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EVALUATION OF CERAMICS FOR STATOR APPLICATIONS—GAS TURBINE ENGINES

FINAL REPORT - STATOR FABRICATION & EVALUATION

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MARCH 1983

Prepared for the
NATIONAL AERONAUTICS & SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-00019

for

U.S. DEPARTMENT OF ENERGY

Conservation and Renewable Energy
Office of Vehicle and Engine Research and Development

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FOREWORD

This report was prepared as the final technical report for work completed on the stator fabrication and stator evaluation tasks under the program for "Evaluation of Ceramics for Stator Applications-Gas Turbine Engines," contract number DEN 3-00019. Work was completed earlier on two other tasks and reported separately.

The program was funded by the U.S. Department of Energy, Conservation and Solar Energy, Division of Transportation and Energy Programs and Administered by the NASA Lewis Research Center under interagency agreement DEAI-01-77CS51040.

Principal investigators of this program were P. H. Havstad and W. Trela, Ford Motor Company, the NASA project manager was G. K. Watson, NASA Lewis Research Center, and the DOE project manager was R. B. Schulz. The co-author, Mr. N. Arnon was the responsible engineer for the evaluation phase of the program, including rig development and automation.

The authors wish to acknowledge the contribution and support of Ford personnel whose efforts were instrumental in the successful completion of this program; R. L. Allor, for coordinating the NDE processing and machining of stators and ceramic support hardware and B. J. Moore, M. Seaman and C. A. Galiette for their careful work in executing over one hundred rig builds and two-hundred test runs required during the program.

ABSTRACT

The objective of the DOE/NASA/Ford program for "Evaluation of Ceramics for Stator Applications in Gas Turbine Engines" was to assess current ceramic materials, fabrication processes, reliability prediction and stator durability when subjected to simulated automotive gas turbine engine operating conditions.

Ceramic one-piece stators were fabricated by AiResearch Casting Co., Carborundum, Ford and Norton of two materials, silicon nitride and silicon carbide, using two near-net-shape processes, slip casting and injection molding. Non-destructive evaluation tests were conducted on all stators identifying irregularities which could contribute to failures under durability testing.

Development of the test rig and automatic control system for repeatably controlling air flow rate and temperature over a highly transient durability duty cycle is discussed.

Durability results are presented for repeated thermal cycle testing of the ceramic one-piece stators. Two duty cycles were used, encompassing the temperature ranges of 704 to 1204°C (1300 to 2200°F) and 871 to 1371°C (1600 to 2500°F). Tests were conducted on 28 stators, accumulating 135,551 cycles in 2441 hours of hot testing. Cyclic durability for the ceramic one-piece stator was demonstrated to be in excess of 500 hours, accumulating over 28,850 thermal cycles. Ceramic interface forces were found to be the significant factor in limiting stator life rather than the scatter in material strength properties or the variation in component defects encountered.

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SUMMARY

Introduction

This is the final report on two segments of the DOE/NASA Ford program entitled "Evaluation of Ceramics for Stator Applications in Gas Turbine Engines". The program encompassed four tasks: 1) Reliability Prediction, 2) Material Property Characterization, 3) Stator Fabrication, and 4) Ceramic Stator Evaluation. The test component was a one-piece ceramic stator designed for the Ford Model 820 Gas Turbine Engine. This report covers the stator fabrication and evaluation tasks. A final report on the first two tasks was published in 1980 [1].

Objectives

The overall program objectives were to:

1. Assess the capability for reliability prediction of ceramic components subjected to simulated automotive duty cycle conditions.

2. Assess the ceramic industry capability for fabricating near net shape components.

3. Evaluate current ceramic materials for use as stators in an automotive turbine under cyclic temperature conditions up to 1371°C (2500°F).

The program goal was to demonstrate 500 hours of duty cycle durability.

Accomplishments

The materials selected for the ceramic stator fabrication were silicon nitride and silicon carbide which had the capability of operating at least to 1204°C (2200°F) with potential for use at 1371°C (2500°F). Four ceramic component suppliers participated in the program, providing stators of silicon nitride and silicon carbide materials using the slip casting and injection molding processes (Table 1, Page 7). The stator design was an axial turbine stator as shown in Figure 1, Page 6.

All four participants successfully fabricated stators with net shape air foil surfaces. Stator quality and condition were documented by dimensional, visual, radiographic and fluorescent dye penetrant techniques before finish machining. Stators were successfully machined to final dimensions normally required for engine installation. Diamond grinding wheels were used, employing conventional machining techniques such as OD and ID grinding and flat face machining. The only special processing involved a water soak to remove residual grinding fluid from the interconnected porosity in the silicon nitride stators.

A high temperature test rig was modified and automated to accurately reproduce duty cycles representative of automotive turbine engine operation. Previously developed test rigs were used to conduct preliminary screening tests to qualify stators for durability evaluation.

The durability evaluation was conducted using a transient duty cycle typical of automotive applications. Stators from all four participants were evaluated using a duty cycle consisting of one-minute thermal cycles with temperatures ranging from 704 to 1204°C (1300 to 2200°F) as shown in Figure 14, Page 28. Additional testing was then conducted on stators considered to be capable of operation to 1371°C (2500°F). Essentially the same type of duty cycle was used, but with all temperatures raised by 167°C (300°F).

Durability evaluation at the 1204°C (2200°F) level was conducted on 23 stators, with 514 hours successfully accumulated on one stator (Table 11, Page 40). Six stators of three different types were evaluated at the higher temperature level of 1371°C (2500°F). Over 150 hours durability was achieved on both silicon nitride and silicon carbide stators at the higher temperature level. Upon completion of the durability test phase, supplemental testing was conducted in which complete cool downs were made between hot cyclic tests, conditions typical of passenger car operation. Four silicon carbide stators were tested, interfacing with silicon nitride flowpath components, without any failures. Altogether over 2400 hours of durability testing were completed accumulating over 135,500 cycles in the automated test rig.

A simple vane bend test technique was used to generate comparative strength data for stators with and without durability time. No strength degradation was evident on any of the stator materials.

Conclusions

One-piece ceramic stators can be fabricated from silicon nitride and silicon carbide materials using either the slip casting or injection molding processes. Airfoil surfaces can be produced which require no machining. With additional tooling and process development, components such as stators could be produced which require minimal, relatively simple machining such as OD and ID grinding, flat face machining and, if necessary, radiusing of corners. Production of low cost near-net-shape, one-piece stators seems achievable.

Ceramic stators can operate successfully under the highly transient thermal cycling conditions typical of a passenger car turbine engine application. Both silicon nitride and silicon carbide materials can be used for stators where maximum turbine inlet temperatures reach 1371°C (2500°F). Stator failures on durability test resulted primarily from time dependent ceramic interface surface reactions affecting interface friction. A complete investigation of ceramic interface phenomena and development of successful interfaces was clearly beyond the scope of this program. However, it was shown that the effects of interface friction could be mitigated by frequent disassembly during an initial "break in" period.

Fabrication and processing technologies used in producing complex shaped components require additional development in order to take full advantage of ceramic material strength properties. Weibull statistical bend strength data obtained from simple test bars had less scatter than comparable bend strength data obtained on the more complex shaped stators.

Recommendations

Investigations should be conducted to extensively explore the interface problem. Such an investigative program should encompass studies of surface chemistry, interaction of dissimilar materials and friction measurements under carefully controlled steady state and transient conditions. The test rig and procedures used in this program are ideal for this purpose.

Work should also be continued to develop component fabrication technology. Although impressive strengths have been demonstrated for ceramic materials, the need to duplicate these properties throughout large numbers of complex shaped parts still exists.

INTRODUCTION

Ford Motor Company started research on the use of brittle materials in gas turbine engines in 1961 when development was initiated on a ceramic regenerator system for gas turbine engines. In 1967, work on high temperature turbine research was started along with initial design investigations of an experimental high temperature gas turbine engine, designated Model 820.

By the end of 1970, based on design studies and experimental research, it was decided to concentrate research and development on an all-ceramic flowpath rather than on using an air-cooled metal turbine wheel. Since 1971 government funding has helped to accelerate the development of such ceramic turbine technology. Progress on these programs has generated considerable interest in the technical community and has stimulated the establishment of activities in ceramic material and process development and in ceramic turbine components and engine development on a worldwide basis.

Of particular interest are the areas of ceramic structural component technology including:

- .Designing with ceramics
- .Ceramic material and process development
- .Ceramic test rig development
- .Ceramic component testing methodology
- .Reliability prediction and failure analysis

As a step in technology progression, the United States Department of Energy (through NASA-Lewis) initiated a program in January, 1978, which would provide an assessment of the capability of the ceramics industry to fabricate ceramic one-piece stators having the quality and structural integrity required for automotive turbine engine applications.

Ceramic stators of the Ford Model 820 turbine engine design were selected for this program. This stator was considered to be representative of size and design required for automotive turbine engines. Prior experience existed in fabricating silicon nitride and silicon carbide stators of this design, rig and engine tests had been conducted with these components and the facilities were in place for further testing under realistic gas turbine engine conditions.

The work to be accomplished under the program, "Evaluation of Ceramics for Stator Applications - Gas Turbine Engines," was divided into four technical tasks that included development of a reliability prediction model for ceramic stators, fabrication of ceramic stators, material property characterization, and simulated engine duty cycle testing of the stators.

This report presents the work performed on two tasks - stator fabrication and stator evaluation.

STATOR FABRICATION

OBJECTIVES

The main objective of the fabrication effort was to assess the ceramic industry's capability for fabricating one-piece ceramic gas turbine stators from current materials using near-net-shape processing. The stator design was to be representative of an automotive gas turbine engine. Materials chosen were to be capable of operation at temperatures up to 1204°C (2200°F) with potential for 1371°C (2500°F) use. Near-net-shape processes chosen must have potential for low cost production. The stators produced would subsequently be durability tested under conditions representative of an automotive turbine engine.

Another objective was to produce a supply of physical property samples for use in characterizing the materials. Test samples were to be representative of both the materials selected and the fabrication process used for the stators.

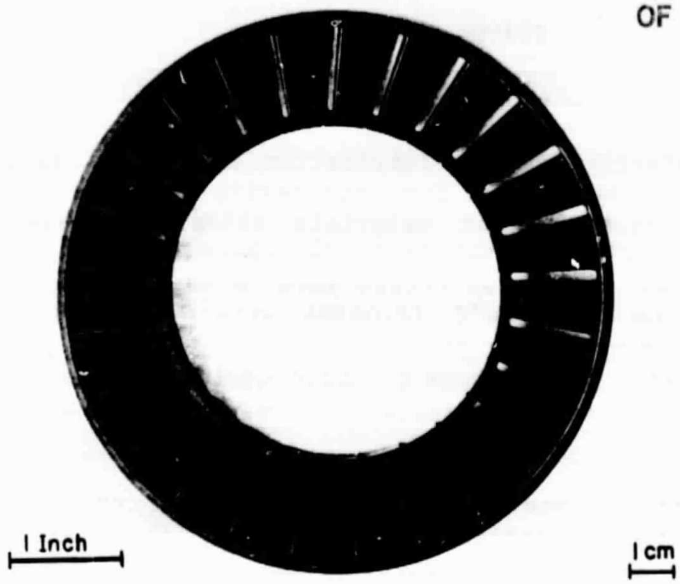
APPROACH

The stator design selected was that of the Ford Model 820, axial flow, automotive gas turbine engine which was concurrently being used as the test bed under a government sponsored Brittle Materials Design, High Temperature Gas Turbine program [2]. The stator design featured one-piece construction with twenty-five vanes and an integral, segmented inner shroud. Some nominal dimensions and the general configuration are shown in Figure 1.

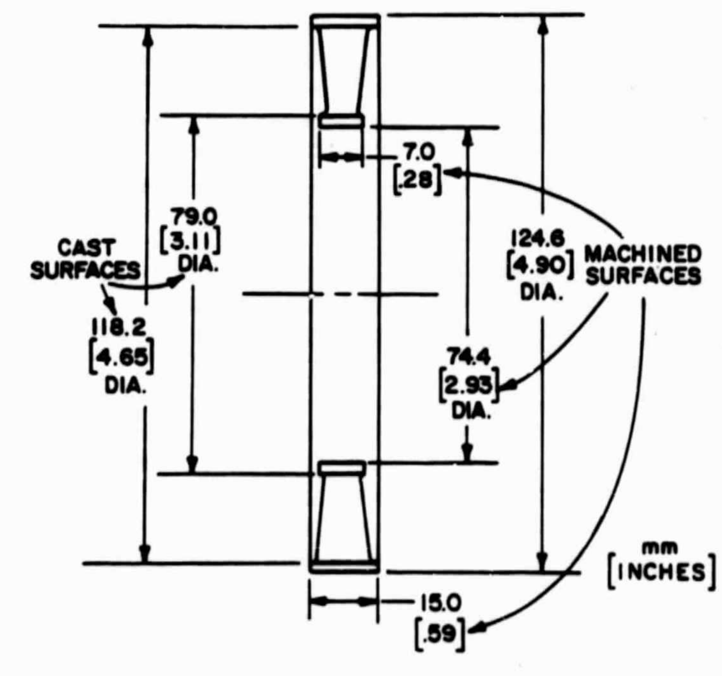
Organizations selected for the fabrication effort included the Ford Motor Company and three ceramic component suppliers, AiResearch Casting Company (ACC), the Carborundum Company (CBO) and Norton Company. Each participant was contracted to supply a minimum of twelve stators for evaluation. The material/process combination for each supplier is outlined in Table 1. Thus the assessment included silicon carbide (SiC) and silicon nitride (Si_3N_4) materials and two near-net-shape fabrication processes: slip casting and injection molding. Except for the Norton stators, all machining of stator castings was Ford's responsibility.

Responsibility for the necessary tooling remained with each vendor. However, an existing Ford injection molding tool was used to make wax patterns for the slip casting efforts (ACC and Norton). Small shrinkages were anticipated and were addressed in the casting tooling by adding enough material to insure adequate cleanup stock on machined surfaces. A new molding tool was procurred by Carborundum since approximately 17% shrinkage was anticipated from molded to sintered parts.

All stators submitted were accepted as being representative of the material/process/supplier capabilities. Stators were given



(a)



(b)

Figure 1 (a) Typical Model 820 Stator (b) Cross-Section Nominal Dimensions - mm [inches]

TABLE 1
STATOR FABRICATION

PARTICIPANTS	MATERIALS	PROCESSES
AIRESEARCH	REACTION BONDED Si_3N_4	SLIP CASTING
CARBORUNDUM	SINTERED α SIC	INJECTION MOLDING
FORD	REACTION BONDED Si_3N_4	INJECTION MOLDING
NORTON	REACTION SINTERED SIC	SLIP CASTING

"as-received" inspections consisting of dimensional, visual, x-ray and fluorescent dye penetrant (on SiC only). Irregularities observed were documented primarily for use in determining their influence should any failures occur during the durability evaluation. Where machining of vendor parts was Ford responsibility, an additional post machining inspection was also performed.

The types of material property specimens contracted for are listed in Table 2 and a typical set of samples is shown in Figure 2. Specifications for the modulus of rupture (MOR) bars required that at least one face be unmachined and representative of the surface finish normally produced by the fabrication process used. Thus bend strength data could be generated using the "as-processed" surface in tension.

TABLE 2
MATERIAL PROPERTY SPECIMENS

SPECIMEN NAME	NOMINAL SIZE MM (INCHES)	QUANTITY REQUIRED
MOR BAR	3.2 × 6.4 × 31.8 (0.12 × 0.25 × 1.25)	300
THERMAL DIFFUSIVITY	1.0 × 14.3 DIA (0.04 × 0.56 DIA)	5
SPECIFIC HEAT	6.4 × 6.4 × 76.2 (0.25 × 0.25 × 3.0)	10
SONIC MODULUS	3.2 × 25.4 × 101.6 (0.12 × 1.0 × 4.0)	10
THERMAL EXPANSION[1]	6.4 × 6.4 × 50.8 (0.25 × 0.25 × 2.0)	—
BILLET[2]	7.0 × 26.5 × 102.4 (0.26 × 1.02 × 4.03)	15

[1] MADE FROM SPECIFIC HEAT SAMPLES AFTER SPECIFIC HEAT EVALUATION.

[2] MACHINED TO MAKE PHYSICAL PROPERTY SPECIMENS. ONLY REQUIRED FROM PARTICIPANTS USING INJECTION MOLDING FABRICATION PROCESS.

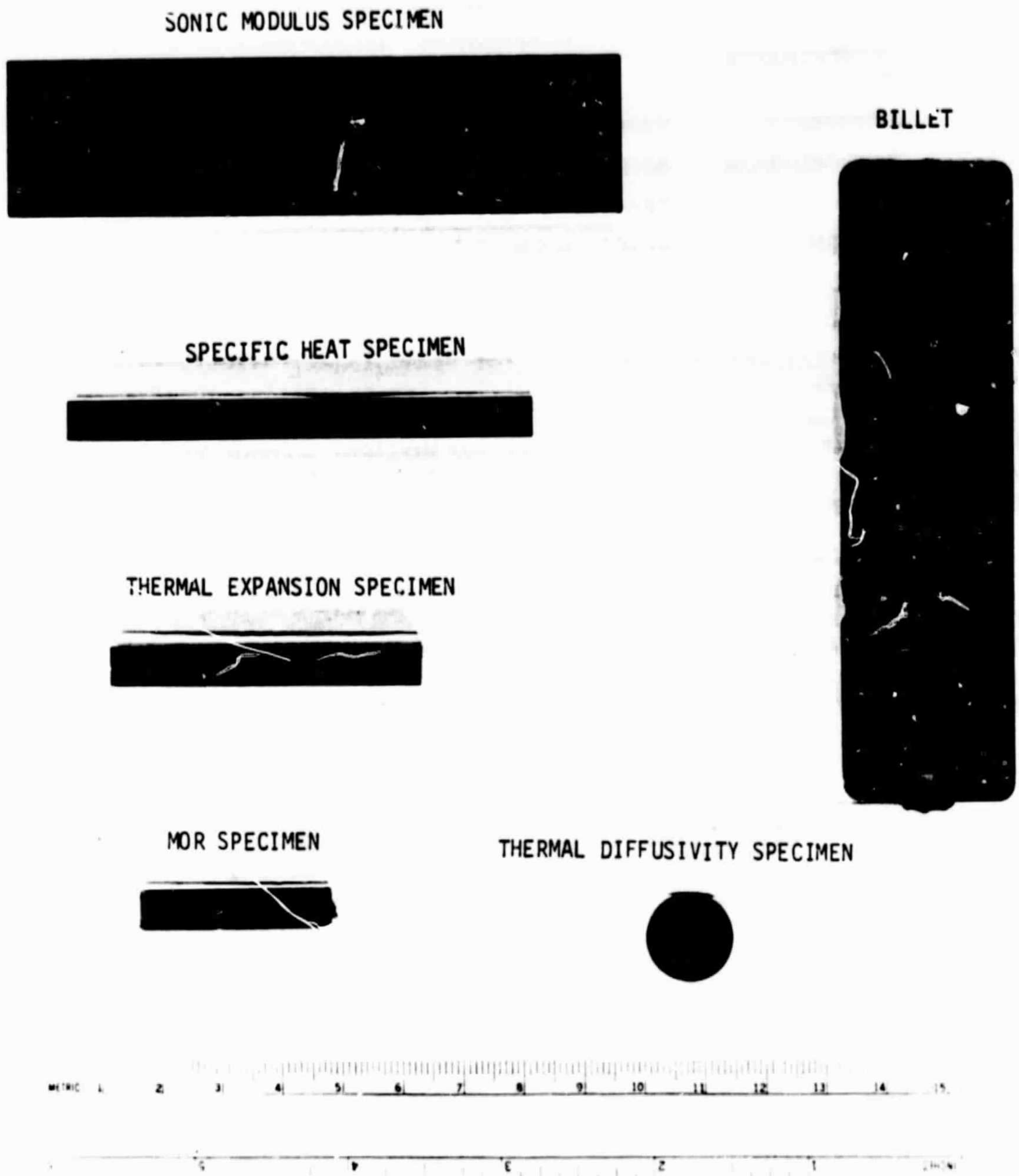


Figure 2 Set of Typical Material Property Samples Used for Material Characterization

Machining of the physical property specimens from the large injection molded billets of the Carborundum and Ford materials was the responsibility of Ford. All other physical property samples were to be delivered fully machined.

Additional ceramic support hardware was furnished by Ford to maintain the test rigs used in the stator evaluation task. The materials and designs for these components were those which had demonstrated reasonable reliability under earlier Ford/government programs.

AIRESEARCH CASTING CO. (ACC) - SLIP CAST SILICON NITRIDE

Stators and physical property samples were fabricated by ACC of Airceram RBN-101, a reaction bonded silicon nitride with a nominal density of 2.7 g/cc. Wax patterns were fabricated using the Ford stator tool and water soluble wax material supplied by ACC. In total, 82 wax patterns were made. A typical wax pattern is shown in Figure 3 and a typical nitrided stator casting is shown in Figure 4. Although a continuous pour ring was used for the inner shroud, the ring "bridged" adjacent segments and thus produced the castings with the segmented inner shroud (Figure 4c).

