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TURBINE BLADE THERMAL FATIGUE TESTING PRATT AND WHITNEY AIRCRAFT HOLLOW CORE BLADES

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16. ABSTRACT

The results of low cycle fatigue testing on turbine blades for use in hydrogen/oxygen rocket engines is covered in this report. Cored blade and cored blades with circulation were tested in the MSFC thermal fatigue tester. Both blade configurations showed significant low cycle fatigue life improvements when compared to baseline solid blades.

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INTRODUCTION

Low cycle fatigue failures are a particularly severe problem in oxygen/hydrogen rocket engine turbines. The very high thermal gradients to which turbine hot section components are subjected during start and shutdown transients combined with the very high heat transfer coefficients of high pressure oxygen/hydrogen combustion products cause very high thermal stresses. The stresses result in low cycle fatigue cracking of the hot section components after only a few operating cycles and require repair or replacement of the cracked parts.

Pratt and Whitney Aircraft in an advanced turbine study, Contract NAS8-33821, suggested the use of hollow core blades, with and without hot gas circulation, as an approach for increasing the low cycle fatigue (LCF) life of turbine blades. The hollow core decreases the wall thickness and, thus, decreases the metal temperature differences and thermal stresses to which the airfoil is subject during transient. Providing gas circulation through the blade core further reduces the potential temperature difference by heating and cooling the internal wall during the transients. Hot gas circulation is provided by a small hole in the pressure surface of the blade platform to the core. The pressure difference between the pressure and suction side of the blade causes flow through the core. An improvement in cycles to the first crack by a factor of 2.5 for the hollow core blades and 3.5 for the hollow core with circulation blades in low cycle fatigue life was predicted by Pratt and Whitney for typical SSME configuration blades. To verify this LCF gain, Pratt and Whitney fabricated solid, hollow core, and hollow core with circulation blades. Two sets of these blades (three each) have been tested in the MSFC turbine blade thermal fatigue tester. This report documents the tests, a description of the test blades, an analysis of the test data, and conclusions drawn from the program.

TEST PROCEDURE

The MSFC turbine blade tester (Fig. 1) was used to generate the thermal environments needed for LCF tests of the turbine blades. The turbine blade tester is a device that burns liquid hydrogen with oxygen to generate a 2500 psi, 1700°F hot gas stream which is used to rapidly heat the turbine blades.

Prior to testing, the blades shown in Figure 2 were bolted into the holder as shown in Figure 3. The holder was then bolted into one of the blade positions in the turbine blade tester. During testing, the blades were exposed to a number of thermal cycles. The severity of these cycles is shown in Figure 4, a plot that illustrates the relationship between hot gas temperature (this closely approximates the blades surface temperature) and elapsed test time. Liquid hydrogen and liquid oxygen were ignited in the combustion chamber to create the hot gas stream which heated the blade surfaces to 1700°F. During start, the blades were exposed to a maximum temperature gradient of 1900°F/sec over a 0.12 sec interval. After approximately 8 sec of combustion, both the igniter and preburner were shut down and liquid hydrogen flowed through the chamber cooling the blade surfaces to a -350°F. During shutdown cooling, the blades were exposed to a maximum temperature gradient of -3100°F/sec over a 0.12 sec interval. After 8 sec of cooling, the igniter was turned on again and the cycle was repeated. After each planned test exposure, the turbine blades were taken to the Metallic Materials Division of the MSFC Materials and Processes Laboratory for inspection. The blades were then inspected for cracks with a microscope (25X) and by doing a dye-penetrant examination that was photographed under black light. The blades were then returned to the test area for the next test series.

BLADE DESCRIPTION

The test blades were designed with a simple, easy to fabricate profile representative of the hub profile of the SSME fuel turbine blades. The blades are untapered and untwisted. The 0.055 in. thickness blade is representative of the minimum platform wall thickness which could be used in the SSME blades while the 0.035 in. wall is representative of the minimum tip wall thickness possible in a hollow cored SSME blade. The blades were all cast in PWA 1480 SC (single crystal) material.

