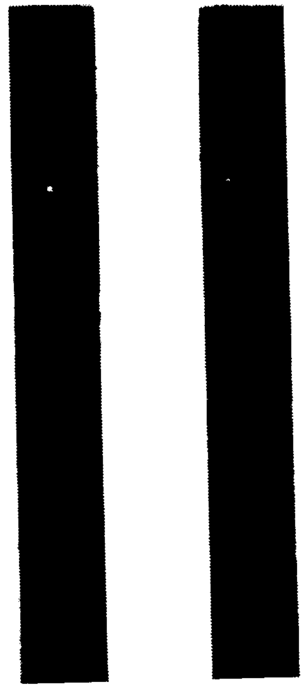
G6253-204

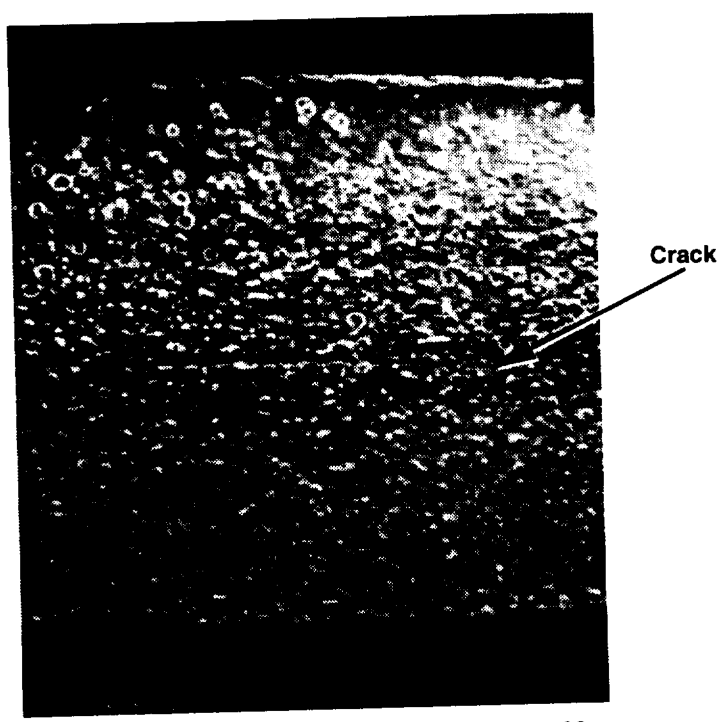
Figure 204. Refel Si-SiC Specimens Exhibited Cracking And Silicon Material Exuding From Exposed Areas Following 168 Hours Exposure At 1371C (2500F).



G6253-205

Figure 205. Refel Si-SiC Specimens Exhibited Cracking Following 143 Hours Exposure At 1316C (2400F).





G6253-206

Figure 206. A Single Refel Si-SiC Specimen Exhibited Cracking Following 350 Hours Exposure At 1260C (2300F).

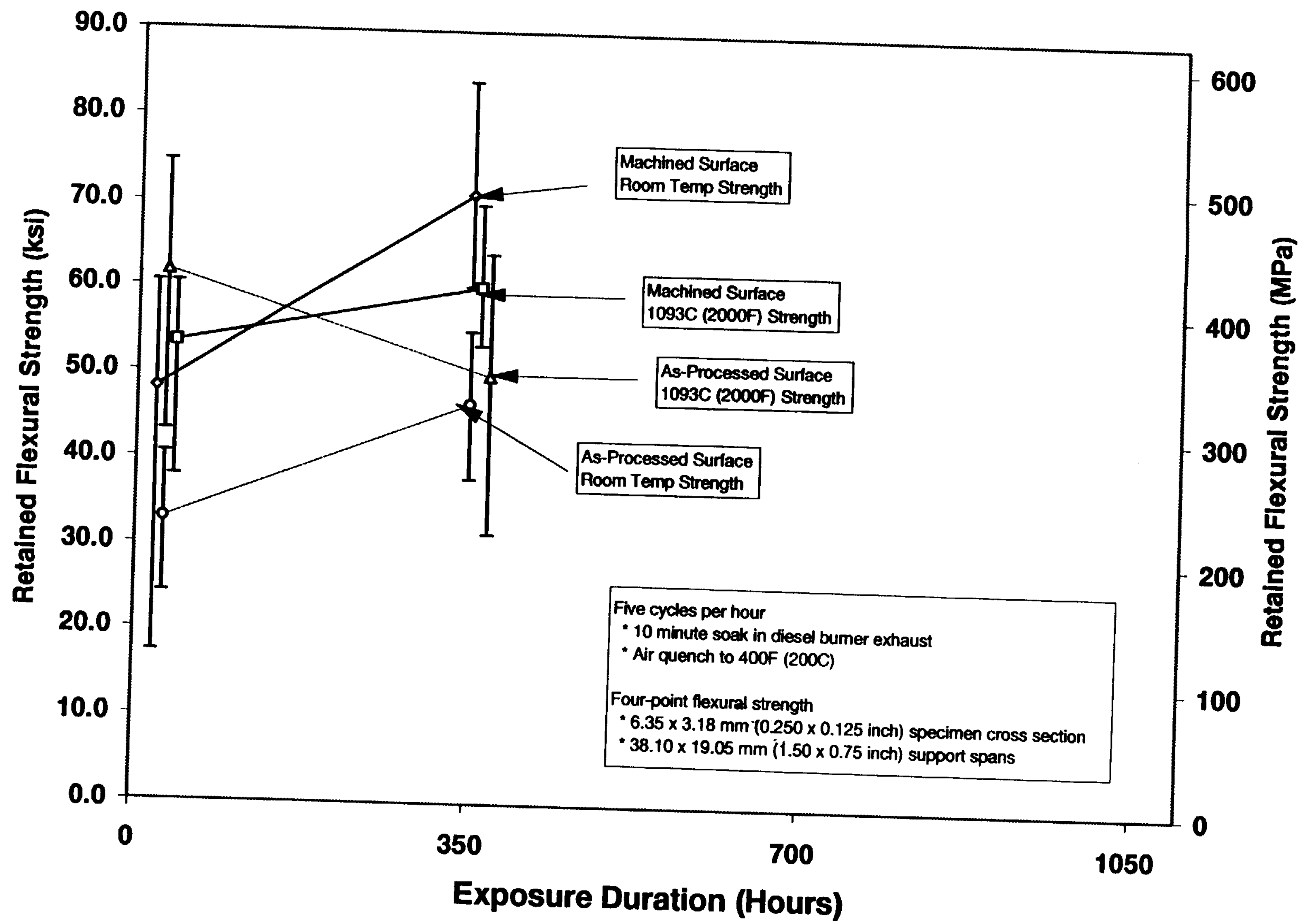


Figure 207. Refel Si-SiC Post-Exposure Flexure Test Results.

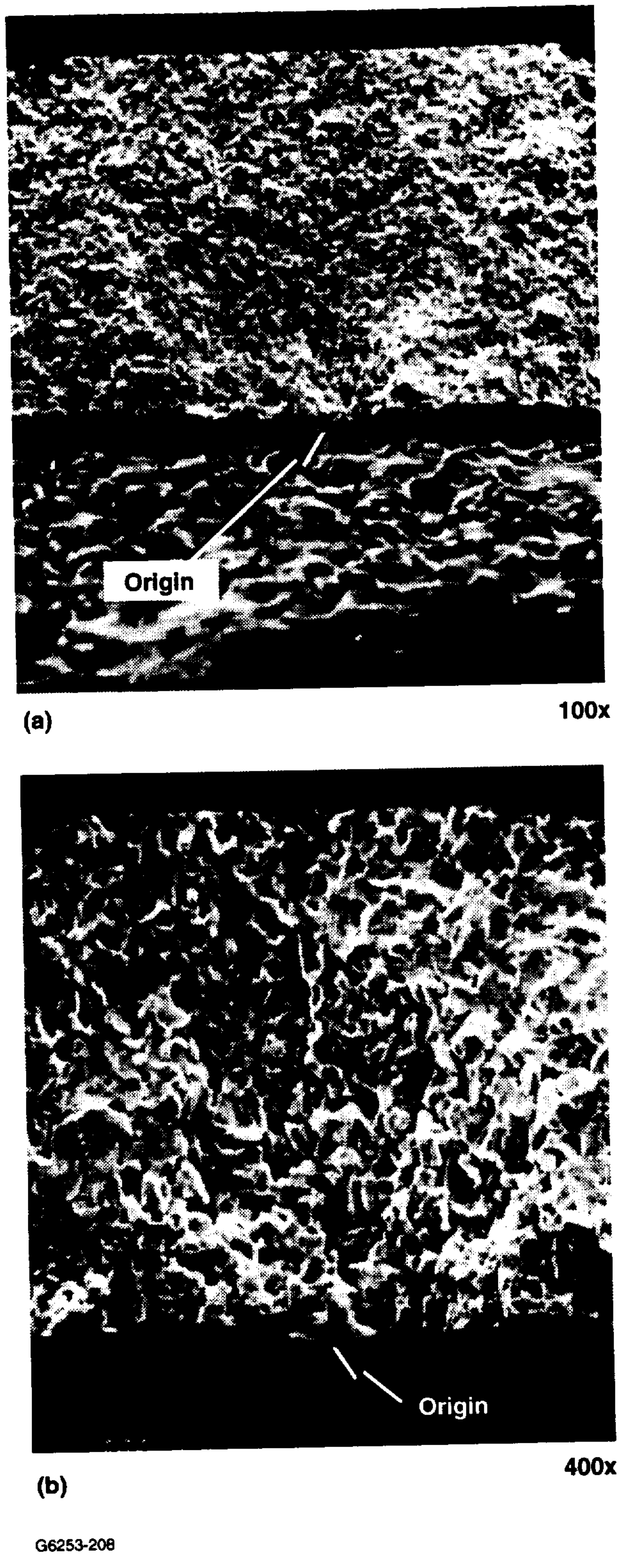
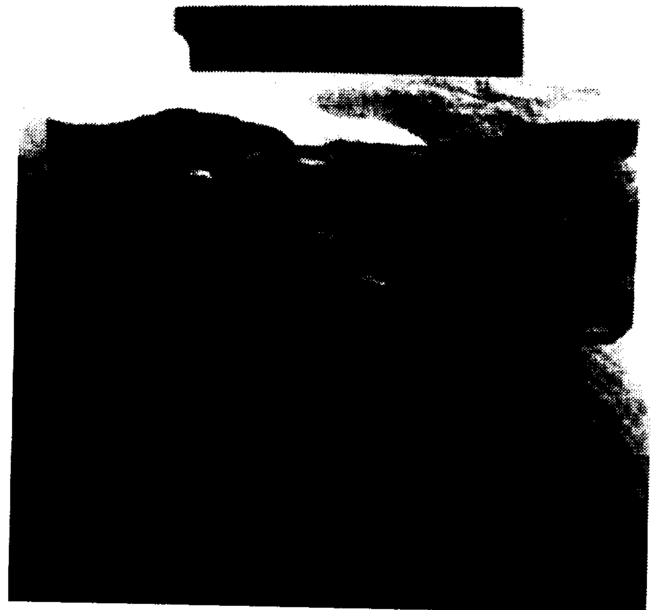


Figure 208. Typical Refel Si-SiC Specimen Failure Originating From Flame-Exposed Surface Following 350 Hours Exposure At 1260C (2300F).

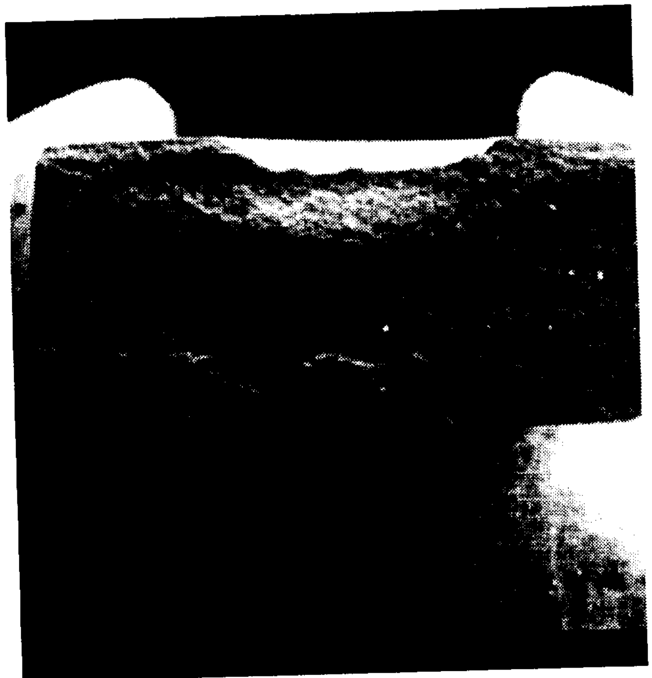


10x

200x

G6253-209

Figure 209. Refel Si-SiC Machined-Surface Baseline Test Specimen Failure Originating From Subsurface Porosity.

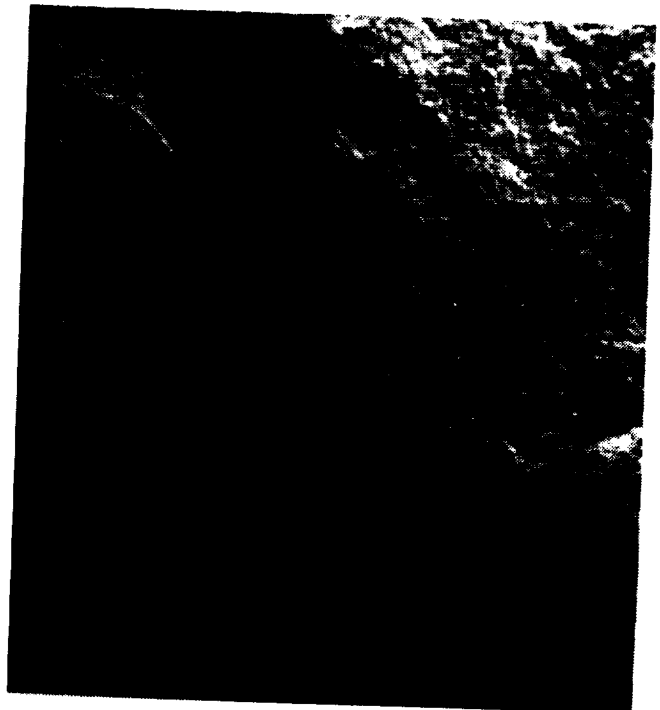


10x

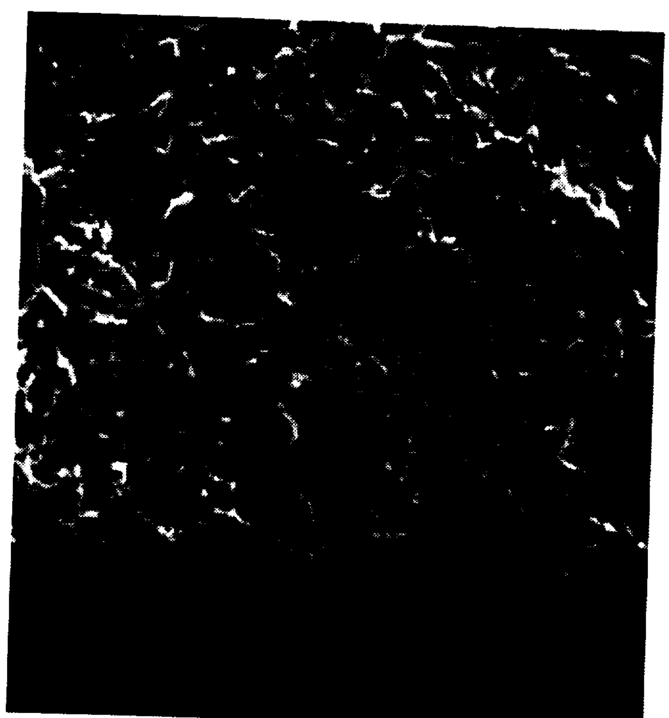
40x

G6253-210

Figure 210. Refel Si-SiC Baseline Test Specimen Failure Originating From As-Processed Surface



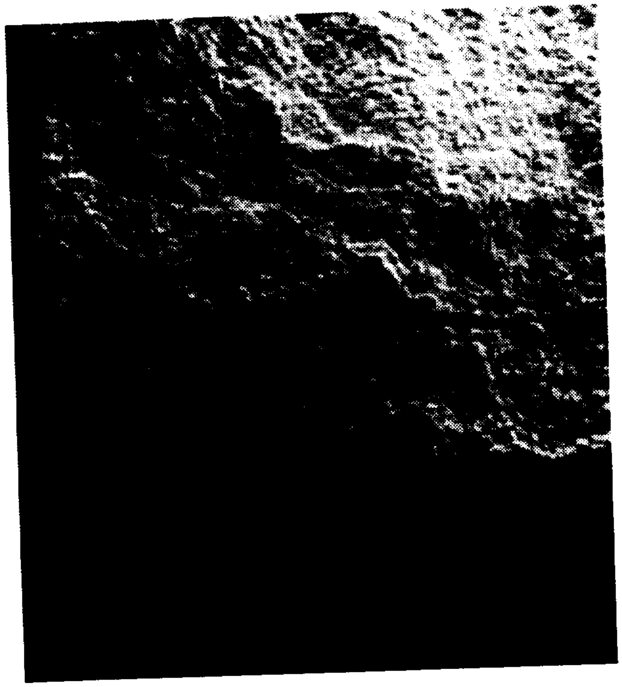
40x



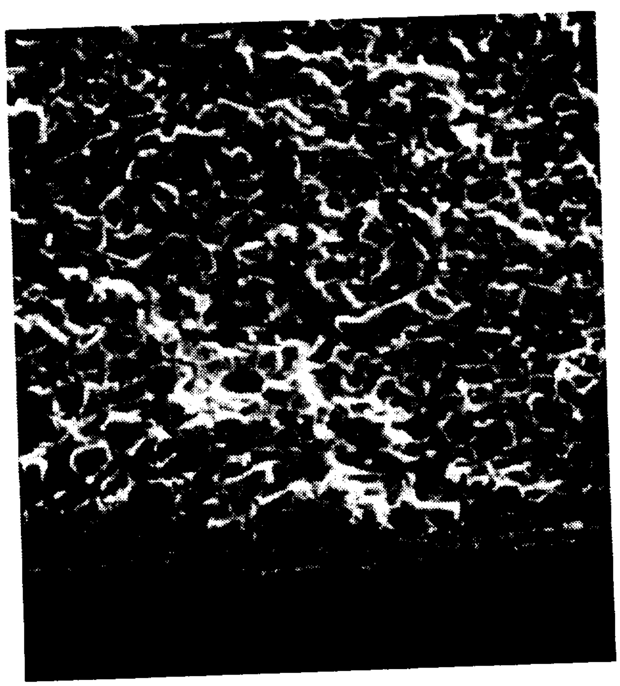
400x

G6253-211

Figure 211. Refel Si-SiC Machined Surface Specimen Failure Originating From Surface-Connected Pore Following 350 Hours Exposure At 1093C (2000F).



40x



400x

G6253-212

Figure 212. Refel Si-SiC As-Processed Surface Specimen Failure Originating From Flame-Exposed Surface Following 350 Hours Exposure At 1093C (2000F).

40x

400x

G6253-213

Figure 213. Typical Toshiba Si_3N_4 Baseline Test Specimen Failure Originating From Subsurface Porosity.

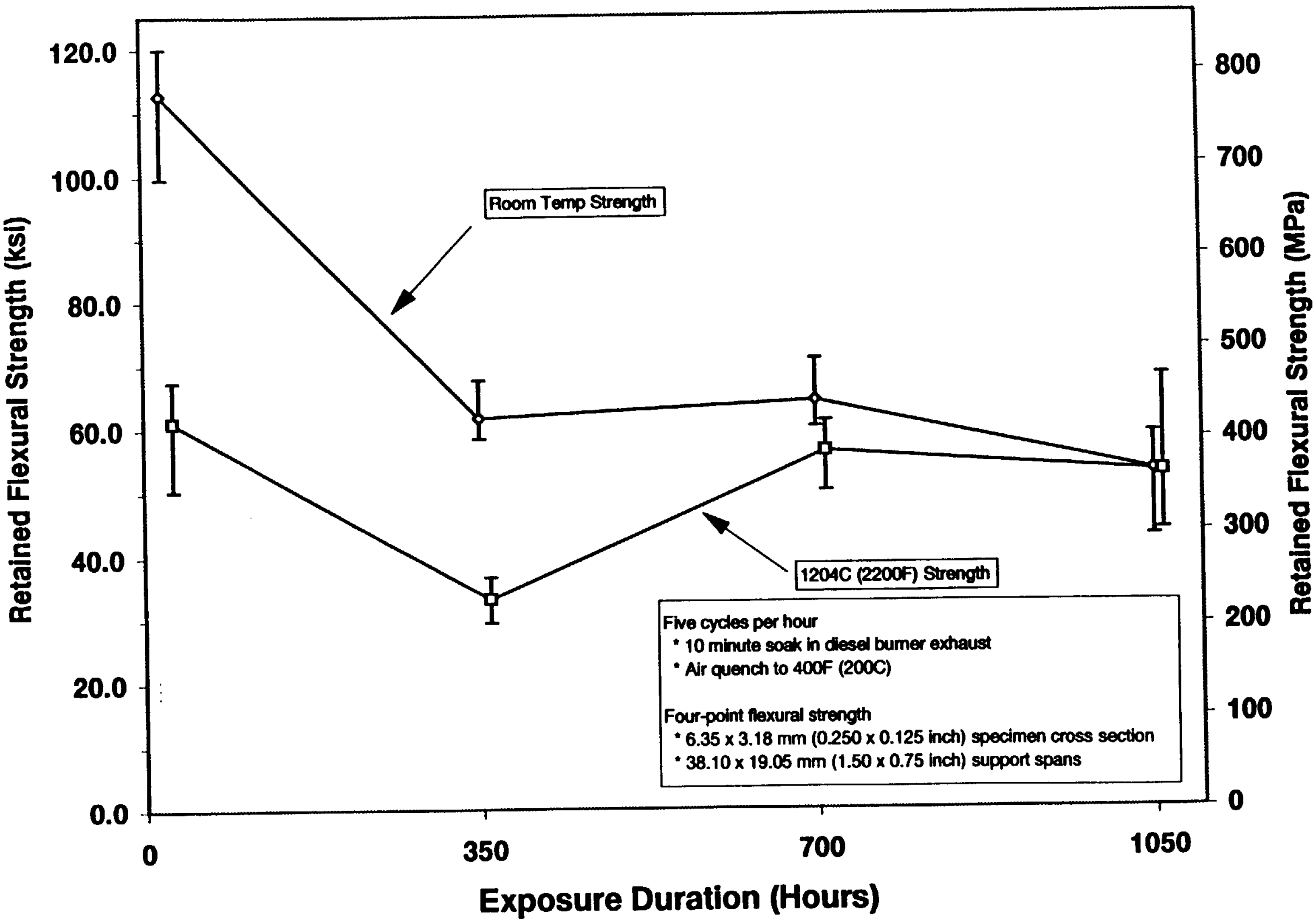


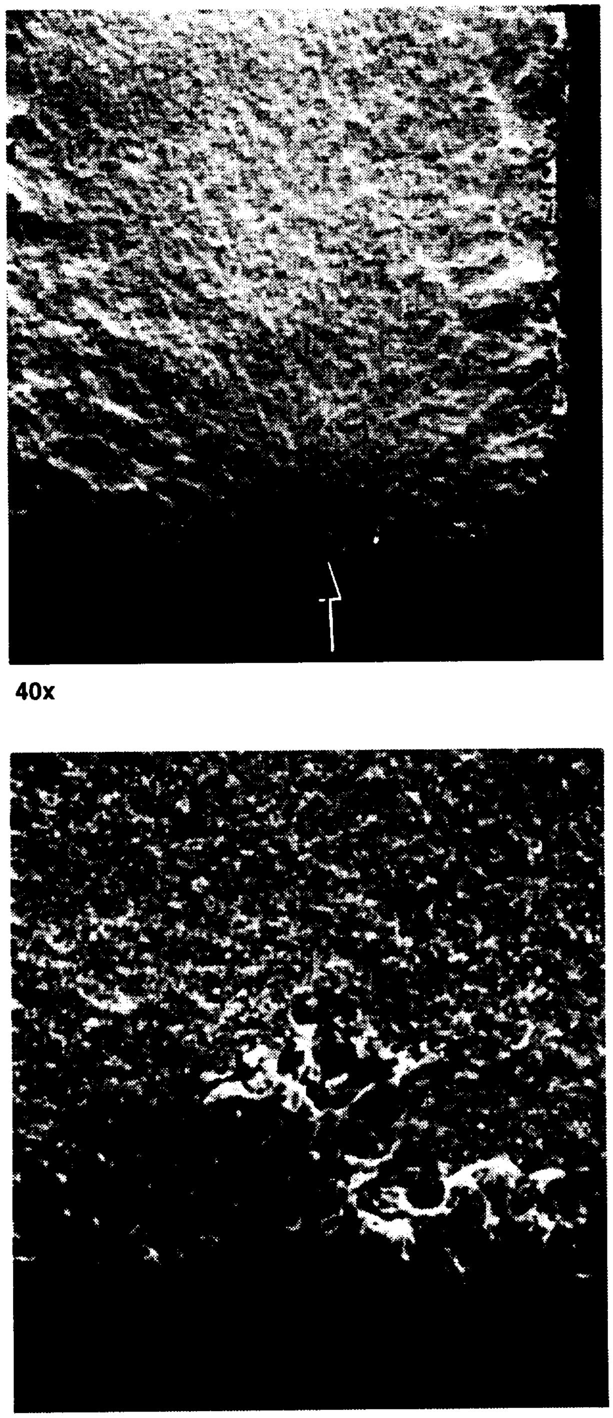
Figure 214. Toshiba Si_3N_4 Post-Exposure Room-Temperature And 1204C (2200F) Strength Test Results Following 1204C (2200F) Cyclic Oxidation Durability Testing.