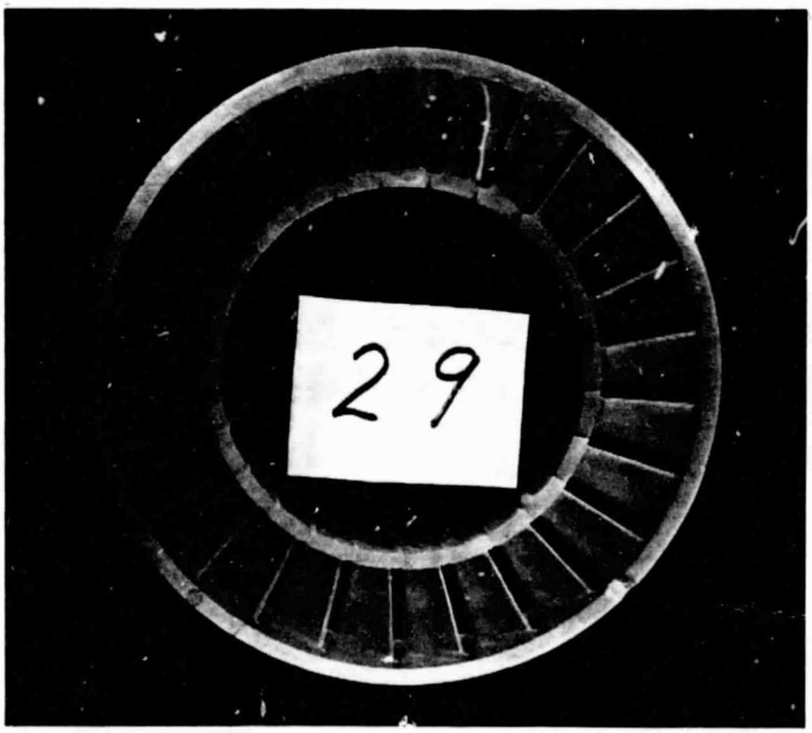
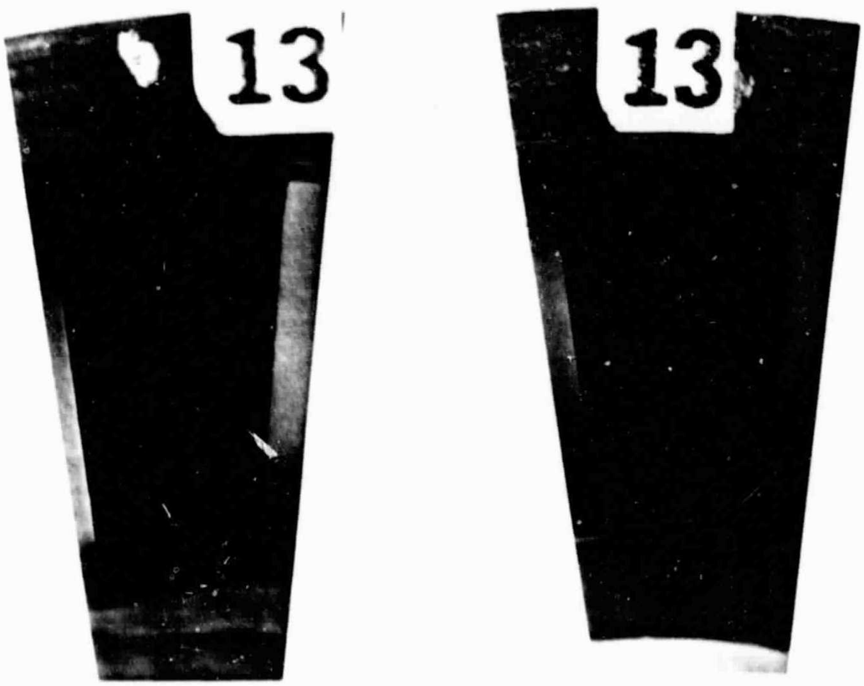


Figure 3 Wax Pattern for ACC Slip Casting Made From Ford Model 820 Stator Injection Molding Tool

(a)



(b) (c)

Figure 4 AiResearch Nitrided Stator Casting: (a) Leading Edge View. (b) and (c) Airfoil Cast Surface Detail

The typical nitrided casting delivered for machining weighed approximately 250 grams, compared to approximately 100 grams for a finished machined stator. The greatest portion of this excess weight was contained in the pour ring and outside diameter reservoir. No attempt was made to minimize the excess stock since it was all on surfaces which required machining for the finished part.

In total ACC delivered twelve castings (eleven were cast with the leading edge up) and a complete set of MOR bars and physical property specimens. All MOR bars were delivered with as-cast surfaces. Physical property samples were delivered fully machined.

CARBORUNDUM - INJECTION MOLDED SILICON CARBIDE

The Carborundum Company fabricated stators, MOR bars and billets for physical property samples of their α phase SiC material using the injection molding/sintering process.

The initial stator tool design featured continuous inner and outer shrouds, an integral MOR bar cavity and single point gating through the inner shroud, as shown in Figure 5a. Good quality moldings were obtained; however, problems were encountered in subsequent processing steps. Sintering of stators without the slotted inner shroud usually resulted in cracks in at least one of the shrouds. Attempts by Carborundum to machine slots before sintering were only marginally successful.

An interim tool modification with integral slots and diaphragm gating through each of the inner shroud segments proved unsuccessful. Multiple knit lines were produced in the outer shroud, resulting in frequent knit line cracks after sintering.

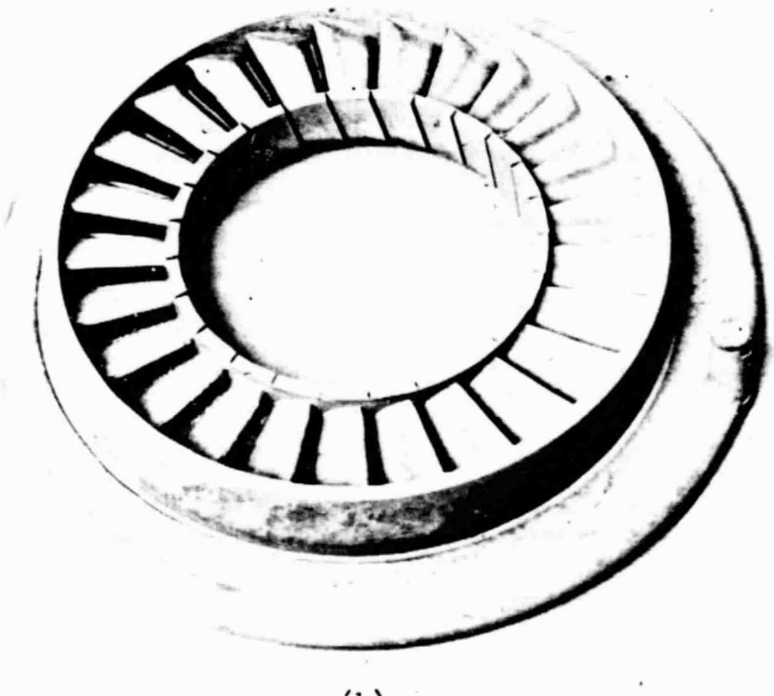
A redesign and rework of the tool was then completed which incorporated inserts for molding in the slots and a diaphragm gate through the outer shroud. Figure 5b is an illustration of a typical as-molded stator made in the redesigned tool. All stators delivered by Carborundum were fabricated with this configuration. A typical stator is shown in Figure 6.

Carborundum delivered twelve sintered stators, 300 unmachined MOR bars and 18 billets for machining them into the physical property samples.

FORD-INJECTION MOLDED SILICON NITRIDE

Ford fabricated stators, MOR bars and billets for the physical property samples of a nominal 2.7 g/cc density reaction bonded silicon nitride material using the injection molding process. Tooling used was from an earlier Ford/government program [2]. The tool included cavities for two MOR bars, integral inserts for inner shroud slots and single point gating at the outer shroud.

(a)

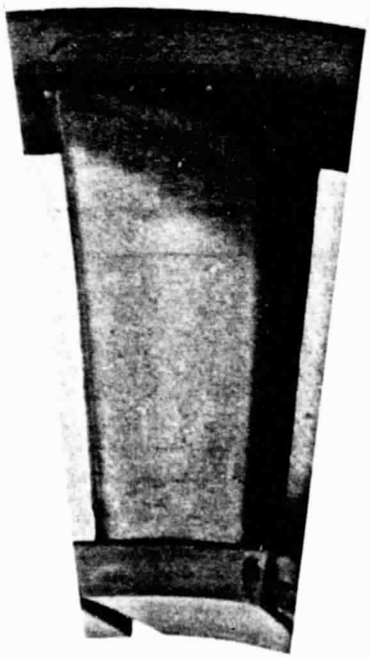


(b)

Figure 5 Features of Carborundum Tooling for Molding Silicon Carbide Stators: (a) Replica of Original Design. (b) Casting from Reworked Tool with Integral Slots and Outer Shroud Gating

(a)

(b)



(c)

Figure 6 Carborundum Sintered Stator Casting: (a) Leading Edge View. (b) and (c) Airfoil Surface Detail

In order to have an adequate supply of MOR bars (300 were required for the materials characterization effort) a total of 223 stator shots (with 2 test bars per shot) were made. Twenty-nine stators were submitted for machining. Of these, 19 were candidates for the durability evaluation and the remainder designated for use during development of durability test rig control system. A typical nitrided stator before finish machining is shown in Figure 7.

A new tool was designed and fabricated for molding the billets needed for the physical property samples. The tool is shown in Figure 8. A total of 42 billets were molded, nitrided and submitted as candidates for machining.

NORTON-SLIP CAST SILICON CARBIDE

Norton fabricated stators, MOR bars and physical property samples of Noralide NC-433 reaction sintered silicon carbide material using the slip casting process. Wax patterns were produced for Norton using the Ford 820 stator tool and pattern materials supplied by Norton.

Initially 70 patterns were produced (35 from each of two different wax materials). A second batch of 50 patterns was produced (25 of each material), however, because of inadequate packaging and shipping procedures this group of patterns were distorted and rendered unusable.

Norton fabricated, machined and delivered 7 stators for evaluation made from the first lot of patterns as well as a complete set of MOR bars and physical property samples. A typical fully machined stator is shown in Figure 9.

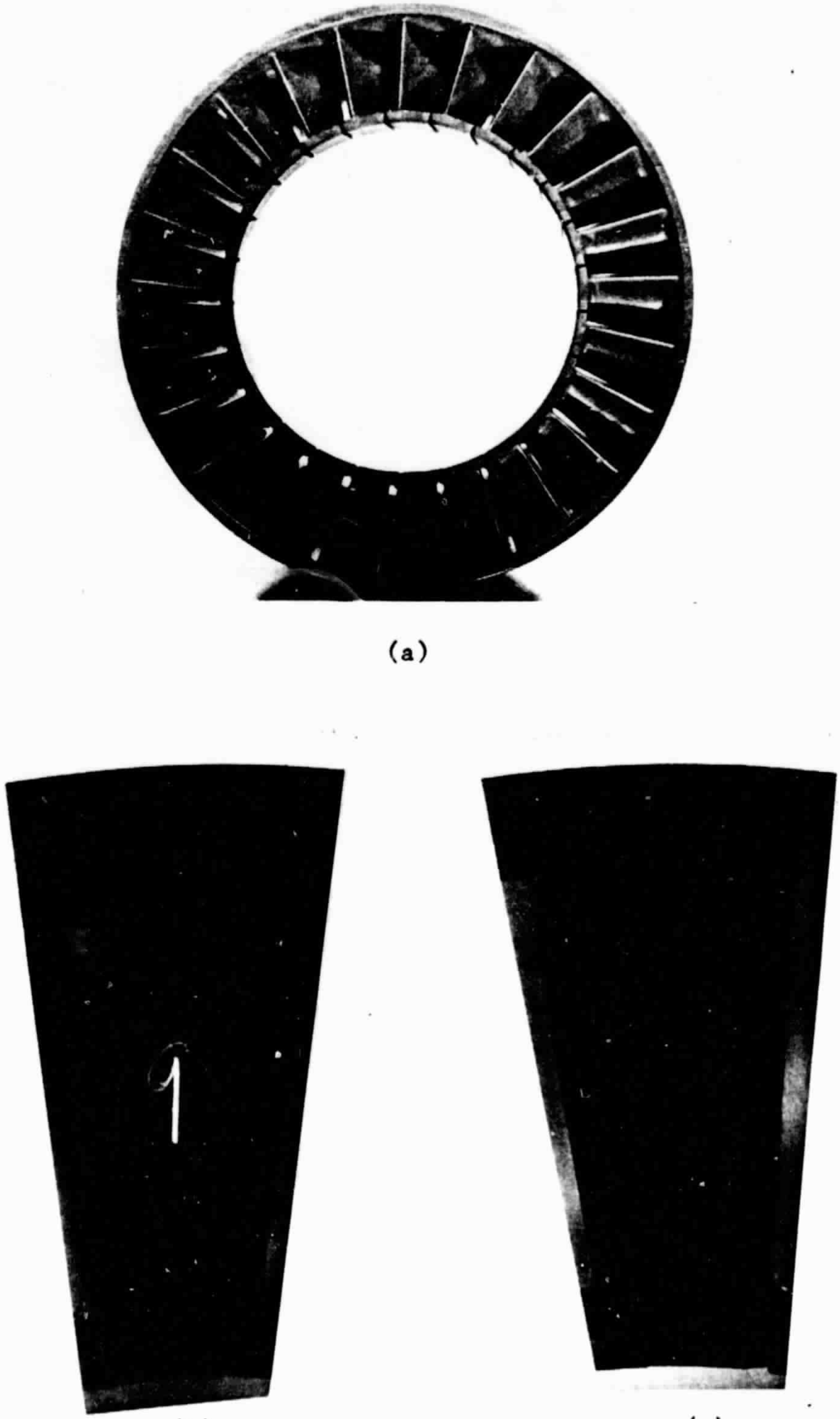
INSPECTION OF AS-RECEIVED COMPONENTS

All stators received from outside vendors were processed through several non-destructive evaluation (NDE) processes prior to machining or testing. The 19 Ford stators submitted as durability candidates were processed through the same NDE steps when in the nitrided but unmachined stage of fabrication.

The NDE tests provided data for documenting the stator condition and was not intended as criteria for acceptance or rejection. These tests and documentation consisted of:

- .Overall view photographs
- .Dimensional checks for machinability
- .Radiographic inspection of vanes
- .Fluorescent dye penetrant inspection

All 50 stators inspected had some type of anomolous indication. In many cases the number of indications was considerable and too numerous to present in detail. Since the significance of the "defects" would not be determined until the test phase of the program, the approach used was to record all observations. The results of each inspection were marked on separate traveler sheets.



(a)

(b) (c)

Figure 7 Ford Nitrided Stator: (a) Leading Edge View. (b) and (c) Airfoil Surface Detail

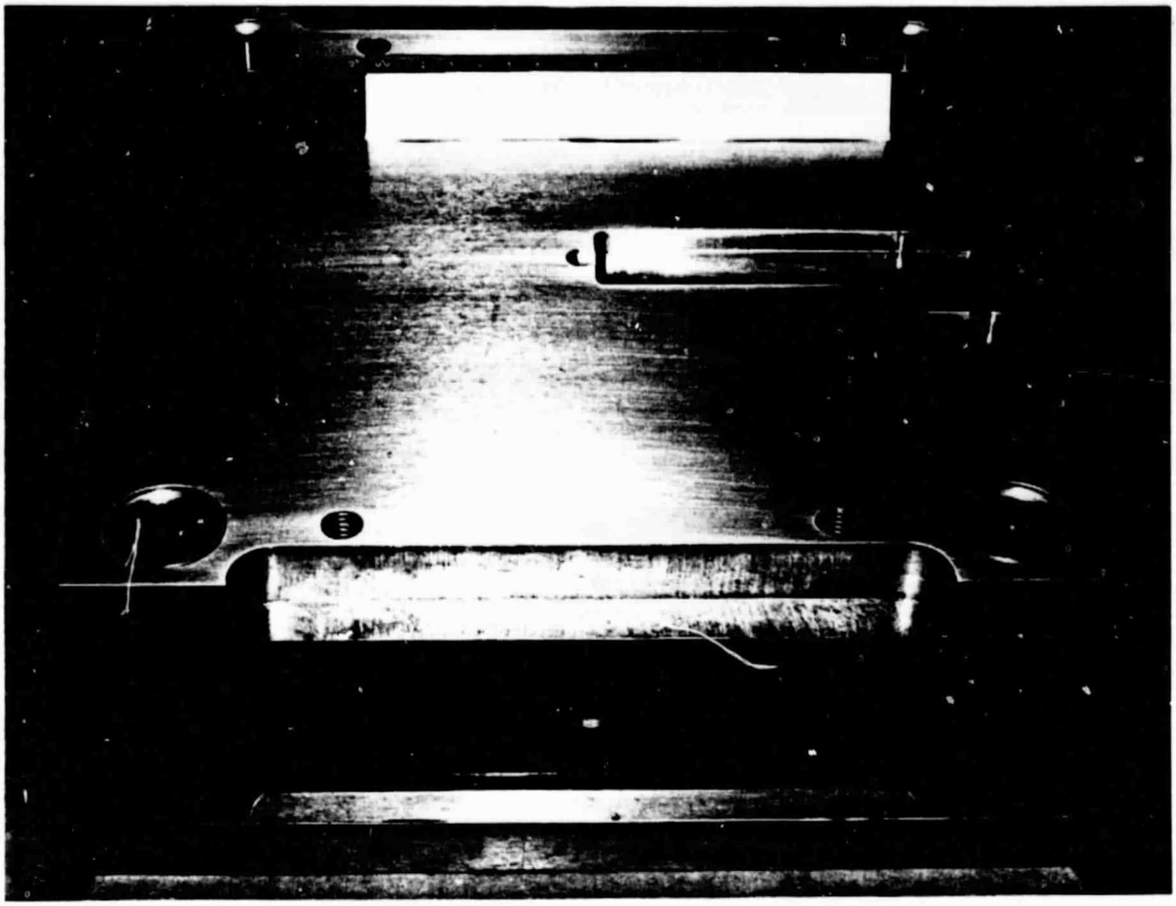
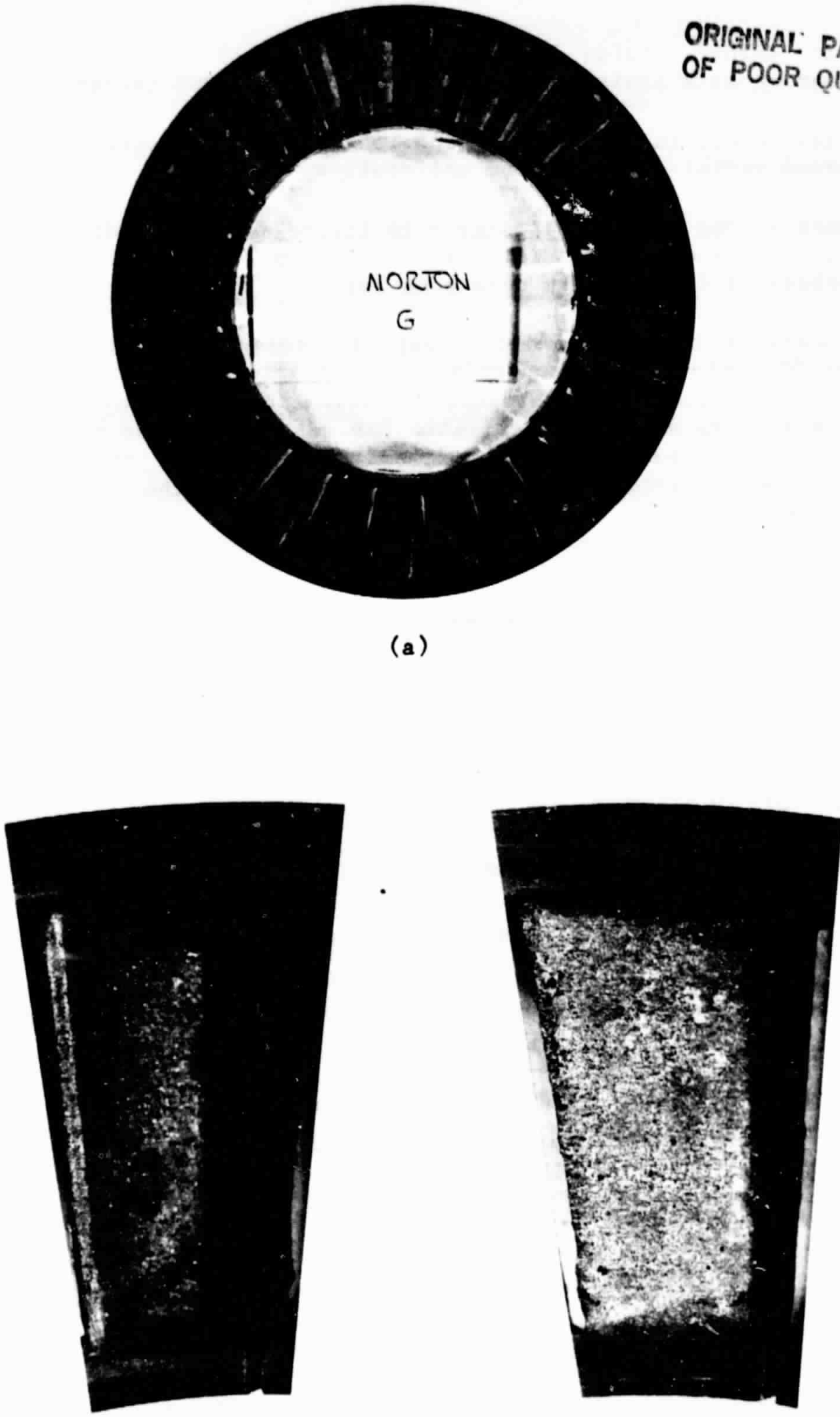


Figure 8 Tool for Injection Molding Physical Property Sample Billets

Specific examples of typical indication will be presented later in the durability evaluation section. The examples will include indications having no influence on stator performance, observed indications contributing to failure, and flaws contributing to failure which were not previously observed. The following sections describe the general nature of NDE test results for as-received stators.