The first set of blades was machined using an electro-chemical milling process that left the blade surfaces slightly pitted. The set consisted of one solid blade and two hollow blades with wall thicknesses of 0.055 in. each. One of the hollow blades had a thermocouple attached to the inside wall to measure the inside wall temperature during testing. The other hollow blade had a 0.05 in. diameter hole drilled through one wall on the pressure surface at the platform to allow hot gas to flow through.

The second set of blades was also machined using an electro-chemical milling process; however, the surfaces of the blades were reworked to approximate a cast finish. The finishing removed the surface pits. The solid blade was also buffed prior to test. This set consisted of one solid blade, one hollow blade (0.055 in. wall thickness), and one hollow blade with a wall thickness of 0.035 in.

TEST RESULTS

Testing of the first set of turbine blades was completed on October 10, 1984, after the blades had been exposed to 71 thermal cycles. Table 1 shows when cracks were first observed in each blade and Figures 5, 6 and 7 show maps of the cracks on each blade as seen on the photographs of the dye-penetrant inspections of the blades. The blades were inspected for cracks after being exposed to 5, 10, 15, 23, 33, 43, 53, 63, and 71 thermal cycles.

Testing of the second set of turbine blades were completed on November 20, 1984, after the blades had been exposed to 73 thermal cycles. Table 1 shows when cracks were first observed in each blade and Figures 8, 9 and 10 show maps of the cracks on each blade as seen on the photographs of the dye-penetrant inspections of the blades. The blades were inspected for cracks after being exposed to 3, 10, 15, 23, 26, 30, 47, 62, and 73 thermal cycles.

Figure 11 shows the blade's inside wall temperature for the first test run on the first set of blades. During the first thermal cycle, the thermocouple remained bonded to the blade and data was obtained. The blade's inside wall temperature climbed to 500°F during combustion and dropped to -300°F during cooling. During the second cycle, the thermocouple came loose from the blade wall and as a result it measured the gas temperature. During the third cycle, the thermocouple failed. Because the thermocouple had been welded into the blade holder, it was not replaced.

DATA ANALYSIS

Pratt and Whitney predicted the hollow blade (0.055 in. wall) low cycle fatigue life to be 2.5 times that of the solid blade. They expected the vented hollow blade low cycle fatigue life to be 3.5 times that of a solid blade. They also predicted the thin walled hollow blade to last longer than both the vented and regular hollow blades.

The purpose of this data analysis was to calculate the improvement of hollow blade life over solid blade life. (Blade life was defined to be the number of cycles a blade lasted before it cracked.) The improvement was calculated using equation (1):

$$\text{IMPROVEMENT} = \text{HOLLOW BLADE LIFE} \,/\, \text{SOLID BLADE LIFE} \tag{1}$$

In order to calculate the improvement, it was necessary to know the cycle during which a blade first cracked; however, the blades were not inspected after every thermal cycle. Therefore, it was not possible to determine the cycle during which a blade first cracked. For this reason, the improvement was calculated on the assumption that each hollow blade cracked during the earliest possible cycle. For instance, the thin wall hollow blade had not cracked after 47 cycles, but it had cracked after 62 cycles. Therefore, the earliest cycle during which the blade could have cracked was the 48th.

Solid blade life was used as a baseline for comparison with the hollow blades. Since the first solid blade cracked between one and five cycles and the second solid blade cracked between four and ten cycles, the baseline was chosen to lie in the overlapping lifespan of the two blades (four or five cycles). Five cycles was chosen as a conservative baseline. Table 2 shows the improvement of the hollow blades over the solid blades.

CONCLUSIONS

The test results as tabulated in Table 2 suggest that an improvement in LCF life, at least as great as predicted by Pratt and Whitney Aircraft, was achieved in the cored and ventilated blades. Although the data is very limited, it was analyzed in the most conservative possible manner; and thus, the results are considered defensible. Since the blade section thicknesses are representative of those which could be cast in SSME fuel turbine blades, substantial improvements in LCF life are achievable in redesigned SSME turbine blades.