40x

400x

G6253-215

Figure 215. Toshiba Si_3N_4 Specimen Failure Originating From Oxidation Pit Following 350 Hours Exposure At 1204C (2200F).



40x

400x

G6253-216

Figure 216. Toshiba Si_3N_4 Specimen Failure Originating From Oxidation Pit Following 700 Hours Exposure At 1204C (2200F).

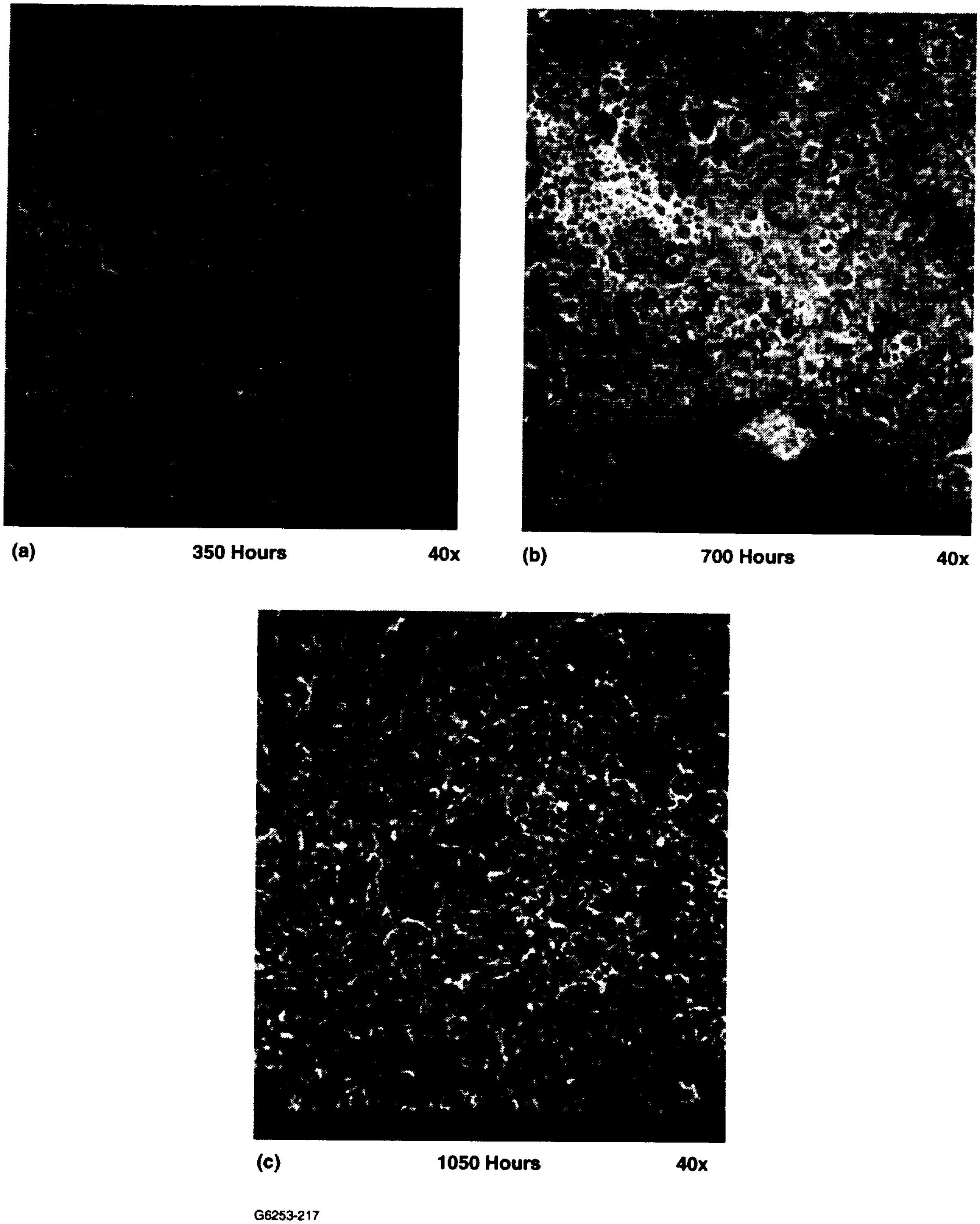


Figure 217. Toshiba Si_3N_4 Specimen Surface Topography Following Cyclic Oxidation Durability Exposures At 1204C (2200F): (a) 350 Hours; (b) 700 Hours; (c) 1050 Hours.

7.0 CONCLUSIONS

A durability test facility for burner rig exposures of ceramic test bars to a thermal cyclic combustion environment up to 1371C (2500F) was designed and built by AlliedSignal. Twenty-nine ceramic materials were cyclically exposed in forty rig tests, accumulating more than 45,000 hours of rig operation. A total of seven silicon carbides, twenty-one silicon nitrides, and one glass ceramic were characterized during the 18-year span of this durability test program.

Table 78 summarizes a subjective assessment of material use temperature for gas turbine applications between 1204C and 1371C (2200F and 2500F) based on data accumulated during this program. Overall, dense silicon carbide materials, including Carborundum Co. Hexoloy SA, General Electric Co. β–SiC, and Kyocera SC-201, exhibited the best oxidation durability in the 1371C (2500F) cyclic exposure tests. Other silicon carbide materials tested, such as Carborundum Co. Hexoloy ST and KX01, Norton Advanced Ceramics NT-230, and Pure Carbon Co. Refel Si-SiC showed relatively good durability at lower temperatures. However, these silicon carbide materials are deemed not suitable for 1371C (2500F) applications, since their secondary phases (elemental silicon or titanium diboride) compromise the high-temperature oxidation resistance.

TABLE 78. CERAMIC MATERIAL USE TEMPERATURE ASSESSMENT (BASED ON DURABILITY TEST RESULTS).

Class	1371C (2500F)	1316C (2400F)	1260C (2300F)	1204C (2200F)
Primary Candidates	GE β-SiC Carbo. Hexoloy SA Kyocera SC-201	NAC NT-164 NAC NT-154	NAC NT-164 NAC NT-15, NGK SN-88	NAC NT-154 NAC NT-164 NGK SN-88 Kyocera SN-250M Kyocera SN-251
Secondary Candidates	---	GE β-SiC Carbo. Hexoloy SA Kyocera SC-201	GE β-SiC Carbo. Hexoloy SA Kyocera SC-201 Kyocera SN-281 NAC NT-230	ACC GN-10 GE β-SiC GTE PY6 (HIPped) Carbo. Hexoloy SA Carbo. Hexoloy KX01 Carbo. Hexoloy ST Kyocera SC-201 Kyocera SN-252 Kyocera SN-281 NAC NT-230 NGK SN-82 NGK SN-84 Refel Si-SiC
Potential Candidates	NAC NT-164 NAC NT-154	NGK SN-88	Kyocera SN-250M Kyocera SN-251 Kyocera SN-252 Carbo. KX01	---

ACC = AlliedSignal Ceramic Components
Carbo. = Carborundum Co.
GE = General Electric Co.
NAC = Norton Advanced Ceramics

Porous silicon nitrides, such as AlliedSignal Ceramic Components RBN101 and RBN104 reaction-bonded silicon nitrides, successfully completed the 1371C (2500F) durability exposures. However, the measured post-exposure retained strength values were typically low. No dense silicon nitride materials were tested successfully at 1371C (2500F), although a few dense silicon nitrides, such as Norton Advanced Ceramics NT-154 and NT-164, showed potential for use at 1371C (2500F) based on encouraging results in the 1316C (2400F) durability tests. The low sintering additive levels for NT-154 and NT-164 contribute to superior oxidation durability compared to the higher additive silicon nitride compositions tested during this program.

For applications with operating temperatures up to 1316C (2400F), dense silicon nitrides would be preferred over the high-temperature silicon carbides. The dense silicon nitrides typically exhibit substantially higher baseline (pre-exposure) strength values than the silicon carbide materials characterized in this program. Although the dense silicon nitrides may exhibit a higher percentage of strength loss following exposure, the post-exposure retained strength values for these material usually well exceeded the baseline strength and post-exposure strength values of the carbide materials.

NT-154 and NT-164 from Norton Advanced Ceramics demonstrated good oxidation durability in the 1316C (2400F) exposure tests. NT-164 is deemed the benchmark for silicon nitride material oxidation durability, exhibiting virtually no strength loss following 1050 hours exposure at 1316C (2400F). For lower-temperature applications, several additional silicon nitride and silicon carbide materials are also considered suitable candidates.

The cyclic oxidation durability testing proved to be a valuable tool for screening out materials having catastrophic stability problems, that could otherwise go undetected until engine testing. Three dense silicon nitride materials, including Norton NCX-34 and Kyocera SN-253 and SN-260, exhibited specimen cracking in the cooler specimen attachment areas. Studies revealed this cracking resulted from intermediate-temperature oxidation-induced phase instability in these materials. Additionally, Pure Carbon Co. Refel siliconized silicon carbide (Si-SiC) exhibited severe cracking in the test gage section during exposure, due to accelerated oxidation and seeping of elemental silicon. For this reason, completion of cyclic oxidation burner rig testing is recommended, prior to consideration of <u>any</u> ceramic material candidate for use in a development or production gas turbine engine application. In some instances, static gradient furnace testing may also be effective (and more economical) in identifying intermediate-temperature oxidation instability. However, cyclic oxidation durability exposure testing in a combustion environment is judged the most-effective and lowest-risk screening method for oxidation phase instability.

8.0 REFERENCES

(1) Carruthers, W.D., Richerson, D.W., and Benn, K.W., "3500-Hour Durability Testing Of Commercial Ceramic Materials, Interim Report," DOE/NASA/0027-80/1, NASA CR-159785, prepared for NASA Lewis Research Center, Cleveland, OH 44135 under Contract No. DEN3-27, for U.S. Dept. of Energy Office of Transportation Programs, Washington, DC 20545; AiResearch Report No. 31-3575A, AiResearch Manufacturing Co. of Arizona, Phoenix, AZ 85010, July 1980.

(2) Lindberg, L.G., and Benn, K.W., "3500-Hour Durability Testing Of Commercial Ceramic Materials, Interim Report," DOE/NASA/0027-84/2, NASA CR-174821, prepared for NASA Lewis Research Center, Cleveland, OH 44135 under Contract No. DEN3-27, for U.S. Dept. of Energy Office of Transportation Programs, Washington, DC 20545; Garrett Report No. 31-5279, Garrett Turbine Engine Co., Phoenix, AZ 85010, December, 1984.

(3) (Anon.),"Conceptual Design Study of Improved Automotive Gas Turbine Powertrain - Final Report, Contract No. DEN3-37, EC-77-A-31-1040," NASA CR-159580, DOE/NASA/0037-79/1, prepared for NASA Lewis Research Center, Cleveland, OH by Ford Motor Company, Dearborn, MI and AiResearch Manufacturing Co., Phoenix, AZ; May, 1979.

(4) Richerson, David W., and Johansen, Keith M., "Ceramic Gas Turbine Engine Demonstration Program - Final Report, Contract N00024-76-C-5352, DARPA Order No. 3155", Report No. AD-A117-088/5, prepared for Dept. of the Navy, Naval Air Systems Command, Washington, DC 30362; Garrett Report No. 21-4410, Garrett Turbine Engine Co., Phoenix, AZ 85010; May, 1982.

(5) McLean, A.F., and Baker, R.R., "Brittle Materials Design, High Temperature Gas Turbine," IR-10, (AMMRC CTR 76-31, AD-B015331), Ford Motor Company, Detroit, MI, 1976.

(6) Strangman, T.E., and Schienle, J.L., "Tailoring Zirconia Coatings for Performance in a Marine Gas Turbine Environment," ***Journal of Engineering For Gas Turbines and Power***, Vol. 112, No. 4, pp. 531-535, October, 1990.

(7) Lindberg, L.J., Richerson, D.W., Carruthers, W.D., and Gersch, H., "Oxidation Stability of Advanced Reaction-Bonded Si_3N_4 Materials," ***Bulletin of the American Ceramic Society***, Vol. 61, No. 5, pp. 574-578, May, 1982.

(8) (Anon.), "Advanced Gas Turbine (AGT) Powertrain System Development For Automotive Applications Progress Report Number 1, Contract No. DEN3-167," NASA CR-165175, DOE/NASA/0167-80/1, prepared for NASA Lewis Research Center, Cleveland, OH; AiResearch Report No. 31-3725, AiResearch Manufacturing Co., Phoenix. AZ; November, 1980.

(9) Lange, F.F., Singhal, S.C., and Kusnicki, R.C., "Phase Relations and Stability Studies in the Si_3N_4-Y_2O_3 Pseudoternary Systems," ***Journal of the American Ceramic Society***, Vol. 60 [5-6], pp. 249-252, 1977.

APPENDIX I

BASELINE SPECIMEN FLEXURE TEST RESULTS

(38 Pages)

APPENDIX I

TABLE I-1.
SUMMARY OF BASELINE SPECIMEN FLEXURE TEST RESULTS.

Manufacturer	Material Designation	Material	Vintage, Mo/Yr	Surface Condition	Test Results Section No.	Appendix I Page No.
AiResearch Casting Co.	RBN101	Reaction-Bonded Silicon Nitride (RBSN)	6/78	Machined	6.1.1	310
AiResearch Casting Co.	RBN104	RBSN	12/80	As-Processed	6.2.1	311
AiResearch Casting Co.	Code 2	Sintered Silicon Nitride	3/85	As-Processed	6.3.1	312
AlliedSignal Ceramic Components (ACC)	GN-10	Hot Isostatically Pressed (HIPped) Silicon Nitride	5/89	Machined	6.4.1	313
Carborundum Co.	Hexoloy KX01	Siliconized Silicon Carbide (Si-SiC)	4/83	As-Processed	6.5.1	314
Carborundum Co.	Hexoloy SA	Sintered Alpha Silicon Carbide (α-SiC)	6/78	Machined	6.6.1	315
		Injection Molded α-SiC	7/83	As-Processed	6.6.5	316
Carborundum Co.	Hexoloy ST	Titanium Diboride (TiB2) Toughened Silicon Carbide	10/87	As-Processed	6.7.1	317
			11/88	As-Processed	6.7.3	318
Corning Glass Works	Code 9458	Lithium Aluminum Silicate (LAS)	8/81	Machined	6.8.1	319
Ford Motor Company	Ford RBSN	RBSN	11/82	As-Processed	6.9.1	320
General Electric Company	GE β–SiC	Beta Sintered Silicon Carbide (β-SiC)	12/84	As-Processed	6.10.1	321
GTE	AY6	Sintered Silicon Nitride	7/83	Machined	6.11.1	322
GTE	PY6	Sintered Silicon Nitride	4/81	Machined	6.12.1	323
			1/90	As-Processed	6.12.3	324
Kyocera Corporation	SC-201	Sintered Silicon Carbide	5/84	As-Processed	6.13.1	325
Kyocera Corporation	SN-250M	Sintered Silicon Nitride	10/86	Machined	6.14.1	326
Kyocera Corporation	SN-251	Sintered Silicon Nitride	2/90	Machined	6.15.1	327
Kyocera Corporation	SN-252	Sintered RBSN	5/90	Machined	6.16.1	328
Kyocera Corporation	SN-253	Sintered Silicon Nitride	5/95	As-Processed	6.17.1	329
Kyocera Corporation	SN-260	Sintered Silicon Nitride	2/91	As-Processed	6.18.1	330
Kyocera Corporation	SN-281	Sintered Silicon Nitride	5/95	As-Processed	6.19.1	331
NGK	SN-50	Sintered Silicon Nitride	9/84	As-Processed	6.20.1	332
NGK	SN-82	Sintered Silicon Nitride	1/86	As-Processed	6.21.1	333
NGK	SN-84	Sintered Silicon Nitride	9/87	Machined	6.22.1	334
NGK	SN-88	Sintered Silicon Nitride	7/91	As-Processed	6.23.1	335
Norton Company	NCX-34	Hot Pressed Silicon Nitride	6/78	Machined	6.24.1	336
Norton Advanced Ceramics (NAC)	NT-154	Hot Isostatically Pressed (HIPped) Silicon Nitride	10/88	Machined	6.25.1	337
			4/90	Machined	6.25.3	338
			9/93	As-Processed	6.25.5	339
NAC	NT-164	HIPped Silicon Nitride	8/93	As-Processed	6.26.1	340
NAC	NT-230	Si-SiC	5/91	As-Processed	6.27.1	341
Pure Carbon Co.	Refel	Si-SiC	10/78	Machined	6.28.1	342
		Injection Molded Si-SiC	10/81	Machined	6.28.5	343
			10/81	As-Processed	6.28.5	344
Toshiba Corporation	Toshiba Si_3N_4	Sintered Silicon Nitride	7/84	Machined	6.29.1	345

Baseline Flexure Fast Fracture Strength Of AirResearch Casting Company RBN101 Reaction Bonded Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 6/1/78

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5035A	2.800	75	35.7	Subsurface	
5035B	2.800	75	40.6	Subsurface	Flaw
5039A	2.820	75	35.7	Subsurface	Inclusion
5039B	2.820	75	44.6	Subsurface	Pore
5053A	2.880	75	36.0	Subsurface	Inclusion
5053B	2.880	75	38.0	Subsurface	Inclusion
5299A	2.810	75	37.7	Subsurface	Inclusion
5299B	2.810	75	36.6	Subsurface	Inclusion
5301	2.820	75	37.2	Subsurface	Inclusion
5302	2.800	75	35.7	Chamfer	Scratch
5305	2.810	75	39.5	Subsurface	Flaw
5306A	2.830	75	37.7	Subsurface	Flaw
5306B	2.830	75	39.8	Subsurface	Flaw
5308A	2.800	75	36.0	Subsurface	Flaw
5308B	2.800	75	42.1	Subsurface	Flaw
5314	2.840	75	35.5	Subsurface	Pore
5315	2.840	75	33.7	Surface	Flaw
5317A	2.820	75	35.4	Subsurface	Flaw
5317B	2.820	75	33.4	Subsurface	Flaw
5041	2.850	2200	46.1	Subsurface	Pore
5296	2.840	2200	47.2	Subsurface	Pore
5298	2.830	2200	51.3	Subsurface	Inclusion
5300	2.840	2200	51.8	Chamfer	Inclusion
5316	2.780	2200	48.7	Subsurface	Inclusion
5318	2.800	2200	44.9	Surface	Pore
5320	2.820	2200	36.2	Surface	Pore
5322	2.810	2200	48.7	Surface	Inclusion
5323	2.800	2200	45.2	Chamfer	
5324	2.800	2200	45.5	Subsurface	Pore
5325	2.820	2200	43.2	Chamfer	
5328	2.820	2200	44.6	Subsurface	Inclusion

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	37.4	44.6	33.4	2.8	19
2200	46.1	51.8	36.2	4.1	12

Baseline Flexure Fast Fracture Strength Of AirResearch Casting Company RBN104 Reaction Bonded Silicon Nitride With As-Processed Surfaces

Vintage = 12/1/80

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
1921		75	59.3	Sursurface	Porosity
9089		75	49.5	Sursurface	Porosity
9107		75	46.7	Sursurface	Porosity
9111		75	42.6	Surface	Porosity
9116		75	49.8	Surface	Pore
9144		75	49.5	Sursurface	Porosity
9145		75	47.5	Surface	Porosity
9160		75	46.1	Sursurface	Porosity
9165		75	49.2	Sursurface	Porosity
9404		75	52.4	Sursurface	Porosity
9438		75	55.9	Sursurface	Pore
9459		75	52.1	Sursurface	Pore
9075		2200	59.0	Missing	
9089a		2200	55.6	Chamfer	
9096		2200	59.0	Sursurface	
9098		2200	62.5	Sursurface	Porosity
9103		2200	56.2	Sursurface	Porosity
9117		2200	57.6	Surface	Porosity
9139		2200	65.1		
9148		2200	56.2	Surface	Porosity
9158		2200	55.9	Sursurface	Porosity
9164		2200	59.6	Sursurface	Porosity
9166		2200	58.5	Sursurface	Porosity

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	50.0	59.3	42.6	4.5	12
2200	58.7	65.1	55.6	3.0	11

Baseline Flexure Fast Fracture Strength Of AirResearch Casting Company Code 2 Sintered Silicon Nitride With As-Processed Surfaces

Vintage = 3/1/85

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
16108A	3.240	75	57.6	Surface	
16118A	3.240	75	55.5	Internal	Pore
16124A	3.250	75	49.0	Internal	Pore
16130A	3.250	75	60.5	Surface	
16132A	3.250	75	76.1	Internal	Pore
16146A	3.230	75	49.6	Internal	Pore
16149A	3.240	75	56.2	Internal	Pore
16156A	3.250	75	82.8	Internal	Pore
16164A	3.250	75	59.0	Internal	Pore
16166A	3.250	75	57.9	Surface	
16172A	3.250	75	70.5	Surface	
16179A	3.250	75	73.4	Internal	Pore
16108B	3.240	2200	48.4	Internal	Pore
16118B	3.240	2200	43.1	Internal	Pore
16124B	3.250	2200	37.8	Internal	Pore
16130B	3.250	2200	44.1	Internal	Pore
16132B	3.250	2200	41.5	Internal	Pore
16146B	3.230	2200	45.1	Internal	Pore
16149B	3.240	2200	38.6	Surface	
16156B	3.250	2200	46.9	Internal	Pore
16164B	3.250	2200	46.9	Surface	Pore
16166B	3.250	2200	45.7	Internal	Pore
16172B	3.250	2200	37.2	Surface	
16179B	3.250	2200	41.2	Internal	Pore

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	62.3	82.8	49.0	10.8	12
2200	43.0	48.4	37.2	3.8	12

Baseline Flexure Fast Fracture Strength Of AlliedSignal Ceramic Components GN-10 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 5/1/89

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
29856	3.330	75	151.2	Internal	Inclusion
29858	3.320	75	146.9	Missing	
29860	3.340	75	143.1	Chamfer	
29862	3.320	75	141.7	Surface	
29864	3.350	75	70.6	Surface	
29866	3.340	75	127.3	Internal	Inclusion
29868	3.320	75	123.8	Surface	
29870	3.350	75	146.3	Surface	
29872	3.330	75	126.4	Surface	
29874	3.340	75	121.2	Surface	
29876	3.330	75	118.9	Surface	
29878	3.340	75	118.7	Surface	
29857	3.350	2200	102.5	Surface	
29859	3.330	2200	108.3	Surface	
29861	3.340	2200	113.2	Surface	
29863	3.380	2200	110.3	Internal	Inclusion
29865	3.340	2200	109.0	Surface	
29867	3.350	2200	107.7	Internal	Inclusion
29869	3.360	2200	113.2	Internal	Inclusion
29871	3.320	2200	108.0	Internal	Inclusion
29873	3.370	2200	107.4	Internal	Inclusion
29875	3.330	2200	115.8	Missing	
29877	3.370	2200	107.4	Surface	
29879	3.330	2200	101.7	Surface	

Baseline Strength Summary

Temp (F)	Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
75	128.0	151.2	70.6	21.7	12
2200	108.7	115.8	101.7	4.1	12

Baseline Flexure Fast Fracture Strength Of Carborundum Hexoloy KX01 Siliconized Silicon Carbide With As-Processed Surfaces

Vintage = 4/1/83

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
11970A	2.880	75	67.4	Surface	
12000A	2.890	75	70.6	Surface	
12075A	2.910	75	46.7	Surface	
12075B	2.910	75	57.3	Surface	
12076A	2.900	75	59.8	Surface	
12076B	2.900	75	53.4	Surface	
12077A	2.900	75	46.9	Surface	
12077B	2.900	75	63.8	Surface	
12078A	2.930	75	54.7	Surface	
12078B	2.930	75	50.3	Surface	
12079A	2.930	75	61.7	Missing	
12079B	2.930	75	55.8	Surface	Machining Groove
11960B	2.900	2200	57.0	Surface	
11970B	2.880	2200	56.4	Surface	Pit
11980B	2.920	2200	55.4	Surface	
11990B	2.890	2200	42.0	Surface	
12000B	2.890	2200	46.7	Surface	
12010B	2.910	2200	68.9	Surface	
12020B	2.900	2200	64.2	Missing	
12030B	2.920	2200	60.9	Chamfer	
12040B	2.910	2200	46.7	Surface	
12050B	2.910	2200	57.5	Surface	Pit
12060B	2.910	2200	64.6	Surface	Pit
12070B	2.910	2200	38.6	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	57.4	70.6	46.7	7.6	12
2200	54.9	68.9	38.6	9.5	12

Baseline Flexure Fast Fracture Strength Of Carborundum Hexoloy SA Sintered Silicon Carbide With Longitudinally Machined Surfaces