Dimensional Inspections

The ACC, Ford and Norton fabrication efforts had a common dimensional base as the starting point which was the cavity in the Ford injection molding tool. However, since the processes diverged from that point some variability in finished component dimensions was anticipated. For the Carborundum effort the tool cavity dimensions were based on the best estimate of shrinkage (17%) to yield the desired sintered casting dimensions. Some margin for error from the original shrinkage estimate could be accommodated by adjusting the size of mating components in the hot flowpath.



(a)

(b)

(c)

Figure 9 Norton Finish Machined Stator: (a) Leading Edge View. (b) and (c) Airfoil Surface Detail

The critical dimensions for the as-received stators included:

- Outer shroud outside diameter - to insure full circumferential clean up at a finish diameter of 124.54 mm (4.903 inches).
- Outer shroud inside diameter and roundness - to insure adequate shroud radial thickness and uniformity.
- Inner shroud outside diameter - to insure adequate radial thickness when inside diameter finished to 74.42 mm (2.930 inches) to fit over the nose cone bell.

A summary of the machinability inspections is presented in Table 3. Of the 50 stators submitted only 3 were considered as impractical for finish machining for durability evaluation. Seven of the Carborundum stators would be machinable for test with minor modifications of the finish machined stator dimensions and rework of the nose cone. The modifications are discussed further in the Durability Evaluation section.

TABLE 3
CHECK FOR MACHINABILITY AS-RECEIVED STATORS

VENDOR	QTY. OF STATORS	COMMENTS
ACC	12	OK FOR STANDARD CONFIGURATION
CBO	2	OK FOR STANDARD OR MODIFIED CONFIGURATION
	7	OK FOR MODIFIED CONFIGURATION
	3	OUT-OF-ROUND 3.302/3.759 mm(0.130/0.148 inches) WITHHELD FROM MACHINING FOR DURABILITY TEST.
FORD	19	OK FOR STANDARD CONFIGURATION
NORTON	7	MACHINED AS RECEIVED OK FOR STANDARD CONFIGURATION

Measurements of the outer shroud inside diameters for the ACC, Ford and Norton stators also provided some information relative to the shrinkages associated with the respective materials/processes. Using a known tool dimension of 118.89 mm (4.680 inches) for the outer shroud inside diameter and measurements of actual stator dimensions, shrinkage could be calculated. The process shrinkages data is shown in Table 4. The shrinkage values represent the percentage change in diameter for the total process: from the tool cavity dimension, to molded part or wax pattern, to unmachined net shape surface dimension.

TABLE 4
PROCESS SHRINKAGE

	OUTER SHROUD INSIDE DIAMETER		STARTING DIMENSION (TOOL CAVITY)	AVERAGE SHRINKAGE
	AVERAGE	RANGE		
ACC	117.37 (4.621)	117.04-117.55 (4.608-4.628)	118.87 (4.680)	1.37%
FORD	118.87 (4.680)	118.72-119.02 (4.674-4.686)		0.00%
NORTON	117.40 (4.622)	117.09-117.80 (4.610-4.638)		1.24%

DIMENSIONS IN mm & (inches)

Radiographic Inspection

All stators were radiographically inspected as received. X-rays were taken in the axial direction only and with the exposure intensity adjusted to reveal indications in the vanes. Only 12 of the 50 stators inspected had no indications. Voids were observed in stators from all four participants while inclusions were only observed in Ford stators.

Table 5 summarizes the general observations. Most voids were circular in nature and appeared randomly in the vanes except for the ACC stators where void indications generally appeared near the vane leading or trailing edges.

Visual Inspection

Visual inspections of as-received stators were primarily directed toward identification of irregularities on surfaces which would remain unmachined. Microscopic examination of unmachined surfaces at 10X invariably reveals some type of abnormal surface condition. However, the significance of the observed "flaw" cannot easily be judged. The microscopic inspections were therefore conducted on the basis of identifying all irregularities and recording the observations with a code describing the nature of the observation. In addition the areas of irregularities were marked directly on the stator with a ceramic marking pencil. Since visual observations are subject to individual interpretation, only one inspector was used for all the stators.

Table 6 summarizes the relative frequency and type of irregularities observed. For the Norton stators, the combination of dark color and rough surface texture made visual inspection extremely difficult.

TABLE 5
RADIOGRAPHIC INSPECTION SUMMARY
AS-RECEIVED STATORS

VENDOR	QTY. INSPECTED	QTY. W/NO INDICATIONS	DESCRIPTION OF OBSERVATIONS
ACC	7	0	7-15 INDICATIONS PER STATOR PRIMARILY VOIDS AT VANE LE & TE CIRCULAR:400-1000 μ DIA. LINEAR: 1000-2500 μ
CBO	12	2	1-10 INDICATIONS OF CIRCULAR VOIDS PER STATOR RANDOMLY LOCATED 250-400 μ DIA.
FORD	19	6	1-3 INDICATIONS PER STATOR SOME VOIDS BUT PRIMARILY INCLUSIONS, RANDOMLY LOCATED CIRCULAR VOIDS: 250-400 μ DIA. INCLUSIONS: 250 μ DIA. CIRCULAR & 150 × 750 μ LINEAR
NORTON	7	4	1-9 INDICATIONS PER STATOR RANDOMLY LOCATED PRIMARILY CIRCULAR VOIDS: 250-1000 μ DIA.

LE - LEADING EDGE
TE - TRAILING EDGE

TABLE 6
VISUAL INSPECTION SUMMARY
AS-RECEIVED STATORS

VENDOR	TYPE OF OBSERVATION	COMMENTS/LOCATION
ACC	FLOW/FOLD LINES	VANE LE AND TE USUALLY WITHIN 6.3 mm (1/4 inches) OF OUTER SHROUD
	VOIDS/PITS	VANE LE AND TE
CBO	FLOW/FOLD LINES	VANE TE/OUTER SHROUD JUNCTION
	CRACKS	VANE TE
	CHIPS	RANDOM LOCATION
FORD	FLOW/FOLD LINES	VANE TE AND VANE SURFACES
	VOIDS (TEAR OUT)	FILLET-VANE TO OUTER SHROUD AND AT INLET GATE
NORTON	VERY FEW INDICATIONS, ROUGH SURFACE TEXTURE.	

LE - LEADING EDGE
TE - TRAILING EDGE

Zyglo Inspection

Zyglo (fluorescent dye penetrant) inspection was conducted on the SiC (Carborundum and Norton) stators. Previous experience with RBSN components indicated that the surface porosity retained enough of the dye penetrant to mask any but the most obvious cracks. Zyglo inspection was found to be especially useful on the Norton stators where simple visual inspection was inadequate.

A summary of the inspection results is presented in Table 7. Black light photographs were used to document those indications judged to be most significant.

TABLE 7

ZYGLO INSPECTION SUMMARY

AS-RECEIVED STATORS

VENDOR	TYPE OF INDICATION	COMMENT/LOCATION
CBO	LINEAR	VANE TO OUTER SHROUD FILLET, LE & TE VANE SURFACE (POSSIBLY FLOW LINE)
	POROSITY	ALONG TOOL PARTING LINE ON ID OF OUTER SHROUD INNER SHROUD FACES NEAR SLOTS
NORTON	LINEAR	VANE TO OUTER SHROUD FILLET, LE & TE OUTER SHROUD, RANDOM (ID, OD, FACES)
	POROSITY	OUTER SHROUD, LE FACE

LE - LEADING EDGE
TE - TRAILING EDGE

MACHINING AND PRE-OXIDATION

Machining of ACC, Carborundum and Ford stators was performed using diamond grinding wheels of 220-320 grit with flood cooling using water soluble coolants. ACC and Ford stators were given a post machining pre-oxidation heat treatment; each vendor treating their own stators. The pre-oxidation heat treatment was included in the Si_3N_4 stator fabrication processes since it had been shown to be effective in reducing the oxidation rate of this material [3,4]. Previous engine simulator rig tests at Ford had shown that stators were likely to fail when the oxidation weight gain reached 2% [2]. In most cases the 2% weight gain of untreated stators occurred in less than 200 hours at 1054°C (1930°F).

A special fixture (Figure 10) was used for the first machining setup. Wax was used to bond the stator shrouds to the fixture and for filling the slots in the inner shroud. The stator OD, ID and one face of each shroud were machined with this setup. Conventional techniques and setups were used for the remainder of the machining. The wax filler in the inner shroud slots was present during any inner shroud grinding. Of the Carborundum stators two were broken during machining due to operator error, and a large void was uncovered in the outer shroud of a third stator. All ACC and Ford stators were machined without incident.

The first group of 6 Ford stators processed through the pre-oxida tion treatment developed an unusually heavy glassy coating. This was attributed to sodium nitrite contained in the grinding coolant fluid. Careful washing of the remaining stators with distilled water and thorough drying before pre-oxidation eliminated the problem. All ACC stators were given the same cleaning and drying treatment before returning to ACC for their pre-oxidation processing.

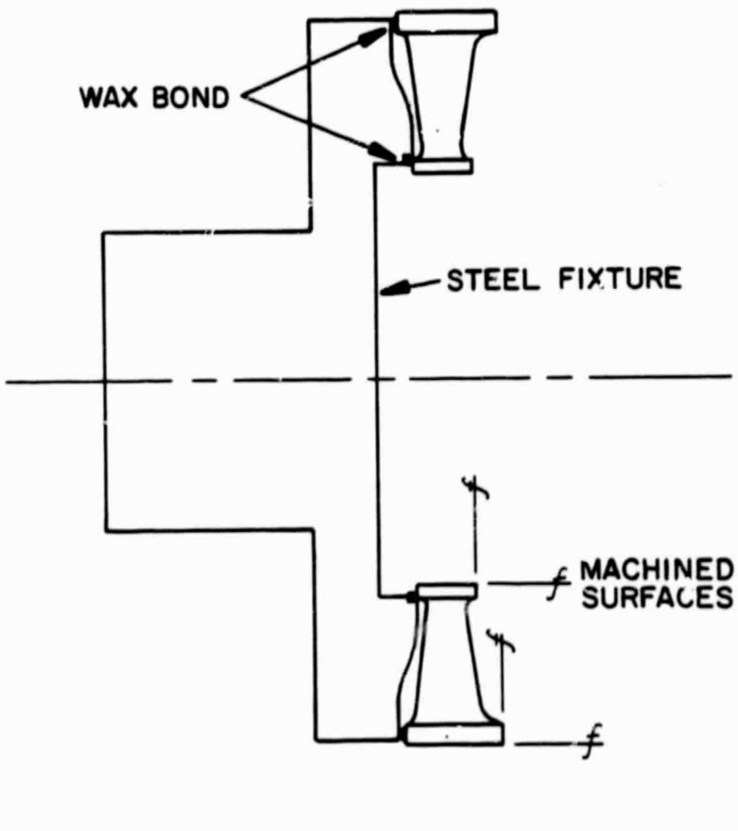


Figure 10 Fixture and Stator Mounting for First Machining Steps

CERAMIC SUPPORT HARDWARE

The typical ceramic support hardware used in the durability test rig is shown in Figures 11 and 12. All the structural ceramic components were procured through outside ceramic suppliers while the majority of the ceramic hot flowpath components were fabricated by Ford from reaction bonded Si_3N_4. The specific materials and sources used for each component are presented in Table 8. The need for the special adaptor rings developed during the test phase of the program, and these were fabricated from extra stator castings supplied by Carborundum.

DISCUSSION

The primary objectives of the fabrication effort were to assess the ceramic industry's capability to fabricate one-piece ceramic stators using near-net-shape processes, and to obtain stators for durability testing. The success of all four participants clearly demonstrates the capability for fabricating complex components from two processes, slip casting and injection molding. Good airfoil contours and surfaces, requiring no machining, were produced from Si_3N_4 and SiC materials. Although fairly extensive diamond grinding was required to remove excess stock off the shrouds, with some additional process and tooling changes, it is anticipated that the excess stock could be minimized. If this step is successful, stators could then be fabricated requiring minimal, relatively simple machining such as OD and ID grinding, flat face machining and, if necessary, radiusing of corners. Production of low cost near-net-shape stators seems achievable.

The NDE procedures used in conjunction with the fabrication effort clearly could identify numerous imperfections, both surface and internal. Emphasis was placed on identifying as many "flaws" as possible. In addition, as more sophisticated techniques are developed and applied the number of indications would likely be increased.

Past experience has shown that, for a given ceramic component, certain fabrication imperfections can be tolerated without impairing its intended function. As such, NDE can be coupled with component evaluation at design operating conditions. Then, as successes are achieved (or failures analyzed) the relevance of the NDE observations can be assessed. The end product can then be improved by providing direction for developing appropriate accept/reject criteria, improving the NDE detectability in critical areas, or altering the processing or design to allow the "flaws" to be moved to non-critical areas.

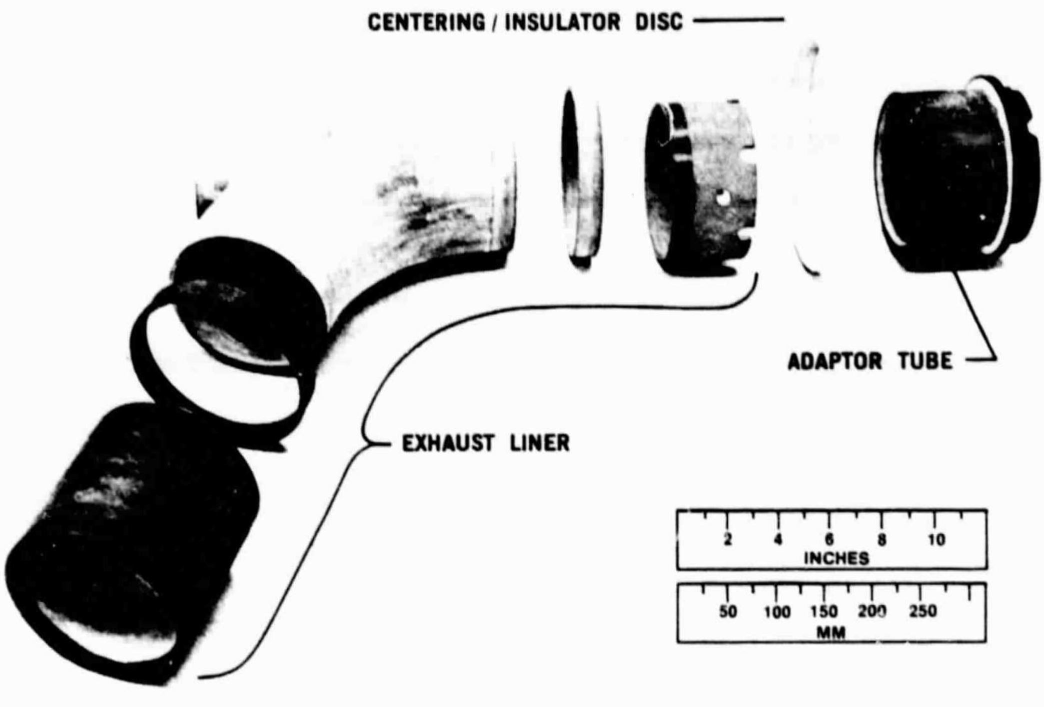


Figure 11 Structural Ceramic Components Used in Durability Cycle Test Rig

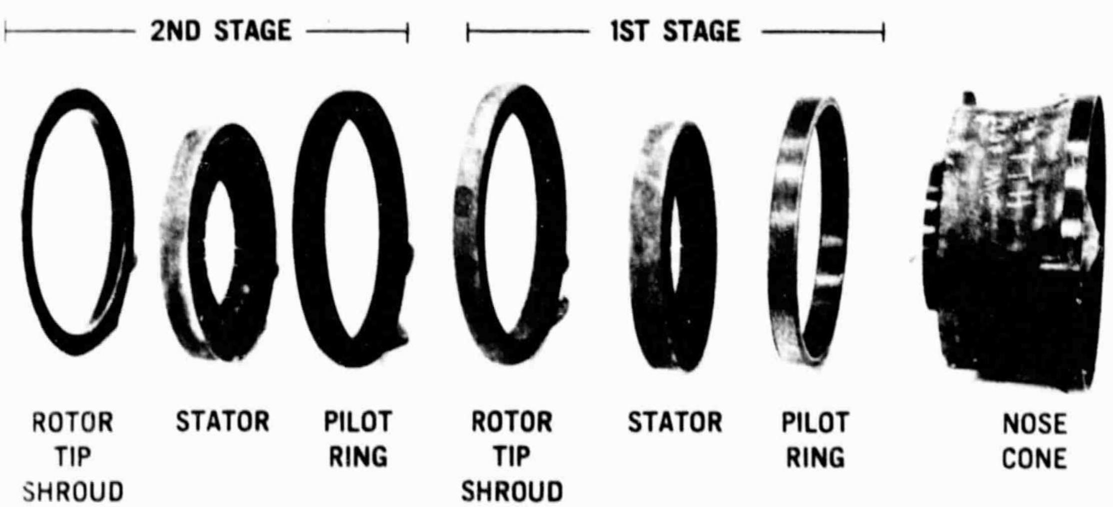


Figure 12 Ceramic Hot Flowpath Components Used in Durability Cycle Test Rig

TABLE 8
CERAMIC SUPPORT HARDWARE
DURABILITY TEST RIG

PART NAME	MATERIAL	SOURCE
	STRUCTURAL CERAMIC COMPONENTS	
ADAPTOR TUBE	REFEL SIC	PURE CARBON CO
CENTERING/ INSULATOR DISC	LITHIUM ALUMINA SILICATE (9458)	CORNING GLASS WORKS
EXHAUST LINER (ELBOW, TUBES, RINGS)	CRYSTAR SIC	NORTON CO.
	HOT FLOWPATH COMPONENTS	
NOSE CONE	Si_3N_4	FORD (injection molded)
	Si_3N_4	BSA GROUP RES. CEN.
CENTERING RINGS	Si_3N_4	FORD (slip cast)
TIP SHROUDS	Si_3N_4	FORD (slip cast)
ADAPTOR RINGS	α SIC	CBO

STATOR EVALUATION

OBJECTIVES

The primary objective of the stator evaluation effort was to assess the durability of the one-piece ceramic stators when subjected to cyclic operating conditions representative of automotive turbine engines. The goal was to demonstate 500 hours of life for a one-piece ceramic stator.

The durability evaluation was to be conducted in two phases representing two levels of engine operation. The first phase consisted of 1,600 hours of testing under a duty cycle having a maximum temperature of 1204°C (2200°F). Stators from all four suppliers would be evaluated. In the second phase 300 hours of testing would be accumulated under a duty cycle with a maximum temperature of 1371°C (2500°F). Only those stators made from materials considered to have potential use as automotive turbine components at this elevated temperature would be tested in this phase.

Stator durability would be assessed in terms of integrity, dimensional stability and weight gain.

APPROACH

The durability evaluation was conducted in the Ford Hot Flowpath Test Rig (HFTR), originally designed for steady state, high temperature testing of turbine components [5]. Duty cycles were developed based on predicted passenger car turbine engine usage, and included airflow and temperature variations. An automatic, closed loop control system was developed for the HFTR to accurately reproduce the duty cycle for all the stator evaluations. All stators selected for duty cycle evaluation were subjected to preliminary qualification tests. Cyclic testing was conducted on 23 stators at the lower temperature and 6 at the higher temperature, accumulating over 2,400 total hot test hours and over 135,500 thermal cycles.

Durability Test Rig

The Ford Hot Flowpath Test Rig (HFTR) which was used as the durability test rig is shown in cross section in Figure 13. It was designed to test turbine stationary hot flowpath components at temperatures up to 1371°C (2500°F). The rig consists of a stainless steel shell and inner ceramic flowpath separated by high temperature insulation. Pre-heated compressed air is delivered to the plenum and combustor at temperatures up to 593°C (1100°F) from the test facility. Combustor exit temperture is controlled by metering fuel flow and monitored by three thermocouples. Airflow is metered by a sharp edge orifice and adjusted via a series of valves. Test components are housed in the adaptor tube immediately downstream of the metal turbine combustor. The hot gases are cooled by water spray before dumping into the cell exhaust system. A view port is provided for visual observation of the test components.