No conclusions can be reached with respect to the surface finish of the airfoils. The time of crack initiation on comparable samples was not significantly different. It is observed in Figure 7 that many of the cracks appear to follow surface markings left by the buffing process.

TABLE 1. TEST RESULTS

Blade Set	Blade Description	First Cracks Observed
1	Solid; ECM finish (Electro Chemical Milling)	After 5 cycles
1	Hollow; 0.055 in. wall thickness; ECM finish	After 33 cycles
1	Hollow; 0.055 in. wall thickness; ECM finish; 0.05 in. diameter vent hole	After 43 cycles
2	Solid; buff polish finish	After 10 cycles
2	Hollow; 0.055 in. wall thickness; cast finish	After 23 cycles
2	Hollow; 0.035 in. wall thickness; cast finish	After 62 cycles

TABLE 2. HOLLOW BLADE IMPROVEMENT

Blade Set	Blade Type	Blade Life	Improvement of Hollow Over Solid
1	Solid	5 cycles	Baseline
1	Thick Hollow	24 cycles	4.8 times
1	Vented Hollow	34 cycles	6.8 times
2	Solid	5 cycles	Baseline
2	Thick Hollow	16 cycles	3.2 times
2	Thin Hollow	48 cycles	9.6 times

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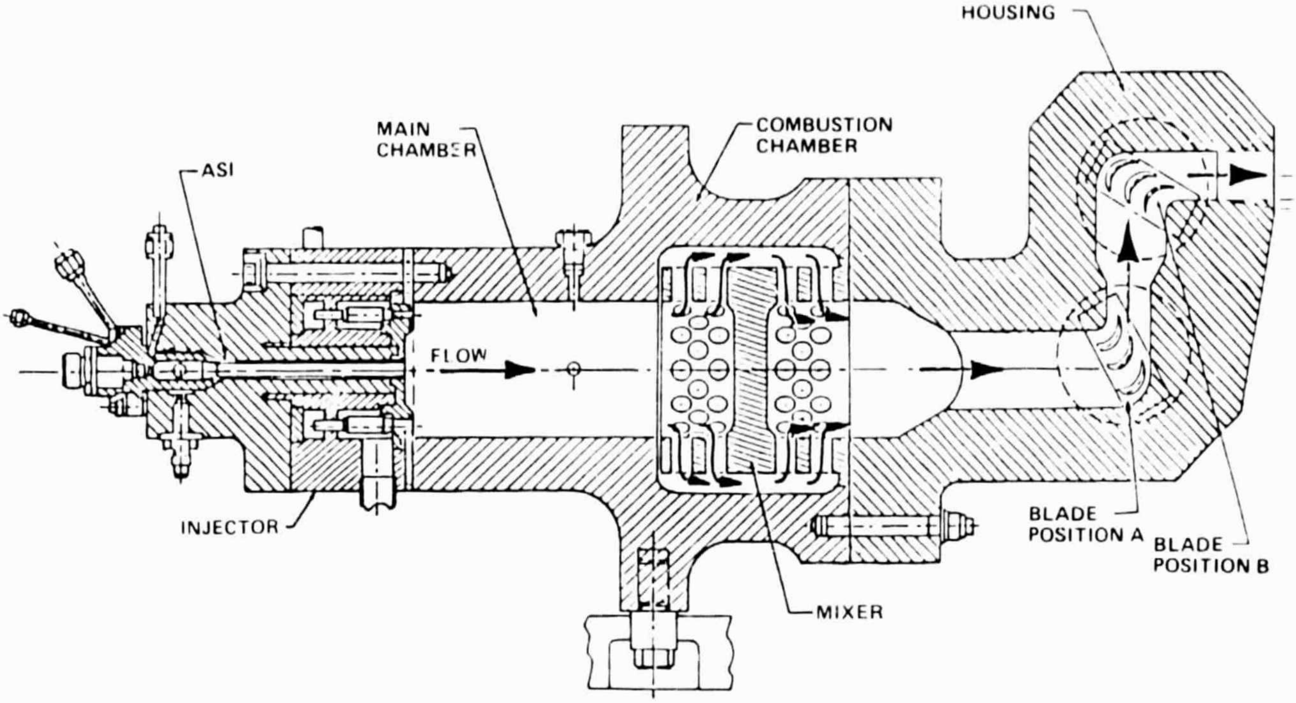

Figure 1. Thermal cycling tester.