Vintage = 6/1/78

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5162	3.100	75	44.9	Chamfer	
5185	3.100	75	47.5	Chamfer	
5204	3.080	75	31.7	Chamfer	
5220	3.130	75	38.9	Surface	
5250	3.110	75	27.1	Surface	
5258	3.130	75	53.6	Chamfer	
5261	3.140	75	58.2	Surface	
5264	3.130	75	55.3	Surface	
5267	3.120	75	49.0	Surface	
5272	3.130	75	45.5	Chamfer	
5278	3.080	75	56.2	Surface	
5287	3.110	75	41.8	Chamfer	
5152	3.100	2200	38.3	Surface	Pit
5177	3.090	2200	55.6	Surface	
5208	3.090	2200	50.4	Subsurface	Pore
5248	3.120	2200	50.1	Surface	Pit
5254	3.110	2200	59.9	Subsurface	Pore
5256	3.120	2200	53.0	Subsurface	Pore or Inclusion
5260	3.120	2200	57.6	Surface	Pit
5269	3.110	2200	51.4	Surface	Pit
5274	3.120	2200	53.3	Chamfer	
5276	3.090	2200	47.8	Surface	Pore
5282	3.130	2200	37.2	Surface	Pit
5290	3.100	2200	54.4	Surface	Pit

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	45.8	58.2	27.1	9.7	12
2200	50.8	59.9	37.2	6.9	12

Baseline Flexure Fast Fracture Strength Of Carborundum Hexoloy SA Injection Molded Sintered Silicon Carbide With As-Processed Surfaces

Vintage = 7/1/83

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
12201A	3.110	75	61.4	Surface	Anomaly
12202A	3.110	75	68.3	Subsurface	
12203A	3.120	75	45.8	Chamfer	
12204A	3.120	75	48.3	Chamfer	Porosity
12205A	3.120	75	57.8	Surface	Porosity
12206A	3.120	75	61.4	Surface	Porosity
12207A	3.110	75	66.0	Surface	Porosity
12208A	3.110	75	65.0	Surface	
12209A	3.110	75	72.0	Surface	Porosity
12210A	3.110	75	72.0	Subsurface	Porosity
12211A	3.110	75	75.2	Subsurface	Porosity
12212A	3.130	75	69.1	Subsurface	Porosity
12201B	3.110	2200	57.8	Surface	Pore
12202B	3.110	2200	64.8	Surface	Porosity
12203B	3.120	2200	66.1	Chamfer	
12204B	3.120	2200	49.8	Subsurface	Pore
12205B	3.120	2200	63.6	Chamfer	
12206B	3.120	2200	48.0	Subsurface	Pore
12207B	3.110	2200	67.2	Subsurface	Pore
12208B	3.110	2200	57.8	Surface	Pit
12209B	3.110	2200	60.5	Surface	Porosity
12210B	3.110	2200	52.4	Surface	Pit
12211B	3.110	2200	71.5	Chamfer	
12212B	3.130	2200	68.7	Surface	Pit
12162A	3.120	2500	59.3	Subsurface	Porosity
12162B	3.120	2500	33.1	Internal	Delamination
12163A	3.110	2500	51.0	Subsurface	Porosity
12163B	3.110	2500	57.4	Subsurface	Porosity
12164A	3.110	2500	43.5	Surface	Porosity
12164B	3.110	2500	61.9	Missing	
12200A	3.110	2500	51.3	Surface	
12200B	3.110	2500	63.0	Surface	Porosity
12220	3.130	2500	55.8	Surface	
12224A	3.120	2500	53.0	Surface	Porosity
12224B	3.120	2500	51.5	Surface	Porosity
12254	3.120	2500	53.1	Surface	Porosity

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	63.5	75.2	45.8	9.2	12
2200	60.7	71.5	48.0	7.6	12
2500	52.8	63.0	33.1	8.2	12

Baseline Flexure Fast Fracture Strength Of Carborundum Hexoloy ST TiB2 Toughened Sintered Silicon Carbide With As-Processed Surfaces

Vintage = 10/1/87

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
26904	3.330	75	63.7	Internal	
26905	3.330	75	51.8	Chamfer	
26906	3.340	75	51.9	Internal	
26907	3.340	75	51.9	Internal	
26908	3.330	75	44.2	Surface	
26909	3.330	75	59.2	Surface	
26910	3.340	75	59.4	Internal	
26911	3.340	75	50.6	Internal	
26912	3.330	75	50.7	Internal	
26913	3.330	75	57.3	Internal	
26914	3.340	75	66.8	Surface	
26915	3.330	75	54.1	Internal	
26916	3.330	2200	54.3	Missing	
26917	3.340	2200	62.9	Internal	
26918	3.330	2200	51.4	Surface	
26919	3.340	2200	66.2	Internal	
26920	3.340	2200	51.6	Surface	
26921	3.330	2200	62.6	Surface	
26922	3.330	2200	51.8	Surface	
26923	3.330	2200	59.9	Internal	
26924	3.330	2200	39.6	Surface	
26925	3.330	2200	62.4	Internal	
26926	3.340	2200	54.0	Internal	
26927	3.340	2200	54.5	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	55.1	66.8	44.2	6.3	12
2200	55.9	66.2	39.6	7.3	12

Baseline Flexure Fast Fracture Strength Of Carborundum Hexoloy ST TiB2 Toughened Sintered Silicon Carbide With As-Processed Surfaces

Vintage = 11/1/88

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
29507A	3.330	75	47.3	Chamfer	
29508A	3.340	75	66.0	Internal	Pore
29509A	3.340	75	68.5	Chamfer	
29510A	3.340	75	55.6	Internal	Pore
29511A	3.340	75	59.0	Surface	
29512A	3.330	75	61.6	Chamfer	
29513A	3.340	75	47.9	Chamfer	
29514A	3.340	75	55.3	Surface	Pore
29515A	3.340	75	61.1	Internal	Pore
29516A	3.340	75	58.8	Surface	Pore
29517A	3.340	75	72.8	Internal	Pore
29518A	3.350	75	51.6	Internal	Pore
29507B	3.340	2300	63.7	Surface	
29508B	3.340	2300	55.4	Internal	Pore
29509B	3.340	2300	50.7	Internal	Pore
29510B	3.340	2300	60.7	Surface	
29511B	3.340	2300	49.7	Surface	
29512B	3.330	2300	60.7	Chamfer	
29513B	3.350	2300	57.4	Internal	Pore
29514B	3.340	2300	48.2	Surface	
29515B	3.350	2300	58.0	Chamfer	
29516B	3.340	2300	50.2	Surface	Pore
29517B	3.350	2300	67.1	Surface	
29518B	3.330	2300	52.2	Chamfer	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	58.8	72.8	47.3	7.9	12
2300	56.2	67.1	48.2	6.1	12

Baseline Flexure Fast Fracture Strength Of Corning Glass Works Code 9458 Lithium Aluminosilicate With Longitudinally Machined Surfaces

Vintage = 8/1/81

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
10226A		75	12.8	Surface	Porosity
10235A		75	14.0	Surface	Porosity
10238A		75	12.7	Surface	Porosity
10244A		75	13.8	Surface	Porosity
10251A		75	14.3	Surface	Porosity
10258A		75	13.8	Surface	Porosity
10266A		75	13.2	Surface	Porosity
10272A		75	12.4	Surface	Porosity
10280A		75	13.8	Surface	Porosity
10290A		75	14.7	Surface	Porosity
10295A		75	14.7	Surface	Porosity
10300A		75		Surface	Porosity
10226B		2000	14.0	Chamfer	Large Inclusion
10235B		2000	14.2	Surface	Porosity
10238B		2000	11.4	Surface	Porosity
10244B		2000	12.0	Surface	Porosity
10251B		2000	14.1	Missing	
10258B		2000	13.9	Surface	Porosity
10266B		2000	11.5	Surface	Porosity
10272B		2000	11.5	Chamfer	
10280B		2000	12.0	Surface	Porosity
10290B		2000	14.1	Surface	Porosity
10300B		2000	14.5	Surface	Porosity

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	13.7	14.7	12.4	0.8	11
2000	13.0	14.5	11.4	1.3	11

Baseline Flexure Fast Fracture Strength Of Ford Reaction Bonded Silicon Nitride With As-Processed Surfaces

Vintage = 11/1/82

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
11758	2.830	75	41.3	Internal	Pore
11759	2.830	75	44.2	Surface	Pit
11762	2.770	75	40.2	Surface	Oxidation Pit
11767	2.820	75	41.3	Internal	Pore
11774	2.820	75	44.4	Internal	Pore
11775	2.770	75	42.8	Surface	Oxidation Pit
11785	2.770	75	35.3	Surface	Oxidation Pit
11788	2.830	75	39.6	Surface	Oxidation Pit
11789	2.830	75	41.3	Internal	Pore
11794	2.830	75	42.7	Internal	Pore
11860	2.850	75	43.6	Surface	Pit
11868	2.820	75	44.3	Internal	Pore
11771	2.800	2200	47.5	Internal	Pore
11773	2.790	2200	43.8	Missing	
11799	2.830	2200	47.4	Surface	
11825	2.830	2200	43.1	Internal	Pore
11826	2.810	2200	48.5	Internal	Pore
11840	2.780	2200	42.0	Surface	Glass Filled Pit
11843	2.790	2200	35.5	Missing	
11846	2.810	2200	39.9	Internal	Pore
11858	2.800	2200	42.4	Internal	Pore
11861	2.810	2200	44.5	Surface	
11862	2.850	2200	47.2	Internal	Large Discolored Ar
11867	2.840	2200	48.4	Internal	Pore

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	41.8	44.4	35.3	2.6	12
2200	44.2	48.5	35.5	3.9	12

Baseline Flexure Fast Fracture Strength Of GE Beta - Sintered Silicon Carbide With As-Processed Surfaces

Vintage = 12/1/84

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
14850A	3.110	75	61.9	Missing	
14851A	3.120	75	65.1	Internal	Porosity
14852A	3.080	75	52.3	Missing	
14853A	3.090	75	61.9	Surface	
14854A	3.050	75	63.2	SubSurface	Porosity
14855A	3.090	75	67.3	Surface	Porosity
14856A	3.090	75	61.0	SubSurface	Porosity
14857A	3.090	75	60.3	Internal	Porosity
14858A	3.080	75	62.2	Internal	Porosity
14859A	3.080	75	52.3	Internal	Large Grain
14862A	3.100	75	64.3	Chamfer	
14863A	3.100	75	64.3	Internal	
14850B	3.110	2500	60.7	Internal	Porosity
14851B	3.120	2500	65.9	SubSurface	Porosity
14852B	3.080	2500	70.0	Internal	Porosity
14853B	3.090	2500	51.6	Surface	
14854B	3.050	2500	74.1	Surface	
14855B	3.090	2500	68.1	Surface	Porosity
14856B	3.090	2500	64.9	Internal	Porosity
14857B	3.090	2500	51.2	Surface	
14858B	3.080	2500	45.1	Surface	
14859B	3.080	2500	65.7	Surface	
14862B	3.100	2500	53.3	Surface	
14863B	3.100	2500	63.7	Internal	Porosity

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	61.3	67.3	52.3	4.6	12
2500	61.2	74.1	45.1	8.9	12

Baseline Flexure Fast Fracture Strength Of GTE AY6 Sintered Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 7/1/83

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
12556A		75	90.7	Surface	
12557A		75	94.5	Surface	
12558A		75	88.9	Surface	
12559A		75	96.9	Surface	
12560A		75	89.5	Surface	
12561A		75	76.8	Internal	Porosity
12562A		75	93.0	Missing	
12563A		75	83.6	Surface	
12564A		75	77.9	Internal	Porosity
12565A		75	83.3	Surface	
12594A		75	89.3	Surface	
12605A		75	83.8	Surface	
12556B		2200	38.2	Surface	
12557B		2200	48.1	Surface	
12558B		2200	45.2	Surface	
12559B		2200	43.2	Surface	
12560B		2200	33.0	Surface	
12561B		2200	31.6	Surface	
12562B		2200	46.3	Surface	
12563B		2200	42.9	Surface	
12564B		2200	43.4	Surface	
12565B		2200	39.8	Surface	
12594B		2200	43.2	Chamfer	
12605B		2200	35.0	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	87.3	96.9	76.8	6.3	12
2200	40.8	48.1	31.6	5.3	12

Baseline Flexure Fast Fracture Strength Of GTE PY6 Sintered Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 4/1/81

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
9902B		75	48.4	Surface	Pore
9912B		75	55.0	Chamfer	Metallic Inclusion
9913		75	25.9	Missing	
9923B		75	37.7	Surface	
9931		75	39.0	Subsurface	Pore
9932B		75	44.6	Subsurface	Pore
9937B		75	39.7	Surface	Pit
9944B		75	39.7	Surface	Pore
9948		75	31.4	Chamfer	
9957B		75	47.2	Subsurface	Pore
9966B		75	36.0	Subsurface	Pore
9975B		75	34.0	Internal	Large Metallic Inclu
9894A		2200	50.2	Subsurface	Pore
9896A		2200	33.7	Subsurface	Pore
9902A		2200	44.6	Subsurface	Pore
9912A		2200	44.6	Surface	Pore
9923A		2200	49.0	Surface	Pore
9932A		2200	55.9	Subsurface	Pore
9937A		2200	56.2	Subsurface	Pore
9944A		2200	50.1	Subsurface	Pore
9957A		2200	47.8	Surface	
9962A		2200	47.7	Subsurface	Pore
9966A		2200	50.3	Subsurface	
9975A		2200	40.9	Missing	

Baseline Strength Summary

Temp (F)	Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
75	39.9	55.0	25.9	8.0	12
2200	47.6	56.2	33.7	6.2	12

Baseline Flexure Fast Fracture Strength Of GTE PY6 Hot Isostatically Pressed Silicon Nitride With As-Processed Surfaces

Vintage = 1/1/90

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
30485	3.250	75	77.6	Surface	Pit
30486	3.260	75	89.7	Surface	Pit
30487	3.220	75	77.8	Surface	Pit
30488	3.230	75	101.1	Surface	Pit
30489	3.260	75	90.7	Surface	Pit
30490	3.260	75	85.2	Surface	Pit
30491	3.260	75	85.7	Surface	Pit
30492	3.260	75	70.0	Surface	Pit
30493	3.230	75	92.7	Corner	Edges Not Chamfer
30494	3.260	75	68.5	Surface	Pit
30495	3.230	75	96.2	Surface	Pit
30496	3.260	75	61.9	Surface	Pit
30497	3.250	2200	67.0	Corner	Edges Not Chamfer
30498	3.260	2200	56.5	Corner	Edges Not Chamfer
30499	3.220	2200	55.1	Surface	Pit
30500	3.230	2200	50.1	Corner	Edges Not Chamfer
30501	3.260	2200	58.4	Surface	Pit
30502	3.260	2200	55.6	Surface	Pit
30503	3.260	2200	57.5	Surface	Pit
30504	3.260	2200	63.6	Surface	Pit
30505	3.230	2200	59.6	Surface	Pit
30506	3.260	2200	56.9	Surface	Pit
30507	3.230	2200	55.0	Surface	Pit
30508	3.260	2200	55.3	Surface	Pit

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	83.1	101.1	61.9	12.0	12
2200	57.5	67.0	50.1	4.4	12

Baseline Flexure Fast Fracture Strength Of Kyocera SC-201 Sintered Silicon Carbide With As-Processed Surfaces

Vintage = 5/1/84

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
14208A	3.120	75	67.4	Surface	
14209A	3.130	75	52.1	Surface	
14210A	3.140	75	72.5	Chamfer	
14211A	3.130	75	73.0	Internal	Pore
14212A	3.100	75	48.2	Chamfer	
14213A	3.110	75	66.0	Surface	
14220B	3.080	75	73.9	Missing	
14221B	3.120	75	57.1	Surface	
14222B	3.140	75	57.8	Surface	
14223B	3.130	75	41.5	Surface	
14224B	3.140	75	56.2	Surface	
14225B	3.120	75	77.1	Chamfer	
14208B	3.120	2200	64.1	Surface	
14209B	3.130	2200	72.6	Surface	
14210B	3.140	2200	62.6	Chamfer	
14211B	3.130	2200	54.9	Surface	
14212B	3.100	2200	76.5	Surface	
14213B	3.110	2200	73.0	Surface	
14214A	3.140	2200	62.6	Surface	
14215A	3.130	2200	67.4	Surface	
14216A	3.090	2200	72.4	Surface	
14217A	3.130	2200	50.5	Surface	
14218A	3.140	2200	62.2	Subsurface	Grain
14219A	3.130	2200	75.5	Internal	Pore
14214B	3.140	2500	71.3	Surface	
14215B	3.130	2500	60.8	Surface	
14216B	3.090	2500	62.5	Subsurface	
14217B	3.130	2500	82.5	Surface	
14218B	3.140	2500	76.7	Surface	
14219B	3.130	2500	78.9	Surface	
14220A	3.080	2500	54.5	Missing	
14221A	3.120	2500	77.6	Internal	Pore
14222A	3.140	2500	78.9	Surface	
14223A	3.130	2500	77.5	Surface	
14224A	3.140	2500	66.1	Surface	
14225A	3.120	2500	67.7	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	61.9	77.1	41.5	11.4	12
2200	66.2	76.5	50.5	8.2	12
2500	71.3	82.5	54.5	8.8	12

Baseline Flexure Fast Fracture Strength Of Kyocera SN-250M Sintered Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 10/1/86

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
25399B	3.310	75	126.7	Missing	
25400B	3.310	75	127.9	Surface	
25401B	3.300	75	128.7	Chamfer	
25402B	3.290	75	138.2	Surface	
25403B	3.310	75	131.6	Surface	
25404B	3.310	75	124.1	Internal	
25405B	3.310	75	120.1	Surface	
25406B	3.300	75	135.9	Chamfer	
25407B	3.310	75	123.8	Missing	
25408B	3.310	75	115.8	Surface	
25409B	3.300	75	137.4	Surface	
25410B	3.310	75	129.9	Missing	
25399A	3.310	1800	73.7	Surface	
25400A	3.310	1800	79.2	Surface	
25401A	3.300	1800	83.5	Surface	
25402A	3.290	1800	95.0	Surface	
25403A	3.310	1800	65.4	Chamfer	
25404A	3.310	1800	87.3	Surface	
25411B	3.310	1800	95.6	Surface	
25412B	3.300	1800	81.2	Chamfer	
25413B	3.300	1800	80.4	Surface	
25414B	3.310	1800	85.8	Surface	
25415B	3.300	1800	95.6	Surface	
25416B	3.310	1800	74.6	Chamfer	
25405A	3.310	2200	72.9	Surface	
25406A	3.300	2200	76.6	Surface	
25407A	3.310	2200	69.1	Surface	
25408A	3.310	2200	80.4	Surface	
25409A	3.300	2200	79.8	Chamfer	
25410A	3.300	2200	84.7	Surface	
25411A	3.290	2200	82.4	Surface	
25412A	3.300	2200	82.4	Chamfer	
25413A	3.310	2200	92.2	Chamfer	
25414A	3.310	2200	84.1	Chamfer	
25415A	3.300	2200	86.4	Surface	
25416A	3.310	2200	86.1	Chamfer	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	128.3	138.2	115.8	6.9	12
1800	83.1	95.6	65.4	9.4	12
2200	81.4	92.2	69.1	6.3	12

Baseline Flexure Fast Fracture Strength Of Kyocera SN-251 Sintered Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 2/1/90

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
30225B	3.390	75	109.4	Surface	Large Grain
30226B	3.430	75	110.0	Surface	Large Grain
30227B	3.400	75	108.6	Internal	Large Grain
30228B	3.410	75	112.3	Surface	Large Grain
30229B	3.380	75	126.7	Surface	Large Grain
30230B	3.400	75	118.4	Surface	Large Grain
30231B	3.390	75	114.3	Surface	Large Grain
30232B	3.400	75	125.6	Surface	Large Grain
30233B	3.390	75	125.9	Missing	
30234B	3.390	75	99.6	Surface	Large Grain
30235B	3.400	75	110.0	Surface	Large Grain
30236B	3.400	75	108.6	Chamfer	Large Grain
30225A	3.390	2200	86.7	Internal	Large Grain
30226A	3.430	2200	90.7	Surface	Large Grain
30227A	3.400	2200	81.8	Surface	Large Grain
30228A	3.410	2200	93.3	Surface	Large Grain
30229A	3.380	2200	78.9	Chamfer	Large Grain
30230A	3.400	2200	81.2	Surface	Large Grain
30231A	3.390	2200	81.8	Internal	Large Grain
30232A	3.400	2200	89.9	Internal	Large Grain
30233A	3.390	2200	79.2	Internal	Large Grain
30234A	3.390	2200	87.3	Internal	Large Grain
30235A	3.400	2200	82.7	Surface	
30236A	3.400	2200	85.2	Surface	Large Grain

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	114.1	126.7	99.6	8.4	12
2200	84.9	93.3	78.9	4.7	12

Baseline Flexure Fast Fracture Strength Of Kyocera SN-252 Sintered Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 5/1/90

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
28487		75	84.4	Surface	Large Acicular Grai
28488		75	77.7	Surface	Large Acicular Grai
28489		75	93.8	Surface	Large Acicular Grai
28490		75	92.9	Surface	Large Acicular Grai
28491		75	101.0	Surface	Large Acicular Grai
28492		75	101.5	Surface	Large Acicular Grai
28493		75	97.5	Surface	Large Acicular Grai
28494		75	103.0	Surface	Large Acicular Grai
28495		75	96.4	Surface	Large Acicular Grai
28496		75	84.4	Surface	Large Acicular Grai
28497		75	86.9	Surface	Large Acicular Grai
28498		75	83.5	Surface	Large Acicular Grai
28499		75	95.5	Surface	Large Acicular Grai
28500		75	92.7	Surface	Large Acicular Grai
28501		75	97.0	Surface	Large Acicular Grai
28502		75	96.7	Surface	Large Acicular Grai
28503		75	101.4	Surface	Large Acicular Grai
28504		75	104.4	Surface	Large Acicular Grai
28505		75	82.3	Surface	Large Acicular Grai
28506		75	95.8	Surface	Large Acicular Grai
28542		2200	68.5	Surface	Large Acicular Grai
28543		2200	69.7	Surface	Large Acicular Grai
28544		2200	70.6	Surface	Large Acicular Grai
28545		2200	77.6	Surface	Large Acicular Grai
28546		2200	74.6	Surface	Large Acicular Grai
28547		2200	72.6	Surface	Large Acicular Grai
28548		2200	76.0	Surface	Large Acicular Grai

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	93.4	104.4	77.7	7.7	20
2200	72.8	77.6	68.5	3.4	7

Baseline Flexure Fast Fracture Strength Of Kyocera SN-253 Sintered Silicon Nitride With As-Processed Surfaces

Vintage = 5/1/95

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
35682	3.450	75	98.6	Surface	Pit
35683	3.450	75	99.5	Surface	Pit
35684	3.450	75	102.8	Chamfer	
35685	3.450	75	86.1	Surface	Pit
35686	3.450	75	100.2	Surface	
35687	3.450	75	78.0	Surface	Pock
35688	3.450	2400	95.0	Surface	
35689	3.450	2400	103.4	Surface	
35690	3.450	2400	92.0	Surface	Pit
35691	3.450	2400	94.6	Surface	
35692	3.450	2400	90.6	Surface	Pit
35693	3.450	2400	101.8	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	94.2	102.8	78.0	9.9	6
2400	96.2	103.4	90.6	5.2	6

Baseline Flexure Fast Fracture Strength Of Kyocera SN-260 Sintered Silicon Nitride With As-Processed Surfaces

Vintage = 2/1/91

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
31426	3.380	75	106.6	Surface	
31427	3.380	75	84.7	Chamfer	
31428	3.380	75	85.5	Surface	
31429	3.380	75	92.4	Surface	Pit
31430	3.380	75	86.1	Chamfer	
31431	3.380	75	111.2	Surface	
31432	3.380	75	108.0	Surface	
31433	3.380	75	89.6	Chamfer	
31434	3.380	75	103.7	Surface	
31435	3.380	75	93.0	Chamfer	
31436	3.380	75	88.1	Internal	Porosity
31437	3.380	75	80.4	Surface	
31438	3.380	2300	87.0	Surface	
31439	3.380	2300	79.5	Surface	
31440	3.380	2300	73.4	Surface	
31441	3.380	2300	63.6	Surface	
31442	3.380	2300	89.0	Surface	
31443	3.380	2300	85.0	Surface	
31444	3.380	2300	75.2	Chamfer	
31445	3.380	2300	75.7	Surface	
31446	3.380	2300	70.0	Surface	
31447	3.380	2300	75.5	Surface	
31448	3.380	2300	89.9	Surface	
31449	3.380	2300	104.5	Internal	Linear Defect

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	94.1	111.2	80.4	10.5	12
2300	80.7	104.5	63.6	11.0	12

Baseline Flexure Fast Fracture Strength Of Kyocera SN-281 Sintered Silicon Nitride With As-Processed Surfaces

Vintage = 5/1/95

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
35622	3.400	75	101.1	Surface	
35623	3.400	75	99.9	Surface	
35624	3.400	75	101.5	Surface	
35625	3.400	75	114.5	Surface	
35626	3.400	75	98.1	Surface	
35627	3.400	75	111.6	Surface	
35628	3.400	2400	84.4	Surface	
35629	3.400	2400	81.6	Surface	
35630	3.400	2400	86.7	Surface	
35631	3.400	2400	90.0	Surface	
35632	3.400	2400	85.5	Surface	
35633	3.400	2400	83.9	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	104.5	114.5	98.1	6.8	6
2400	85.4	90.0	81.6	2.8	6

Baseline Flexure Fast Fracture Strength Of NGK SN-50 Sintered Silicon Nitride With As-Processed Surfaces