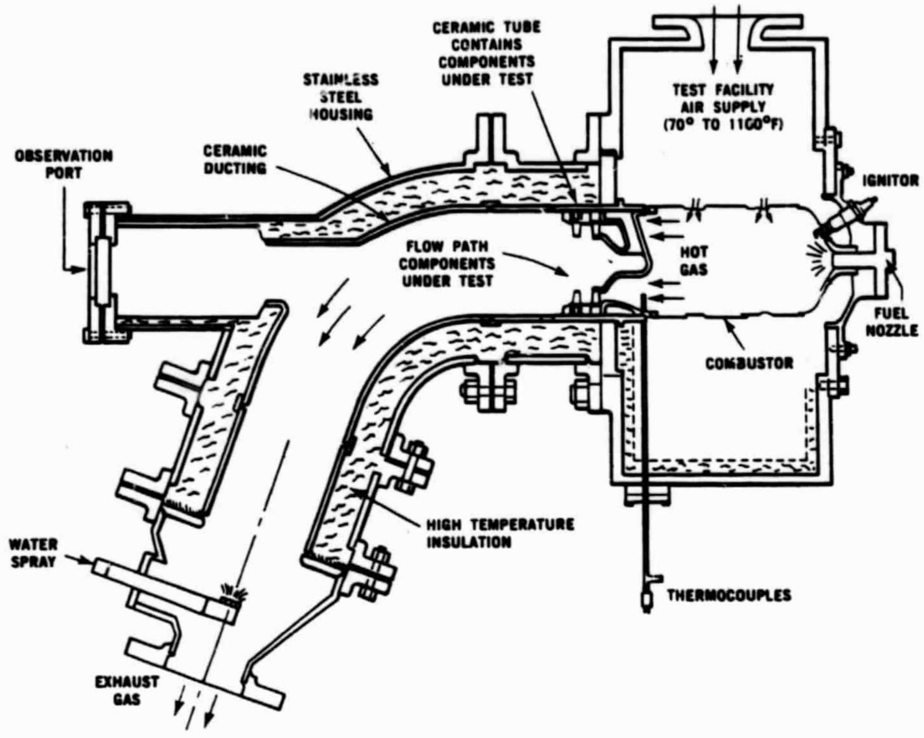


Figure 13 Schematic Cross Section of Durability Test Rig

Durability Duty Cycles

As mentioned earlier, the duty cycles were based on predicted passenger car turbine engine usage and were developed for two levels of engine operation. Because of the complex, highly transient nature of the overall cycle, only the lower, 1204°C (2200°F) temperature cycle will be described in detail. For the 1371°C (2500°F) cycle the time intervals remain the same and only the levels of airflow and temperture are changed.

The basic four-hour cycle (Figure 14), consists of a series of one-minute thermal cycles. Three different airflow rates are used with a different peak turbine inlet temperature for each airflow. The first hour consists of 40 one-minute cycles from 704°C (1300°F) to 1121°C (2050°F) at an airflow of 0.32 Kg/sec. (0.70 lbs./sec.) and 20 one-minute cycles from 704°C to 1177°C (2150°F) at an airflow of 0.41 Kg/sec. (0.93 lbs./sec.). This is repeated for the second and third hours of the cycle.

The fourth hour is different from the first three and consists of 29 and 14 one-minute cycles, respectively, at the same conditions noted earlier plus 17 one-minute cycles at the maximum conditions varying from 704°C to 1204°C (2200°F) at an airflow of 0.64 Kg/sec. (1.40 lbs./sec.). This basic four-hour segment is then repeated over and over again to accumulate the durability objective. Note that each individual one-minute cycle features a very rapid temperature increase from 704°C to the maximum temperature desired, a 40-second hold at that temperature, a sharp temperature drop to 927°C (1700°F) and a slow temperature decrease to the 704°C starting point.

For the 1371°C (2500°F) cycle the airflow and temperature levels are:

Air Flows Kg/sec (lbs/sec)	Temperatures °C (°F)
0.31(0.68)	871-1288-1093-871 (1600-2350-2000-1600)
0.40(0.88)	871-1343-1093-871 (1600-2450-2000-1600)
0.50(1.1)	871-1371-1093-871 (1600-2500-2000-1600)

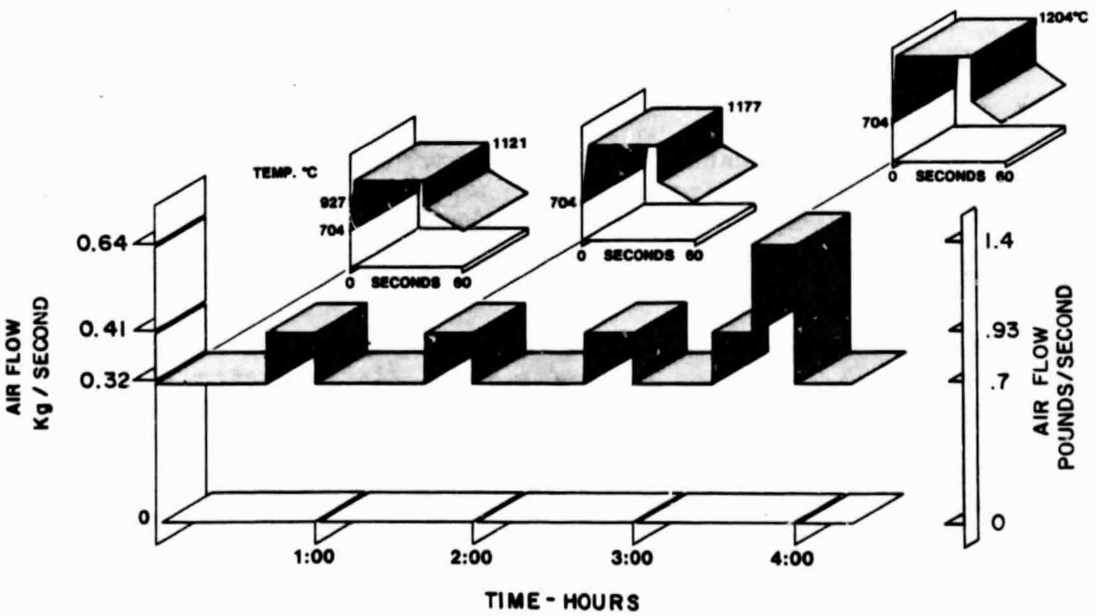


Figure 14 Durability Duty Cycle

Rig Automation

The test rig was originally designed for manual steady state opertion. In order to insure that all stators evaluated be subjected to the same cyclic conditions, an automatic control system was developed. The system was designed to operate closed loop on temperature and airflow. Safety monitoring functions were included which would automatically shut down the rig fuel and airflow in the event of a malfunction which could jeopardize the test. The system was designed to start or stop the test at any of the 240 individual cycle points, or to pre-select several repeats of the basic four-hour cycle. The rig would thus be capable of running around-the-clock without input from the operator.

Qualification Tests/Rigs

Finished machined stators were subjected to qualification tests prior to evaluation on the durability cycle. Such tests had been found useful in screening out defective parts and thereby increasing the reliability of parts selected to run under engine operating conditions. Available test fixtures and rigs were used. The qualification tests planned were a Vane Bend Test (VBT), a Shroud Pressure Test (SPT) and a Light-off Qualification Test (L/O Qual).

The VBT serves to screen out those stators having flaws in the critical vane/shroud junction area. A simple fixture was used to axially load the stator vane through the inner shroud segment (Figure 15). The leading and trailing edges and the back of the vane are subjected to tensile stress, depending on the direction of loading. A load level of 8.6 Kg (19 lbs.) had been developed for screening Ford Si_3N_4 stators having large interior flaws or critical leading and trailing edge flaws [2].

The SPT is intended primarily to screen stators for defects in the stator outer shroud. The test fixture (Figure 16) subjects the outer shroud to a tensile tangential stress by applying an internal hydraulic pressure. Stators are tested in the finish machined condition to include any detrimental effects due to grinding. The internal pressure is adjustable by a pressure control valve. A pressure level which produces 41.4 MPa (6000 psi) tensile stress in the shroud was used based on previous experience with Ford Si_3N_4 stators [2]. The final qualification test is the L/O Qual test in which the stators are subjected to 10 simulated engine cold starts. An engine simulator rig is used which consists of the Ford Model 820 engine with the turbine rotors removed. Stators are installed in the normal first stage position, just downstream of the nose cone and combustor. Engine light-off speed is set, and when a light is detected, engine speed is ramped to "idle" conditions while maintaining a combustor exit temperature of 1054°C (1930°F). Several different hold times are used as shown in Table 9. When the hold time is reached, fuel flow is stopped and the engine speed returned to the light-off point. The thermal transients seen by the stators are shown in Figure 17.

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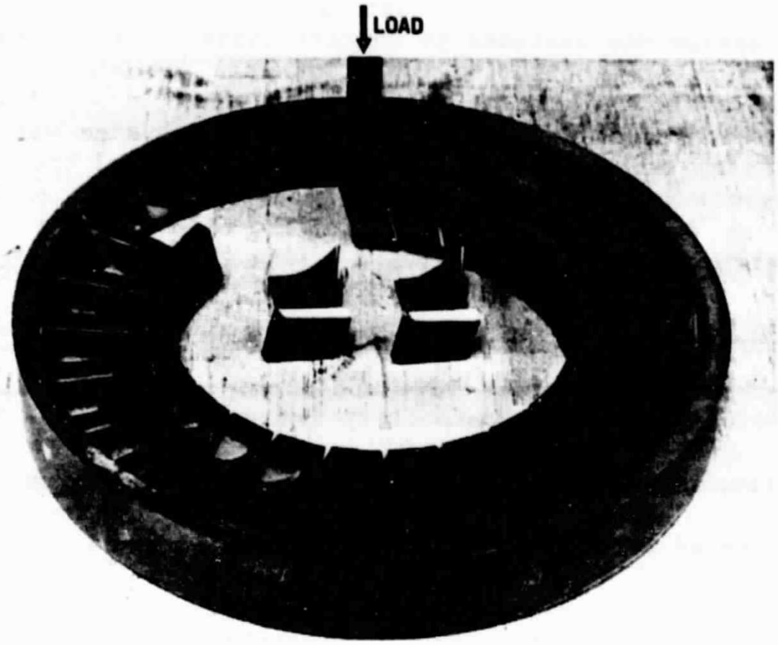

Figure 15 Stator Vane Bend Test Setup

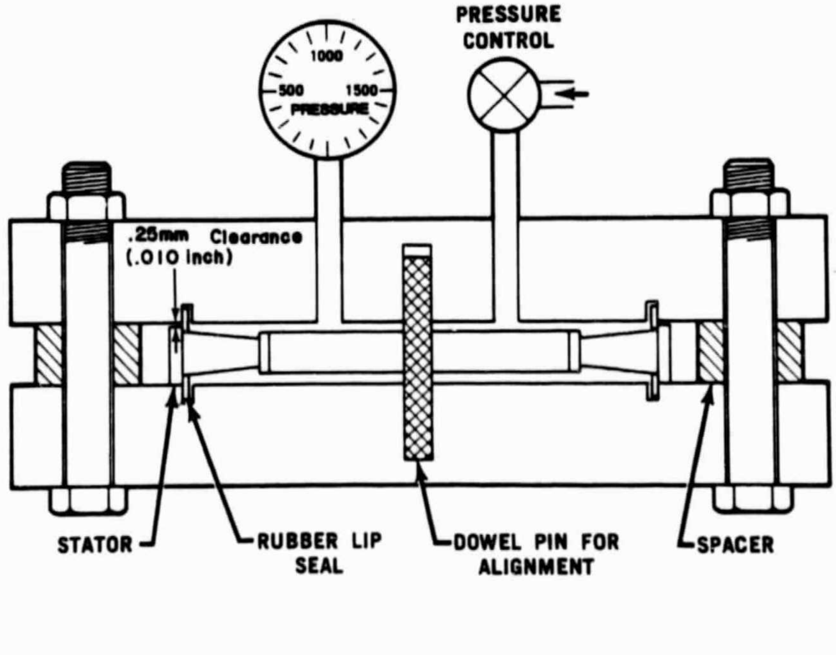

Figure 16 Stator Outer Shroud Pressure Test Fixture

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TABLE 9

LIGHT-OFF QUALIFICATION TEST

NUMBER OF LIGHT	LIGHT-OFF TEMPERATURES* °C (°F)	HOLD TIME AT 1054°C (1930°F) (SECONDS)
1	21 (70)	30
2-5	66 (150)	30
6-9	66 (150)	60
10	66 (150)	300

Total Number Of Light-Offs—10

Total Time At Temperature—420 Seconds

*** Forced Cooling Used Between Lights To Achieve These Temperatures**

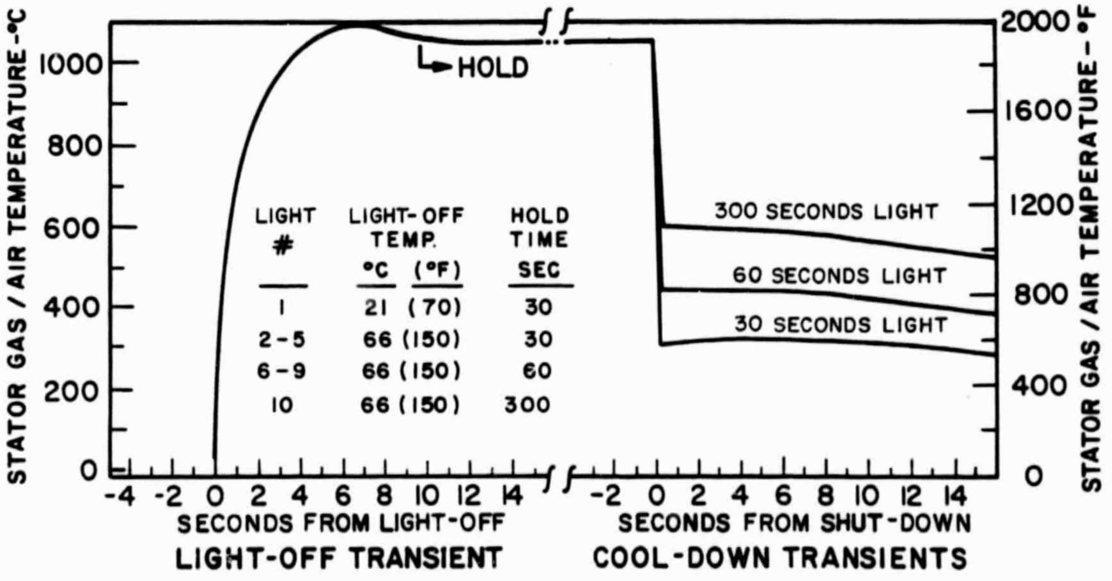

Figure 17 Typical Temperature Transient - Light-Off Qualification Test

TEST RIG DEVELOPMENT AND AUTOMATION

Preparation of the test rig for duty cycle operation centered around two major tasks. The first task was the development of a combustor with suitable durability to operate over the full range of airflows and temperatures of the duty cycles. The second task was to design and develop the control system for fully automatic duty cycle operation.

Combustor Development

An existing combustor design was available which had been developed and demonstrated for hundreds of hours over primarily steady running conditions up to 1371°C (2500°F). However, the durability of this design under the highly transient conditions of the proposed duty cycle was uncertain and therefore of concern since any combustor failure during the durability evaluations could result in damage to the stators. Since relatively low temperature incoming air was available for combustor veil cooling, Hastelloy X combustors were used throughout this program to easily implement design changes. This allowed for the development of a combustor with acceptable transient-cycle durability and performance within the lead time associated with the control system design, procurement and installation.

Slightly different combustor designs evolved for the two duty cycles. This resulted mainly from balancing the requirements for good lean blow out characteristics at the low temperature of the cycle and carbon-free operation at the high temperatures. The first configuration was developed for the lower temperature cycle by modifying the original design by adding appropriate wall cooling. After several minor design iterations a suitable configuration was developed which had good lean blow out performance and carbon-free operation over all cycle airflows and temperatures. The combustor for the high temperature cycle was developed by first increasing the veil cooling air and stiffening the walls. This upset both the lean blow out and carbon formation performance. However, by resizing and relocating the air entry holes, the air to fuel ratio in the primary (combustion) zone was restored to that in the lower temperature configuration and acceptable performance was achieved. This high temperature cycle configuration was found to perform well for the lower temperature cycle also, to subsequently become the standard for both duty cycles. photographs of the two configurations are shown in Figure 18.

Rig Automation

Ultra Electronics Incorporated, having an extensive background in electronic engine and system controls, was selected to design and build the automatic control. The system chosen was their Programmable Analog Control (PAC), a hybrid type, with the unique advantage of computing analog signals directly yet providing digital programmability. A software program is used to define the makeup and nature of the control loops including gains, reference levels, etc. This provided improved flexibility over conventional analog controls during system development. Experimental loops could be added or modified in a matter of minutes or hours compared to days for conventional hand-wired circuits.

(a) (b)

Figure 18 Hastelloy X Combustors Developed for Durability Test Rig: (a) 1204°C (2200°F) Cycle Combustor. (b) 1371°C (2500°F) Cycle Combustor

A block diagram of the sensors and actuators used in the control system is shown in Figure 19. Functionally the system was divided into four main activities:

- .Operating mode selection
- .Sequencing for start and shut down
- .Closed loop control of airflow and temperature
- .Safety monitoring for emergency shut down

Mode selection allowed the operator to choose any of four modes of operation. Manual - giving full authority to the rig operator to set airflow and fuel flow. Auto start - giving full authority to the control system to establish light-off conditions and automatically raising airflow and temperature to "idle" conditions after light-off is detected. Steady state - allowing the operator to independently select airflow and temperature levels for continuous closed loop control running. Duty cycle - for continuous operation under the pre-programmed duty cycle.

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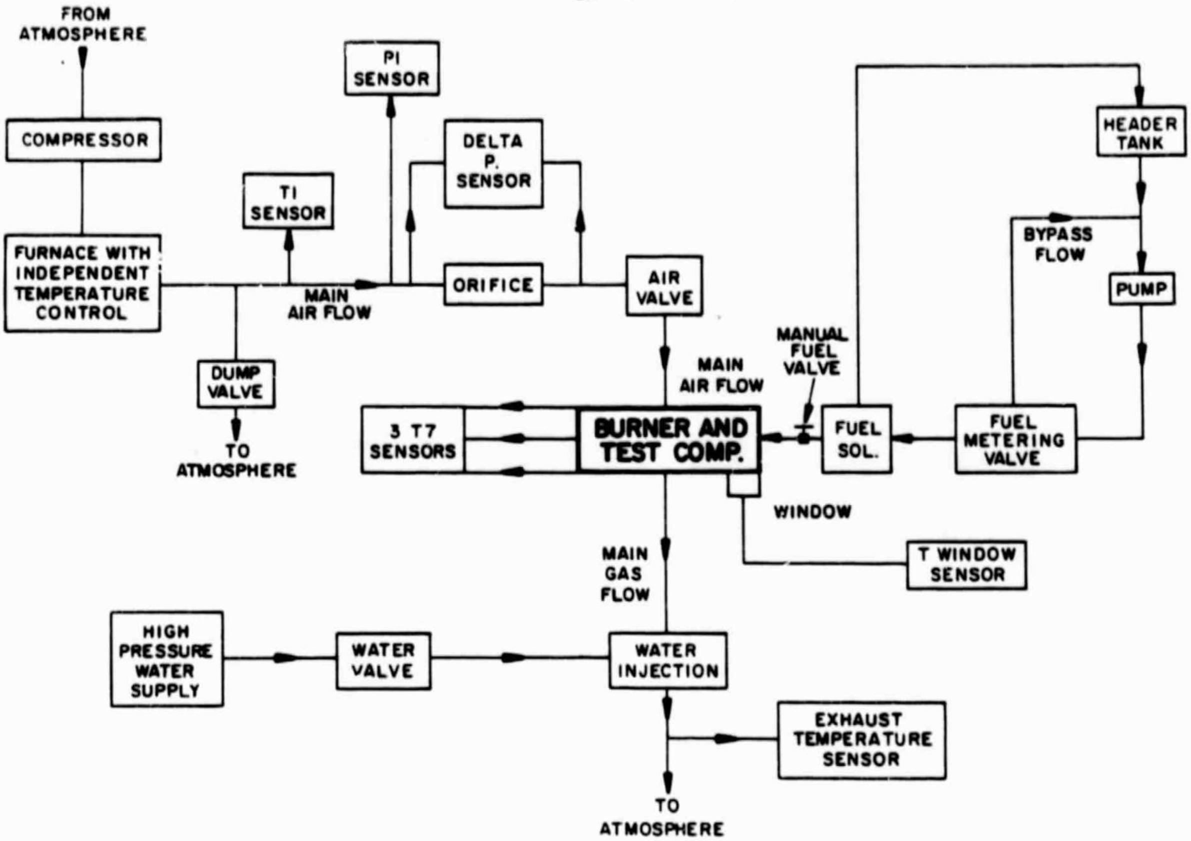

Figure 19 System Block Diagram

Control sequencing functions were written into the computer software. Separate sequences were automatically executed to manipulate the air control valve, dump valve, fuel and water shut off valves and the ignitor, depending on inputs to or conditions sensed by the control system. Sequence triggering conditions include auto start, normal shut down, and end of cycle or emergency shut down conditions.

Closed loop control functions regulate the main airflow, fuel metering and water control valves to maintain the desired airflow, combustor exit temperature and exhaust temperature, respectively. The closed loop control functions are active in all modes except manual.