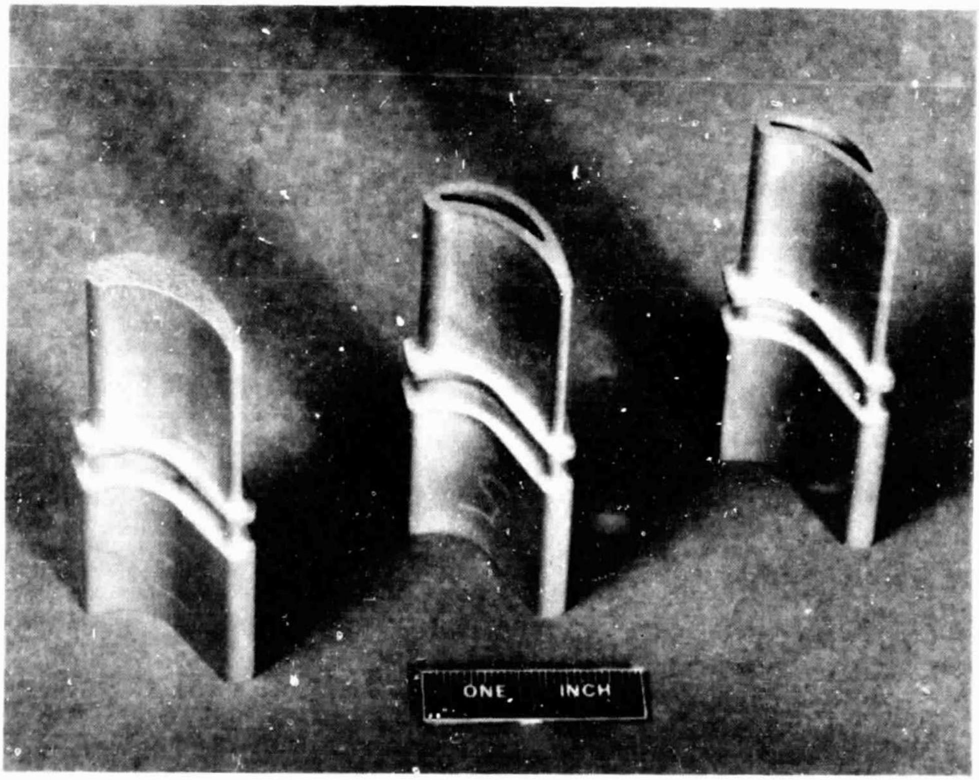

Figure 2. Blades.