Vintage = 9/1/84

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
14516B	3.110	75	77.0	Internal	Pore
14517B	3.120	75	101.1	Surface	
14518B	3.130	75	98.5	Missing	
14519B	3.130	75	95.1	Chamfer	
14520B	3.120	75	91.5	Surface	
14521B	3.130	75	103.3	Surface	
14522B	3.130	75	100.7	Surface	
14523B	3.120	75	99.8	Surface	
14524B	3.120	75	99.6	Missing	
14525B	3.130	75	99.3	Internal	Pore
14526B	3.120	75	95.5	Surface	
14527B	3.110	75	99.0	Surface	
14516A	3.110	2200	51.4	Surface	
14517A	3.120	2200	39.9	Surface	
14518A	3.130	2200	46.4	Surface	
14519A	3.130	2200	48.0	Surface	
14520A	3.120	2200	43.7	Surface	
14521A	3.130	2200	47.8	Chamfer	
14522A	3.130	2200	49.6	Chamfer	
14523A	3.120	2200	48.1	Surface	
14524A	3.120	2200	45.1	Chamfer	
14525A	3.130	2200	49.6	Surface	
14526A	3.120	2200	45.6	Internal	Pore
14527A	3.110	2200	46.8	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	96.7	103.3	77.0	7.0	12
2200	46.8	51.4	39.9	3.1	12

Baseline Flexure Fast Fracture Strength Of NGK SN-82 Sintered Silicon Nitride With As-Processed Surfaces

Vintage = 1/1/86

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
20302A	3.250	75	122.4	Surface	Pore
20303A	3.240	75	124.1	Surface	Pore
20304A	3.260	75	124.1	Surface	
20305A	3.260	75	143.8	Surface	
20306A	3.240	75	106.8	Chamfer	
20307A	3.230	75	102.4	Chamfer	Porosity
20308A	3.250	75	107.1	Surface	
20309A	3.250	75	130.6	Surface	
20310A	3.260	75	130.6	Surface	
20311A	3.260	75	129.7	Surface	
20312A	3.230	75	127.0	Surface	
20313A	3.240	75	96.7	Surface	Pore
20302B	3.250	1800	102.1	Chamfer	
20303B	3.240	1800	81.3	Internal	Pore
20304B	3.260	1800	103.5	Chamfer	
20305B	3.260	1800	110.2	Surface	Pore
20306B	3.240	1800	105.6	Surface	
20307B	3.230	1800	102.1	Surface	
20314A	3.230	1800	100.1	Chamfer	
20315A	3.250	1800	100.6	Internal	Pore
20316A	3.250	1800	115.4	Chamfer	
20317A	3.230	1800	118.3	Surface	
20318A	3.240	1800	105.7	Surface	
20319A	3.240	1800	102.2	Surface	
20308B	3.250	2200	90.1	Surface	
20309B	3.250	2200	98.3	Chamfer	
20310B	3.260	2200	86.2	Internal	Pore
20311B	3.260	2200	103.0	Surface	
20312B	3.230	2200	97.7	Surface	
20313B	3.240	2200	105.0	Surface	
20314B	3.230	2200	92.2	Surface	
20315B	3.250	2200	97.5	Surface	
20316B	3.250	2200	98.6	Surface	
20317B	3.230	2200	103.6	Surface	
20318B	3.240	2200	98.3	Surface	
20319B	3.240	2200	97.3	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	120.4	143.8	96.7	14.0	12
1800	103.9	118.3	81.3	9.2	12
2200	97.3	105.0	86.2	5.5	12

Baseline Flexure Fast Fracture Strength Of NGK SN-84 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 9/1/87

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
27549	3.250	75	165.4	Missing	
27550	3.250	75	161.1	Surface	
27551	3.250	75	144.3	Surface	
27552	3.250	75	127.6	Surface	
27553	3.250	75	158.4	Surface	
27554	3.250	75	115.2	Surface	
27555	3.250	75	130.4	Missing	
27556	3.250	75	154.8	Surface	
27557	3.250	75	136.5	Surface	
27558	3.260	75	137.5	Surface	
27559	3.250	75	91.6	Surface	
27560	3.250	75	153.7	Surface	
27561	3.250	2200	148.6	Surface	
27562	3.250	2200	121.1	Surface	
27563	3.250	2200	152.6	Surface	
27564	3.260	2200	146.9	Surface	
27565	3.250	2200	103.6	Surface	
27566	3.250	2200	142.3	Internal	
27567	3.250	2200	153.9	Surface	
27568	3.250	2200	138.3	Surface	
27569	3.250	2200	138.3	Internal	
27570	3.250	2200	117.1	Internal	
27571	3.250	2200	127.5	Surface	
27572	3.250	2200	123.4	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	139.7	165.4	91.6	21.5	12
2200	134.5	153.9	103.6	15.8	12

Baseline Flexure Fast Fracture Strength Of NGK SN-88 Sintered Silicon Nitride With As-Processed Surfaces

Vintage = 7/1/91

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
32767	3.430	75	90.7	Chamfer	
32768	3.460	75	106.2	Surface	Pit
32769	3.450	75	106.1	Surface	
32770	3.470	75	105.5	Surface	
32771	3.470	75	104.7	Surface	Pit
32772	3.440	75	108.5	Surface	Pit
32773	3.460	75	94.5	Chamfer	
32774	3.480	75	83.3	Surface	Pit
32775	3.450	75	85.7	Surface	
32776	3.460	75	98.0	Surface	Grain/Pit
32777	3.440	75	105.0	Surface	Pit
32778	3.450	75	93.1	Surface	Pit
32779	3.460	2300	89.3	Surface	
32780	3.440	2300	91.6	Surface	
32781	3.450	2300	98.2	Internal	Grain
32782	3.470	2300	92.9	Surface	
32783	3.450	2300	109.4	Chamfer	
32784	3.470	2300	96.6	Surface	Pit
32785	3.460	2300	90.8	Chamfer	Grain
32786	3.450	2300	92.0	Chamfer	
32787	3.470	2300	103.2	Surface	
32788	3.460	2300	89.6	Internal	Grain
32789	3.480	2300	97.4	Missing	
32790	3.470	2300	98.4	Internal	Grain

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	98.4	108.5	83.3	8.8	12
2300	95.8	109.4	89.3	6.0	12

Baseline Flexure Fast Fracture Strength Of Norton Company NCX-34 Hot Pressed Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 6/1/78

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5090	3.370	75	106.6	Surface	Scratch
5104	3.350	75	118.7	Surface	Machining Groove
5116	3.340	75	119.5	Surface	
5146	3.370	75	127.3	Surface	
5232	3.340	75	110.9	Chamfer	
5234	3.350	75	125.6	Subsurface	
5241	3.350	75	113.2	Surface	Machining Groove
5244	3.350	75	129.0	Subsurface	
5326	3.360	75	128.7	Surface	Machining Groove
5330	3.340	75	125.3	Surface	Machining Groove
5335	3.350	75	123.8	Chamfer	
5340	3.370	75	123.0	Surface	
5096	3.360	2200	79.5	Missing	
5115	3.350	2200	69.1	Surface	Oxide
5145	3.360	2200	75.5	Surface	
5147	3.370	2200	69.1	Surface	Oxide
5230	3.350	2200	81.2	Surface	
5233	3.350	2200	86.4	Surface	Machining Groove
5236	3.350	2200	67.7	Surface	
5239	3.350	2200	73.7	Subsurface	Pore
5245	3.350	2200	70.6	Surface	
5327	3.340	2200	90.7	Chamfer	
5333	3.360	2200	96.5	Surface	
5338	3.360	2200	85.0	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	121.0	129.0	106.6	7.3	12
2200	78.8	96.5	67.7	9.4	12

Baseline Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-154 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 10/1/88

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
29143	3.240	75	184.3	Internal	
29145	3.240	75	181.4	Surface	
29147	3.230	75	164.7	Chamfer	
29149	3.240	75	95.6	Chamfer	
29151	3.240	75	103.7	Chamfer	
29153	3.240	75	146.3	Chamfer	
29155	3.230	75	141.7	Surface	
29157	3.240	75	144.0	Chamfer	
29159	3.230	75	184.6	Surface	
29161	3.240	75	176.3	Surface	
29163	3.240	75	159.8	Chamfer	
29165	3.240	75	142.6	Surface	
29144	3.240	2200	102.0	Internal	
29146	3.240	2200	110.6	Surface	
29148	3.230	2200	99.9	Surface	
29150	3.240	2200	88.4	Surface	
29152	3.240	2200	89.9	Surface	
29154	3.240	2200	90.1	Surface	
29156	3.230	2200	99.4	Surface	
29158	3.240	2200	101.1	Surface	
29160	3.230	2200	111.2	Surface	
29162	3.240	2200	115.2	Surface	
29164	3.240	2200	110.3	Surface	
29166	3.240	2200	106.0	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	152.1	184.6	95.6	29.5	12
2200	102.0	115.2	88.4	9.1	12

Baseline Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-154 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 4/1/90

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
30341	3.240	75	103.1	Missing	
30343	3.240	75	114.6	Surface	
30345	3.240	75	110.9	Chamfer	
30347	3.240	75	99.6	Chamfer	
30349	3.240	75	101.1	Chamfer	
30351	3.230	75	122.7	Surface	
30353	3.230	75	112.9	Surface	
30355	3.230	75	131.0	Chamfer	
30357	3.230	75	95.9	Chamfer	
30359	3.230	75	135.1	Surface	
30361	3.230	75	114.3	Surface	
30363	3.230	75	107.7	Surface	
30342	3.240	2300	103.4	Surface	
30344	3.240	2300	101.1	Surface	
30346	3.240	2300	85.5	Surface	
30348	3.240	2300	91.3	Surface	
30350	3.230	2300	111.5	Surface	
30352	3.230	2300	105.7	Missing	
30354	3.230	2300	110.3	Surface	
30356	3.230	2300	113.2	Missing	
30358	3.230	2300	109.7	Surface	
30360	3.230	2300	105.1	Internal	
30362	3.230	2300	95.3	Surface	
30364	3.230	2300	104.8	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	112.4	135.1	95.9	12.2	12
2300	103.1	113.2	85.5	8.5	12

Baseline Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-154 Hot Isostatically Pressed Silicon Nitride With As-Processed Surfaces

Vintage = 9/1/93

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
34553	3.220	75	97.3	Surface	
34554	3.220	75	95.9	Surface	Inclusion
34555	3.220	75	92.2	Surface	
34556	3.220	75	96.4	Surface	
34557	3.220	75	98.9	Surface	
34558	3.220	75	77.9	Surface	Step
34559	3.220	75	102.1	Surface	
34560	3.220	75	97.8	Surface	
34561	3.220	75	94.3	Surface	
34562	3.220	75	103.9	Surface	
34563	3.220	75	102.9	Chamfer	
34564	3.220	75	86.0	Surface	
34565	3.220	2400	89.5	Surface	
34566	3.220	2400	88.6	Surface	
34567	3.220	2400	71.7	Surface	
34568	3.220	2400	73.5	Surface	
34569	3.220	2400	39.3	Surface	Pit
34570	3.220	2400	78.6	Chamfer	
34571	3.220	2400	61.0	Surface	Pit
34572	3.220	2400	54.1	Surface	Pit
34573	3.220	2400	65.8	Surface	
34574	3.220	2400	83.4	Surface	
34575	3.220	2400	75.2	Surface	
34576	3.220	2400	80.8	Chamfer	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	95.5	103.9	77.9	7.4	12
2400	71.8	89.5	39.3	14.8	12

Baseline Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-164 Hot Isostatically Pressed Silicon Nitride With As-Processed Surfaces

Vintage = 8/1/93

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
34469	3.180	75	122.4	Surface	Pit
34470	3.180	75	115.4	Surface	
34471	3.180	75	89.0	Surface	
34472	3.180	75	131.7	Surface	
34473	3.180	75	111.6	Surface	
34474	3.180	75	99.9	Surface	Pit
34475	3.180	75	75.9	Chamfer	Pit
34476	3.180	75	94.6	Chamfer	
34477	3.180	75	115.0	Chamfer	
34478	3.180	75	105.3	Surface	Pit
34479	3.180	75	85.6	Chamfer	
34480	3.180	75	92.7	Chamfer	
34481	3.180	2400	111.8	Surface	
34482	3.180	2400	96.6	Chamfer	
34483	3.180	2400	103.6	Surface	
34484	3.180	2400	105.9	Surface	
34485	3.180	2400	91.8	Internal	Inclusion
34486	3.180	2400	104.3	Surface	
34487	3.180	2400	111.3	Surface	
34488	3.180	2400	73.4	Internal	Inclusion
34489	3.180	2400	108.7	Surface	
34490	3.180	2400	77.3	Chamfer	
34491	3.180	2400	77.2	Internal	Inclusion
34492	3.180	2400	98.0	Surface	Pit

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	103.3	131.7	75.9	16.5	12
2400	96.7	111.8	73.4	13.8	12

Baseline Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-230 Siliconized Silicon Carbide With Longitudinally Machined Surfaces

Vintage = 5/1/91

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
32369	3.110	75	57.9	Internal	Pore
32370	3.110	75	58.2	Internal	Pore
32371	3.110	75	70.6	Missing	
32372	3.110	75	50.1	Chamfer	
32373	3.110	75	73.4	Surface	
32374	3.100	75	44.6	Surface	Porosity
32375	3.100	75	44.9	Surface	Porosity
32376	3.100	75	56.7	Missing	
32377	3.100	75	59.0	Surface	
32378	3.100	75	47.2	Chamfer	
32379	3.100	75	55.9	Internal	Pore
32380	3.100	75	67.4	Surface	
32381	3.110	2300	63.6	Surface	Pore
32382	3.110	2300	76.3	Surface	
32383	3.110	2300	72.6	Internal	Pore
32384	3.110	2300	68.8	Missing	
32385	3.110	2300	70.6	Surface	
32386	3.100	2300	91.9	Internal	Pore
32387	3.100	2300	78.9	Missing	
32388	3.100	2300	58.5	Internal	Pore
32389	3.100	2300	74.6	Internal	Pore
32390	3.100	2300	87.6	Surface	
32391	3.100	2300	63.9	Surface	
32392	3.100	2300	79.2	Internal	Porosity

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	57.2	73.4	44.6	9.6	12
2300	73.9	91.9	58.5	9.8	12

Baseline Flexure Fast Fracture Strength Of Pure Carbon Refel Siliconized Silicon Carbide With Longitudinally Machined Surfaces

Vintage = 10/1/78

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5246	3.080	75	49.0	Surface	
5355	3.080	75	62.8	Subsurface	
5362	3.090	75	59.0	Surface	
5370	3.070	75	57.6	Surface	
5377	3.100	75	71.1	Surface	
5382	3.070	75	59.0	Surface	
5387	3.090	75	52.4	Surface	
5394	3.090	75	62.8	Chamfer	
5398	3.090	75	59.6	Subsurface	
5406	3.080	75	30.5	Chamfer	
5415	3.060	75	53.9	Surface	
5419	3.070	75	46.9	Surface	
5350	3.060	2200	72.0		
5358	3.070	2200	77.2		
5366	3.060	2200	72.0		
5375	3.070	2200	69.1		
5378	3.070	2200	72.9		
5384	3.080	2200	63.9		
5390	3.060	2200	57.0		
5397	3.070	2200	73.7		
5402	3.090	2200	57.6		
5412	3.080	2200	75.5		
5418	3.090	2200	70.6		
5425	3.080	2200	73.2		

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	55.4	71.1	30.5	10.2	12
2200	69.6	77.2	57.0	6.6	12

Baseline Flexure Fast Fracture Strength Of Pure Carbon Refel Injection Molded Siliconized Silicon Carbide With Longitudinally Machined Surfaces

Vintage = 10/1/81

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
11120		75	56.2	Surface	
11121		75	49.0	Surface	
11122		75	57.6	Internal	Anomaly
11123		75	60.5	Chamfer	
11124		75	30.2	Internal	Large Grain
11125		75	50.4	Surface	
11126		75	54.7	Surface	
11127		75	57.6	Surface	
11128		75	17.3	Chamfer	
11129		75	47.5	Surface	Large Grain
11130		2000	49.4	Surface	
11131		2000	50.2	Surface	Large Grain
11132		2000	57.3	Surface	
11133		2000	38.0	Surface	
11134		2000	57.9	Surface	
11135		2000	60.5	Surface	
11136		2000	57.8	Internal	Pore
11137		2000	52.7	Chamfer	
11138		2000	55.0	Chamfer	
11139		2000	55.3	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	48.1	60.5	17.3	13.8	10
2000	53.4	60.5	38.0	6.5	10

Baseline Flexure Fast Fracture Strength Of Pure Carbon Refel Injection Molded Siliconized Silicon Carbide With As-Processed Surfaces

Vintage = 10/1/81

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
10810A		75	38.6	Surface	
10810B		75	38.0	Surface	
10812A		75	32.9	Missing	
10812B		75	25.1	Internal	Large Pore
10813A		75	24.3	Chamfer	
10813B		75	26.4	Surface	Linear Defect
10814A		75	36.9	Internal	Pore
10814B		75	40.6	Surface	
10815A		75	39.0	Surface	
10815B		75	27.7	Chamfer	
10816A		2000	64.9	Surface	
10816B		2000	70.2	Surface	
10817A		2000	74.7	Surface	
10817B		2000	63.6	Surface	Linear Defect
10818A		2000	43.2	Surface	Inclusion
10818B		2000	64.3	Surface	
10819A		2000	59.3	Surface	Pit
10819B		2000	60.7	Surface	
10820A		2000	64.5	Chamfer	Rough Area
10820B		2000	52.1	Surface	Rough Area

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	33.0	40.6	24.3	6.5	10
2000	61.8	74.7	43.2	8.9	10

Baseline Flexure Fast Fracture Strength Of Toshiba Sintered Silicon Nitride With Longitudinally Machined Surfaces

Vintage = 7/1/84

Serial No.	Density (g/cc)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
14282A	3.240	75	118.8	Internal	Dark Inclusion
14283A	3.240	75	106.4	Chamfer	
14284A	3.230	75	119.5	Missing	
14285A	3.240	75	107.3	Surface	
14286A	3.240	75	113.1	Surface	
14287A	3.240	75	111.7	Surface	
14288A	3.240	75	110.5	Surface	Dark Inclusion
14289A	3.240	75	99.6	Surface	Porous Area
14290A	3.230	75	115.0	Surface	
14291A	3.240	75	110.1	Surface	
14292A	3.230	75	119.7	Surface	
14293A	3.240	75	120.0	Missing	
14282B	3.240	2200	63.6	Surface	
14283B	3.240	2200	60.0	Chamfer	
14284B	3.230	2200	67.4	Surface	
14285B	3.240	2200	67.3	Surface	
14286B	3.240	2200	60.7	Chamfer	
14287B	3.240	2200	59.0	Surface	Porosity
14288B	3.240	2200	61.2	Surface	Dark Inclusion
14289B	3.240	2200	50.4	Surface	Dark Inclusion
14290B	3.230	2200	59.6	Surface	Porosity
14291B	3.240	2200	59.6	Surface	
14292B	3.230	2200	60.4	Surface	
14293B	3.240	2200	62.9	Surface	

Baseline Strength Summary

	Flexural Strength (ksi)				
Temp (F)	Average	Max	Min	StDev	Quantity
75	112.6	120.0	99.6	6.4	12
2200	61.0	67.4	50.4	4.4	12

APPENDIX II

POST-EXPOSURE SPECIMEN FLEXURE TEST RESULTS

(62 Pages)

APPENDIX II

TABLE II-1.
SUMMARY OF POST-EXPOSURE SPECIMEN FLEXURE TEST RESULTS.

Manufacturer	Material Designation	Material	Vintage, Mo/Yr	Surface Condition	Exposure Temperature	Test Results Section No.	Appendix II Page No.
esearch Casting Co.	RBN101	Reaction Bonded Silicon Nitride (RBSN)	6/78	Machined	1204C (2200F)	6.1.2	348
			6/78	Machined	1371C (2500F)	6.1.3	350
			6/78	Machined	1371C (2500F)	6.1.4	352
esearch Casting Co.	RBN104	RBSN	12/80	As-Processed	1371C (2500F)	6.2.2	353
esearch Casting Co.	Code 2	Sintered Silicon Nitride	3/85	As-Processed	1204C (2200F)	6.3.2	354
edSignal Ceramic ıponents	GN-10	Hot Isostatically Pressed (HIPped) Silicon Nitride	5/89	Machined	1204C (2200F)	6.4.2	355
ɔorundum Co.	Hexoloy KX01	Siliconized Silicon Carbide (Si-SiC)	4/83	As-Processed	1204C (2200F)	6.5.2	357
ɔorundum Co.	Hexoloy SA	Sintered Alpha Silicon Carbide (α-SiC)	6/78	Machined	1204C (2200F)	6.6.2	359
			6/78	Machined	1371C (2500F)	6.6.3	361
			6/78	Machined	1371C (2500F)	6.6.4	363
		Injection Molded α-SiC	7/83	As-Processed	1371C (2500F)	6.6.6	364
ɔorundum Co.	Hexoloy ST	Titanium Diboride (TiB2) Toughened Silicon Carbide	10/87	As-Processed	1204C (2200F)	6.7.2	365
			11/88	As-Processed	1260C (2300F)	6.7.4	367
ıing Glass Works	Code 9458	Lithium Aluminum Silicate (LAS)	8/81	Machined	1093C (2000F)	6.8.2	369
l Motor Co.	Ford RBSN	RBSN	11/82	As-Processed	1204C (2200F)	(6.9.1)	(N/A)
ɜral Electric Co.	GE β-SiC	Beta Sintered SiC (β-SiC)	12/84	As-Processed	1371C (2500F)	6.10.2	370
: Laboratories	AY6	Sintered Silicon Nitride	7/83	Machined	1204C (2200F)	6.11.2	372
: Laboratories	PY6	Sintered Silicon Nitride	4/81	Machined	1204C (2200F)	6.12.2	373
			1/90	As-Processed	1204C (2200F)	6.12.4	374
ɜera Corporation	SC-201	Sintered Silicon Carbide	5/84	As-Processed	1371C (2500F)	6.13.2	376
ɜera Corporation	SN-250M	Sintered Silicon Nitride	10/86	Machined	1204C (2200F)	6.14.2	378
ɜera Corporation	SN-251	Sintered Silicon Nitride	2/90	Machined	1204C (2200F)	6.15.2	380
ɜera Corporation	SN-252	Sintered RBSN	5/90	Machined	1204C (2200F)	6.16.2	381
ɜera Corporation	SN-253	Sintered Silicon Nitride	5/95	As-Processed	1316C (2400F)	6.17.2	382
ɜera Corporation	SN-260	Sintered Silicon Nitride	2/91	As-Processed	1260C (2300F)	6.18.2	383
ɜera Corporation	SN-281	Sintered Silicon Nitride	5/95	As-Processed	1316C (2400F)	6.19.2	384
: Insulators	SN-50	Sintered Silicon Nitride	9/84	As-Processed	1204C (2200F)	6.20.2	385
: Insulators	SN-82	Sintered Silicon Nitride	1/86	As-Processed	1204C (2200F)	6.21.2	386
: Insulators	SN-84	Sintered Silicon Nitride	9/87	Machined	1204C (2200F)	6.22.2	388
: Insulators	SN-88	Sintered Silicon Nitride	7/91	As-Processed	1260C (2300F)	6.23.2	390
ɔn Co.	NCX-34	Hot Pressed Silicon Nitride	6/78	Machined	1204C (2200F)	6.24.2	(N/A)
			6/78	Machined	1371C (2500F)	6.24.2	(N/A)
ɔn Advanced mics (NAC)	NT-154	Hot Isostatically Pressed (HIPped) Silicon Nitride	10/88	Machined	1204C (2200F)	6.25.2	392
			4/90	Machined	1260C (2300F)	6.25.4	394
			9/93	As-Processed	1316C (2400F)	6.25.6	396
	NT-164	HIPped Silicon Nitride	8/93	As-Processed	1316C (2400F)	6.26.2	398
	NT-230	Si-SiC	5/91	As-Processed	1260C (2300F)	6.27.2	400
Carbon Co.	Refel Si-SiC	Siliconized Silicon Carbide (Si-SiC)	10/78	Machined	1204C (2200F)	6.28.2	402
			10/78	Machined	1260C (2300F)	6.28.4	404
			10/78	Machined	1316C (2400F)	6.28.4	(N/A)
			10/78	Machined	1371C (2500F)	6.28.3	(N/A)
			10/81	Machined	1093C (2000F)	6.28.6	405
			10/81	As-Processed	1093C (2000F)	6.28.6	406
iba Corporation	Toshiba Si_3N_4	Sintered Silicon Nitride	7/84	Machined	1204C (2200F)	6.29.2	407

= Not Available.