The safety monitoring function serves to monitor rig operating conditions and execute an emergency shut down sequence in the event of any one of six malfunctions:

.Overtemperature at combustor exit
.Excessive spread of combustor exit temperature
.Loss of thermocouple at combustor exit

.Overtemperature at rig exhaust
.Overtemperature of view port cooling water
.Combustor flame out

Essentially the monitoring function serves to shut off immediately rig fuel and airflow and display which malfunction initiated the shut down.

Control hardware, other than the sensors and actuators identified in Figure 19, consisted of the Ultra Industrial PAC unit (Figure 20), the operator's switching and display panel (Figure 21), and a power supply.

Several difficulties were experienced with the control system as might be expected during system development. Most of the development problems normally associated with obtaining stable and responsive analog loops were taken care of in a routine manner. However, four problems manifested themselves some time after the initial system development was completed. These were:

.Excessive peak burner temperatures during duty cycle
.Flame-outs occurring during duty cycle
.Flame-outs not properly detected
.False flame-out indications

Initially the flame-out detector feature was much simpler and had no delay. Also, there was no maximum fuel schedule and the minimum fuel schedule was only a function of air flow. Figure 22a shows typical performance characteristics of the system in this initial state.

Some rationalization was made to the system software to generate spare lines and a spare working store. This allowed the following to be incorporated:

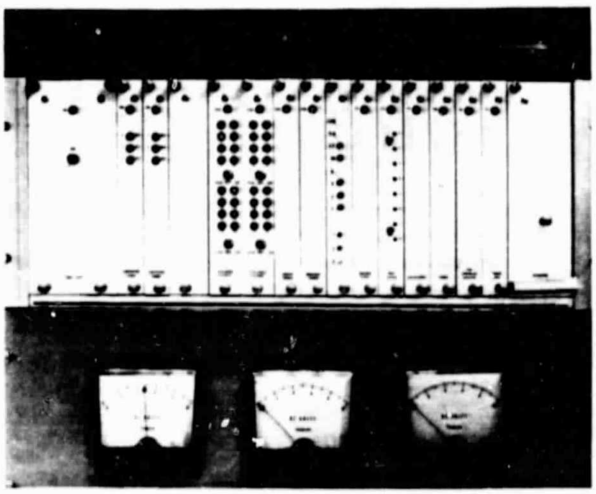

Figure 20 Industrial PAC Unit

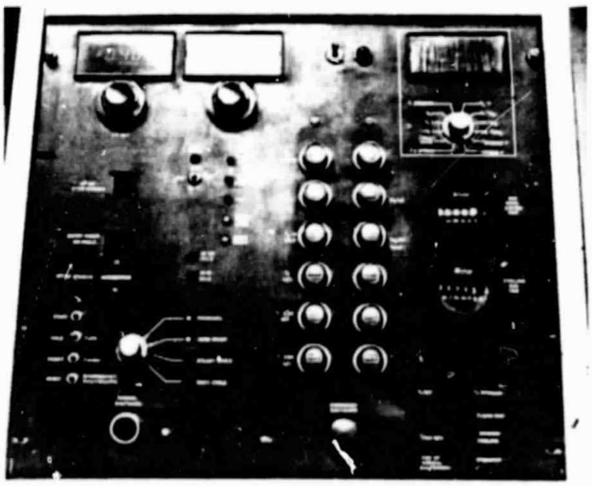

Figure 21 Operator's Control and Display Panel

.Maximum fuel schedule
.Revised minimum fuel schedule
.Revised flame-out detector logic
.A 200-millisecond delay to flame-out detector

The fuel schedule changes effectively prevented excessive peak burner temperature and frequent flame outs. The combination of revised flame out detection logic and time delay eliminated false flame out indications while reliably detecting actual flame outs. Figure 22b shows the improved performance of the fully developed system.

QUALIFICATION TEST RESULTS

Since the specific load levels in the vane bend test (VBT) and shroud pressure test (SPT) were developed from experience with the Ford Si_3N_4 stators, only the Ford stators were automatically subjected to these tests. All of the stators, however, were processed through the light off (L/O Qual.) test to qualify for durability evaluation. Test results for all the qualification tests conducted on durability test candidates are presented in Table 10.

The Ford stator failure in the VBT originated at a pin hole flaw in the vane leading edge. The flaw was not detected by any of the NDE inspections. Of the two SPT failures, one resulted from of misalignment in the fixture and the other was shattered, making it virtually impossible to identify the fracture origin. This experience prompted a revision to both the fixture and SPT technique. A sponge liner was added around the stator to prevent impact damage in the event of failure and care was taken to insure venting of all air inside the pressurized chamber before a significant hydraulic pressure level is reached. The failure of the CBO stator in the L/O Qual. test originated at a large void in the shroud which was uncovered during machining.

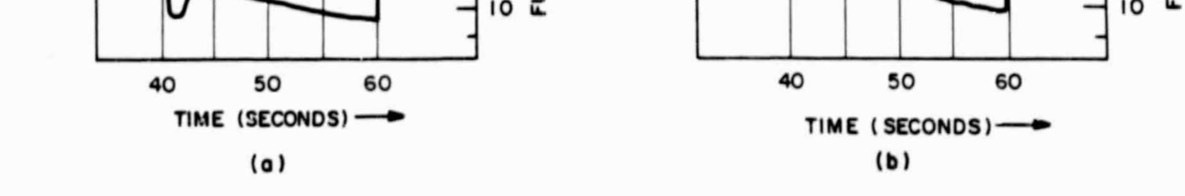

Figure 22 Combustor Exit Temperature Loop Performance. (a) Initial Development Phase - Without Maximum Fuel or Variable Minimum Fuel Flow Limits. (b) After Incorporating Maximum Fuel Flow and Variable Minimum Fuel Flow limits

TABLE 10
QUALIFICATION TEST RESULTS

STATOR VENDOR	VANE BEND TEST (VBT)	SHROUD PRESS. TEST (SPT)	L/O QUAL. TEST
ACC	—	—	12/0
CBO	—	—	10/1
FORD	13/1	12/2	10/0
NORTON	—	—	6/0

Tested/Failed

VBT—8.6 Kg (19 LBS.) Load Applied Axially To Inner Shroud

SPT—Internal Hydraulic Pressure To Produce 41.4 MPa (6000 psi) Tensile Stress In Shroud

L/O Qual-10 Lite Test

DURABILITY EVALUATION

Hot Flowpath Test Configurations

Several different hot flowpath test configurations were investigated in developing the best configurations for stator durability testing. Changes evolved as specific problems arose or to accommodate stator dimensional variations.

The original configuration shown in Figure 23a included an inner shroud extension ring, a non-standard engine part. The ring was intended to prevent hot gas bypassing the second stage stator.

Although some durability testing was successfully completed, three second stage stator failures occurred during the first thirty hours of testing. The ring was removed (Figure 23b) and over 300 hours were accumulated without any major incident. Only Ford stators were run with these configurations.

Configuration "c" was adopted after a nose cone failure, damaging both stators. The first stage stator sustained damage from both the front and rear, complicating failure analysis. The second stage stator was not actually being subjected to engine conditions because of the hot gas swirl generated by the first stage. By eliminating one stator and adjusting the rig back pressure, conditions simulating engine operation would be maintained on the first stage stator without the jeopardy of secondary damage in the event of failure. Stators from all four participants were tested in the first stage with configuration "c".

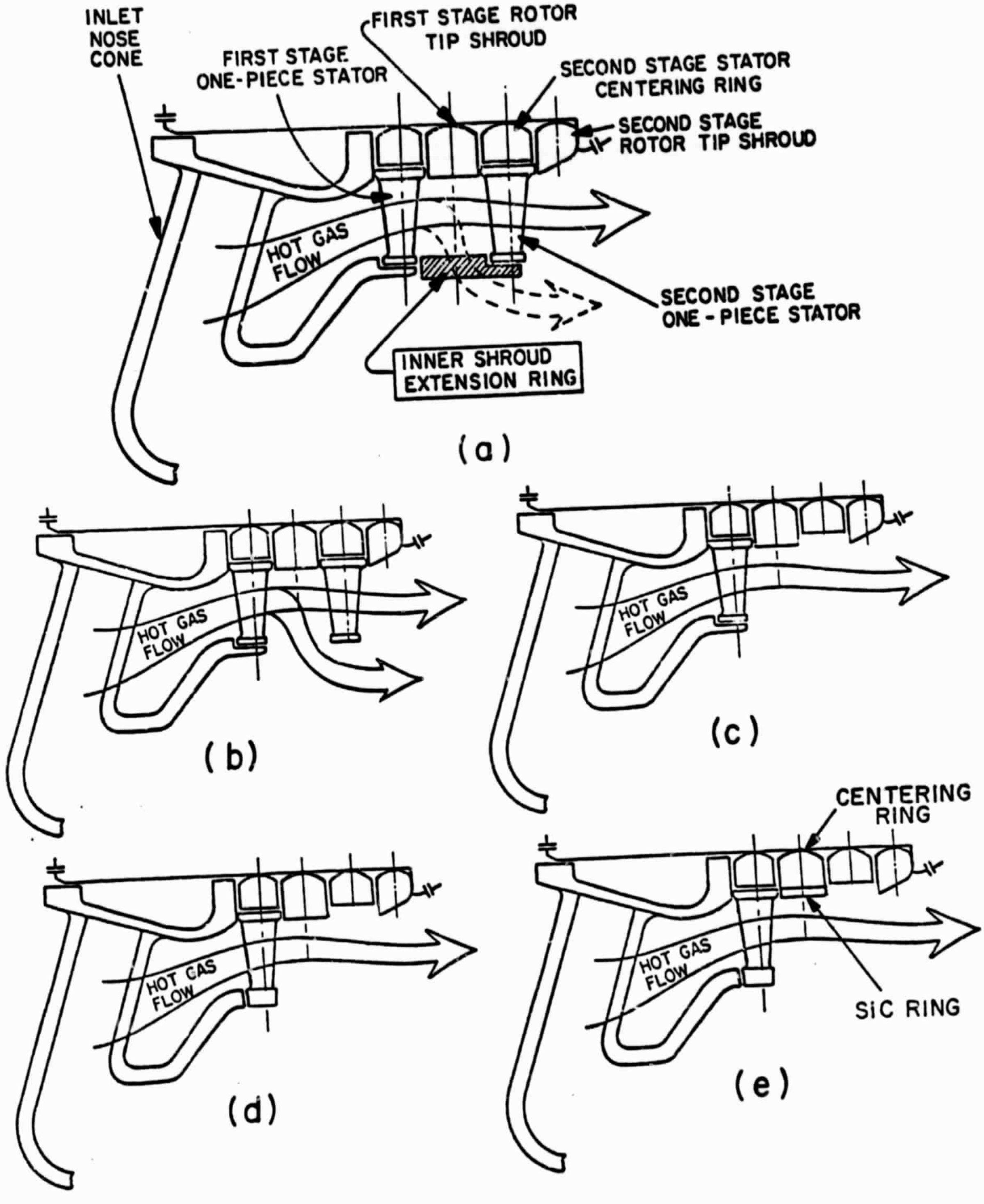

Figure 23 Hot Flowpath Test Confuguration: (a) Complete Hot Flowpath with Inner Shroud Extension. (b) Extension Ring Removed. (c) Test Stator Only in First Stage Position. (d) Nose Cone Lip Removed. (e) SiC Backup Ring for SiC stator

The last two configurations were adopted to accommodate CBO stators. Configuration "d" had a modified nose cone (the pilot lip removed) to allow testing stators without machined inner shroud inside diameters. Configuration "e", with a SiC ring behind the stator outer shroud, was used to overcome interface problems which will be discussed later.

Test Results - 1204°C (2200°F) Cycle

Twenty-three stators were tested under this phase of the program. Included were 9 Ford, 4 Norton, 4 ACC and 6 CBO stators. Table 11 presents the best times demonstrated on each one of the four different types of stators. The data presented represents the hours and cycles accumulated at the time of the last disassembly inspection when no deterioriation was observed.

Tables 12a and 12b present test results for all 23 stators tested. The listing is in chronological order based on the date of the first durability test run. In many cases the stators were tested alternately with one on test while the other was being inspected.

The first four tests in Table 12a, were run in configuration "a", consisting of two stators and the inner shroud extension ring. Seven separate runs were completed without a first stage failure. The three second stage failures were attributed to the extension ring and it was removed from the test assembly, resulting in configuration "b".

Tests 5 and 6 were a continuation of running with the highest durability time stator (S/N 10146) in the first stage position. The second stage stator (S/N 10057) was replaced when the rear face of the outer shroud developed small chips, making precise weight gain measurements difficult. At the time of removal S/N 10057 had completed 8 runs and accumulated 71:20 hours of hot testing, including one continuous 12-hour run. In test 6 the continuous run time was expanded, including two successful runs of more than 50 hours. The high-hour, first stage stator had accumulated 18 runs and 12,134 thermal cycles in over 224 hot test hours. The sixth run in test 6 was intended as a 100 hour continuous run.

After 69 hours a failure was observed. The nose cone bell cracked causing extensive damage to both stators. At the time of shut-down the first stage stator had accumulated 15,998 thermal cycles in 293:28 hot test hours and the second stage had 10,511 thermal cycles in 193:39 hours.

The two damaged stators are shown in Figure 24. Six of the seven vane failures on the first stage stator showed evidence of impact damage from the trailing edge side. The seventh vane was completely missing. All fracture surfaces of the second stage stator had evidence of impact crack initiation. Because the extensive secondary damage made failure analysis unduly difficult, all remaining durability tests were run with only one stator, in the first stage position. The test rig back pressure was adjusted to maintain the same stator inlet pressure as had been run with the two-stator configuration. Thus the gas velocity and aerodynamic loads on the first stage stator were maintained.

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TABLE 11

BEST DEMONSTRATED DURABILITY

1204 °C (2200 °F) CYCLE

VENDOR	MATERIAL	ACCUMULATED DURABILITY RUNS	CYCLES	HOT HOURS
ACC	SLIP CAST Si_3N_4	15	8,003	144
CBO	MOLDED SiC	64	15,994	299
FORD	MOLDED Si_3N_4	50	28,856	514
NORTON	SLIP CAST SiC	4	4,624	82

TABLE 12 (a)

FORD STATORS TESTED IN PAIRS — 1204°C (2200°F) CYCLE

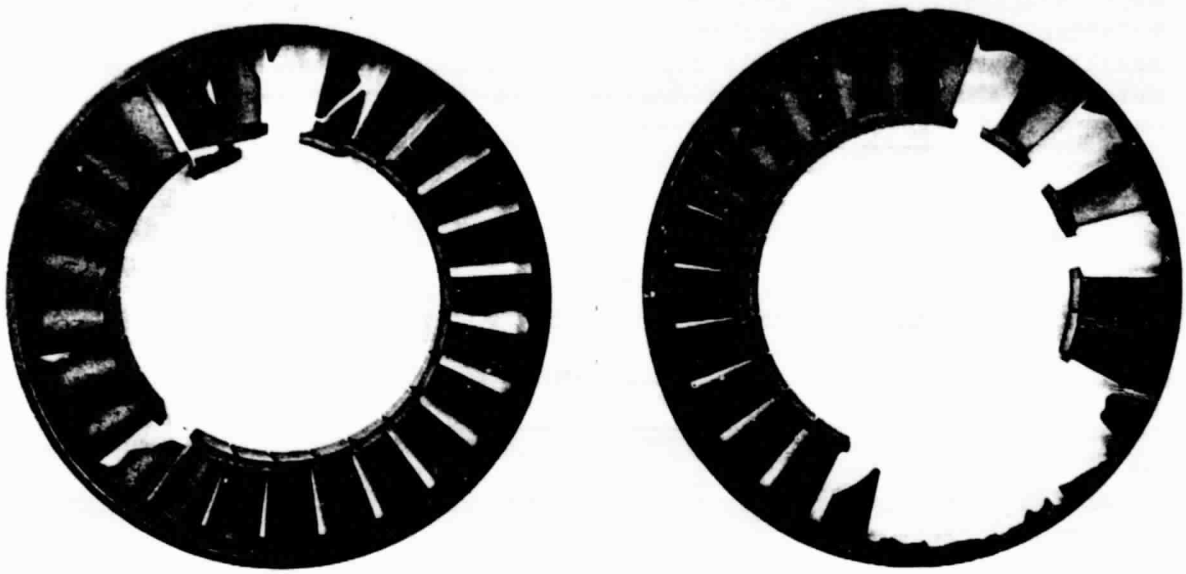
TEST REF NO.	SERIAL NO.	POS. IN RIG	TEST CONFIG.	RUN NO.	CUMULATIVE DATA FOR EACH STATOR NO. RUNS	HOT HOURS	CYCLES	STATOR CONDITION/COMMENTS
1	10127	FIRST	A	1	1	:42	18	OK
	10158	SECOND			1	:42	18	OK
				2	2	2:36	114	OK
					2	2:36	114	FAILED, 3 OUTER SHROUD CRACKS
2	10035	FIRST	A	1	1	4:30	240	OK
	10146	SECOND			1	4:30	240	OK
3	10146	FIRST	A	1	2	8:42	480	OK
	10035	SECOND			2			OK
				2	3	12:42	710	OK
					3			FAILED, IMPROPERLY SECURED EXT. RING
4	10146	FIRST	A	1	4	17:56	1,005	OK
	10127	SECOND			3	7:50	409	OK
				2	5	28:56	1,641	OK
					4	18:50	1,045	FAILED, 4 OUTER SHROUD CRACKS
5	10146	FIRST	B	1-4	9	68:27	3,789	OK
	10057	SECOND			4	39:32	2,148	OK
				5-8	13	100:15	5,487	OK, NO TEARDOWN BETWEEN RUNS
					8	71:20	1,698	OK, CHIPS ON REAR FACE, REMOVED FROM TEST
6	10146	FIRST	B	1-5	18	224:32	12,134	OK } INCLUDED 4 CONSECUTIVE RUNS
	10119	SECOND			5	124:43	6,647	OK } W/O INTERMEDIATE DISASSEMBLY
				6	19	293:28	15,998	} DAMAGED BY NOSE CONE FAILURE
					6	193:39	10,511	

Test number 7 (Table 12b) was the test of a Norton stator S/N J which successfully completed four runs of 4, 8, 35 and 31 hours, accumulating 4,624 thermal cycles. A rig malfunction on the fifth run resulted in a harsh, audible light-off. An immediate overtemperature automatic shut-down occurred; however, the stator had developed two outer shroud cracks and five broken vanes.

TABLE 12 (b)

SUMMARY OF STATORS TESTED SINGLY — 1204°C (2200°F) CYCLE

					CUMULATIVE DATA FOR EACH STATOR			
TEST REF NO.	VENDOR	SERIAL NO.	TEST CONFIG.	RUN NO.	NO. RUNS	HOT HOURS	CYCLES	STATOR CONDITION/COMMENTS
7	NORTON	J	C	1-4	4	82:13	4,624	OK
				5	5	82:13	4,624	FAILED, RIG START-UP MALFUNCTION
8	FORD	10162	C	1	1	4:10	198	NOT DISASSEMBLED
				2	2	6:35	240	FAILED, 1 OUTER SHROUD CRACK
9	FORD	10181	C	1	1	4:44	240	OK
				2	2	56:20	3,240	FAILED, 1 OUTER SHROUD CRACK
10	NORTON	L	C	1	1	3:48	192	NOT DISASSEMBLED
				2	2	6:44	340	FAILED, 1 OUTER SHROUD CRACK
11	NORTON	G	C	1	1	5:55	300	OK
				2	2	56:28	3,300	FAILED, 1 OUTER SHROUD CRACK
12	FORD	10168	C	1-50	50	513:41	28,856	OK
				51	51	523:31	29,363	FAILED, 1 SHROUD, 2 VANE CRACKS
				52	52	535:19	30,046	NO CHANGE
13	NORTON	P	C	1-6	6	69:43	3,957	OK
				7	7	82:19	4,677	FAILED, 1 OUTER SHROUD CRACK
14	ACC	0125911	C	1-15	15	143:34	8,003	OK
				16	16	148:58	8,286	FAILED, 3 VANE CRACKS
15	ACC	01089	C	1	1	5:55	300	OK
				2	2	12:01	610	FAILED, 2 VANE CRACKS
16	ACC	0206957	C	1-13	13	135:10	7,720	OK
17	CBO	55	C	1-3	3	19:55	1,006	OK
				4	4	28:31	1,473	FAILED, 3 OUTER SHROUD CRACKS
18	CBO	58	D	1	1	5:18	251	OK
				2	2	12:28	726	FAILED, 1 OUTER SHROUD CRACK
19	CBO	57	E	1-2	2	17:30	975	OK
				3	3	29:15	1,635	FAILED, 1 OUTER SHROUD CRACK
20	ACC	0116911	C	1	1	4:51	264	OK
21	CBO	68	E	1-31	31	226:50	12,759	OK
22	CBO	67	E	1-2	2	11:45	660	OK
23	CBO	71	E	1-50	50	257:26	13,733	OK



(a) (b)

Figure 24 Stators Damaged by Nose Cone Failure: (a) Trailing Edge View of First Stage Stator. (b) Leading Edge View of Second Stage Stator

Tests 8 through 11 resulted in unexpected early failures for both Norton and Ford stators. An extensive review of the detailed data for all eleven tests revealed several contrasting factors between the long and short life stators. Specifically for the Ford stators:

- Stator S/N 10146 survived over 200 hours. It was removed from the rig and inspected after each hot run and tested in increments of 12 hours or less for the first 68 hours.