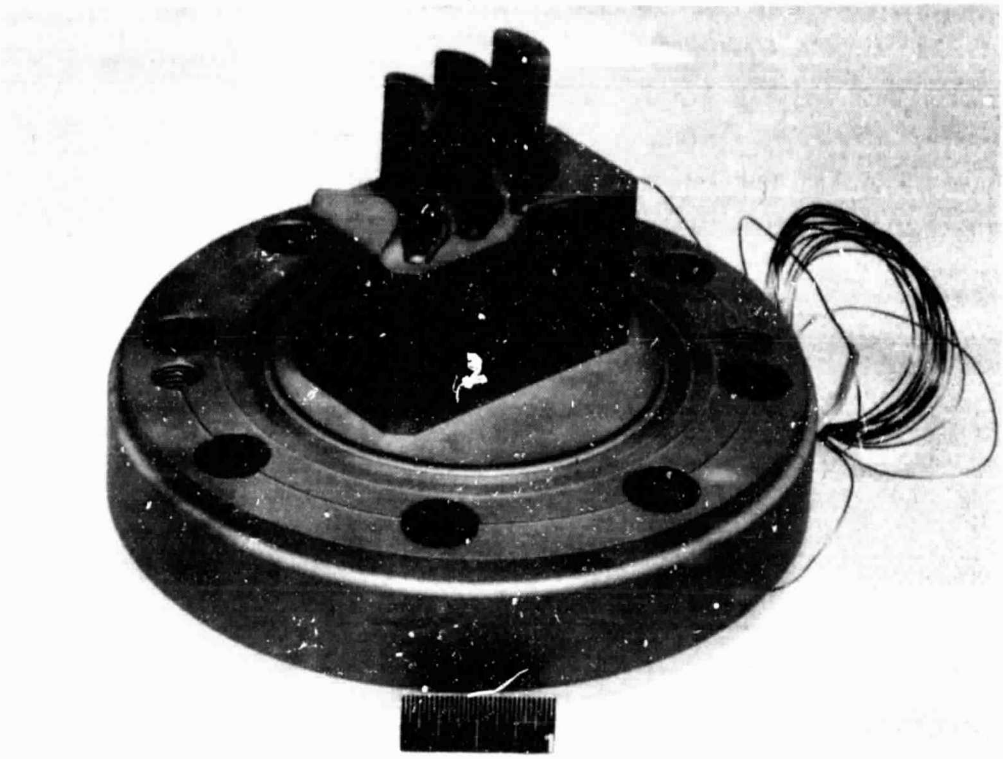

Figure 3. Blade holder with blades.

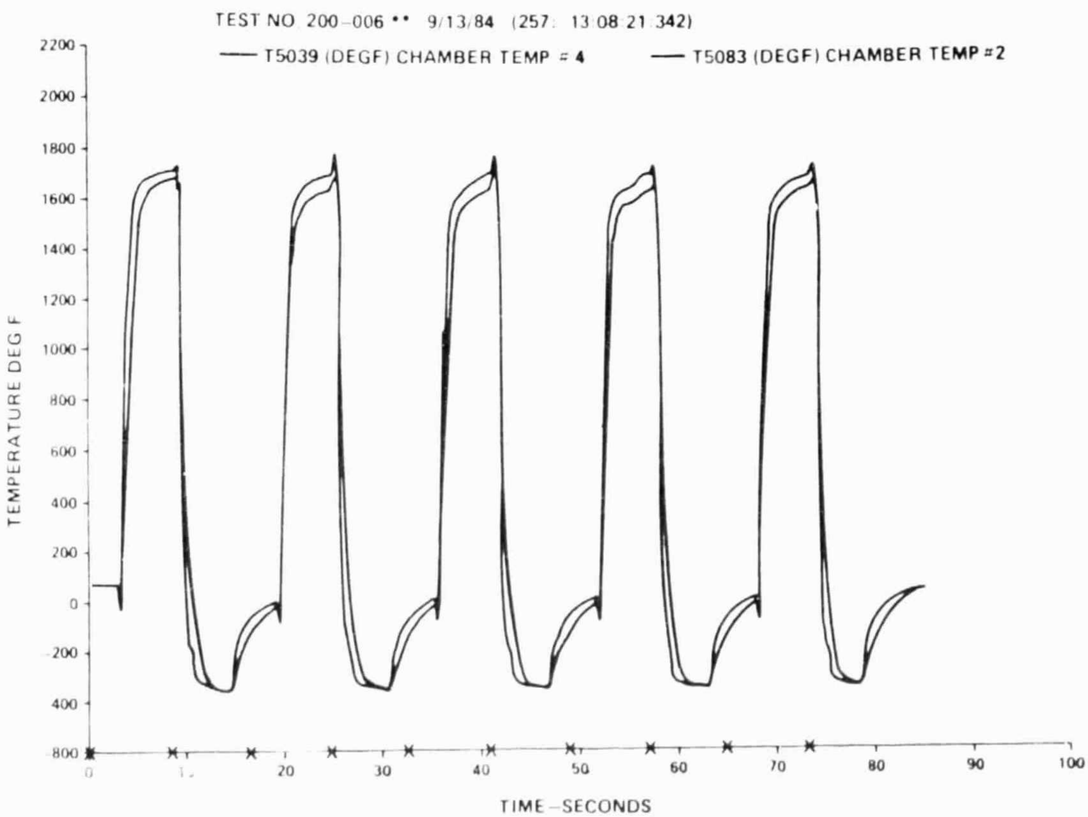

Figure 4. Thermal cycling in the turbine blade tester.