Post-Exposure Flexure Fast Fracture Strength Of AirResearch Casting Company RBN101 Reaction Bonded Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 6/1/78

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5003	2.870	350	-0.04	0.00	75	34.1	Surface	Oxide Reaction
5018	2.820	350	-0.15	0.00	75	39.9	Surface	Oxide Reaction
5020	2.800	350	-0.23	0.00	75	26.9	Surface	Oxide Reaction With Subsurface Pore
5027	2.820	350	-0.15	0.00	75	33.4	Surface	Oxide Reaction
5031	2.830	350	-0.20	0.00	75	32.2	Surface	Oxide Reaction
5040	2.870	350	-0.05	0.00	75	36.3	Surface	
5045	2.860	350	-0.18	0.00	75	37.7	Subsurface	Inclusion
5067	2.820	350	-0.03	0.00	75	36.3	Surface	Oxide Reaction
5295	2.800	350	-0.21	0.00	75	34.8	Subsurface	Pore
5304	2.820	350	-0.12	0.00	75	32.4	Subsurface	Laminar Defect
5310	2.780	350	-0.09	0.00	75	35.1	Surface	Oxide Reaction
5313	2.810	350	-0.01	0.00	75	38.6	Subsurface	Inclusion
5010	2.810	1050	0.07	1.30	75	33.9	Subsurface	Oxide Reaction
5014	2.800	1050	0.32	1.60	75	33.8	Surface	Oxide Reaction
5042	2.800	1050	-0.13	1.50	75	30.9	Subsurface	Inclusion
5062	2.830	1050		1.40	75	38.9	Surface	Oxide Reaction
5437	2.850	1050	0.07	1.60	75	36.4	Surface	Oxide Reaction
5439	2.850	1050		1.40	75	34	Subsurface	Pore
5440	2.870	1050	0.05	1.80	75	32.3	Subsurface	Pore
5441	2.870	1050			75			
5443	2.840	1050	0.13	1.30	75	35.4	Subsurface	Pore
5444	2.860	1050	0.02	1.20	75	37.8	Surface	Oxide Reaction
5446	2.850	1050	0.67	1.40	75	30.3	Surface	Oxide Reaction
5447	2.830	1050	0.12	1.60	75	39.5	Surface	Oxide Reaction
5448	2.810	1050	0.17	1.90	75	36.3	Subsurface	Inclusion or Pore
5007	2.870	2100	-1.00	0.48	75	30		
5029	2.860	2100	-0.86	0.32	75	26.8		
5066	2.890	2100	-0.91	0.96	75	28.2		
5442	2.840	2100	-1.07	0.56	75	29.1		
5578	2.870	2100	-1.01	0.56	75	31.1		
5581	2.850	2100	-0.99	0.48	75	32.5		
5586	2.860	2100	-0.75	0.96	75	29.4		
5589	2.850	2100	-0.79	0.96	75	17.6		
5591	2.830	2100	-0.77	0.64	75	32.2		
5598	2.870	2100	-0.72	0.64	75	31.1		
5602	2.860	2100	-0.75	0.64	75	35.7		
5604	2.830	2100	-0.57	1.04	75	32.3		

Post-Exposure Flexure Fast Fracture Strength Of AirResearch Casting Company RBN101 Reaction Bonded Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	34.8	39.9	26.9	3.4	12
1050	75	35.0	39.5	30.3	3.0	12
2100	75	29.7	35.7	17.6	4.5	12

Post-Exposure Weight .Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-0.1	0.0	12
1050	0.1	1.5	10
2100	-0.8	0.7	12

Post-Exposure Flexure Fast Fracture Strength Of AirResearch Casting Company RBN101 Reaction Bonded Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2500F

Vintage = 6/1/78

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5013	2.860	350	-0.25	0.00	75	27.2	Surface	Oxide Reaction
5019	2.840	350	-0.02	0.00	75	27.3	Surface	Oxide Reaction
5022	2.830	350	-0.09	0.00	75	34.4	Surface	Oxide Reaction
5030	2.820	350	-0.28	0.00	75	27	Surface	Oxide Reaction With Pore
5032	2.830	350	-0.09	0.00	75	31.2	Surface	Oxide Reaction
5043	2.840	350	0.00	0.00	75	26.7	Chamfer	Oxide Reaction With Pore
5059	2.860	350	-0.04	0.00	75	24.6	Surface	Oxide Reaction
5072	2.820	350	-0.30	0.00	75	28.9	Surface	Oxide Reaction
5303	2.790	350	-0.33	0.00	75	35.7	Surface	Oxide Reaction
5307	2.830	350	-0.08	0.00	75	32.7	Surface	Oxide Reaction
5311	2.790	350	-0.46	0.00	75	27.6	Surface	Oxide Reaction
5319	2.780	350	-0.06	0.00	75	29.8	Subsurface	Pore
5577	2.890	1050			75			
5579	2.840	1050	-1.67	-0.32	75	23.3	Chamfer	Oxide Reaction
5583	2.840	1050			75			
5584	2.830	1050	-1.77	-0.32	75	16.7	Subsurface	Pore
5587	2.860	1050	-1.75	0.40	75	22.5	Surface	Oxide Reaction
5593	2.860	1050	-1.72	-0.48	75	22.5	Surface	Oxide Reaction
5594	2.850	1050		0.16	75	21.9	Chamfer	Oxide Reaction
5595	2.860	1050			75			
5599	2.830	1050	-1.71	-0.16	75	22.2	Surface	Oxide Reaction
5601	2.840	1050		0.16	75	21	Surface	Oxide Reaction
5605	2.820	1050		-0.16	75	22.8	Surface	Oxide Reaction
5606	2.860	1050	-1.67	0.32	75	23.3	Surface	Oxide Reaction
5000	2.870	2100	-23.10	-24.50	75	15.1		
5012	2.870	2100			75			
5076	2.880	2100	-26.00	-27.80	75	16.8	Subsurface	Pore
5081	2.880	2100	-24.00	-24.10	75	17.4	Subsurface	Pore
5083	2.900	2100			75			
5580	2.840	2100	-23.50	-25.30	75	18.6	Subsurface	Pore
5582	2.860	2100	-23.50	-24.10	75	17.4	Subsurface	Pore
5585	2.860	2100	-25.30	-25.60	75	20.3	Subsurface	Pore
5588	2.860	2100	-24.20	-24.20	75	18.6	Subsurface	Pore
5590	2.820	2100	-24.00	-24.90	75	17.4	Subsurface	Pore
5592	2.860	2100	-24.30	-23.10	75	19.2	Subsurface	Pore
5597	2.820	2100	-26.80	-26.80	75	16.3	Subsurface	Pore

Post-Exposure Flexure Fast Fracture Strength Of AirResearch Casting Company RBN101 Reaction Bonded Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2500F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	29.4	35.7	24.6	3.4	12
1050	75	21.8	23.3	16.7	2.0	9
2100	75	17.7	20.3	15.1	1.5	10

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-0.2	0.0	12
1050	-1.7	0.0	6
2100	-24.5	-25.0	10

Post-Exposure Flexure Fast Fracture Strength Of AirResearch Casting Company RBN101 Reaction Bonded Silicon Nitride (Retest) With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2500F

Vintage = 6/1/78

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
3689	2.860	2100		-5.40	75	22.6	Surface	Glass Spot
3699	2.880	2100	-8.02	-7.47	75	23.1	Surface	Glass Pit
3702	2.860	2100			75			Glass Spot
5713	2.900	2100	-7.74	-6.69	75	24.6	Subsurface	Porosity
5714	2.900	2100	-7.37	-7.10	75	24.2	Surface	Glass Spot/Pit
5732	2.910	2100	-7.94	-7.83	75	25.5	Surface	Glass Pit
5746	2.890	2100		-7.15	75	22.6	Subsurface	Porosity
5751	2.900	2100		-8.04	75	24.1	Surface	Glass Spot
5766	2.860	2100		-7.58	75	20.5	Surface	Glass Pit
5772	2.880	2100	-7.85	-7.26	75	26	Surface	Glass Spot
5773	2.860	2100	-7.70	-7.74	75	22.7	Surface	Glass Spot
5783	2.870	2100	-7.74	-7.74	75	26	Surface	Glass Spot

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
2100	75	23.8	26.0	20.5	1.7	11

Post-Exposure Weight_Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
2100	-7.8	-7.3	7

Post-Exposure Flexure Fast Fracture Strength Of AirResearch Casting Company RBN104 Reaction Bonded Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2500F

Vintage = 12/1/80

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
9083	2.830	350		0.72	75	39.7	Surface	Pit
9093	2.850	350		0.48	75	40	Surface	Pit
9143	2.820	350		0.72	75	34	Surface	Pit
9111a	2.810	350	-0.30	0.64	2200	57.3	Surface	Pit
9153	2.800	350	-0.36	0.56	2200	54.1	Sursurface	Pore
9154	2.820	350	-0.34	0.64	2200	42.6	Sursurface	Oxidation
9084	2.790	1050		-0.24	75	16.7	Surface	Oxidation Pit
9128	2.810	1050		0.00	75	22	Surface	Oxidation Pit
9167	2.780	1050		0.08	75	23.2	Surface	Oxidation Anomaly
7680	2.790	1050		-0.47	2200	49.2	Surface	Oxidation Pit
7684	2.770	1050		0.32	2200	43.9	MIssing	
7716	2.790	1050		-0.24	2200	41.9	Internal	Inclusion
9068	2.820	2100		-2.30	75	31.8	Surface	Oxidation Pit
9069	2.830	2100		-2.20	75	28.3	Surface	Oxidation Anomaly
9087	2.820	2100		-2.60	75	29.3	Surface	Oxidation Pit
9099	2.830	2100		-1.80	2200	51.1	Surface	Pore
9155	2.800	2100		-2.20	2200	41.9	Subsurface	Porosity
9199	2.830	2100		-1.40	2200	51	Subsurface	Porosity

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi)				
		Average	Max	Min	StDev	Quantity
350	75	37.9	40.0	34.0	3.4	3
350	2200	51.3	57.3	42.6	7.7	3
1050	75	20.6	23.2	16.7	3.5	3
1050	2200	45.0	49.2	41.9	3.8	3
2100	75	29.8	31.8	28.3	1.8	3
2100	2200	48.0	51.1	41.9	5.3	3

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-0.3	0.6	3
1050		-0.1	0
2100		-2.1	0

Post-Exposure Flexure Fast Fracture Strength Of AirResearch Casting Company Code 2 Sintered Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 3/1/85

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
16141	3.230	350	0.01	0.00	75	56.8	Internal	Pore
16150	3.240	350	0.00	1.60	75	62.4	Internal	Pore
16161	3.250	350	0.01	1.60	75	65	Surface	
16116	3.240	350	0.04	1.60	2200	46.7	Internal	Pore
16119	3.240	350	0.04	1.70	2200	40.5	Internal	Pore
16152	3.250	350	0.01	1.60	2200	34.9	Internal	Pore

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	61.4	65.0	56.8	4.2	3
350	2200	40.7	46.7	34.9	5.9	3

Post-Exposure Weight .Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.0	1.4	6

Post-Exposure Flexure Fast Fracture Strength Of AlliedSignal Ceramic Components GN-10 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 5/1/89

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
29892	3.310	350	-0.05	2.40	75	87.7	Surface	Rough Oxide
29894	3.330	350	-0.22	2.40	75	82	Surface	Rough Oxide
29896	3.320	350	-0.24	2.40	75	91.7	Surface	Rough Oxide
29898	3.310	350	-0.22	2.40	75	90.1	Surface	Rough Oxide
29900	3.330	350	0.00	2.40	75	83	Surface	Rough Oxide
29902	3.300	350	-0.12	2.40	75	85.6	Surface	Rough Oxide
29893	3.320	350	-0.02	2.40	2200	79.2	Surface	Rough Oxide
29895	3.320	350	-0.07	2.40	2200	83	Surface	Rough Oxide
29897	3.310	350	-0.05	2.40	2200	77.3	Surface	Rough Oxide
29899	3.310	350	-0.04	2.40	2200	69.8	Surface	Rough Oxide
29901	3.340	350	-0.12	2.40	2200	75.4	Surface	Rough Oxide
29903	3.320	350	-0.19	2.40	2200	85.2	Surface	Rough Oxide
29904	3.320	700	-0.35	3.20	75	82.3	Surface	Rough Oxide
29906	3.330	700	-0.23	2.40	75	86.8	Surface	Rough Oxide
29908	3.300	700	-0.05	2.40	75	91.7	Surface	Rough Oxide
29910	3.330	700	0.00	3.20	75	89.7	Surface	Rough Oxide
29912	3.330	700	-0.08	3.20	75	91	Surface	Rough Oxide
29914	3.330	700	0.00	3.20	75	90.5	Surface	Rough Oxide
29905	3.320	700	-0.24	2.40	2200	79	Surface	Rough Oxide
29907	3.300	700	-0.35	2.40	2200	74.9	Surface	Rough Oxide
29909	3.330	700	-0.19	2.40	2200	80.1	Surface	Rough Oxide
29911	3.310	700	-0.26	2.40	2200	79.8	Surface	Rough Oxide
29913	3.350	700	0.00	2.40	2200	85.5	Surface	Rough Oxide
29915	3.310	700	-0.29	2.40	2200	86.8	Surface	Rough Oxide
29880	3.310	1050	-0.16	3.20	75	84.6	Surface	Rough Oxide
29882	3.310	1050	-0.23	2.40	75	81.9	Surface	Rough Oxide
29884	3.310	1050	-0.23	3.20	75	79.5	Surface	Rough Oxide
29886	3.320	1050	-0.27	2.40	75	84.9	Surface	Rough Oxide
29888	3.340	1050	-0.08	2.40	75	77	Surface	Rough Oxide
29890	3.340	1050	-0.36	2.40	75	79.7	Surface	Rough Oxide
29881	3.300	1050	-0.17	3.20	2200	72.4	Surface	Rough Oxide
29885	3.330	1050	-0.15	3.20	2200	71.9	Surface	Rough Oxide
29887	3.300	1050	-0.27	2.40	2200	72.9	Surface	Rough Oxide
29889	3.340	1050	-0.22	3.20	2200	74.8	Surface	Rough Oxide
29891	3.310	1050	-0.44	3.20	2200	73.7	Surface	Rough Oxide

Post-Exposure Flexure Fast Fracture Strength Of AlliedSignal Ceramic Components GN-10 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	86.7	91.7	82.0	3.9	6
350	2200	78.3	85.2	69.8	5.5	6
700	75	88.7	91.7	82.3	3.6	6
700	2200	81.0	86.8	74.9	4.4	6
1050	75	81.3	84.9	77.0	3.1	6
1050	2200	73.1	74.8	71.9	1.1	5

Post-Exposure Weight .Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-0.1	2.4	12
700	-0.2	2.7	12
1050	-0.2	2.8	11

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy KX01 Siliconized Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 4/1/83

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
11975	2.870	350	0.04	1.60	75	66.5	Surface	Rough Oxide
11977	2.890	350	0.08	0.80	75	50.9	Surface	Rough Oxide
11978	2.910	350	0.08	1.60	75	49.9	Surface	Rough Oxide
12006	2.890	350	0.24	0.80	75	58.3	Surface	Rough Oxide
12007	2.890	350	0.19	0.00	75	56.9	Surface	Rough Oxide
12008	2.900	350		0.00	75	31.2	Surface	Rough Oxide
11979	2.890	350	-0.03	2.40	2200	65.7	Surface	Rough Oxide
11982	2.930	350	0.08	0.80	2200	73.7	Surface	Rough Oxide
11983	2.900	350	0.11	1.60	2200	47.3	Surface	Rough Oxide
12009	2.910	350	0.25	0.00	2200	70.6	Surface	Rough Oxide
12011	2.900	350	0.14	1.60	2200	57	Surface	Rough Oxide
12012	2.890	350	0.14	0.80	2200	60.2	Surface	Rough Oxide
11989	2.900	1050	0.11	4.00	75	60.3	Surface	Rough Oxide
11993	2.880	1050	0.08	4.00	75	67.4	Surface	Rough Oxide
11997	2.900	1050	0.12	4.00	75	48.7	Surface	Rough Oxide
12013	2.890	1050	-0.39	1.60	75	72.3	Surface	Rough Oxide
12015	2.910	1050	-0.59	0.80	75	61.2	Surface	Rough Oxide
12017	2.900	1050	-0.42	1.60	75	62.8	Surface	Rough Oxide
11991	2.900	1050	0.13	4.00	2200	62.4	Surface	Rough Oxide
11996	2.890	1050	0.12	3.10	2200	57.9	Surface	Rough Oxide
11998	2.880	1050	0.12	3.10	2200	57.2	Surface	Rough Oxide
12014	2.890	1050	-0.05	0.00	2200	69.4	Surface	Rough Oxide
12016	2.880	1050	-0.41	0.80	2200	61.5	Internal	
12018	2.910	1050	0.00	0.00	2200	62.4	Surface	Rough Oxide
11987	2.910	2100	1.07	5.60	75	75.7	Surface	
11988	2.900	2100	0.99	6.40	75	65.8	Surface	
11992	2.920	2100	0.94	5.60	75	56.9	Surface	
11999	2.890	2100	-0.76	1.60	75	67.3	Surface	Rough Oxide
12002	2.900	2100	-0.69	0.00	75	56.7	Surface	Rough Oxide
12004	2.910	2100		0.80	75	56	Surface	Rough Oxide
11984	2.910	2100	0.80	5.60	2200	53.5	Surface	
11985	2.920	2100	0.98	5.60	2200	53	Surface	
11986	2.900	2100	1.01	5.60	2200	55.1	Surface	
12001	2.910	2100	-0.45	0.80	2200	62.2	Surface	Rough Oxide
12003	2.880	2100	-0.75	0.80	2200	68	Surface	Rough Oxide
12005	2.900	2100	-0.53	0.00	2200	58.1	Internal	
11958	2.910	3500	-0.02	3.10	75	61.5	Surface	Rough Oxide
11961	2.900	3500	-0.01	4.00	75	59.6	Surface	Rough Oxide
11963	2.900	3500	-0.07	4.80	75	60.2	Surface	Rough Oxide
11965	2.920	3500	-0.08	4.00	75	47.9	Surface	Rough Oxide
11968	2.890	3500	-0.09	4.80	75	57.8	Surface	Rough Oxide
11972	2.880	3500		4.00	75	65.8	Surface	Rough Oxide
11959	2.910	3500	-0.08	4.00	2200	51.4	Surface	Rough Oxide
11962	2.900	3500	-0.03	3.10	2200	54.6	Surface	Rough Oxide
11964	2.920	3500	-0.06	4.00	2200	53.2	Surface	Rough Oxide

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy KX01 Siliconized Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2200F (continued)

11966	2.890	3500	-0.01	4.80	2200	55.2	Surface	Rough Oxide
11969	2.900	3500	-0.06	4.80	2200			
11974		3500			2200	55.2	Surface	Rough Oxide

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	52.3	66.5	31.2	11.9	6
350	2200	62.4	73.7	47.3	9.7	6
1050	75	62.1	72.3	48.7	8.0	6
1050	2200	61.8	69.4	57.2	4.4	6
2100	75	63.1	75.7	56.0	7.9	6
2100	2200	58.3	68.0	53.0	5.8	6
3500	75	58.8	65.8	47.9	6.0	6
3500	2200	53.9	55.2	51.4	1.6	5

Post-Exposure Weight Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.1	1.0	11
1050	-0.1	2.3	12
2100	0.2	3.2	11
3500	-0.1	4.1	10

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy SA Sintered Silicon Carbide With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 6/1/78

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5155	3.090	350	-0.06	0.00	75	59	Subsurface	Pore
5157		350			75	41.5	Subsurface	Pore
5178	3.110	350	-0.02	0.00	75	47.7	Subsurface	Pore
5187		350			75			
5199	3.040	350	-0.03	0.00	75	52.7	Subsurface	Pore
5252	3.110	350		0.00	75	57.6	Surface	Pore
5255	3.110	350			75			
5259	3.110	350	-0.06	0.00	75	59.9	Subsurface	Pore
5265	3.130	350	-0.03	0.00	75	56.6	Subsurface	Pore
5270	3.100	350	-0.09	0.00	75	49.7	Surface	Pore
5273	3.110	350	-0.04	0.00	75	50.7	Surface	Pit
5277	3.090	350	-0.03	0.00	75			
5281	3.140	350	-0.08	0.00	75	46.2	Subsurface	Pore
5291	3.090	350	-0.03	0.00	75	50.4	Missing	
5222	3.100	1050	1.70	2.30	75	51.2	Surface	
5452	3.090	1050	-0.08	1.20	75	57.9	Surface	Oxide Reaction
5455	3.130	1050	-0.09	1.50	75	39.7	Surface	Oxide Reaction
5458	3.130	1050		2.20	75	56.7	Surface	Oxide Reaction
5464	3.080	1050	-0.81	1.50	75	50.1	Subsurface	Pore
5466	3.100	1050	-0.01	1.60	75	59.3	Subsurface	Pore
5469	3.110	1050	0.65	1.50	75	46.1	Surface	Oxide Reaction
5473	3.100	1050	-0.09	1.40	75	56.1	Surface	
5476	3.100	1050	-0.07	1.60	75	52.7	Surface	Oxide Reaction
5479	3.120	1050	-0.75	1.70	75	61.1	Subsurface	Pore
5481	3.110	1050	-0.11	1.80	75	55.9	Surface	Oxide Reaction
5485	3.050	1050	-0.06	1.90	75	53.6	Subsurface	Pore
5166	3.110	2100	-0.69	0.48	75	33.4		
5188	3.120	2100	-0.69	0.64	75	51.3		
5190	3.110	2100	-0.69	0.32	75	35.4		
5210	3.090	2100	-0.69	0.48	75	50.4		
5620	3.110	2100	-0.84	0.72	75	44.1		
5621	3.120	2100	-0.80	0.96	75	53.3		
5626	3.110	2100	-0.62	0.96	75	43.8		
5628	3.090	2100	-0.73	0.80	75	48.1		
5630	3.120	2100	-0.65	0.80	75	53		
5631	3.110	2100	-0.63	0.80	75	52.4		
5633	3.100	2100	-0.56	1.04	75	46.1		
5635	3.090	2100	-0.70	0.96	75	47		
5156	3.080	3500			75			
5176	3.090	3500		0.24	75	42.2	Subsurface	Porosity
5201	3.120	3500	-0.89	0.32	75	46.4	Subsurface	Porosity
5215	3.120	3500		0.32	75	53	Subsurface	Porosity
5224	3.090	3500		0.48	75	54.7	Surface	Oxide
5629	3.110	3500		0.64	75	54	Surface	Oxide Pit
5643	3.090	3500			75			

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy SA Sintered Silicon Carbide With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F (continued)

5648	3.090	3500		0.40	75	46.1	Surface	Oxide Pit
5654	3.100	3500			75			
5661	3.090	3500	-0.80	0.48	75	54.1	Surface	Oxide Pit
5667	3.090	3500		0.16	75	49	Subsurface	Inclusion
5672	3.090	3500	-0.87	0.32	75	51.3	Subsurface	
5165	3.090	3500			2200			
5195	3.120	3500	-0.78	0.24	2200	46.9	Subsurface	Porosity/Large Grain
5203	3.090	3500		1.24	2200	46.4	Surface	Large Grain
5217	3.110	3500	-0.80	0.48	2200	52.4	Missing	
5617	3.110	3500		0.48	2200	48.2	Missing	
5638	3.100	3500		0.32	2200	48.6	Subsurface	Pore
5645	3.090	3500			2200			
5651	3.090	3500		0.56	2200	54.4	Surface	Oxide Pit
5658	3.070	3500		0.24	2200	49	Subsurface	Pore
5664	3.090	3500		0.16	2200	59	Subsurface	Pore
5669	3.090	3500		0.40	2200	48.7	Surface	Pit
5676	3.100	3500		0.32	2200	55.3	Subsurface	Pore

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	52.0	59.9	41.5	5.8	11
1050	75	53.4	61.1	39.7	6.0	12
2100	75	46.5	53.3	33.4	6.6	12
3500	75	50.1	54.7	42.2	4.4	9
3500	2200	50.9	59.0	46.4	4.2	10

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.0	0.0	10
1050	0.0	1.7	11
2100	-0.7	0.7	12
3500	-0.8	0.4	5

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy SA Sintered Silicon Carbide With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2500F

Vintage = 6/1/78

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5175	3.090	350	-0.34	0.00	75	39.2	Chamfer	
5197	3.100	350	-0.37	0.00	75	49.8	Surface	Pore
5221		350			75			
5247	3.130	350	-0.36	0.00	75	43.8	Chamfer	
5253	3.110	350	-0.35	0.00	75	45.5	Surface	Pore
5257	3.120	350	-0.36	0.00	75	49.5	Surface	Pore
5262	3.110	350	-0.35	0.00	75	46.4	Surface	Pore
5268	3.110	350	-0.33	0.00	75	44.4	Subsurface	Pore
5271	3.110	350	-0.33	0.00	75	46.7	Surface	Pore
5275		350			75			
5280	3.120	350	-0.33	0.00	75	47.8	Surface	Pore
5289		350			75			
5174	3.100	1050			75			
5180	3.120	1050		-0.24	75	49.2	Surface	Oxide Reaction
5193	3.060	1050		-0.16	75	45.8	Surface	Oxide Reaction with Pore
5194	3.100	1050			75			
5227	3.110	1050		0.00	75	49.8	Surface	Oxide Reaction
5228	3.100	1050		0.08	75	44.9	Surface	Pore
5646	3.090	1050		-0.08	75	46.9	Surface	Oxide Reaction
5650	3.080	1050	-1.36	-0.08	75	45.5	Surface	Oxide Reaction
5653	3.090	1050	-1.46	-0.08	75	46.4	Subsurface	Pore
5656	3.080	1050		0.00	75	40.6	Surface	Pore
5659	3.100	1050	-1.44	-0.24	75	51.8	Surface	Oxide Reaction
5662	3.090	1050	-1.53	-0.16	75	47.5	Surface	Oxide Reaction
5168	3.100	2100	-13.60	-11.30	75	34.1	Surface	Pit
5184	3.070	2100	-15.00	-11.80	75	31.1	Surface	Pit
5192	3.100	2100	-14.60	-11.80	75	29.1	Surface	Pit
5209	3.110	2100	-13.90	-11.50	75	30.7	Surface	Pit
5614	3.130	2100	-19.30	-11.30	75	27.5	Surface	Pit
5622	3.110	2100			75			
5623	3.100	2100	-13.70	-11.10	75	30.7	Surface	Pit
5625	3.120	2100	-14.60	-11.40	75	24.2	Surface	Pit
5627	3.090	2100	-14.30	-11.40	75	27.5	Surface	Pit
5632	3.120	2100	-14.40	-11.00	75	32.3	Surface	Pit
5634	3.100	2100	-14.70	-11.30	75	30.3	Surface	Pit
5636	3.090	2100	-15.20	-11.60	75	29.5	Surface	Pit
5186	3.100	3500	-2.70	-0.16	75	40.3	Surface	Oxide Pit
5202	3.060	3500		-0.08	75	52.4	Surface	Oxide Layer
5219	3.100	3500		0.56	75	49.5	Surface	Oxide Pit
5616	3.120	3500	-2.80	-0.08	75	47.9	Surface	Oxide Pit
5619	3.110	3500	-2.80	1.20	75	45.4	Surface	Oxide Pit
5660	3.110	3500	-2.90	0.95	75	49.2	Subsurface	Porosity
5663	3.090	3500		1.12	75	45.5	Subsurface	Porosity
5665	3.090	3500	-2.80	0.80	75	53.1	Surface	Oxide
5668	3.090	3500		-0.48	75	44.1	Surface	Oxide Pit