- Stator S/N 10162 failed after only 240 cycles (6:22 hours). It was run twice without an intermediate removal.

- Stator S/N 10181 survived the first 240 cycles (4:30 hours) in one run, but failed to survive a second run of 50 continuous hours.

Essentially, the same contrasts appeared for the Norton stators. Stator S/N J successfully accumulated over 82 hours but was inspected after each hot run; S/N L failed in only 6 hours but was run twice without an intermediate removal; and S/N G survived a single hot test of 300 cycles (5:42 hours) then failed on the second run of 50 hours.

As has been observed in this and other ceramic test programs, it appears that premature ceramic component failures occur under conditions related to ceramic-to-ceramic interfaces. In this program, the first such condition involved a restart of the test after a complete cooldown without some slight reorientation of components as normally occurs during rebuild. The second condition is prolonged hot testing (e.g. 50 hours) before stabilizing component interface surfaces.

In an effort to isolate this situation, durability testing was resumed under a test schedule which allows for a complete hot flowpath teardown after each hot run. In addition, no attempt at a 50-hour run would be made until accumulating at least 100 hours of durability.

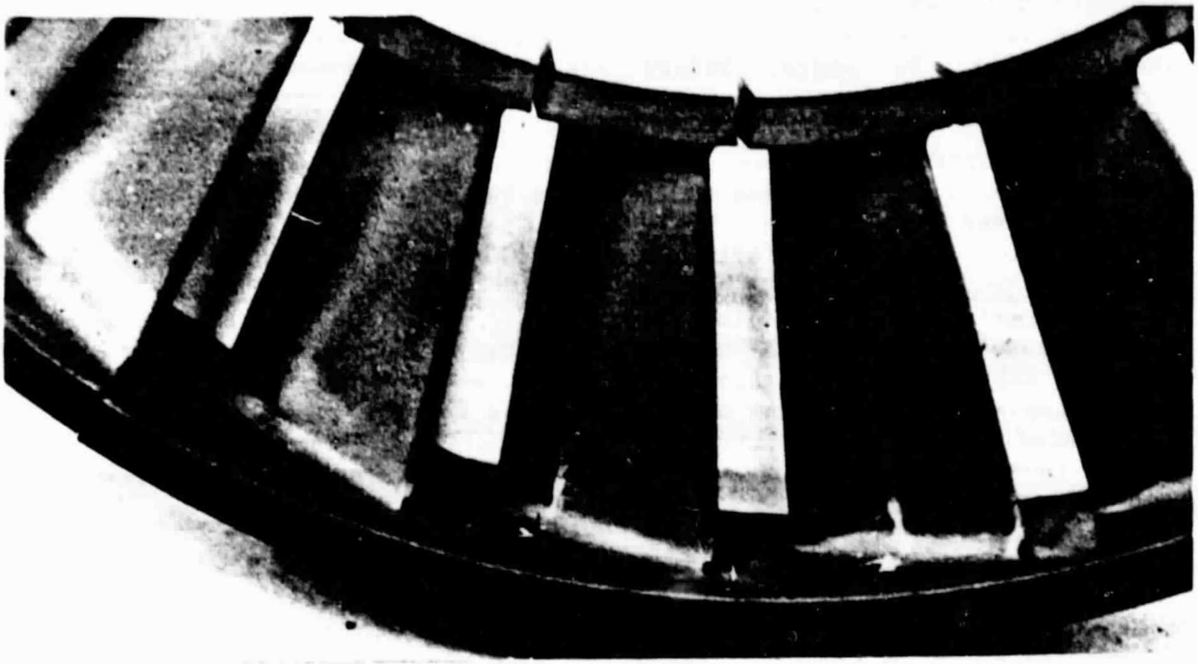
The revised test schedule was first used with a Ford stator (test #12), accumulating over 100 hours in increments of roughly 12 hours. A Norton stator was then started (test #13), and the two alternated on successive tests. One outer shroud crack was found in the Norton stator during routine inspection when the stator had completed 4,677 cycles in 82 hours of testing. The stator was removed from the durability test.

Evaluation of the Ford high-hour stator continued. Routine visual inspection after accumulating 523:31 test hours and 29,363 thermal cycles revealed a crack through the outer shroud and two vane cracks, as shown in Fig. 25. No cracks were observed during the previous inspection, after 28,856 cycles. The stator condition was documented, it was then re-installed in the rig for continued testing to meet the program objectives. The stator, despite the cracks, continued to function satisfactorily and no additional cracks occurred. In total the stator accumulated 535 hours of hot testing, which included 30,046 thermal cycles.

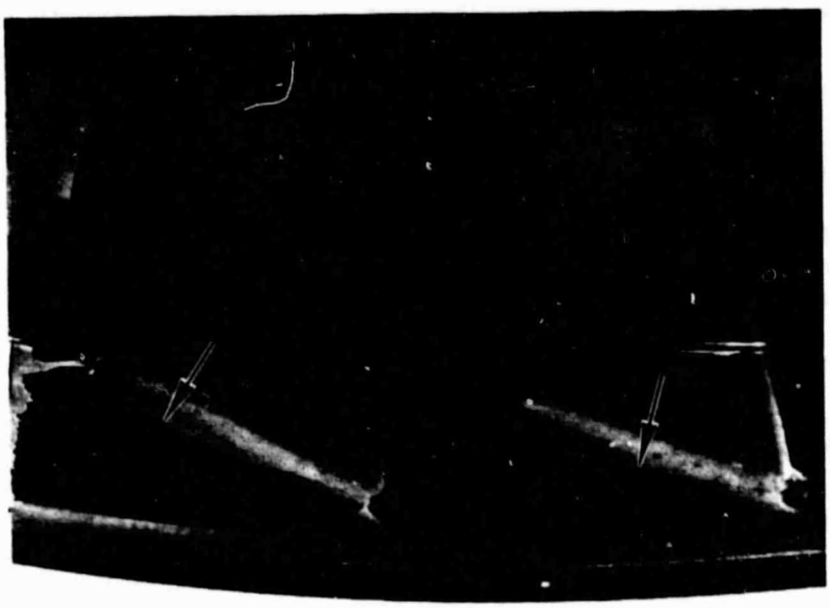
The first ACC stator evaluated (S/N 0125911, test #14) successfully completed 15 runs, accumulating 144 hours and 8,008 thermal cycles. Visual inspection showed no signs of distress except for two small chips on the outer shroud faces which appeared after the third run. Both chips were at the outer diameter. The 16th run was made after a six week interruption in testing.

After running over 4 hours, a vane failure was observed. The inner shroud segment and 6.2 mm (0.25 inches) of vane #24 broke away. The fracture started at the leading edge approximately 3.1 mm (0.12 inches) from the shroud segment. Two other vanes (#19 and #25, Figure 26) developed similar cracks starting at the leading edge and curving outward up the vane. All cracks appear thermally induced as there was no evidence of impact damage and no flaws on the fracture surface of vane #24. The stator had accumulated a total of 149 hours and 8,291 thermal cycles.

In test #15 ACC stator S/N 01089 successfully completed an initial 5-hour run with 300 thermal cycles. The second run was made with no signs of distress. However, the teardown inspection revealed two vane failures (#6 and #8). These vanes were found resting loosely in their normal position, suggesting failure occurred during shut-down. Both failures initiated at fabrication flaws in the vane leading edge (Figure 27). The flaws were pre-nitriding cracks extending approximately 0.51 mm (0.020 inches) in from the leading edge. Both flaws were observed and recorded during the "as-received" inspection.



(a)



(b)

Figure 25 Ford Stator Cracks Observed After Completing 523 Hours and 29,363 Thermal Cycles: (a) Outer Shroud Crack Between Vanes 12 & 13. (b) Fillet Radius Cracks in Vanes 10 & 11 Extend From Trailing Edge to Arrows

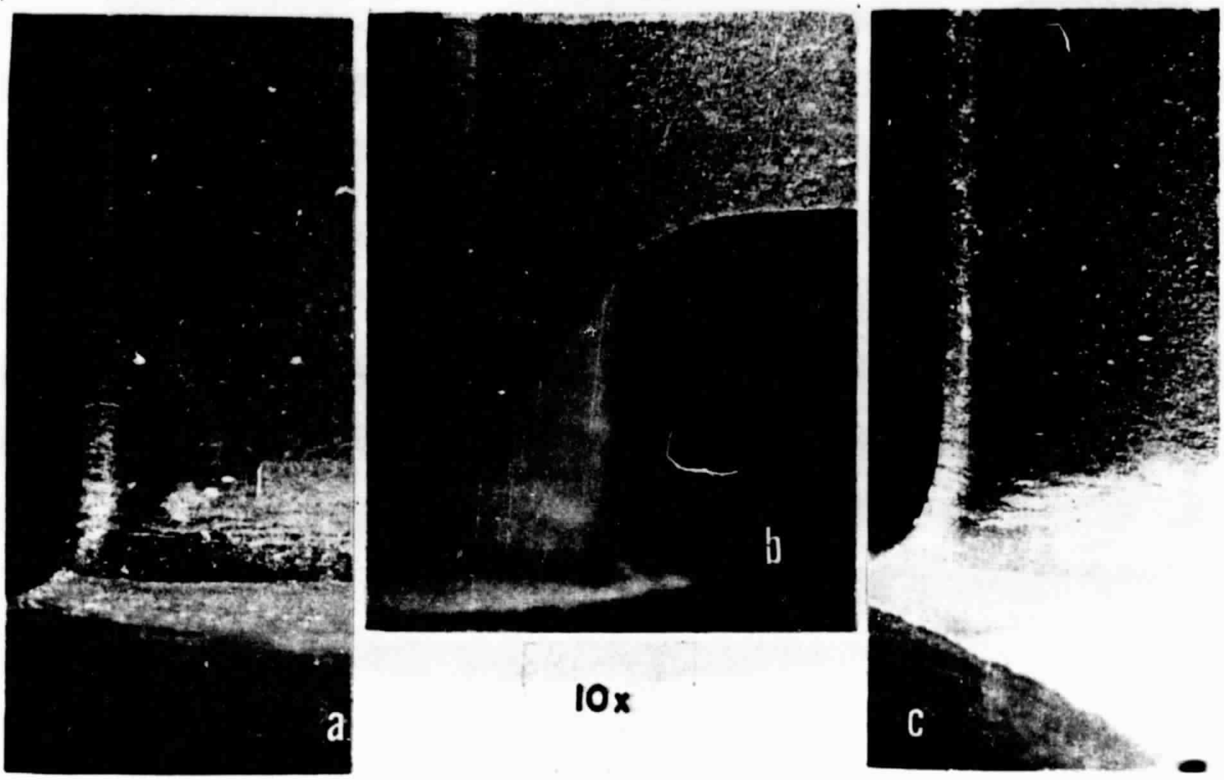


Figure 26 ACC Stator S/N 0125911 Leading Edge Cracks Observed After 149 Hours of Durability Testing: (a) Vane 19; (b) Vane 24; (c) Vane 25

Two other ACC stators were run without incident (tests #16 and #20). Stator S/N 0206957 completed 13 runs, accumulating 135:10 hours and 7,720 thermal cycles. Testing of this stator was interrupted for 8 weeks after the second run, suggesting that test interruption was not a factor in the failure of S/N 0125911 (test #14). ACC stator S/N 0116911 was run once, accumulating 4:51 hours and 264 thermal cycles.

The first CBO stator tested was S/N 55 which was machined to the "c" configuration, i.e. inner shroud fully machined to fit over the nose cone bell as shown in Figure 23d. The stator successfully completed 3 runs (test #17), accumulating 1,006 thermal cycles in 19:42 hours. After the fourth run the stator was found to have cracked through the outer shroud in 3 places. Preliminary investigation of the fracture surfaces indicated that all three fractures originated at the vane trailing edge/shroud junction. The stator was returned to CBO, at their request, for additional fractographic analysis. Their analysis revealed no apparent flaws on the fracture surfaces and a uniform microstructure.

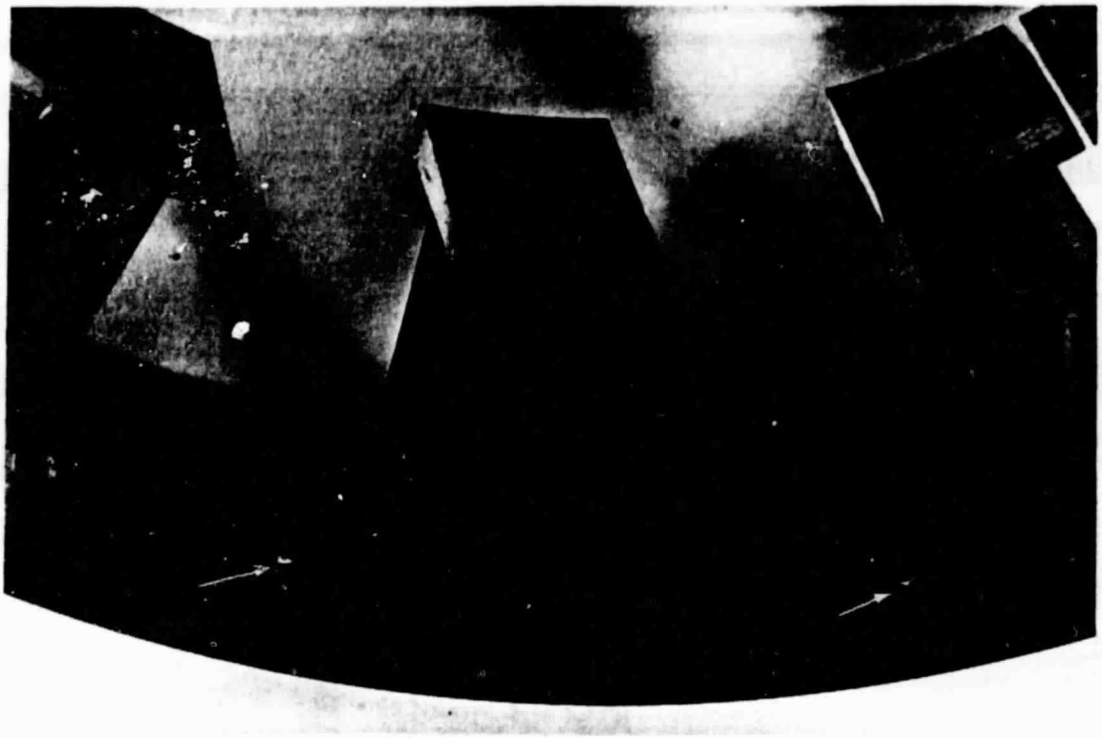


Figure 27 ACC Stator S/N 01089 Vane Failures After Duty Cycle Durability Testing. Arrows Indicate Flaw Locations

For test #18 CBO stator S/N 58 was machined for the "d" configuration. Inner shroud machining was limited to opening up of the slots in 6 locations where the slot widths were below the 0.152 mm (0.006 inch) minimum required. Post machining zyglo inspection indicated vane trailing edge/outer shroud junction cracks on vanes 11, 12 and 14 as shown in Figure 28. In addition, two pressure side fillet radius cracks were indicated on vanes 22 and 25.

The stator survived the first run of 5 hours without incident or signs of crack propagation. After the second run the stator was cracked through the outer shroud and trailing edge of vane #14 as shown in Figure 29. The trailing edge chip shown in the photograph was observed and recorded during the "as received" inspection. In total this stator had completed 977 thermal cycles in 17:46 hours of hot testing.

CBO stator S/N 57 (test 19) was run in the modified configuration with a SiC/SiC interface at the back face of the stator (configuration "e" Figure 23). A specially machined SiC ring was installed in place of the standard Si_3N_4 rotor tip shroud. Two runs of 5 and 12 hours, accumulating 975 thermal cycles, were successfully completed. After the third run (approximately 12 hours) the outer shroud was found cracked at the trailing edge/shroud junction of vane number 22. It

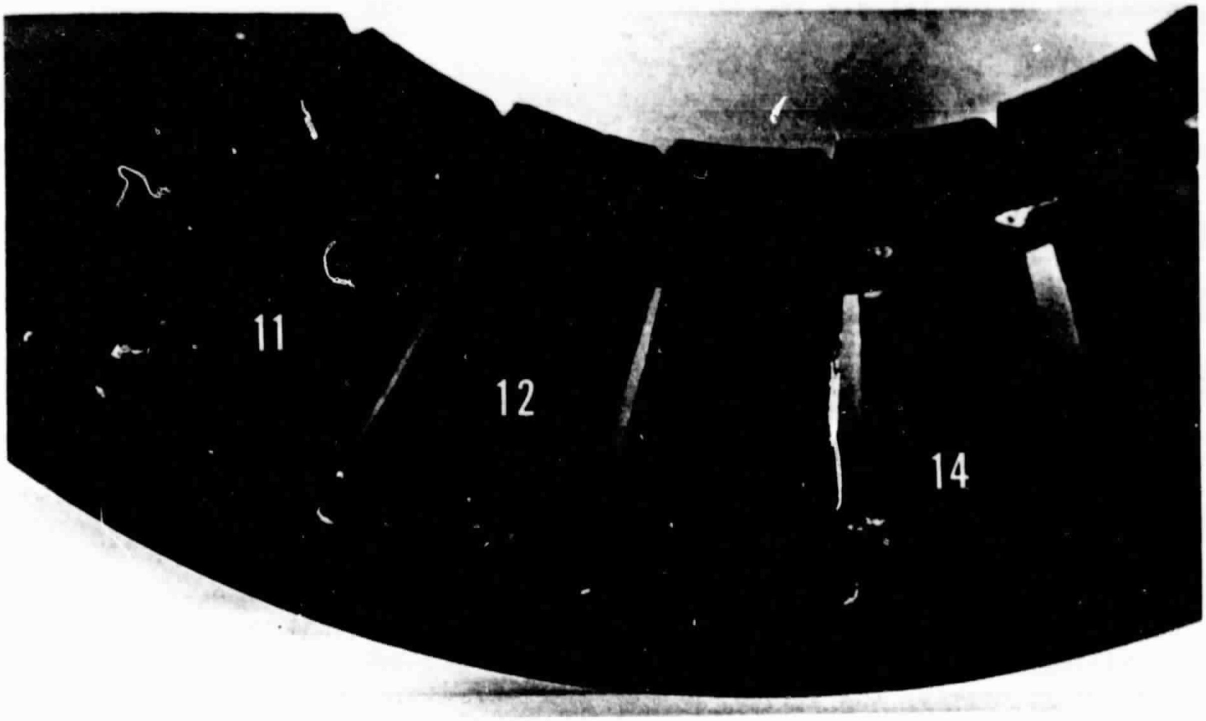


Figure 28 CBO Stator S/N 58. Zyglo Indications at Trailing Edges of Vanes 11, 12 and 14 - After Machining

Figure 29 CBO Stator S/N 58. Crack Through Trailing Edge of Vane 14 and Outer Shroud After Duty Cycle Testing for 17:46 Hours

should be noted that no significant zyglo indications had been observed in the failure region after finish machining.

Visual inspection of stator S/N 57 outer shroud faces revealed numerous small white discoloration areas on both the front face (SiC/Si_3N_4 interface) and rear face (SiC/SiC interface). The surfaces of the discolored areas appeared both as material build-up and as shallow craters.

The first three CBO stators evaluated survived the initial 5 hour runs without incident. These same stators show evidence of the localized interface surface damage after having been run continuously for approximately 12 hours. Consequently a revised test procedure was adopted in which each test run was limited to approximately 5 hours, and the interface surfaces were cleaned with 280 mesh SiC abrasive paper between runs.

Stator S/N 68 survived over 225 hours using this procedure. Stator S/N 67 also survived 2 runs without incident.

CBO stator S/N 71 was originally withheld from the durability evaluation because one vane had been accidentally broken off during machining. Test run number 23 in Table 12b was run in a deliberate attempt to develop the shroud surface discolorations observed earlier. Because of facilities limitations the stator was only run in five hour increments. A complete teardown was made following each run, however no clean-up of the shroud faces was performed. No build-up or surface damaged appeared and the stator survived 51 runs, completing over 252 hours of hot testing and 14,021 cycles before testing in this configuration was discontinued. Some additional test results on this and several other CBO stators will be presented later.

Test Results - 1371°C (2500°F) Cycle

This phase of the evaluation encompassed more than 300 hours of cyclic testing at temperatures up to 1371°C (2500°F). The stators evaluated were those fabricated by ACC, CBO and Ford, all made from materials which had potential for use at the elevated temperature.

As a preliminary evaluation, two stators of each material were initially run for approximately 4 hours. All six tests included the 1371°C (2500°F) portion of the duty cycle. The Si_3N_4 stators (ACC and Ford) were run in the "c" configuration, Figure 21. The CBO SiC stators were run in the "e" configuration. All six stators survived durability cycling without incident.

One each of the CBO and Ford stators were continued on durability test, running alternately. The interface cleaning procedure was applied to both stators after each run. No failures occurred and no new problems developed. The CBO stator accumulated 9,018 thermal cycles in 160 test hours. The Ford stator accumulated 9,085 thermal cycles in 161 hours of testing. A summary table for all stators run on the 1371°C (2500°F) cycle is presented in Table 13.