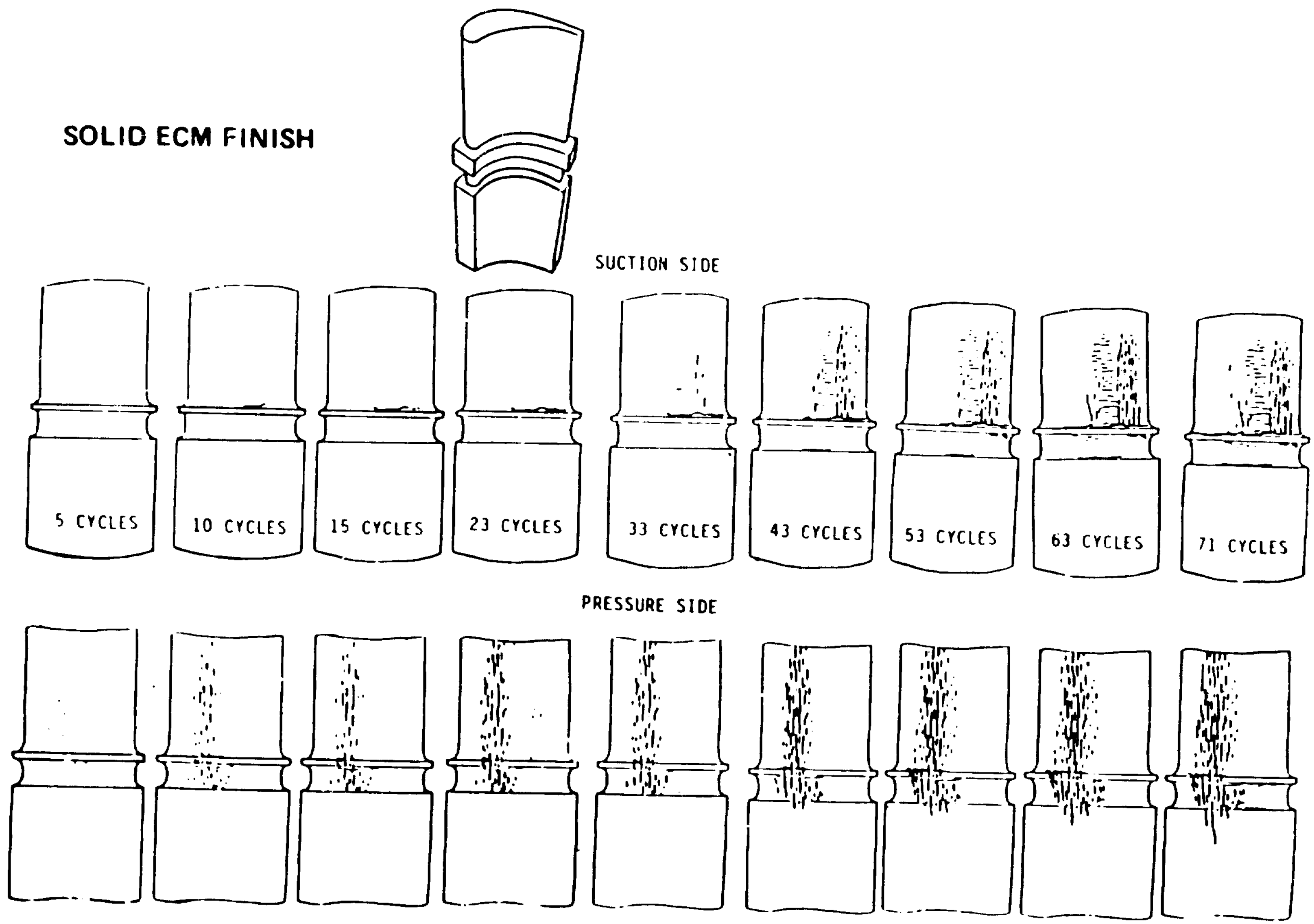

Figure 5. Set 1, solid blade crack maps.