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy SA Sintered Silicon Carbide With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2500F (continued)

5671	3.080	3500	-2.40	0.64	75	52.4	Surface	Oxide
5674	3.080	3500		0.48	75	42.3	Surface	Oxide
5677	3.100	3500		0.64	75	46.7	Subsurface	Pore
5158	3.090	3500		-0.48	2200	29.3	Surface	Transgranular
5171	3.100	3500		0.08	2200	30.3	Surface	Pit
5196	3.080	3500		1.05	2200	28.1	Surface	Transgranular
5212	3.110	3500	-2.50	0.32	2200	35.4	Surface	Transgranular
5216	3.110	3500	-2.60	-0.32	2200	34.9	Surface	Transgranular
5637	3.110	3500		1.12	2200	36.1	Surface	Transgranular
5642	3.080	3500		0.64	2200	28.9	Surface	Transgranular
5644	3.090	3500		-0.16	2200	30.8	Surface	Transgranular
5647	3.110	3500		-0.08	2200	37.6	Surface	Transgranular
5649	3.080	3500		0.96	2200	32.9	Chamfer	
5652	3.090	3500	-2.80	0.72	2200	31.9	Surface	Transgranular
5655	3.070	3500		0.72	2200	31.3	Surface	Transgranular

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	45.9	49.8	39.2	3.2	9
1050	75	46.8	51.8	40.6	3.1	10
2100	75	29.7	34.1	24.2	2.7	11
3500	75	47.4	53.1	40.3	4.1	12
3500	2200	32.3	37.6	28.1	3.1	12

Post-Exposure Weight Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-0.3	0.0	9
1050	-1.4	-0.1	4
2100	-14.8	-11.4	11
3500	-2.7	0.4	9

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy SA Sintered Silicon Carbide (Retest) With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2500F

Vintage = 6/1/78

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5153	3.110	2100	-6.16	-5.44	75	41.1	Surface	
5164	3.100	2100	-6.24	-5.85	75	41.6	Surface	
5456	3.130	2100		-5.74	75	42.3	Surface	Reaction
5459	3.130	2100	-6.19	-5.57	75	48.4	Surface	
5462	3.060	2100		-5.72	75	49.4	Subsurface	Pore
5465	3.100	2100		-5.73	75	28.3	Surface	Oxide Reaction
5474	3.130	2100	-5.97	-5.60	75	49.6	Surface	
5477	3.110	2100		-5.61	75	50.5	Surface	
5483	3.100	2100		-5.92	75	41.4	Surface	
5486	3.080	2100			75			
5639	3.100	2100		-6.12	75	48.8	Surface	
5640	3.090	2100	-6.18	-5.60	75	51.3	Surface	Glass Pit

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
2100	75	44.8	51.3	28.3	6.8	11

Post-Exposure Weight .Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
2100	-6.1	-5.7	5

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy SA Injection Molded Sintered Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2500F

Vintage = 7/1/83

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
12230	3.140	350	1.69	2.40	75	60.8	Surface	
12232	3.130	350	1.19	2.40	75	67.4	Surface	
12234	3.130	350	2.43	3.30	75	49.6	SubSurface	Porosity
12229	3.130	350	4.56	2.40	2500	40.7	SubSurface	Pore
12231	3.140	350			2500			
12233	3.140	350	6.31	0.80	2500	55.3	SubSurface	Pore
12241	3.100	1050	-1.10	2.40	75	54.4	Surface	
12243	3.130	1050	0.80	0.00	75	58.4	Chamfer	
12258	3.130	1050	0.00	2.40	75	51.1	Surface	Oxidation Pit/Porosity
12259	3.120	1050	0.10	2.40	75	49	Surface	Oxidation Pit/Porosity
12272	3.130	1050	-3.10	3.20	75	62.9	Surface	Oxidation Pit/Porosity
12276	3.120	1050	-0.10	0.80	75	57.2	Surface	Oxidation Pit/Porosity
12242	3.120	1050	-0.20	1.60	2500	48.7	Internal	Porosity
12246	3.140	1050	-5.00	0.00	2500	52.3	Internal	Porosity
12260	3.130	1050	0.20	0.80	2500	57.3	Internal	Porosity
12262	3.110	1050	0.10	2.40	2500	55.1	Internal	Porosity
12273	3.130	1050	0.50	3.20	2500	65.7	Surface	
12221	3.140	2700	-7.00	-5.50	75	39.5	Surface	
12227	3.130	2700	-1.10	-4.80	75	51.8	Surface	Pore
12235	3.130	2700	-4.30	-4.00	75	48.5	Surface	Oxidation Pit
12225	3.140	2700	-11.80	-4.80	2500	50.5	Surface	
12228	3.130	2700	-9.10	-4.00	2500	48.9	Surface	Pore
12236	3.140	2700	-5.50	-3.30	2500	42.2	Internal	Pore

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	59.3	67.4	49.6	9.0	3
350	2500	48.0	55.3	40.7	10.3	2
1050	75	55.5	62.9	49.0	5.1	6
1050	2500	55.8	65.7	48.7	6.4	5
2700	75	46.6	51.8	39.5	6.4	3
2700	2500	47.2	50.5	42.2	4.4	3

Post-Exposure Weight .Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	3.2	2.3	5
1050	-0.7	1.7	11
2700	-6.5	-4.4	6

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy ST TiB2 Toughened Sintered Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 10/1/87

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
26940	3.340	350	0.30	2.50	75	55.3	Internal	Pore
26942	3.340	350	0.10	5.70	75	57.2	Internal	Pore
26944	3.330	350	0.20	2.50	75	61	Internal	Pore
26946	3.330	350	0.10	2.40	75	53	Internal	Pore
26948	3.330	350	0.20	2.40	75	57.5	Internal	Pore
26950	3.330	350	0.20	2.40	75	58	Internal	Pore
26941	3.330	350	0.20	0.00	2200	53.3	Missing	
26943	3.340	350	0.20	0.00	2200	56.2	Internal	Pore
26945	3.330	350	0.10	1.00	2200	53.8	Internal	Pore
26947	3.330	350	0.10	2.40	2200	46.6	Internal	Pore
26949	3.340	350	0.10	2.40	2200	46.7	Internal	Pore
26951	3.330	350	0.20	1.60	2200	52.7	Internal	Pore
26952	3.340	587		6.50	75	42.2	Internal	Pore
26954	3.340	587		2.40	75	54.4	Internal	Pore
26956	3.330	587		2.50	75	55.1	Internal	Pore
26959	3.330	587		-0.80	75	54.3	Internal	Pore
26961	3.340	587		0.80	75	47.1	Chamfer	Damage
26963	3.340	587		3.20	75	56.5	Internal	Pore
26953	3.330	587		2.40	2200	44.8	Not Determined	Obscured By Oxide
26955	3.340	587		0.80	2200	52.5	Not Determined	Obscured By Oxide
26957	3.330	587		4.90	2200	50	Not Determined	Obscured By Oxide
26960	3.330	587		3.20	2200	48.9	Internal	Pore
26962	3.340	587		1.60	2200	49.4	Not Determined	Obscured By Oxide
26928	3.330	937		4.00	75	52.8	Internal	Pore
26930	3.340	937		6.60	75	44.9	Internal	Pore
26932	3.330	937		6.60	75	43.5	Chamfer	
26934	3.340	937		3.10	75	47.6	Internal	Pore
26936	3.330	937		6.30	75	51.5	Chamfer	
26938	3.330	937		2.40	75	31.2	Chamfer	Damage
26929	3.330	937		3.60	2200	43.8	Not Determined	Obscured By Oxide
26931	3.340	937		3.20	2200	46	Not Determined	Obscured By Oxide
26933	3.330	937		1.60	2200	42.5	Internal	Pore
26935	3.340	937		4.90	2200	46.2	Not Determined	Obscured By Oxide
26939	3.340	937		6.40	2200	39.6	Chamfer	Damage

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy ST TiB2 Toughened Sintered Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2200F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	57.0	61.0	53.0	2.7	6
350	2200	51.6	56.2	46.6	4.0	6
587	75	51.6	56.5	42.2	5.7	6
587	2200	49.1	52.5	44.8	2.8	5
937	75	45.3	52.8	31.2	7.8	6
937	2200	43.6	46.2	39.6	2.7	5

Post-Exposure Weight Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.2	2.1	12
587		2.5	0
937		4.4	0

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy ST TiB2 Toughened Sintered Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2300F

Vintage = 11/1/88

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
29519	3.340	350	0.18	2.40	75	59.3	Surface	Rough Oxide Layer
29521	3.340	350	0.22	1.60	75	58.8	Surface	Rough Oxide Layer
29523	3.340	350	0.20	2.40	75	48	Surface	Rough Oxide Layer
29525	3.340	350	0.23	1.60	75	55.5	Surface	Rough Oxide Layer
29527	3.340	350	0.06	3.40	75	47.2	Surface	Rough Oxide Layer
29529	3.340	350	0.16	0.80	75	56.2	Surface	Rough Oxide Layer
29520	3.340	350	0.22	2.40	2300	40.5	Surface	
29522	3.340	350	0.09	2.40	2300	41.9	Surface	
29524	3.340	350	0.16	1.60	2300	43.6	Chamfer	
29526	3.340	350	0.19	4.90	2300	42.3	Surface	
29528	3.340	350	0.18	0.80	2300	44.5	Chamfer	
29530	3.340	350	0.20	4.00	2300	43.2	Surface	
29531	3.340	700	0.25	2.40	75	46.9	Surface	Rough Oxide Layer
29533	3.340	700	0.32	3.20	75	47.1	Surface	Rough Oxide Layer
29535	3.340	700		3.20	75	47.3	Internal	Porosity
29537	3.340	700	0.33	3.20	75	51.8	Surface	Rough Oxide Layer
29539	3.340	700		4.00	75	53.7	Internal	Pore
29541	3.340	700	0.34	0.80	75	51	Surface	Rough Oxide Layer
29532	3.340	700	0.16	3.20	2300	45.1	Surface	
29534	3.340	700	0.19	2.40	2300	44.5	Surface	
29536	3.340	700	0.34	1.60	2300	41.6	Chamfer	
29538	3.340	700	0.26	3.20	2300	42.5	Surface	
29540	3.340	700	0.28	3.20	2300	43.9	Surface	
29542	3.340	700	0.14	0.00	2300	41.6	Surface	
29543	3.340	1050	0.18	0.13	75	44.2	Surface	Rough Oxide Layer
29545	3.340	1050	0.16	0.13	75	44	Surface	Rough Oxide Layer
29547	3.330	1050	0.21	0.13	75	45.4	Surface	Rough Oxide Layer
29549	3.340	1050	0.19	0.13	75	45.6	Internal	Pore
29551	3.340	1050	0.22	0.13	75	50.6	Surface	Rough Oxide Layer
29553	3.340	1050	0.14	0.13	75	47.1	Chamfer	
29544	3.340	1050	0.18	0.13	2300	38	Surface	
29546	3.340	1050	0.11	0.13	2300	39.2	Surface	
29548	3.340	1050	0.19	0.13	2300	35.9	Chamfer	
29550	3.340	1050		0.13	2300	40.5	Surface	
29552	3.340	1050	0.09	0.13	2300	35	Surface	

Post-Exposure Flexure Fast Fracture Strength Of Carborundum Hexoloy ST TiB2 Toughened Sintered Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2300F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi)				
		Average	Max	Min	StDev	Quantity
350	75	54.2	59.3	47.2	5.3	6
350	2300	42.7	44.5	40.5	1.4	6
700	75	49.6	53.7	46.9	2.9	6
700	2300	43.2	45.1	41.6	1.5	6
1050	75	46.2	50.6	44.0	2.4	6
1050	2300	37.7	40.5	35.0	2.3	5

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.2	2.4	12
700	0.3	2.5	10
1050	0.2	0.1	10

Post-Exposure Flexure Fast Fracture Strength Of Corning Glass Works Code 9458 Lithium Aluminosilicate With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2000F

Vintage = 8/1/81

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
10312		350			75	10.2	Surface	Pit
10323		350			75	10.4	Surface	
10324		350			75	11.3	Surface	Porosity
10325		350			75	10.7	Surface	Porosity
10598		350			75	8.3	Surface	Pit
10599		350			75	9.2	Chamfer	Porosity

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	10.0	11.3	8.3	1.1	6

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350			0

Post-Exposure Flexure Fast Fracture Strength Of GE Beta - Sintered Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2500F

Vintage = 12/1/84

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
14795	3.090	350	2.20	1.60	75	55.6	Surface	Oxide Filled Pore
14797	3.100	350	2.40	2.40	75	62.4	Internal	Pore
14806	3.080	350	2.50	1.60	75	59.6	Internal	Pore
14811	3.060	350	1.00	2.40	75	54	Internal	Pore
14816	3.100	350	0.80	1.60	75	60.5	Internal	Pore
14818	3.110	350	1.60	0.80	75	40	Surface	Large Grain
14796	3.110	350	1.30	2.30	2500	57.3	Internal	Pore
14798	3.120	350	1.70	2.30	2500	64	Surface	
14805	3.100	350	1.70	2.30	2500	58.3	Surface	
14810	3.110	350	2.40	3.20	2500	54.8	Internal	Pore
14814	3.090	350	1.90	3.20	2500	47.8	Internal	Pore
14817	3.100	350	2.10	3.20	2500	59.3	Internal	Pore
14826	3.070	1050	-0.23	3.20	75	64.9	Internal	Porosity
14828	3.110	1050	-0.31	3.20	75	55.8	Surface	Porosity
14832	3.080	1050	-0.44	3.20	75	57.3	Internal	Pore
14836	3.110	1050	-0.31	2.40	75	63.3	Internal	Porosity
14827	3.100	1050	-0.36	0.80	2500	67.3	Internal	Porosity
14833	3.110	1050		0.00	2500	59.9	Chamfer	
14835	3.070	1050	-0.18	0.00	2500	53.6	Internal	Pore
14837	3.090	1050	-0.59	0.00	2500	54.8	Internal	Porosity
14799	3.120	1400	-0.50	0.80	75	57.5	Surface	Pore
14803	3.060	1400	-0.20	2.30	75	60.1	Internal	Pore
14808	3.100	1400	-0.90	0.00	75	55	Internal	Pore
14813	3.100	1400	-0.60	3.10	75	54.1	Internal	Porosity
14802	3.090	1400	-0.50	1.60	2500	56.1	Internal	Pore
14807	3.080	1400	-0.30	0.00	2500	63.5	Surface	
14809	3.060	1400	-1.20	0.80	2500	59.1	Surface	Pore
14815	3.080	1400	-0.50	1.60	2500	59.1	Internal	Pore

Post-Exposure Flexure Fast Fracture Strength Of GE Beta - Sintered Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2500F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	55.4	62.4	40.0	8.1	6
350	2500	56.9	64.0	47.8	5.4	6
1050	75	60.3	64.9	55.8	4.4	4
1050	2500	58.9	67.3	53.6	6.2	4
1400	75	56.7	60.1	54.1	2.7	4
1400	2500	59.5	63.5	56.1	3.0	4

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	1.8	2.2	12
1050	-0.3	1.6	7
1400	-0.6	1.3	8

Post-Exposure Flexure Fast Fracture Strength Of GTE AY6 Sintered Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 7/1/83

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
12566	3.170	377	2.90	3.20	75	72.7	Surface	Oxide Layer
12567	3.170	377	2.60	2.50	75	69.4	Internal	Inclusion
12568	3.170	377	2.90	2.10	75	74.9	Surface	Rough Oxide Layer
12569	3.160	377	3.10	3.20	75	64	Internal	Pore
12570	3.160	377	3.00	2.70	75	73.3	Chamfer	Rough Oxide Layer
12571	3.170	377	2.90	2.70	75	73.4	Surface	Rough Oxide Layer
12578	3.170	377	2.50	2.30	2200	31.4	Surface	Rough Oxide Layer
12579	3.160	377	2.80	2.30	2200	38.7	Surface	Rough Oxide Layer
12580	3.150	377	2.50	3.20	2200	40.6	Surface	Rough Oxide Layer
12581	3.160	377	2.60	3.20	2200	34.5	Surface	Rough Oxide Layer
12582	3.160	377	2.70	3.20	2200	34.7	Surface	Rough Oxide Layer
12583	3.160	377	2.80	4.00	2200	36.8	Surface	Rough Oxide Layer

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
377	75	71.3	74.9	64.0	4.0	6
377	2200	36.1	40.6	31.4	3.3	6

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
377	2.8	2.9	12

Post-Exposure Flexure Fast Fracture Strength Of GTE PY6 Sintered Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 4/1/81

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
9922		350	-0.12	1.11	75	39.7	Surface	Oxidation/Porosity
9955		350		0.16	75	40.6	Surface	Oxidation/Porosity
9964		350	-0.03	1.42	75	30.5	Surface	Oxidation/Porosity
9907		350		1.35	2200	41.5	Surface	Oxidation/Porosity
9916		350	-0.07	0.00	2200	46.5	Surface	Glassy Spot
9959		350		1.52	2200	43.2	Surface	Oxidation

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	36.9	40.6	30.5	5.6	3
350	2200	43.7	46.5	41.5	2.5	3

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-0.1	0.9	3

Post-Exposure Flexure Fast Fracture Strength Of GTE PY6 Hot Isostatically Pressed Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 1/1/90

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
30509	3.260	350	0.13	0.80	75	72	Internal	Inclusion
30511	3.260	350	0.13	0.80	75	67.1	Internal	Pore
30513	3.260	350	0.13	0.00	75	79.5	Surface	Pit
30515	3.260	350	0.12	0.80	75	76.1	Internal	Inclusion
30517	3.260	350	0.13	0.80	75	65.9	Surface	Pit
30519	3.260	350	0.13	1.60	75	66.5	Surface	Pit
30510	3.260	350	0.16	0.00	2200	66.3	Surface	Pit
30512	3.260	350	0.15	1.60	2200	72.3	Surface	Pit
30514	3.260	350	0.14	0.80	2200	70	Chamfer	Pit
30516	3.260	350	0.13	0.80	2200	77.5	Chamfer	Sharp Corner
30518	3.230	350	0.14	1.60	2200	78.3	Surface	Pit
30520	3.230	350	0.10	0.80	2200	77.2	Chamfer	Pit
30521	3.260	700	-0.06	1.60	75	70.6	Surface	Pit
30523	3.260	700	0.00	2.40	75	72.9	Internal	Pore
30525	3.260	700	-0.01	0.00	75	73.5	Surface	Pit
30527	3.260	700	-0.02	0.80	75	68.5	Surface	Pit
30529	3.260	700	-0.03	1.60	75	71.1	Surface	Pit
30531	3.260	700	-0.02	1.60	75	72	Surface	Pit
30522	3.220	700	-0.03	1.60	2200	61.3	Surface	Pit
30524	3.260	700	-0.03	0.00	2200	67.1	Surface	Pit
30526	3.250	700	-0.04	1.60	2200	67.6	Surface	Pit
30528	3.260	700	-0.02	2.40	2200	77.5	Surface	Pit
30530	3.230	700	-0.04	1.60	2200	69.3	Surface	Pit
30532	3.260	700	-0.01	1.60	2200	68.4	Surface	Pit
30533	3.260	1050	-0.11	2.40	75	68	Surface	Pit
30535	3.260	1050	-0.03	2.40	75	84.8	Surface	Pit
30537	3.260	1050	-0.03	1.60	75	70.3	Surface	Pit
30539	3.260	1050	-0.03	2.40	75	78.9	Chamfer	Pit
30541	3.230	1050	-0.06	2.40	75	71.4	Surface	Pit
30543	3.260	1050	-0.06	1.60	75	62.9	Surface	Pit
30534	3.260	1050	-0.01	2.40	2200	75.6	Surface	Pit
30536	3.260	1050	-0.02	2.40	2200	82.1	Surface	Pit
30538	3.260	1050	-0.03	3.20	2200	84.6	Surface	Pit
30540	3.260	1050	-0.03	2.40	2200	75.9	Surface	Pit
30542	3.260	1050	-0.03	2.40	2200	80.5	Surface	Pit
30544	3.250	1050	-0.11	2.40	2200	72.6	Surface	Pit

Post-Exposure Flexure Fast Fracture Strength Of GTE PY6 Hot Isostatically Pressed Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2200F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	71.2	79.5	65.9	5.7	6
350	2200	73.6	78.3	66.3	4.9	6
700	75	71.4	73.5	68.5	1.8	6
700	2200	68.5	77.5	61.3	5.2	6
1050	75	72.7	84.8	62.9	7.9	6
1050	2200	78.6	84.6	72.6	4.6	6

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.1	0.9	12
700	0.0	1.4	12
1050	0.0	2.3	12

Post-Exposure Flexure Fast Fracture Strength Of Kyocera SC-201 Sintered Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2500F

Vintage = 5/1/84

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
14170	3.150	350	-1.40	0.00	75	68.6	SubSurface	Pore
14172	3.150	350	-1.00	1.60	75	70.3	Chamfer	
14174	3.120	350	-1.20	4.30	75	66.9	Surface	
14171	3.060	350	-1.40	1.60	2500	74.4	Internal	Pore
14173	3.140	350	-1.00	1.50	2500	72.2	Surface	
14175	3.150	350	-1.00	2.30	2500	63.5	Surface	
14183	3.130	1050	-1.50	0.70	75	77.9	Surface	
14184	3.130	1050	-1.90	2.30	75	76.1	SubSurface	Pore
14185	3.110	1050	-2.00	0.80	75	71.7	Surface	
14186	3.070	1050	-2.10	1.60	2500	69.4	Surface	
14187	3.120	1050	-1.80	2.30	2500	74.4	SubSurface	Pore
14188	3.120	1050	-1.50	0.80	2500	88.8	Surface	
14176	3.140	2100	-4.40	2.20	75	58.8	Surface	
14178	3.140	2100	-1.40	3.30	75	50.1	Chamfer	
14180	3.100	2100	-1.10	5.60	75	61.4	Surface	
14179	3.150	2100	-2.30	6.50	2500	58.2	Surface	Oxidation Pit
14181	3.140	2100	-6.40	4.00	2500	59.5	SubSurface	
14157	3.090	2270		3.10	75	71.6	Surface	
14160	3.120	2270		4.80	75	66.9	Surface	
14163	3.090	2270		3.10	75	60.2	Surface	
14159	3.140	2270		3.10	2500	67.1	Surface	
14166	3.150	2270		2.30	2500	53.4	Chamfer	
14182	3.140	2270		0.00	2500	46.2	Chamfer	

Post-Exposure Flexure Fast Fracture Strength Of Kyocera SC-201 Sintered Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2500F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	68.6	70.3	66.9	1.7	3
350	2500	70.0	74.4	63.5	5.8	3
1050	75	75.2	77.9	71.7	3.2	3
1050	2500	77.5	88.8	69.4	10.1	3
2100	75	56.8	61.4	50.1	5.9	3
2100	2500	58.9	59.5	58.2	0.9	2
2270	75	66.2	71.6	60.2	5.7	3
2270	2500	55.6	67.1	46.2	10.6	3

Post-Exposure Weight _Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-1.2	1.9	6
1050	-1.8	1.4	6
2100	-3.1	4.3	5
2270		2.7	0

Post-Exposure Flexure Fast Fracture Strength Of Kyocera SN-250M Sintered Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 10/1/86