TABLE 13

1371 °C (2500 °F) DURABILITY TEST RESULTS

VENDOR	STATOR SERIAL NO.	TEST CONFIG.	NO. RUNS	HOT HOURS	CYCLES	STATUS
ACC	0312901	C	1	3:36	170	OK
ACC	0221922	C	1	5:12	280	OK
CBO	60	E	22	159:54	9,018	OK
CBO	67	E	1	4:12	220	OK
FORD	10208	C	23	161:11	9,085	OK
FORD	10081	C	1	4:24	235	OK

Supplemental Durability Testing

After completing all contractual durability evaluation requirements, the effect on durability of the Si_3N_4/SiC interface, polishing of interface surfaces and disassembly between runs was still in question. Supplemental durability testing was conducted on four Carborundum stators to further evaluate these variables.

Stator testing had shown that SiC stators could survive when running against Si_3N_4 shrouds as in tests 7,11,13,17 and 18 (Table 12b). Yet, all those stators failed in less than 100 hours (30 hours for CBO stators). Stators tested with a SiC/SiC interface failed in as few as 3 runs, as in test 19, but also survived 50 runs, as in test 23. Polishing of interface surfaces appeared highly beneficial, as in tests 21,22 and the two successful tests in Table 13. Yet, CBO stator S/N 71 accumulated over 250 hours in 50 runs without polishing (test 23, Table 12b). The need for disassembly between runs seemed significant based on the results of tests 8 and 10.

Examination of fracture surfaces of CBO stators suggested that still another factor could be influencing durability test results. Fracture surfaces of all three stators which failed on durability had coarse grains as well as the fine grain α SiC. Stator S/N 71 which had accumulated the highest time of all CBO stators had none of the coarse grains on the fracture surface of the vane broken off during machining.

The four CBO stators run in the supplemental durability testing are identified in Table 14. All had successfully accumulated some durability test time as shown in the table.

In order to identify the type of grain structure in the stators, one vane was bend tested to failure in each stator. Only S/N 71 had the fine, uniform grain structure. Stators S/N 60,67 and 68 all had grain structures similar to that on stators which had previously failed on durability test.

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TABLE 14

CARBORUNDUM STATORS

HISTORY PRIOR TO SUPPLEMENTAL DURABILITY TESTS

SERIAL NUMBER	ACCUMULATED TESTING RUNS	HOURS	CYCLES	TESTING CONDITIONS
60	22	159:54	9,018	1371 °C (2500 °F) CYCLE
67	2	11:45	660	1204 °C (2200 °F) CYCLE
	1	4:12	220	1371 °C (2500 °F) CYCLE
	3	15:57	880	
68	31	226:50	12,759	1204 °C (2200 °F) CYCLE
71	50	257:26	13,733	1204 °C (2200 °F) CYCLE

The supplemental durability testing was conducted using the lower temperature cycle since failures had only been encountered with that cycle. All testing was done in the "d" configuration, shown earlier in Figure 23. A summary of the supplemental durability testing is presented in Table 15.

Stators 71 and 67 were initially tested for 9 and 5 runs, respectively, with disassembly between runs, but without polishing. Run times ranged from 1.5 to 8 hours. Both stators survived. Both stators were then tested without disassembly between runs on separate days after a complete shut down. S/N 67 successfully completed tests of two and four consecutive runs. Stator S/N 71 successfully completed a test of five consecutive runs. The last two stators S/N 68 and 60, also successfully completed tests of four consecutive runs.

TABLE 15

CARBORUNDUM STATORS

SUPPLEMENTAL DURABILITY TESTING

SERIAL NUMBER	TEST RUN NUMBER	ACCUMULATED DURABILITY HOURS	CYCLES	CONDITION
71	1-9	28:06	1,530	OK
	(10-14)	13:42	731	OK
67	1-5	19:24	1,076	OK
	(6-7)	6:54	367	OK
	(8-11)	12:18	629	OK
68	1	2:24	110	OK
	(2-5)	17:39	955	OK
60	(1-4)	13:15	700	OK

All Tests Run With SiC/Si_3N_4 Rear Interface

( ) Consecutive Test Runs Incorporating Complete Cool Down And Restart Without Intermediate Disassembly

Since none of these four stators failed, these tests clearly demonstrate that SiC stators can run with mating Si_3N_4 components and that polishing of the interface surfaces is not essential. Also these material combinations can withstand cool-down and restarts representative of automotive turbine engine operation. However, since all four stators had accumulated some running time (35 to 285 hours) before the consecutive run testing, the possibility of a "run-in" mitigating the interface problem still exists.

All four stators were subsequently vane bend tested to failure for bend strength data. The test results are presented later in the Vane Bend Strength Testing section. The test results, however, did not show any significant differences between CBO stators which failed or survived durability testing.

Weight Gain

Stator weight was recorded during each of the routine teardown inspections throughout the durability evaluation. All the SiC stators (CBO and Norton) showed virtually no weight change. The Si_3N_4 stators (ACC and Ford) all exhibited weight gain, with the rate of weight gain decreasing with increasing durability time.

Weight gain curves for high-hour Ford stators are shown in Figure 30. The initial weight gain is the same under both duty cycles.

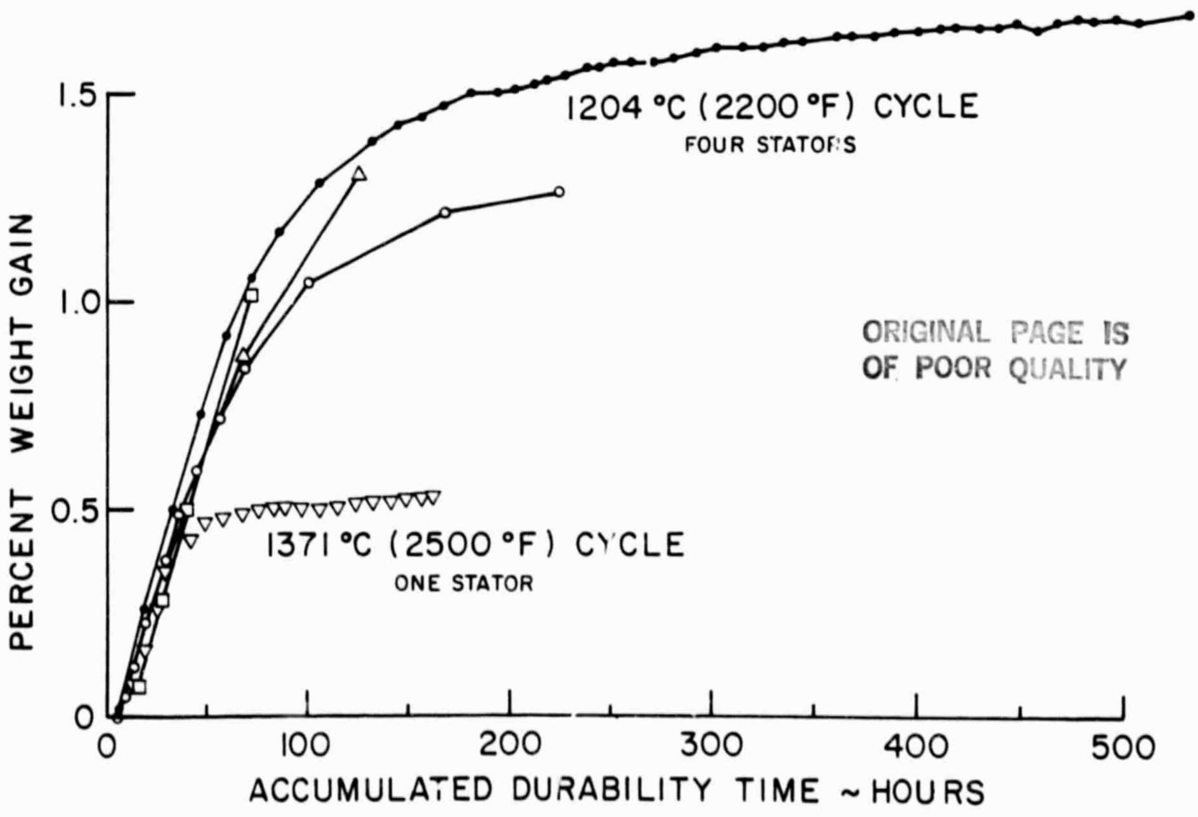

Figure 30 Weight Gain of Ford Si_3N_4 Stators

However, the stator run under the 1371°C (2500°F) cycle has stabilized after 75 hours while stators tested under the 1204°C (2200°F) cycle exhibited an increasing weight even after 500 hours of testing. Weight gain for the ACC Si_3N_4 stators showed a significantly different trend for the two different cycles. At the lower temperatures the weight gain was similar to Ford Si_3N_4 stators. However, during the short times run under the higher temperature cycle the initial weight gain was approximately four times as high as those for the lower temperature cycle as shown in Figure 31.

Dimensional Stability

Stator dimensional stability was monitored during the durability evaluations. The dimensional checks included the outer shroud flatness, roundness and maximum and minimum diameters. Data was recorded before test, after the first run, and thereafter in approximately 50 hour increments.

All SiC stators showed excellent dimensional stability throughout the durability testing. No significant changes were observed for any of the measurements.

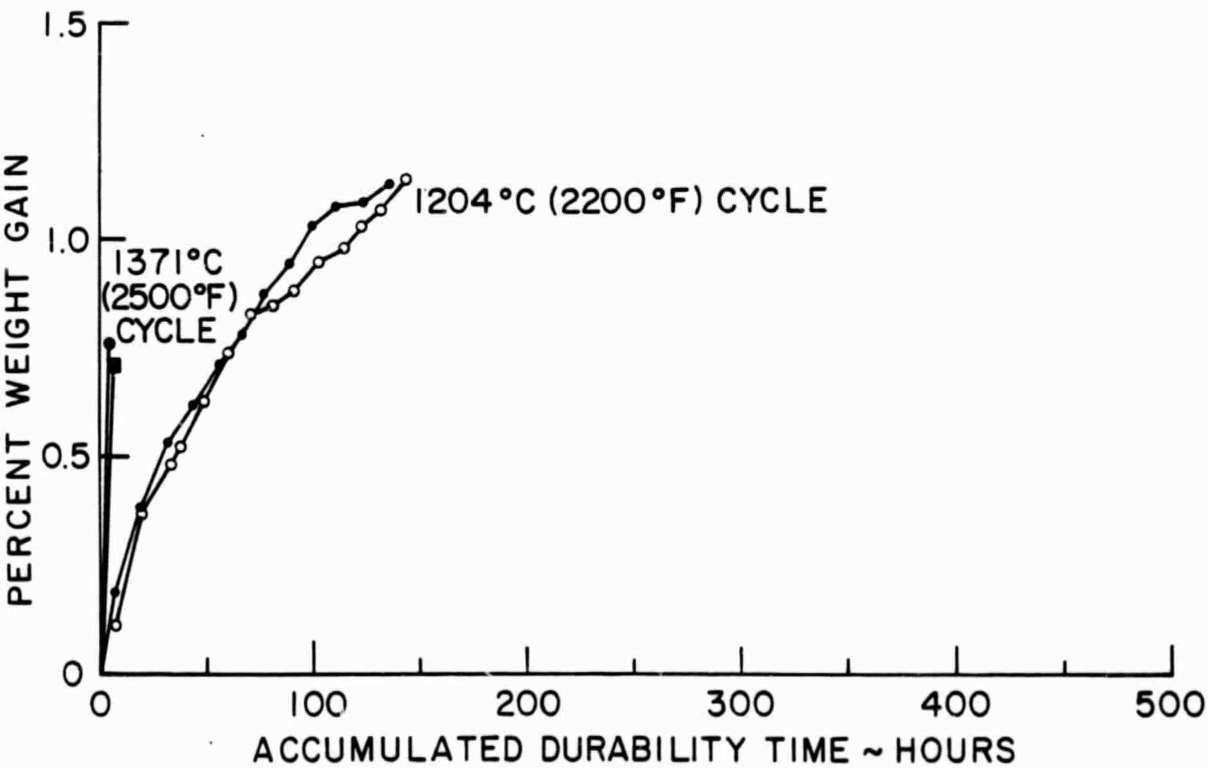

Figure 31 Weight Gain of ACC Si_3N_4 Stators

The Si_3N_4 stators showed no significant changes in outer shroud front face flatness. However measurable changes were obtained for the outer shroud nominal diameters (average of max. and min. diameters). Data obtained on all Si_3N_4 stators having successfully completed over 50 hours of durability is shown in Figure 32. At least 3 stators show clear trends of increase in diameter with durability time. Four other stators show no clear trend in dimensional variations and the data shown may merely reflect the inherent error in measurement.

Vane Bend Strength Testing

Vane bend testing was useful not only in qualifying Ford stators but also in generating data for determining proof-test levels on other stators, the effect of durability on stator strength, and for analyzing durability test results. Data was obtained on several stators of each type with and without durability hours accumulated. The data generated was plotted using Weibull statistics and a population line estimated for a two parameter Weibull distribution using a Maximum Likelihood Estimator (MLE) computer program [6]. All vane bend strength data was obtained by loading from the leading edge side.

The first phase of the Norton fabrication effort involved the delivery of one stator to demonstrate process capability and for preliminary evaluation other than durability. In an attempt to establish

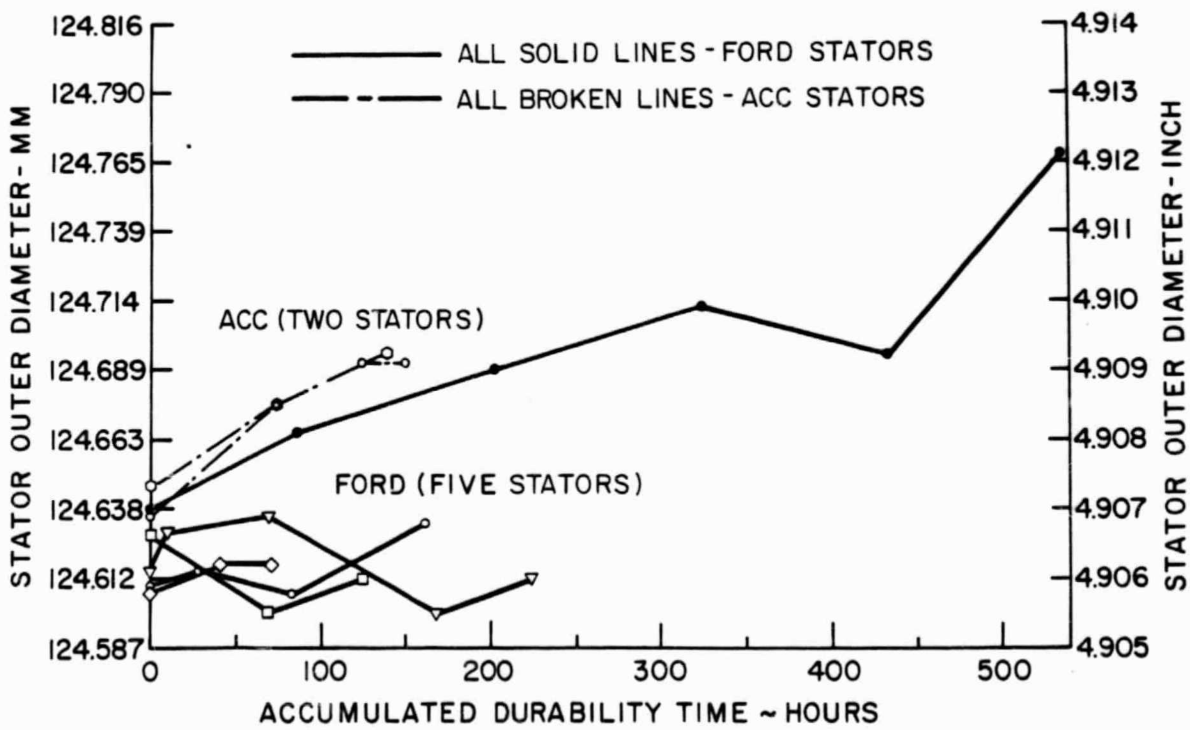

Figure 32 Stator Outer Shroud Dimensional Variation for ACC and Ford Si_3N_4 Stators

a VBT load level, this stator was first zygloed and 5 vanes with flaw indications were loaded to failure. The stator was then light-off tested with no failures and no new zyglo indications. All remaining vanes were tested to failure. The resulting failure load distributions are shown in Figure 33. The curves indicated that although an 8.6 Kg.(19 lb.) proof test load would break 90% of flawed vanes, it would also break 70% of the vanes able to withstand the light-off test. Consequently the VBT was not used for qualifying Norton stators for durability.

ACC stator S/N 01089, which had failed two vanes on the second durability test subsequently had all remaining vanes bend tested to failure. Fracture surfaces were visually examined at 30X for failure origin or flaw evidence. All fractures originated at the leading edge area. Seventeen of the 23 vanes had pre-nitriding, α Si_3N_4 planar defects near the leading edge. Twelve of the vane flaws had previously been recorded during the "as-received" visual inspection.

Weibull plots for three groupings of the failure load data are shown in Figure 34. The first group (Curve A) includes only the data from vanes with surface flaws detected in the "as-received" condition.

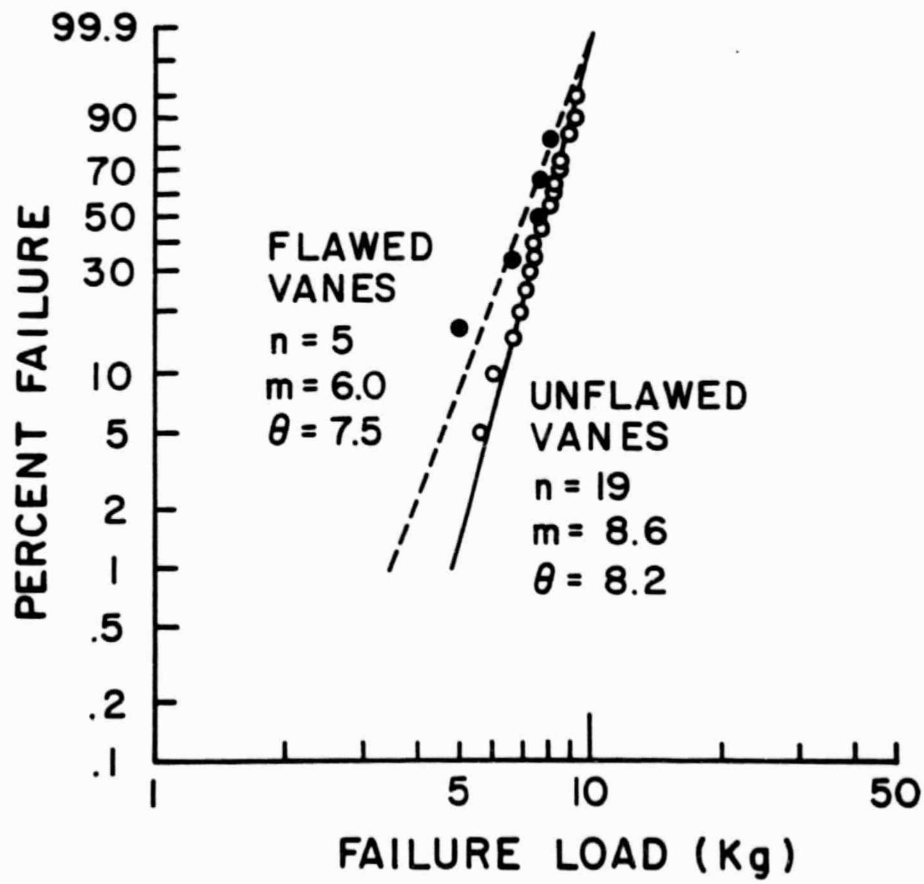

Figure 33 Failure Load Distribution of Flawed and Unflawed Vanes Loaded From Leading Edge Direction-Norton Slip Cast SiC Phase I Stator

These vanes exhibited a low characteristic strength of 7.1 Kg (15.7 Lbs.) and considerable scatter (m=5.0) but could readily be screened out by visual NDE. The second group (Curve B) includes the 11 vanes with no visible surface cracks in the failure region. A significantly higher strength is achieved but the scatter remains due to the presence of sub-surface flaws such as those shown in Figure 35. Screening out of such flawed vanes requires more elaborate NDE beyond visual inspection or use of qualification tests such as the vane bend test. In the case of this stator, 84% (16/19) of the flawed vanes would have failed at the 8.6 Kg (19 lb) load level.

The third grouping in Figure 34 (Curve C) includes only those vanes with no observed flaws at the fractured surface. The characteristic strength was improved still further to 13.1 Kg (29.0 lbs.) and a significant reduction in the scatter achieved (m=9.9).

A summary of all the vane bend test data obtained on CBO stators is presented in Table 16. The data does not indicate any clear relationship between bend strength and durability life. The highest hour stator, S/N 71, had the best slope and characteristic strength.