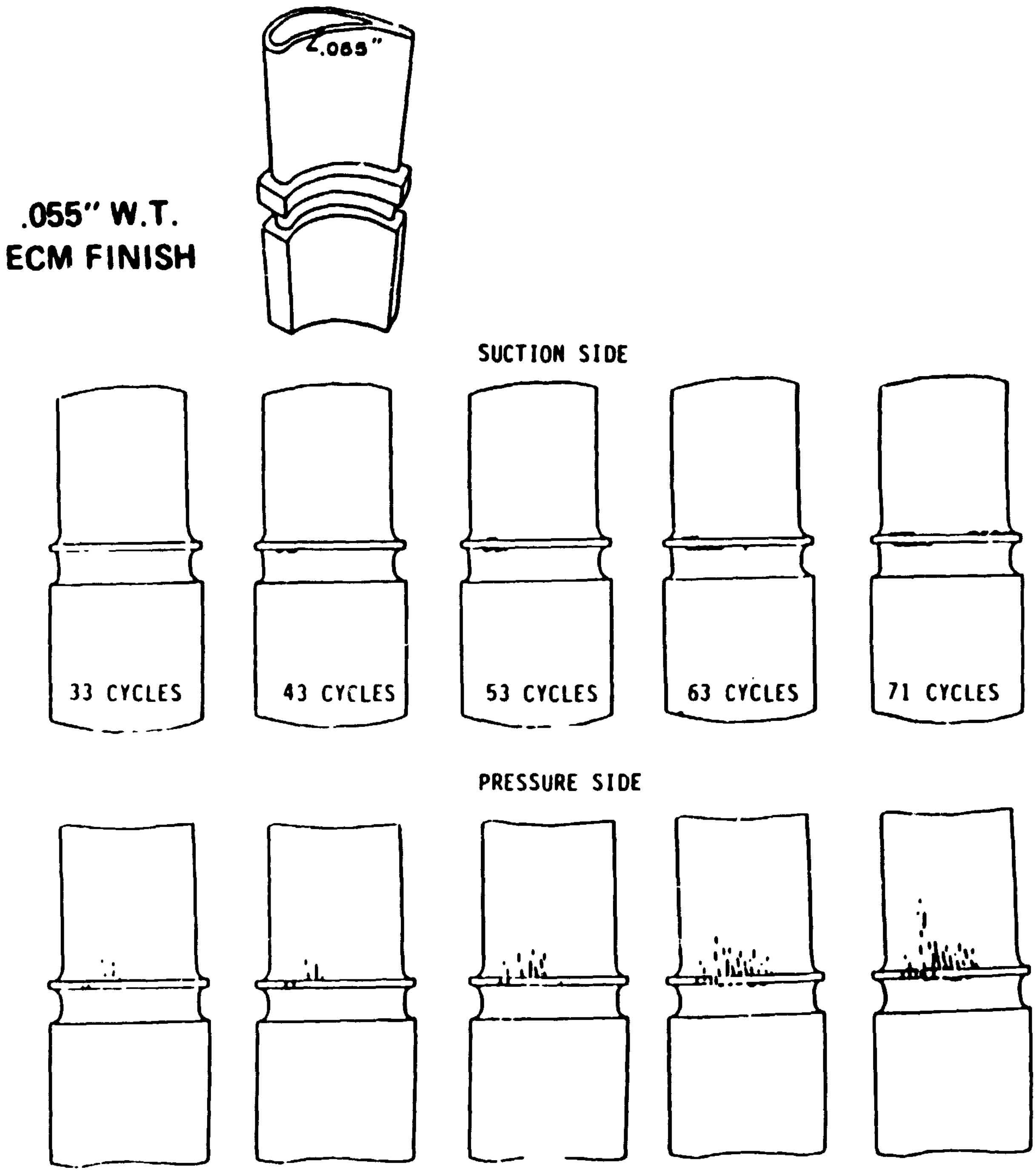

Figure 6. Set 1, hollow blade crack maps.