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
25442	3.300	350	0.15	3.20	75	85.9	Surface	
25444	3.340	350	0.15	3.20	75	106.2	Chamfer	
25446	3.270	350	0.16	3.20	75	112.7	Chamfer	
25448	3.290	350	0.15	3.20	75	104.7	Chamfer	
25450	3.310	350	0.15	3.20	75	101.3	Chamfer	
25452	3.320	350	0.16	2.40	75	95	Surface	
25443	3.300	350	0.16	3.20	2200	86.2	Surface	
25445	3.300	350	0.16	2.40	2200	81.4	Chamfer	
25447	3.300	350	0.15	3.20	2200	84	Surface	
25449	3.310	350	0.15	2.40	2200	74.8	Chamfer	
25451	3.300	350	0.15	3.20	2200	78.7	Surface	
25453	3.300	350	0.16	3.20	2200	84.3	Surface	
25454	3.320	700	0.19	2.40	75	122.6	Surface	
25456	3.310	700	0.20	1.60	75	117.7	Surface	
25458	3.320	700	0.20	1.60	75	106.4	SubSurface	Inclusion
25460	3.320	700	0.17	1.60	75	117.4	Surface	
25462	3.300	700	0.21	1.60	75	116	Surface	
25464	3.300	700	0.19	1.60	75	113.7	Surface	
25455	3.290	700	0.18	1.60	2200	83.3	Chamfer	
25457	3.340	700	0.17	1.60	2200	90.8	Surface	
25459	3.320	700	0.17	1.60	2200	85.1	Chamfer	
25463	3.330	700	0.18	1.60	2200	87.1	Surface	
25465	3.300	700	0.14	1.60	2200	77.6	Surface	
25466	3.310	700	0.17	1.60	2200	85.8	Surface	Pore
25430	3.310	1050	0.12	2.40	75	118.1	Chamfer	
25432	3.280	1050	0.13	2.40	75	103.4	Surface	
25434	3.300	1050	0.13	2.40	75	102.9	Internal	Inclusion
25436	3.280	1050	0.13	1.60	75	103.3	Surface	
25438	3.300	1050	0.14	2.40	75	101.4	Surface	
25440	3.300	1050	0.11	2.40	75	107.1	Surface	
25431	3.290	1050	0.11	2.40	2200	68.4	Surface	
25433	3.280	1050	0.15	1.60	2200	73.5	Surface	
25435	3.300	1050	0.13	2.40	2200	81.6	Chamfer	
25437	3.270	1050	0.14	2.40	2200	87.4	Surface	
25439	3.310	1050	0.12	2.40	2200	80.1	Surface	
25441	3.310	1050	0.10	2.40	2200	68.1	Surface	

Post-Exposure Flexure Fast Fracture Strength Of Kyocera SN-250M Sintered Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	101.0	112.7	85.9	9.4	6
350	2200	81.6	86.2	74.8	4.2	6
700	75	115.6	122.6	106.4	5.4	6
700	2200	85.0	90.8	77.6	4.4	6
1050	75	106.0	118.1	101.4	6.2	6
1050	2200	76.5	87.4	68.1	7.8	6

Post-Exposure Weight .Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.2	3.0	12
700	0.2	1.7	12
1050	0.1	2.3	12

Post-Exposure Flexure Fast Fracture Strength Of Kyocera SN-251 Sintered Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 2/1/90

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
30213	3.400	350	0.09	1.60	75	111.1	Surface	Oxide Layer
30215	3.400	350	0.09	1.60	75	107	Surface	Oxide Layer
30217	3.390	350	0.08	0.80	75	106.6	Surface	Oxide Layer
30214	3.380	350	0.08	1.60	2200	96.4	Missing	
30216	3.400	350	0.08	1.60	2200	101.7	Chamfer	Oxide Layer
30218	3.400	350	0.08	1.60	2200	94.7	Surface	Oxide Layer
30219	3.400	700	0.11	1.60	75	95.5	Surface	Oxide Layer
30221	3.410	700	0.09	1.60	75	103.2	Surface	Oxide Layer
30223	3.400	700	0.11	1.60	75	120.9	Surface	Oxide Layer
30220	3.410	700	0.10	1.60	2200	92	Surface	Oxide Layer
30222	3.410	700	0.10	1.60	2200	82.2	Internal	Inclusion
30224	3.400	700	0.10	1.60	2200	97.3	Surface	Large Grain
30207	3.400	1050	0.10	1.60	75	110.7	Surface	Oxide Layer
30209	3.390	1050	0.00	1.60	75	101.4	Chamfer	Oxide Layer
30211	3.400	1050	0.02	1.60	75	107	Chamfer	Oxide Layer
30208	3.410	1050	0.02	2.40	2200	88	Surface	Large Grain
30210	3.420	1050	0.01	1.60	2200	90	Surface	Oxide Layer
30212	3.410	1050	0.03	1.60	2200	91.3	Surface	Oxide Layer

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	108.2	111.1	106.6	2.5	3
350	2200	97.6	101.7	94.7	3.7	3
700	75	106.5	120.9	95.5	13.0	3
700	2200	90.5	97.3	82.2	7.7	3
1050	75	106.4	110.7	101.4	4.7	3
1050	2200	89.8	91.3	88.0	1.7	3

Post-Exposure Weight Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.1	1.5	6
700	0.1	1.6	6
1050	0.0	1.7	6

Post-Exposure Flexure Fast Fracture Strength Of Kyocera SN-252 Sintered Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 5/1/90

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
28918	3.357	350	0.06	1.60	75	79.8	Missing	
28920	3.366	350	0.01	1.60	75	83.5	Surface	Large Grain/Oxide Layer
28922	3.392	350	0.03	0.80	75	85.8	Surface	Large Grain/Oxide Layer
28919	3.373	350	0.02	1.60	2200	66.7	Surface	Large Grain/Oxide Layer
28921	3.375	350	-0.02	1.60	2200	70.9	Surface	Large Grain/Oxide Layer
28923	3.383	350	0.03	1.60	2200	72	Internal	Large Grain
28924	3.379	700	0.03	1.60	75	81.4	Surface	Large Grain/Oxide Layer
28926	3.356	700	0.03	1.60	75	83.3	Surface	Oxide Layer
28928	3.373	700	0.03	1.60	75	87.7	Chamfer	Oxide Layer
28925	3.378	700	0.03	1.60	2200	68.1	Surface	Large Grain/Oxide Layer
28927	3.376	700	0.04	1.60	2200	67	Surface	Large Grain/Oxide Layer
28929	3.375	700	0.04	1.60	2200	66.1	Surface	Large Grain/Oxide Layer
28912	3.363	1050	-0.06	1.60	75	74.7	Surface	Large Grain/Oxide Layer
28914	3.396	1050	-0.09	1.60	75	85	Chamfer	Oxide Layer
28916	3.380	1050	-0.13	1.60	75	82.5	Chamfer	Oxide Layer
28913	3.404	1050	-0.06	1.60	2200	66.4	Internal	Large Grain
28915	3.373	1050	-0.25	1.60	2200	60.1	Surface	Large Grain/Oxide Layer
28917	3.372	1050	-0.13	1.60	2200	67.8	Internal	Large Grain

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	83.0	85.8	79.8	3.0	3
350	2200	69.9	72.0	66.7	2.8	3
700	75	84.1	87.7	81.4	3.2	3
700	2200	67.1	68.1	66.1	1.0	3
1050	75	80.7	85.0	74.7	5.4	3
1050	2200	64.8	67.8	60.1	4.1	3

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.0	1.5	6
700	0.0	1.6	6
1050	-0.1	1.6	6

Post-Exposure Flexure Fast Fracture Strength Of Kyocera SN-253 Sintered Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2400F

Vintage = 5/1/95

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
35652	3.450	350	-0.19	0.26	75	88.3	Surface	Pit
35653	3.448	350	-0.18	0.33	75	85.3	Surface	
35654	3.449	350	-0.18	-0.04	75	92.5	Surface	
35655	3.445	350	-0.19	0.02	2400	90.5	Surface	
35656	3.453	350	-0.20	0.27	2400	78.3	Surface	Pit
35657	3.455	350	-0.19	0.38	2400	82.5	Surface	Pit
35658	3.454	700	-0.29	2.33	75	64.3	Surface	Pit
35659	3.446	700	-0.34	-1.98	75	78.1	Chamfer	Pit
35660	3.452	700	-0.27	3.43	75	78.5	Chamfer	Pit
35661	3.455	700	-0.29	2.30	2400	64.9	Chamfer	Pit
35662	3.452	700	-0.31	2.13	2400	66.5	Chamfer	Pit
35663	3.449	700	-0.22	2.58	2400	79.2	Chamfer	
35664	3.448	1050	-0.54	-0.06	75	85.5	Chamfer	Pit
35665	3.447	1050	-0.50	1.60	75	73	Chamfer	Pit
35666	3.449	1050	-0.50	1.37	75	56.6	Chamfer	Pit
35667	3.452	1050	-0.44	2.67	2400	64.6	Chamfer	Pit
35668	3.445	1050	-0.48	1.51	2400	71.2	Chamfer	Pit
35669	3.448	1050	-0.46	1.42	2400	80.1	Surface	Pit

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	88.7	92.5	85.3	3.6	3
350	2400	83.8	90.5	78.3	6.2	3
700	75	73.6	78.5	64.3	8.1	3
700	2400	70.2	79.2	64.9	7.8	3
1050	75	71.7	85.5	56.6	14.5	3
1050	2400	72.0	80.1	64.6	7.8	3

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-0.2	0.2	6
700	-0.3	1.8	6
1050	-0.5	1.4	6

Post-Exposure Flexure Fast Fracture Strength Of Kyocera SN-260 Sintered Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2300F

Vintage = 2/1/91

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
31379		303	0.22	1.20	75	90	Internal	Pore
31380		303	0.79		75	79.5	Surface	Oxide Layer
31383		303		1.80	75	91.7	Chamfer	
31384		303		1.80	75	84.1	Surface	Oxide Layer
31387		303		1.60	75	89.1	Surface	Oxide Layer
31388		303		1.40	75	67.5	Chamfer	Oxide Layer
31402		303	0.23	1.80	2300	75.4	Surface	Large Grain
31403		303		2.21	2300	68.7	Surface	Oxide Layer
31405		303		1.60	2300	69.5	Surface	Oxide Layer
31406		303		1.61	2300	76.1	Surface	Oxide Layer
31408		303	0.26	1.60	2300	69.2	Surface	Oxide Layer
31409		303		1.60	2300	85.3	Surface	Oxide Layer

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
303	75	83.6	91.7	67.5	9.1	6
303	2300	74.0	85.3	68.7	6.4	6

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
303	0.4	1.7	4

Post-Exposure Flexure Fast Fracture Strength Of Kyocera SN-281 Sintered Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2400F

Vintage = 5/1/95

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
35634	3.396	350	-0.20	0.32	75	83.3	Chamfer	
35635	3.397	350	-0.19	0.28	75	66.2	Chamfer	
35636	3.399	350	-0.19	0.36	75	72.1	Chamfer	
35637	3.397	350	-0.18	0.32	2400	73.4	Surface	
35638	3.399	350	-0.18	0.24	2400	81.6	Surface	
35639	3.394	350	-0.19	0.60	2400	73.5	Surface	
35640	3.396	700	-0.21	0.64	75	71.7	Chamfer	Pit
35641	3.396	700	-0.23	0.86	75	69.8	Surface	Pit
35642	3.396	700	-0.24	0.70	75	64	Chamfer	Pit
35643	3.398	700	-0.24	1.70	2400	74.1	Chamfer	Pit
35644	3.395	700	-0.23	2.02	2400	68.1	Surface	Pit
35645	3.397	700	-0.18	2.38	2400	70.7	Surface	Pit
35646	3.394	1050	-0.19	0.62	75	70.6	Surface	
35647	3.396	1050	-0.52	1.14	75	61.6	Chamfer	Pit
35648	3.398	1050	-0.49	0.62	75	71.2	Surface	Pit
35649	3.397	1050	-0.53	1.58	2400	65.1	Surface	Pit
35650	3.394	1050	-0.55	1.16	2400	62.2	Surface	Pit
35651	3.396	1050	-0.53	2.19	2400	65	Chamfer	Pit

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi)				
		Average	Max	Min	StDev	Quantity
350	75	73.9	83.3	66.2	8.7	3
350	2400	76.2	81.6	73.4	4.7	3
700	75	68.5	71.7	64.0	4.0	3
700	2400	71.0	74.1	68.1	3.0	3
1050	75	67.8	71.2	61.6	5.4	3
1050	2400	64.1	65.1	62.2	1.6	3

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-0.2	0.4	6
700	-0.2	1.4	6
1050	-0.5	1.2	6

Post-Exposure Flexure Fast Fracture Strength Of NGK SN-50 Sintered Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 9/1/84

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
14528	3.120	350	0.05	2.30	75	59.8	Surface	
14529	3.130	350	0.07	1.50	75	55.2	Surface	
14530	3.120	350	0.07	2.30	75	69.3	Surface	
14531	3.140	350	0.05	3.30	75	64.2	Surface	
14532	3.120	350	0.08	2.30	75	63.9	Surface	
14533	3.120	350	0.01	2.30	75	61.5	Surface	
14534	3.120	350	0.04	1.50	2200	15.9	Surface	Slow Crack Growth
14535	3.120	350	0.02	1.50	2200	15.4	Surface	Slow Crack Growth
14536	3.110	350	0.04	1.60	2200	13	Surface	Slow Crack Growth
14537	3.110	350	0.03	2.30	2200	14.4	Surface	Slow Crack Growth
14538	3.130	350	0.02	0.70	2200	17.4	Surface	Slow Crack Growth
14539	3.130	350	0.03	1.50	2200	18.5	Surface	Slow Crack Growth

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	62.3	69.3	55.2	4.7	6
350	2200	15.8	18.5	13.0	2.0	6

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.0	1.9	12

Post-Exposure Flexure Fast Fracture Strength Of NGK SN-82 Sintered Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 1/1/86

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
20332	3.240	350	-0.10	2.30	75	85.8	Surface	
20334	3.240	350	-0.14	2.30	75	95.7	Surface	
20336	3.230	350	-0.10	1.50	75	84.2	Chamfer	
20333	3.260	350	-0.11	1.50	2200	56.2	Surface	
20335	3.240	350	-0.15	2.30	2200	56.6	Surface	
20337	3.250	350	-0.14	1.50	2200	57.9	Chamfer	
20344	3.240	1050	1.60	1.50	75	78	Surface	
20346	3.250	1050	1.60	1.50	75	83.8	Chamfer	
20348	3.240	1050	1.50	1.50	75	75.8	Surface	
20362	3.260	1050	1.30	3.80	75	65.6	Surface	
20366	3.240	1050	0.40	0.00	75	74.7	Surface	
20634	3.240	1050	1.10	3.80	75	69.8	Surface	
20345	3.240	1050	1.60	3.10	2200	61.7	Chamfer	
20347	3.260	1050	1.50	2.30	2200	60.3	Surface	
20349	3.240	1050	1.50	3.10	2200	60.9	Chamfer	
20363	3.240	1050	0.30	3.80	2200	77.7	Surface	
20365	3.240	1050	0.40	3.80	2200	73.2	Surface	
20367	3.240	1050	0.10	2.30	2200	76.1	Surface	
20338	3.240	2100	1.03	1.50	75	71.9	Surface	
20340	3.240	2100	1.05	1.50	75	76.6	Surface	
20342	3.250	2100	1.01	3.10	75	75.1	Surface	
20350	3.240	2100	1.10	1.50	75	71.2	Surface	
20352	3.250	2100	0.70	3.10	75	72.8	Surface	
20354	3.240	2100	0.90	2.30	75	79.4	Surface	
20339	3.260	2100	1.14	0.80	2200	73.1	Chamfer	
20341	3.240	2100	0.98	3.10	2200	65.9	Surface	
20343	3.240	2100	1.02	1.50	2200	75.3	Surface	
20351	3.240	2100	0.50	3.10	2200	67.1	Surface	
20353	3.240	2100	1.10	3.80	2200	72.5	Chamfer	
20355	3.240	2100	0.60	2.30	2200	74.1	Chamfer	
20320	3.250	3500	1.70	3.10	75	76.7	Surface	
20322	3.240	3500	2.20	3.80	75	81.3	Surface	
20324	3.240	3500	2.30	2.30	75	74.4	Surface	
20326	3.230	3500	2.30	3.10	75	84.4	Surface	
20328	3.240	3500	2.00	3.80	75	73.6	Surface	
20330	3.240	3500	2.50	3.80	75	75.3	Surface	
20321	3.240	3500	2.00	3.80	2200	63.9	Surface	
20323	3.240	3500	2.00	2.30	2200	62.6	Surface	
20327	3.250	3500	2.90	2.30	2200	65.6	Surface	
20329	3.240	3500	2.40	2.30	2200	57.1	Surface	
20331	3.240	3500	1.80	2.30	2200	62.6	Surface	

Post-Exposure Flexure Fast Fracture Strength Of NGK SN-82 Sintered Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2200F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	88.6	95.7	84.2	6.2	3
350	2200	56.9	57.9	56.2	0.9	3
1050	75	74.6	83.8	65.6	6.4	6
1050	2200	68.3	77.7	60.3	8.2	6
2100	75	74.5	79.4	71.2	3.1	6
2100	2200	71.3	75.3	65.9	3.9	6
3500	75	77.6	84.4	73.6	4.3	6
3500	2200	62.4	65.6	57.1	3.2	5

Post-Exposure Weight _Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-0.1	1.9	6
1050	1.1	2.5	12
2100	0.9	2.3	12
3500	2.2	3.0	11

Post-Exposure Flexure Fast Fracture Strength Of NGK SN-84 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 9/1/87

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
27585	3.250	350	0.18	2.40	75	62.4	Surface	Rough Oxide
27587	3.250	350	0.18	1.60	75	59.8	Surface	Rough Oxide
27589	3.250	350	0.20	1.60	75	67	Surface	Rough Oxide
27591	3.250	350	0.19	2.40	75	58.1	Surface	Rough Oxide
27593	3.250	350	0.18	1.60	75	66.2	Surface	Rough Oxide
27595	3.250	350	0.18	2.40	75	53.4	Surface	Rough Oxide
27586	3.250	350	0.18	2.40	2200	70.5	Surface	Rough Oxide
27588	3.250	350	0.19	2.40	2200	73.5	Chamfer	Rough Oxide
27590	3.250	350	0.18	2.40	2200	73.5	Chamfer	Rough Oxide
27592	3.250	350	0.19	3.20	2200	73.7	Chamfer	Rough Oxide
27594	3.260	350	0.19	2.40	2200	67.6	Chamfer	Rough Oxide
27597	3.250	700	0.18	3.20	75	72.2	Surface	Rough Oxide
27599	3.250	700	0.19	1.60	75	76.1	Chamfer	Rough Oxide
27601	3.250	700	0.17	2.40	75	65.1	Chamfer	Rough Oxide
27603	3.250	700	0.17	1.60	75	70.3	Chamfer	Rough Oxide
27605	3.250	700		1.60	75	73.8	Chamfer	Rough Oxide
27607	3.250	700	0.18	2.40	75	65.4	Surface	Rough Oxide
27596	3.250	700	0.19	2.40	2200	78.7	Surface	Rough Oxide
27598	3.250	700	0.16	2.40	2200	84.1	Surface	Rough Oxide
27600	3.250	700	0.17	2.40	2200	76.7	Surface	Rough Oxide
27602	3.250	700	0.18	2.40	2200	81.2	Surface	Rough Oxide
27604	3.250	700	0.18	2.40	2200	86	Surface	Rough Oxide
27606	3.250	700	0.18	1.60	2200	116.3	Chamfer	Rough Oxide
27608	3.250	700	0.17	1.60	2200	86	Surface	Rough Oxide
27573	3.250	1050	0.13	2.40	75	49.2	Surface	Rough Oxide
27575	3.250	1050	0.09	3.20	75	47.5	Surface	Rough Oxide
27577	3.250	1050	0.10	3.20	75	50.9	Surface	Rough Oxide
27579	3.250	1050	0.09	3.20	75	53.6	Chamfer	Rough Oxide
27581	3.250	1050	0.10	3.20	75	49.9	Surface	Rough Oxide
27583	3.250	1050	0.11	3.20	75	53.6	Surface	Rough Oxide
27574	3.250	1050	0.11	2.40	2200	85.4	Surface	Rough Oxide
27576	3.250	1050	0.10	3.20	2200	86.7	Surface	Oxide
27578	3.250	1050		3.20	2200	80.1	Surface	Oxide
27580	3.250	1050	0.12	3.20	2200	70.2	Surface	Rough Oxide
27582	3.250	1050	0.10	3.20	2200	76.5	Surface	Rough Oxide
27584	3.250	1050	0.12	3.20	2200	75.5	Surface	Rough Oxide

Post-Exposure Flexure Fast Fracture Strength Of NGK SN-84 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	61.2	67.0	53.4	5.1	6
350	2200	71.8	73.7	67.6	2.7	5
700	75	70.5	76.1	65.1	4.5	6
700	2200	87.0	116.3	76.7	13.4	7
1050	75	50.8	53.6	47.5	2.4	6
1050	2200	79.1	86.7	70.2	6.3	6

Post-Exposure Weight .Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.2	2.3	11
700	0.2	2.2	12
1050	0.1	3.1	11

Post-Exposure Flexure Fast Fracture Strength Of NGK SN-88 Sintered Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2300F

Vintage = 7/1/91

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
32991	3.490	350	0.20	1.76	75	94	Surface	Oxide
32992	3.508	350	0.16	3.34	75	96.1	Surface	Oxide
32993	3.508	350	0.13	2.87	75	93.4	Surface	Oxide
32994	3.510	350	0.13	1.63	75	98.9	Surface	Oxide
32995	3.511	350	0.14	1.74	75	98.4	Chamfer	
32996	3.494	350	0.15	0.71	75	86.1	Chamfer	
33027	3.494	350	0.14		75	84.6	Surface	Oxide
32997	3.507	350	0.13	1.86	2300	77.6	Surface	Oxide
32998	3.509	350	0.14	1.76	2300	76	Surface	Grain
32999	3.507	350	0.14	1.43	2300	83.3	Surface	Grain
33000	3.511	350	0.14	1.44	2300	88.1	Surface	Grain
33001	3.489	350	0.15	2.12	2300	88.2	Surface	Oxide
33002	3.508	350	0.15	0.92	2300	84	Surface	Grain
33003	3.510	700	0.25	2.07	75	94.8	Surface	Pit
33015	3.497	700	0.19	1.64	75	85.5	Surface	Oxide
33016	3.512	700	0.18	1.86	75	97.8	Surface	Oxide
33017	3.492	700	0.18	1.97	75	86.4	Surface	Pit
33018	3.505	700	0.09	1.73	75	91.2	Chamfer	
33019	3.504	700	0.15	2.19	75	85.2	Surface	Pit
33020	3.517	700	0.20	1.76	75	92.6	Surface	Oxide
33021	3.511	700	0.17	1.54	2300	94.5	Surface	Oxide
33022	3.498	700	0.19	1.86	2300	87.4	Surface	Pit
33023	3.494	700	0.21	1.96	2300	98.4	Internal	Grain
33024	3.500	700	0.11	1.73	2300	83.9	Internal	Grain
33025	3.488	700	0.20	1.54	2300	81.4	Surface	Pit
33026	3.492	700	0.15	1.55	2300	85.4	Chamfer	Pit
33004	3.503	1050	0.03	2.04	75	87.1	Surface	Pit
33005	3.500	1050	0.05	1.55	75	86.6	Surface	Pit
33006	3.498	1050	0.03	1.88	75	76.3	Chamfer	Pit
33007	3.503	1050	-0.03	2.48	75	89.5	Surface	Pit
33008	3.513	1050	0.02	2.58	75	80.9	Surface	Pit
33009	3.510	1050	0.00	1.44	2300	81.8	Internal	Grain
33010	3.507	1050	-0.02	1.42	2300	78.5	Surface	Grain
33011	3.514	1050	-0.09	1.93	2300	88.6	Surface	Pit
33012	3.500	1050	-0.10	2.03	2300	83.2	Surface	Pit
33013	3.505	1050	-0.06	1.52	2300	89.8	Surface	Pit
33014	3.508	1050	0.02	1.82	2300	88.1	Internal	Grain

Post-Exposure Flexure Fast Fracture Strength Of NGK SN-88 Sintered Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2300F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	93.1	98.9	84.6	5.7	7
350	2300	82.9	88.2	76.0	5.1	6
700	75	90.5	97.8	85.2	4.9	7
700	2300	88.5	98.4	81.4	6.6	6
1050	75	84.1	89.5	76.3	5.4	5
1050	2300	85.0	89.8	78.5	4.5	6

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.1	1.8	13
700	0.2	1.8	13
1050	0.0	1.9	11

Post-Exposure Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-154 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 10/1/88

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
29179	3.240	350	0.03	0.80	75	111.1	Surface	
29180	3.240	350	0.07	0.80	75	114.4	Surface	
29181	3.240	350	0.07	0.80	75	103.5	Surface	
29182	3.240	350	0.06	0.80	75	108.3	Surface	
29183	3.240	350	0.04	0.80	75	108.3	Surface	
29184	3.240	350	0.05	0.80	75	93.6	Chamfer	
29185	3.230	350	0.06	0.80	2200	111	Surface	
29186	3.240	350	0.06	0.80	2200	120.4	Surface	
29187	3.240	350	0.06	1.60	2200	118.7	Surface	
29188	3.240	350	0.08	0.80	2200	96.2	Surface	
29189	3.240	350	0.07	1.60	2200	109.9	Chamfer	
29190	3.240	350	0.07	1.60	2200	108.2	Surface	
29191	3.240	700	0.07	1.60	75	90.2	Chamfer	
29192	3.230	700	0.05	1.60	75	94.1	Chamfer	
29193	3.240	700	0.08	1.60	75	92.2	Chamfer	
29194	3.240	700	0.08	1.60	75	83.6	Chamfer	
29195	3.230	700	0.07	1.60	75	88.6	Surface	
29196	3.230	700	0.06	1.60	75	95.5	Surface	
29197	3.240	700	0.06	1.60	2200	121.8	Chamfer	
29198	3.240	700	0.07	1.60	2200	116.6	Surface	
29199	3.240	700	0.03	1.60	2200	120.7	Surface	
29200	3.240	700	0.07	1.60	2200	118.5	Surface	
29201	3.240	700	0.08	1.60	2200	119.1	Surface	
29202	3.240	700	0.09	1.60	2200	117.6	Surface	
29167	3.240	1050	0.00	1.60	75	90.4	Surface	
29168	3.240	1050	0.01	1.60	75	86.3	Surface	
29169	3.240	1050	0.02	1.60	75	104.8	Surface	
29170	3.240	1050	-0.01	1.60	75	89.6	Surface	
29171	3.240	1050	-0.01	1.60	75	81.9	Surface	
29172	3.240	1050	0.00	1.60	75	83.3	Chamfer	
29173	3.230	1050	0.01	2.40	2200	112.6	Surface	
29174	3.240	1050	-0.05	2.40	2200	107.5	Surface	
29175	3.240	1050	-0.02	2.40	2200	108.6	Chamfer	
29176	3.240	1050	-0.02	2.40	2200	95.8	Surface	
29177	3.240	1050	0.01	2.40	2200	101.8	Chamfer	
29178	3.240	1050	0.04	2.40	2200	113.4	Chamfer	