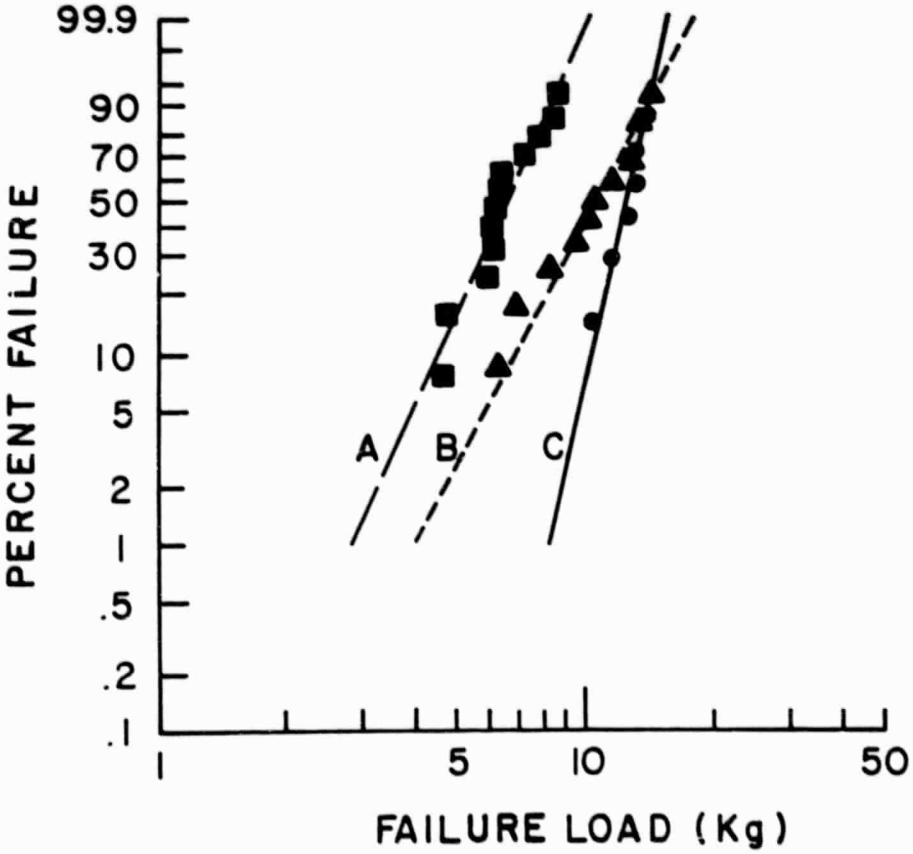

Figure 34 Weibull Curves for Vane Bend Test Results From ACC Stator S/N 01089. (A) Vanes With Flaws Observed During "as-received" Visual Inspection. (B) Vanes Without Flaws Observed During "as-received" Visual Inspection. (C) Six Vanes From (B) Without Flaws on Fracture Surface

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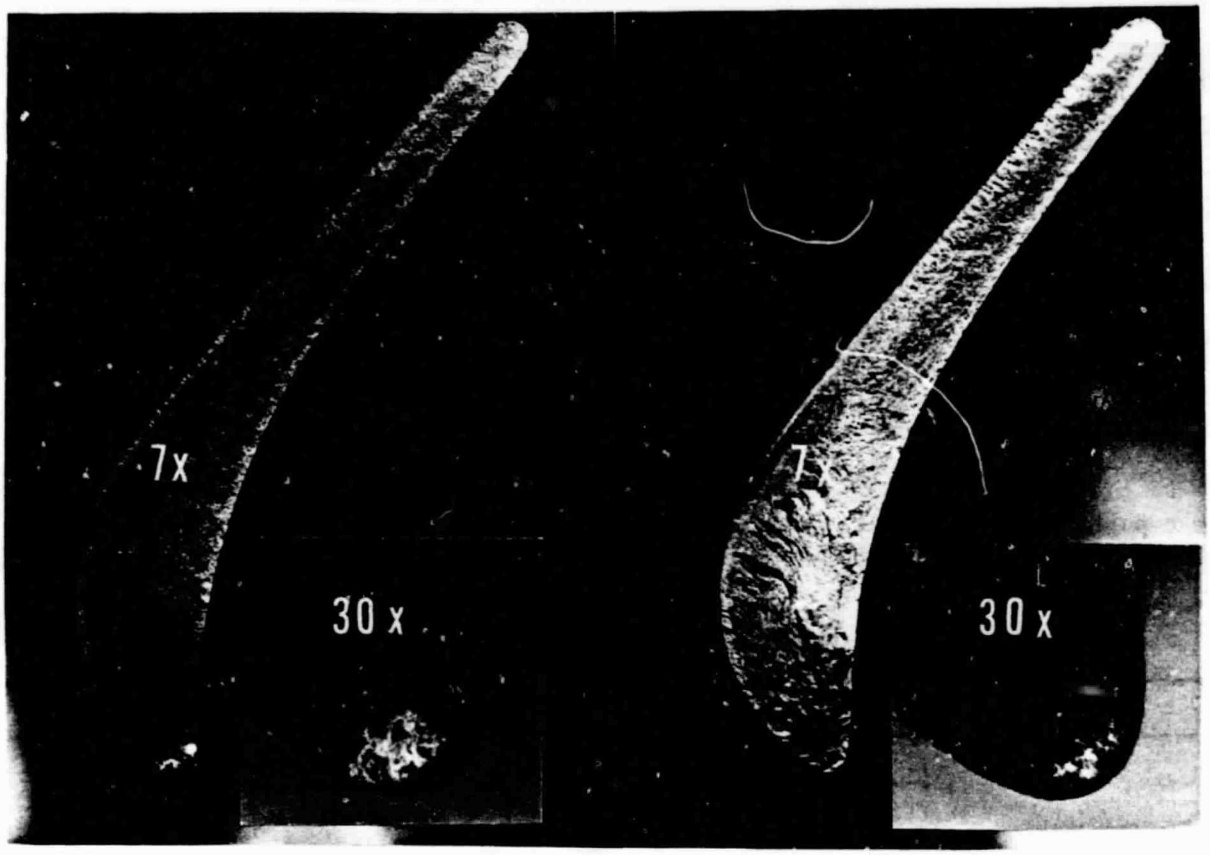


(a) (b)

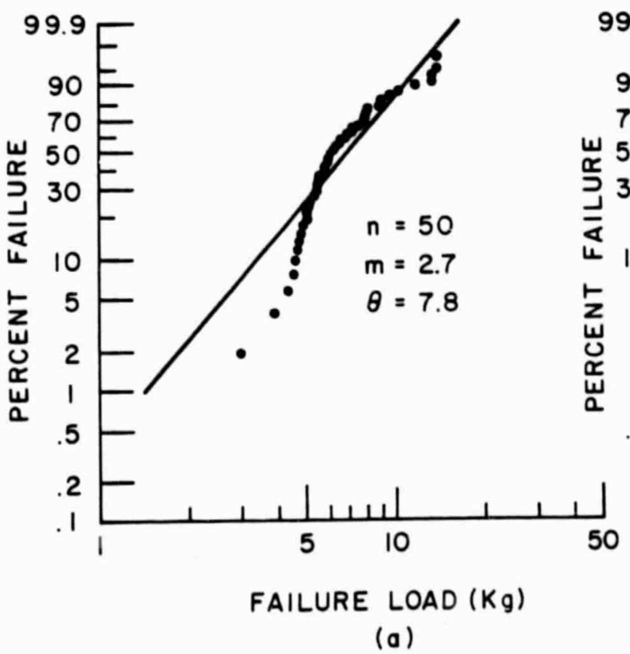
Figure 35 Typical Vane Flaws on Fracture Surface Not Observed on Vane Surface During "as-received" Visual Inspection. ACC Stator S/N 01089: (a) Vane #5; (b) Vane #19

However, other stators such as S/N 67 and 68, which successfully completed 54 and 246 hours, respectively, had slopes and characteristic strengths essentially the same as for S/N 57 which failed in less than 30 hours.

Figures 36 through 39 present vane bend strength data generated for evaluating the effect of durability testing. Four stators from each participant were vane bend tested to failure; two with no (or very little) test time and two with the highest durability times. Vanes which had been cracked or damaged during durability testing were not included. Based on the computer generated population estimate line, no significant reduction in Weibull slopes or characteristic strengths occurred during durability testing for any of the materials. The MLE straight line fit to the data in these figures will be discussed later.

TABLE 16
CARBORUNDUM STATORS
VANE BEND STRENGTH SUMMARY

STATOR SERIAL NUMBER	DURABILITY CYCLE TEST RESULTS	STATISTICAL STRENGTH DATA SAMPLE SIZE	WEIBUL PARAMETERS m	θ(Kg)
57	FAILED IN 29:15 HOURS	24	4.5	18.2
60	SURVIVED 173:09 HOURS	23	8.6	17.0
67	SURVIVED 54:49 HOURS	24	5.1	18.1
68	SURVIVED 246:53 HOURS	24	4.7	18.3
71	SURVIVED 299:14 HOURS	20	8.9	18.8
56	NOT DURABILITY TESTED	17	5.5	15.4
59	NOT DURABILITY TESTED	14	6.3	15.5



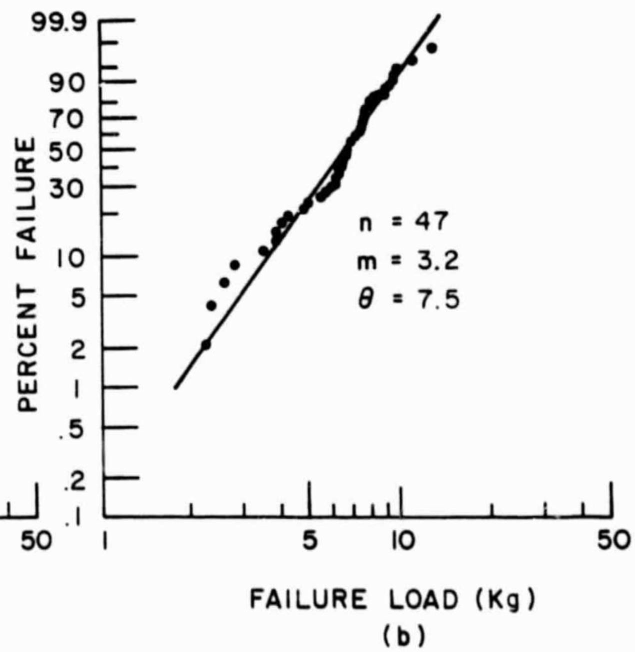


Figure 36 Vane Bend Strengths of ACC Si_3N_4 Stators: (a) Without Durability Cycle Testing - S/N 0227922 and 0212926. (b) After Testing - S/N 0125911 (149 hrs) and S/N 0206957 (135 hrs)

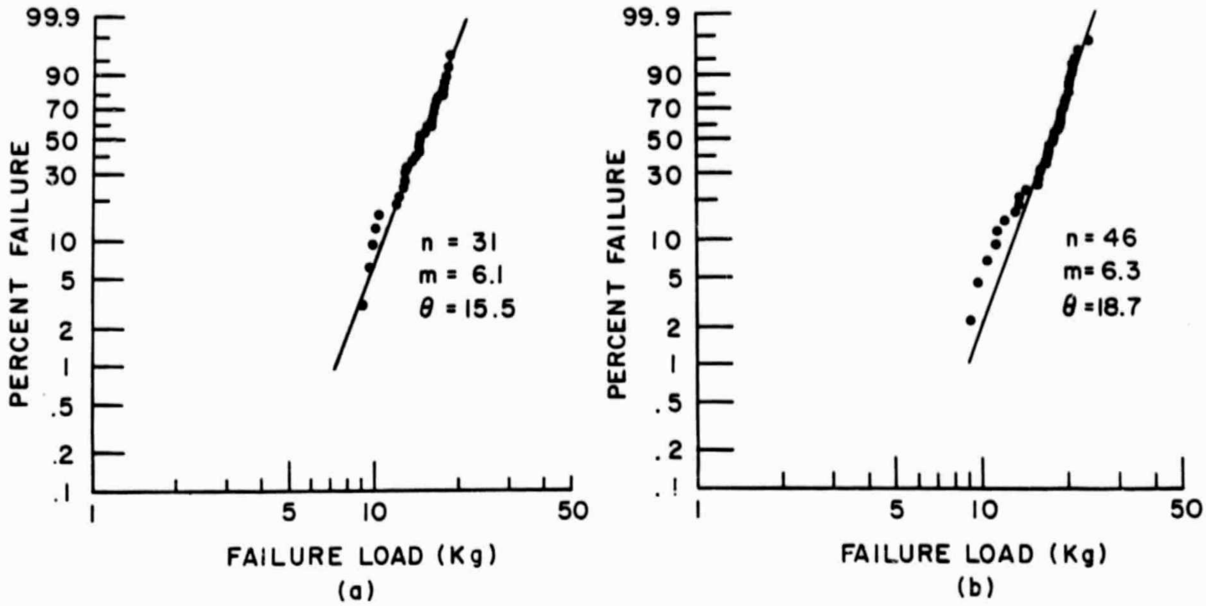


Figure 37 Vane Bend Strengths of CBO SiC Stators: (a) Without Durability Cycle Testing - S/N 56 and 59. (b) After Testing - S/N 68 (247 hrs) and S/N 71 (299 hrs)

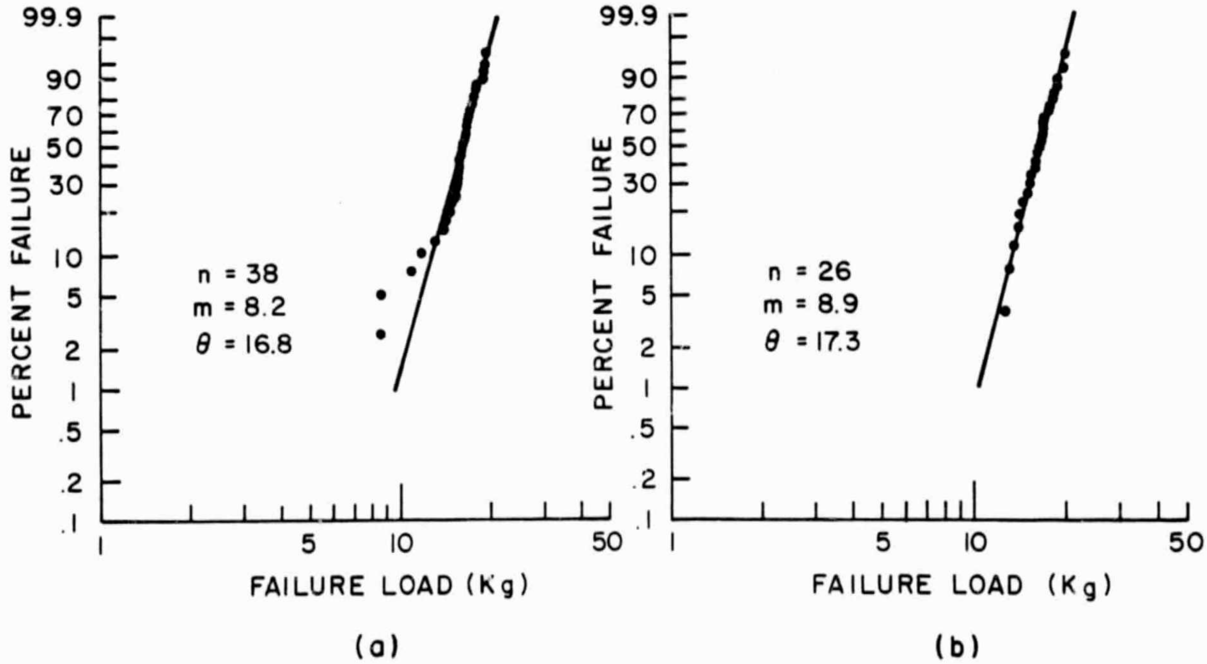


Figure 38 Vane Bend Strengths of Ford Si_3N_4 Stators: (a) With 0-10 hrs Testing - S/N 10137 and 10082. (b) After Testing - S/N 10146 (293 hrs) and 10068 (535 hrs)

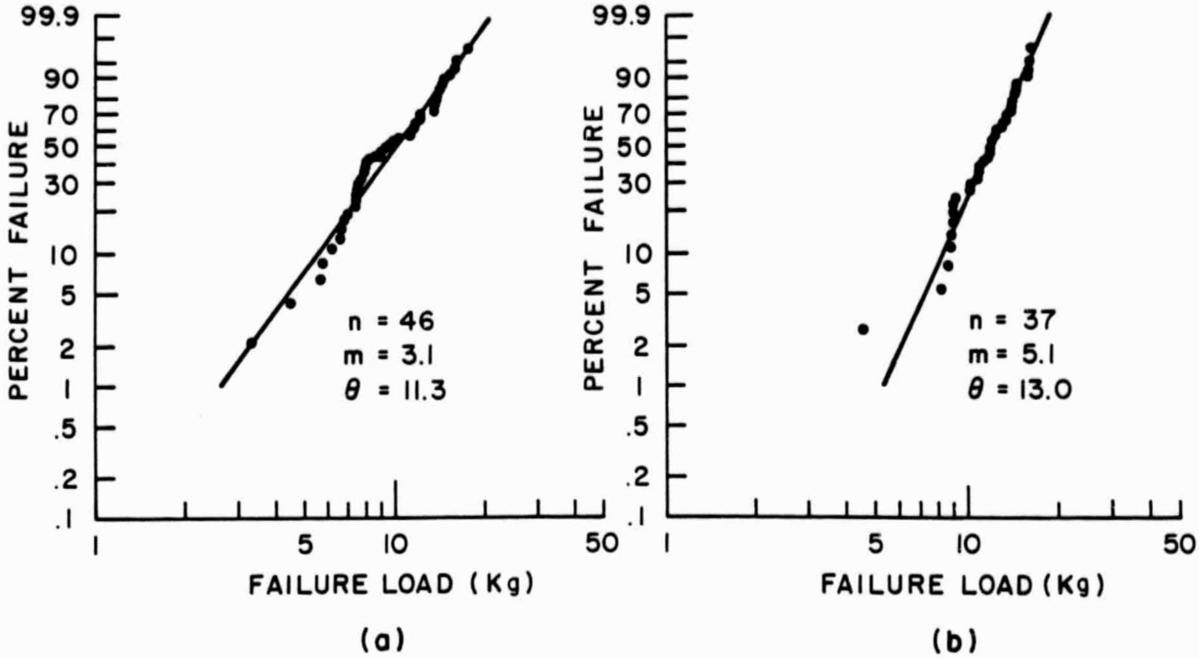


Figure 39 Vane Bend Strengths of Norton SiC Stators:
(a) Without Durability Cycle Testing - S/N H and O.
(b) After Testing - S/N J (82 hrs) and P (82 hrs)

Discussion

The durability evaluations conducted have clearly demonstrated that ceramic one-piece stators of Si_3N_4 and SiC materials can survive under the severely transient conditions typical of automotive gas turbine operation. In fact, no failures occurred in 20 test attempts where the stator was initially run for one complete, uninterrupted 4-hour duty cycle. These 20 tests included stators from all four participants and subjected the stators to the full range of predictable aerodynamic loads and thermal stresses.

However, numerous failures were experienced which are believed caused by ceramic interface forces acting on the stator outer shroud. Differential thermal expansions between the stator shroud and adjacent parts are generated because of differences in thermal response and materials. The specific stress pattern developed in the stator shroud depends on a number of variables: whether or not relative movement occurs, location and magnitude of friction forces, and direction of forces (during upshock or downshock). The effects of interface friction are clearly evident from the test results. Specifically:

. Most stator failures occurred in the outer shroud.

- Stators tested in the second stage position, with increased axial loads, developed extensive chipping on their rear face.

- Localized sticking of stators to adjacent parts was observed frequently.

- Stators tested using the disassembly/polishing procedure survived for hundreds of hours.

A complete investigation of ceramic interface phenomenon was beyond the scope of this program, however, it is significant that the interface friction problem could be circumvented by frequent disassembly to meet the program durability time objectives. Further work is obviously needed to fully understand ceramic interface problems and develop the material/design criteria necessary for successful long term operation. The test rig and procedures used in this program are ideal for this purpose and some initial in-house work is showing some promising interface developments.

The vane bend testing conducted has served to reinforce the usefulness of such tests as a quality check on ceramic components. For example, the data in Figure 34, for an ACC stator, shows that even if that stator contained none of the flawed vanes of curve A (observable by visual NDE) the stator would have failed 3 vanes at an 8.6 Kg (19 lb.) qualification level. Such a situation occurred in Stator S/N 10137 which was used in generating the data for Figure 38a. The stator was judged acceptable by NDE, but failed to pass the VBT. The inferior quality of that stator is further evidenced by the fact that all four of the lowest data points plotted in Figure 38a are from that stator.

Two further observations regarding Figures 36 through 39 should be considered. First, the two-parameter MLE fit to the data points is obviously not a good fit. This suggests that mixed failure modes or distributions are present in complex shaped parts such as the stator. Second, the slopes of the MLE lines are lower than usually observed for material characterization samples. For example, in the material property characterization effort in this program, test bar strength data for the Ford and Norton materials had slopes of 10.6 and 5.8 respectively. The slopes of the VBT data on these same two materials were in the ranges of 8.2 to 8.9 and 3.1 to 5.1, respectively.

These observations regarding the VBT data suggest that additional work is needed in the component fabrication technology. Future work should include the fabrication and testing of large numbers of ceramic components to improve the component processing technology and to develop correlation between materials development data and materials properties achievable in structural ceramic components.

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