Post-Exposure Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-154 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	106.5	114.4	93.6	7.3	6
350	2200	110.7	120.4	96.2	8.7	6
700	75	90.7	95.5	83.6	4.3	6
700	2200	119.1	121.8	116.6	1.9	6
1050	75	89.4	104.8	81.9	8.3	6
1050	2200	106.6	113.4	95.8	6.7	6

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.1	1.0	12
700	0.1	1.6	12
1050	0.0	2.0	12

Post-Exposure Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-154 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2300F

Vintage = 4/1/90

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
30377	3.240	350	-0.05	0.80	75	91.8	Surface	Oxide
30379	3.240	350	-0.05	0.80	75	81.3	Chamfer	Oxide
30381	3.230	350	-0.05	0.80	75	94.6	Surface	Oxide
30383	3.230	350	-0.05	0.00	75	88.4	Surface	Oxide
30385	3.230	350	-0.05	0.00	75	92.9	Surface	Oxide
30387	3.230	350	-0.05	0.00	75	93.2	Surface	Oxide
30378	3.240	350	-0.05	0.80	2300	93.4	Surface	Oxide
30380	3.240	350	-0.04	0.80	2300	103.3	Chamfer	Oxide
30382	3.230	350	-0.05	0.80	2300	85	Surface	Oxide
30384	3.230	350	-0.05	0.80	2300	112.6	Surface	Oxide
30386	3.230	350	-0.05	0.80	2300	106.7	Surface	Oxide
30388	3.230	350	-0.05	0.80	2300	99.7	Surface	Oxide
30389	3.240	700	-0.05	0.80	75	88.9	Surface	Oxide
30391	3.240	700	-0.06	0.80	75	70.6	Surface	Oxide
30393	3.230	700	-0.05	1.60	75	86.7	Surface	Oxide
30395	3.230	700	-0.08	1.60	75	82.3	Surface	Oxide
30397	3.230	700	-0.09	0.80	75	84.7	Surface	Oxide
30399	3.230	700	-0.08	0.80	75	92.6	Surface	Oxide
30390	3.240	700	-0.08	0.80	2300	83.6	Surface	Oxide
30392	3.230	700	-0.06	0.80	2300	101.6	Surface	Oxide
30394	3.230	700	-0.07	0.80	2300	89.2	Surface	Oxide
30396	3.230	700	-0.09	0.80	2300	97.2	Surface	Oxide
30398	3.230	700	-0.08	0.80	2300	89.2	Surface	Oxide
30400	3.230	700	-0.06	0.80	2300	86.7	Surface	Oxide
30365	3.240	1050	-0.22	0.80	75	91.2	Surface	Oxide
30367	3.240	1050	-0.22	0.80	75	72.3	Chamfer	Oxide
30369	3.230	1050	-0.17	1.60	75	81.1	Surface	Oxide
30371	3.230	1050	-0.20	0.80	75	89.2	Surface	Oxide
30373	3.230	1050	-0.19	0.80	75	94.6	Surface	Oxide
30375	3.230	1050	-0.23	0.80	75	89.5	Surface	Oxide
30366	3.240	1050	-0.21	0.80	2300	84.1	Surface	Oxide
30368	3.230	1050	-0.19	0.80	2300	82.2	Surface	Oxide
30370	3.230	1050	-0.21	0.80	2300	87.2	Surface	Oxide
30372	3.230	1050	-0.21	0.80	2300	90.9	Surface	Oxide
30374	3.230	1050	-0.21	0.80	2300	85	Surface	Oxide
30376	3.230	1050	-0.19	0.80	2300	96	Chamfer	Oxide

Post-Exposure Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-154 Hot Isostatically Pressed Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2300F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	90.4	94.6	81.3	4.9	6
350	2300	100.1	112.6	85.0	9.8	6
700	75	84.3	92.6	70.6	7.6	6
700	2300	91.3	101.6	83.6	6.8	6
1050	75	86.3	94.6	72.3	8.2	6
1050	2300	87.6	96.0	82.2	5.1	6

Post-Exposure Weight _Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.0	0.6	12
700	-0.1	0.9	12
1050	-0.2	0.9	12

Post-Exposure Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-154 Hot Isostatically Pressed Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2400F

Vintage = 9/1/93

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
34505	3.224	350	-0.12	2.73	75	58.7	Surface	Pit
34506	3.223	350	-0.12	0.54	75	100.8	Surface	
34507	3.225	350	-0.14	-0.74	75	88.6	Chamfer	
34508	3.224	350	-0.13	-0.70	75	95.3	Surface	
34509	3.222	350	-0.13	1.55	75	108.7	Surface	
34510	3.223	350	-0.13	0.33	75	103.1	Internal	Inclusion
34511	3.223	350	-0.14	0.49	2400	78.9	Surface	
34512	3.224	350	-0.13	1.33	2400	75.9	Surface	
34513	3.223	350	-0.14	0.08	2400	111.1	Missing	
34514	3.223	350	-0.13	1.39	2400	83.5	Surface	
34515	3.223	350	-0.13	1.59	2400	71.7	Surface	
34516	3.223	350	-0.12	0.42	2400	91.8	Surface	
34517	3.222	700	-0.57	0.56	75	65.2	Surface	Pit
34518	3.225	700	-0.42	0.47	75	100.4	Chamfer	
34519	3.223	700	-0.46	0.65	75	84.6	Chamfer	
34520	3.223	700	-0.40	1.36	75	82.8	Chamfer	
34521	3.224	700	-0.44	0.96	75	84.7	Chamfer	
34522	3.224	700	-0.46	0.62	75	85.9	Chamfer	
34523	3.222	700	-0.45	2.00	2400	73.8	Chamfer	Inclusion
34524	3.222	700	-0.45	1.01	2400	83.1	Surface	
34525	3.222	700	-0.33	1.83	2400	90	Surface	Pit
34526	3.223	700	-0.47	1.77	2400	94.2	Surface	
34527	3.224	700	-0.46	0.56	2400	66.1	Chamfer	
34528	3.225	700	-0.48	0.20	2400	87.2	Internal	Inclusion
34529	3.222	1050	-0.66	2.21	75	95.1	Chamfer	
34530	3.223	1050	-0.61	-0.51	75	49.8	Surface	Pit
34531	3.225	1050	-0.48	0.80	75	66.3	Surface	Pit
34532	3.225	1050	-0.48	0.76	75	75.7	Surface	Pit
34533	3.223	1050	-0.50	0.86	75	66	Surface	Pit
34534	3.222	1050	-0.52	0.16	75	70.9	Chamfer	
34535	3.223	1050	-0.50	1.56	2400	76.4	Chamfer	
34536	3.223	1050	-0.48	1.53	2400	75.2	Chamfer	
34537	3.222	1050	0.79	1.24	2400	75.9	Chamfer	
34538	3.221	1050	-1.41	1.05	2400	60.1	Surface	Inclusion
34539	3.222	1050	-0.37	1.53	2400	91.4	Surface	Pit
34540	3.224	1050	0.52	0.28	2400	103.8	Surface	Pit

Post-Exposure Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-154 Hot Isostatically Pressed Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2400F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	92.5	108.7	58.7	17.9	6
350	2400	85.5	111.1	71.7	14.3	6
700	75	83.9	100.4	65.2	11.2	6
700	2400	82.4	94.2	66.1	10.6	6
1050	75	70.6	95.1	49.8	14.8	6
1050	2400	80.5	103.8	60.1	15.1	6

Post-Exposure Weight .Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-0.1	0.8	12
700	-0.4	1.0	12
1050	-0.4	1.0	12

Post-Exposure Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-164 Hot Isostatically Pressed Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2400F

Vintage = 8/1/93

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
34433	3.181	350	0.00	0.10	75	103	Surface	
34434	3.178	350	0.01	0.12	75	98.8	Internal	Inclusion
34435	3.178	350	0.01	0.17	75	101	Surface	
34436	3.177	350	0.00	0.19	75	73.7	Chamfer	
34437	3.178	350	0.01	0.20	75	98.3	Surface	
34438	3.178	350	0.00	0.18	75	96.7	Surface	
34439	3.179	350	0.00	0.10	2400	112.1	Surface	Inclusion
34440	3.177	350	0.00	-0.14	2400	103.6	Surface	Inclusion
34441	3.176	350	0.00	0.67	2400	135.8	Surface	
34442	3.177	350	0.00	0.68	2400	71.4	Internal	Inclusion
34443	3.179	350	0.00	0.74	2400	90.3	Surface	Inclusion
34444	3.178	350	0.00	0.34	2400	78.1	Surface	Inclusion
34445	3.178	700	-0.01	-0.79	75	80.7	Chamfer	Inclusion
34446	3.178	700	-0.02	0.74	75	77	Surface	Pit
34447	3.177	700	-0.02	0.76	75	112.6	Surface	
34448	3.178	700	-0.02	0.54	75	113.3	Surface	
34449	3.178	700	0.01	-0.35	75	104.7	Surface	
34450	3.177	700	0.00	0.63	75	97.6	Surface	
34451	3.178	700	0.00	1.01	2400	103.6	Missing	
34452	3.178	700	0.00	0.68	2400	111.8	Internal	
34453	3.179	700	0.00	0.19	2400	140.8	Internal	Inclusion
34454	3.179	700	0.01	0.96	2400	90.2	Internal	Inclusion
34455	3.177	700	-0.02	1.26	2400	77.1	Internal	Inclusion
34456	3.177	700	0.01	0.86	2400	94.1	Internal	Inclusion
34457	3.180	1050	-0.05	-0.27	75	95.4	Surface	
34458	3.178	1050	-0.04	1.38	75	106.6	Chamfer	
34459	3.178	1050	-0.05	0.26	75	101.3	Internal	Inclusion
34460	3.179	1050	-0.04	1.34	75	97.1	Surface	
34461	3.180	1050	-0.05	0.65	75	74.6	Chamfer	
34462	3.178	1050	-0.06	2.41	75	120.9	Surface	
34463	3.180	1050	-0.05	1.39	2400	117	Surface	Pit
34464	3.178	1050	-0.05	0.93	2400	92.2	Surface	Pit
34465	3.178	1050	-0.06	0.15	2400	69.5	Internal	Inclusion
34466	3.180	1050	-0.07	2.02	2400	79.7	Internal	Inclusion
34467	3.179	1050	-0.06	0.65	2400	107.8	Internal	Inclusion
34468	3.179	1050	-0.07	1.93	2400	110.9	Internal	Inclusion

Post-Exposure Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-164 Hot Isostatically Pressed Silicon Nitride With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2400F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	95.3	103.0	73.7	10.8	6
350	2400	98.6	135.8	71.4	23.7	6
700	75	97.7	113.3	77.0	15.7	6
700	2400	102.9	140.8	77.1	22.0	6
1050	75	99.3	120.9	74.6	15.2	6
1050	2400	96.2	117.0	69.5	18.9	6

Post-Exposure Weight .Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.0	0.3	12
700	0.0	0.5	12
1050	-0.1	1.1	12

Post-Exposure Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-230 Siliconized Silicon Carbide With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2300F

Vintage = 5/1/91

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
32321		350	0.17	1.40	75	62.6	Internal	
32322		350	0.20	1.40	75	64	Surface	
32323		350	0.21	1.40	75	64.8	Surface	
32324		350	0.22	2.00	75	53.3	Surface	
32325		350	0.20	1.80	75	47.2	Surface	Aggomerate
32326		350	0.19	1.80	75	44.5	Internal	
32327		350	0.20	0.90	2300	71.3	Internal	Pore
32328		350	0.20	1.40	2300	62.8	Internal	
32329		350	0.18	0.80	2300	62.1	Internal	Pore
32330		350	0.19	1.30	2300			
32331		350	0.19	1.50	2300	69.1	Surface	Pore
32332		350	0.20	1.70	2300	58.4	Internal	
32345		700	0.12	1.00	75	65.8	Surface	
32346		700	0.10	1.61	75	63.7	Internal	Grain
32347		700	0.12	1.20	75	58.1	Internal	
32348		700	0.16	1.60	75	41.7	Internal	
32349		700	0.18	1.60	75	58	Internal	Aggomerate
32350		700	0.19	1.20	75	62.6	Internal	Aggomerate
32351		700	0.18	1.00	2300	90.1	Surface	
32352		700	0.18	1.00	2300	76.7	Internal	Grain
32353		700	0.17	1.20	2300	75.8	Internal	
32354		700	0.19	1.50	2300	67.4	Surface	Aggomerate
32355		700	0.19	1.90	2300	58.2	Surface	
32356		700	0.23	1.60	2300	74.4	Internal	Pore
32333		1050	0.20	1.20	75	68.9	Internal	
32334		1050	0.14	1.80	75	75.2	Chamfer	
32335		1050	0.20	2.00	75	67.3	Surface	
32336		1050	0.15	1.80	75	52.9	Surface	Pit
32337		1050	0.31	1.80	75	48	Internal	Pore
32338		1050	0.12	1.80	75	51.6	Internal	Aggomerate
32339		1050	0.21	1.60	2300	91.4	Internal	
32340		1050	0.20	1.60	2300	68.9	Chamfer	
32341		1050	0.24	1.60	2300	62.1	Missing	
32342		1050	0.19	1.80	2300	56.5	Internal	Pore
32343		1050	0.21	1.70	2300	61.7	Internal	Pore
32344		1050	0.20	1.80	2300	61.1	Internal	Pore

Post-Exposure Flexure Fast Fracture Strength Of Norton Advanced Ceramics NT-230 Siliconized Silicon Carbide With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2300F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	56.1	64.8	44.5	9.0	6
350	2300	64.7	71.3	58.4	5.3	5
700	75	58.3	65.8	41.7	8.7	6
700	2300	73.8	90.1	58.2	10.6	6
1050	75	60.7	75.2	48.0	11.2	6
1050	2300	67.0	91.4	56.5	12.6	6

Post-Exposure Weight _Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.2	1.4	12
700	0.2	1.4	12
1050	0.2	1.7	12

Post-Exposure Flexure Fast Fracture Strength Of Pure Carbon Refel Siliconized Silicon Carbide With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 10/1/78

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5345	3.080	350	0.30	0.00	75	45.6	Surface	
5352	3.080	350	-2.80	0.30	75	41.9	Subsurface	Pore
5360	3.090	350	-3.14	0.30	75	52.5	Surface	
5368	3.080	350	-2.16	0.30	75	46.7	Surface	Oxide
5373	3.080	350	-0.80	0.30	75	51.4	Surface	
5389	3.090	350	-1.38	0.30	75	41.1	Subsurface	Pore
5396	3.080	350	-5.03	0.30	75	46.6	Surface	
5410	3.100	350	-1.36	0.30	75	41.8	Subsurface	Pore
5417	3.060	350	-0.96	0.30	75	61.5	Surface	
5423	3.080	350	-2.92	0.30	75	56.5	Subsurface	Pore
5429	3.060	350	-1.69	0.30	75	53.1	Subsurface	Oxidation Pit
6380	3.070	350	-2.21	0.30	75	39	Subsurface	Pore
5343	3.080	1050	0.09	2.20	75	44.5	Surface	Oxide Reaction
5347	3.050	1050	0.09	2.60	75	39.7	Subsurface	Porosity
5363	3.070	1050	0.06	2.60	75	43.6	Subsurface	Porosity
5367	3.080	1050	0.07	2.60	75	38.3	Chamfer	
5374	3.060	1050	0.06	3.00	75	36.3	Subsurface	Porosity
5381	3.070	1050	0.07	3.00	75	41.7	Surface	
5401	3.090	1050	0.10	3.00	75	38.1	Surface	
5403	3.090	1050	0.08	2.80	75	69.5	Surface	Oxide Reaction, Pore
5405	3.070	1050	0.09	2.50	75	38.3	Surface	Oxide Reaction
5411	3.090	1050	0.11	2.70	75	44.6	Surface	
5424	3.090	1050	0.05	3.40	75	43.1	Surface	Oxide Reaction
5430	3.080	1050	-0.06	3.10	75	51.1	Surface	
5120	3.050	2100	-0.63	2.00	75	40.3		
5349	3.060	2100	-0.34	1.90	75	36.9		
5351	3.070	2100	-0.51	2.00	75	48.4		
5353	3.070	2100	-0.54	1.90	75	34.6		
5357	3.050	2100	-1.37	2.20	75	45.8		
5371	3.090	2100	-0.43	2.40	75	26.5		
5379	3.090	2100	-1.53	1.50	75	30		
5383	3.050	2100	-0.73	1.70	75	41.2		
5395	3.050	2100	-1.10	0.60	75	33.4		
5399	3.090	2100	-1.74	1.60	75	30.5		
5407	3.060	2100	-0.63	1.50	75	34.6		
5416	3.090	2100	-0.67	1.00	75	41.8		

Post-Exposure Flexure Fast Fracture Strength Of Pure Carbon Refel Siliconized Silicon Carbide With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F (continued)

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	48.1	61.5	39.0	6.9	12
1050	75	44.1	69.5	36.3	9.0	12
2100	75	37.0	48.4	26.5	6.6	12

Post-Exposure Weight-Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-2.0	0.3	12
1050	0.1	2.8	12
2100	-0.9	1.7	12

Post-Exposure Flexure Fast Fracture Strength Of Pure Carbon Refel Siliconized Silicon Carbide With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2300F

Vintage = 10/1/78

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5549	3.080	350	0.30	0.00	75	17.9	Surface	Oxide/Porosity
5550	3.090	350	0.30	-0.94	75	20.3	Surface	Oxide/Porosity
5557	3.080	350	0.30	50.00	75	23.9	Surface	Oxide/Porosity
5564	3.080	350	0.30	0.16	75	19.2	Surface	Oxide/Porosity
8734	3.090	350	0.30	-41.41	75	28	Surface	Oxide/Porosity
8739	3.080	350	0.30	-20.48	75	25.6	Surface	Oxide/Porosity
8747	3.100	350	0.30	10.81	75	25.7	Surface	Oxide/Porosity
8749	3.060	350	0.30	10.91	75	30	Surface	Oxide/Porosity
8751	3.080	350	0.30	-35.29	75	25.9	Surface	Oxide/Porosity
8754	3.060	350	0.30	-19.51	75	26	Surface	Oxide/Porosity
8756	3.070	350	0.30	44.83	75	33.4	Surface	Oxide/Porosity

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	25.1	33.4	17.9	4.6	11

Post-Exposure Weight - Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.3	-0.1	11

Post-Exposure Flexure Fast Fracture Strength Of Pure Carbon Refel Injection Molded Siliconized Silicon Carbide With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2000F

Vintage = 10/1/81

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
5502	3.070	350	0.05	0.80	75	71.1	Surface	Pore
5515	3.100	350	0.06	1.28	75	84.1	Surface	Pore
5518	3.050	350	0.07	1.04	75	64.8	Internal	Pore
8732	3.080	350	0.06	1.04	75	77.2	Internal	Pore
8750	3.070	350	0.06	0.88	75	68.8	Surface	
8757	3.080	350	0.06	0.81	75	60.2	Internal	Pore
5507	3.060	350	0.06	0.72	2000	57.6	Internal	Pore
5517	3.060	350	0.05	0.96	2000	59.3	Internal	Pore
8731	3.070	350	0.07	0.88	2000	53.3	Internal	Pore
8735	3.100	350	0.09	0.72	2000	69.9	Internal	Pore
8741	3.060	350	0.06	0.88	2000	61.3	Surface	Linear Defect
8759	3.080	350	0.05	0.96	2000	59.3	Internal	Pore

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	71.0	84.1	60.2	8.6	6
350	2000	60.1	69.9	53.3	5.5	6

Post-Exposure Weight -Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.1	0.9	12

Post-Exposure Flexure Fast Fracture Strength Of Pure Carbon Refel Injection Molded Siliconized Silicon Carbide With As-Processed Surfaces Following Cyclic Oxidation Exposure At 2000F

Vintage = 10/1/81

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
10799	3.080	350	0.06	1.61	75	55	Surface	
10801	3.080	350	0.05	-0.39	75	49	Surface	
10803	3.060	350	0.06	0.00	75	37.8	Surface	Large Grain
10805	3.090	350	0.04	0.55	75	40.8	Surface	Anomaly
10807	3.070	350	0.04	0.32	75	50	Missing	
10809	3.080	350	0.06	0.62	75		Surface	
10800	3.060	350	0.03	-0.08	2000	46.6	Surface	
10802	3.070	350	0.05	0.24	2000	53	Surface	
10804	3.080	350	0.03	0.98	2000	56	Surface	
10806	3.050	350	0.01	4.06	2000	64.1	Surface	
10808	3.070	350	0.02	-0.31	2000	47.9	Surface	
10811	3.060	350	0.01	0.38	2000	31.4	Surface	

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	46.5	55.0	37.8	7.1	5
350	2000	49.8	64.1	31.4	11.0	6

Post-Exposure Weight .Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	0.0	0.7	12

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13. ABSTRACT *(Maximum 200 words)*
Reports technical efforts by AlliedSignal Engines in DOE/NASA-funded project from February, 1978 through December, 1995. Topics include: ceramic materials for gas turbine engines; cyclic thermal durability testing. Program was conducted for U.S. Dept. of Energy (DoE) and administered by NASA Lewis Research Center. Project objective was to evaluate commercially-available, advanced structural ceramic materials for suitability in gas turbine engines A total of 29 materials were evaluated in 40 cyclic oxidation exposure durability tests. Ceramic test bars were cyclically thermally exposed to a hot combustion environment at temperatures up to 1371C (2500F) for periods of up to 3500 hours, simulating conditions typically encountered by hot flowpath components in an automotive gas turbine engine. Before and after exposure, quarter-point flexure strength tests were performed on the specimens, and fractography examinations including scanning electron microscopy (SEM) were performed to determine failure origins.

14. SUBJECT TERMS
Ceramic Materials; Cyclic Thermal Testing, Durability Testing, Gas Turbine Engine; Silicon Nitride. Silicon Carbide. Lithium Aluminum Silicate

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Post-Exposure Flexure Fast Fracture Strength Of Toshiba Sintered Silicon Nitride With Longitudinally Machined Surfaces Following Cyclic Oxidation Exposure At 2200F

Vintage = 7/1/84

Serial No.	Density (g/cc)	Duration (hours)	Weight Change (%)	Dimensional Change (%)	Temp (F)	Strength (ksi)	Failure Origin Location	Flaw Type
14306	3.240	350	-0.44	6.10	75	58.9	Internal	
14307	3.230	350	-0.38	5.40	75	58.4	Surface	Oxidation Pit
14308	3.240	350	-0.27	5.30	75	67.6	Internal	Pore
14309	3.230	350	-0.83	5.30	2200	33.5	Surface	
14310	3.240	350	-0.98	5.40	2200	29.5	Surface	
14311	3.240	350	-0.98	6.20	2200	36.7	Surface	
14318	3.240	700	-0.45	6.10	75	60.1	Surface	Pit
14319	3.240	700	0.13	4.50	75	70.8	Surface	
14320	3.230	700	-0.72	5.40	75	61.7	Surface	Pit
14321	3.240	700	0.17	3.10	2200	61	Surface	
14322	3.230	700	-0.06	5.30	2200	50.1	Surface	
14323	3.240	700	0.25	5.30	2200	57.7	Surface	
14294	3.230	1050	-0.58	8.50	75	48.7	Chamfer	
14296	3.230	1050	-0.05	5.40	75	58.8	Chamfer	Pit
14298	3.220	1050	-0.77	4.60	75	57.5	Surface	Pit
14300	3.240	1050	-0.03	6.10	75	57.3	Surface	
14302	3.240	1050	-0.02	6.10	75	52.6	Chamfer	
14304	3.230	1050	-0.02	5.50	75	42.8	Chamfer	
14295	3.240	1050	-0.04	6.10	2200	67.9	Chamfer	
14297	3.230	1050	-0.01	6.20	2200	56.3	Surface	Pit
14299	3.240	1050	-0.53	6.90	2200	43.7	Surface	
14301	3.240	1050	0.08	5.30	2200	49.1	Chamfer	
14303	3.240	1050	0.04	3.10	2200	51.9	Surface	
14305	3.240	1050	-0.01	5.30	2200	47.2	Surface	

Post-Exposure Strength Summary

Exposure Duration (Hours)	Temp (F)	Retained Flexural Strength (ksi) Average	Max	Min	StDev	Quantity
350	75	61.6	67.6	58.4	5.2	3
350	2200	33.2	36.7	29.5	3.6	3
700	75	64.2	70.8	60.1	5.8	3
700	2200	56.3	61.0	50.1	5.6	3
1050	75	53.0	58.8	42.8	6.2	6
1050	2200	52.7	67.9	43.7	8.6	6

Post-Exposure Weight _Dimensional Change Summary

Exposure Duration (Hours)	Weight Change (%)	Dimensional Change (%)	Quantity
350	-0.6	5.6	6
700	-0.1	5.0	6
1050	-0.2	5.8	12