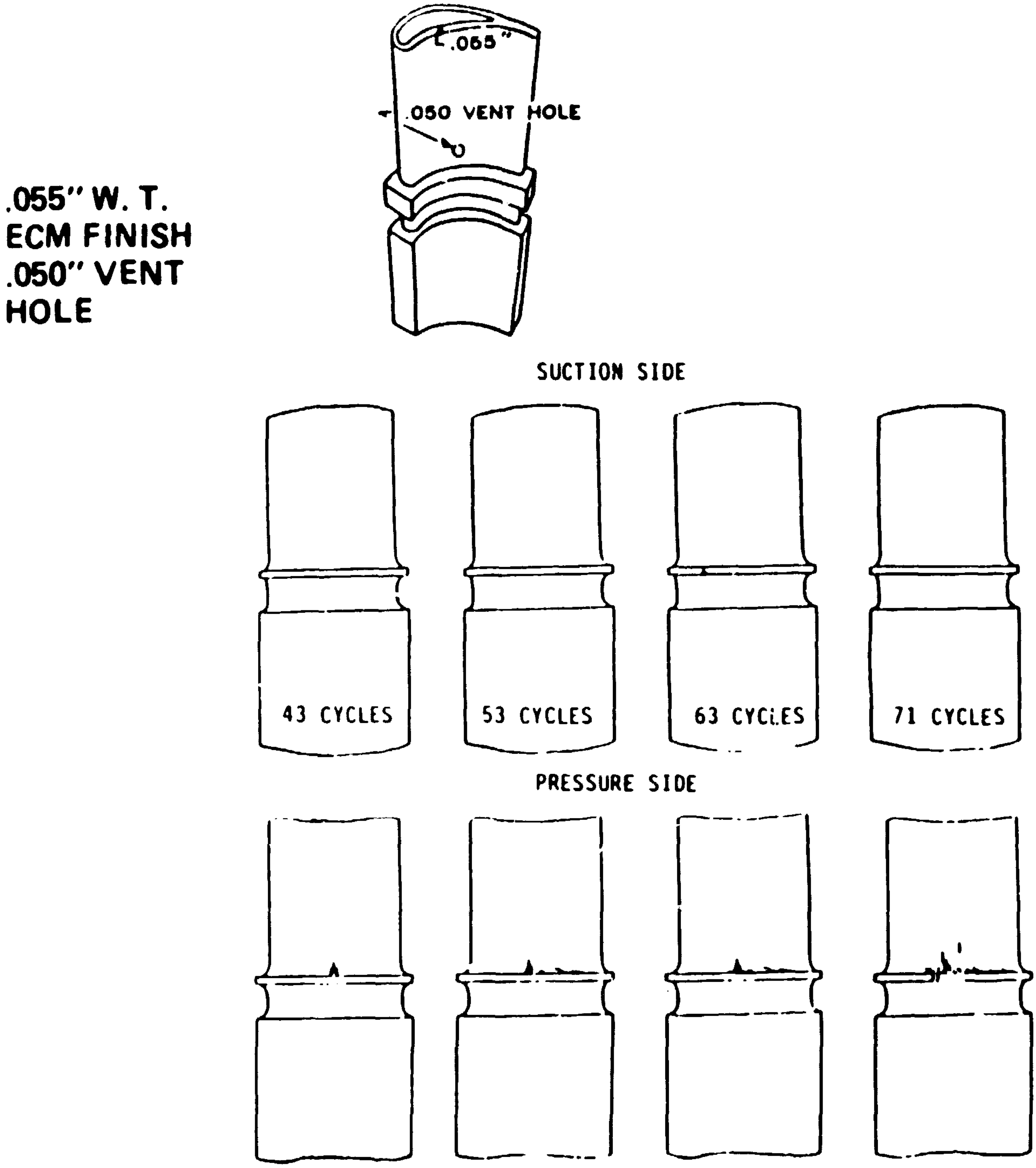

Figure 7. Set 1, vented hollow blade crack maps.

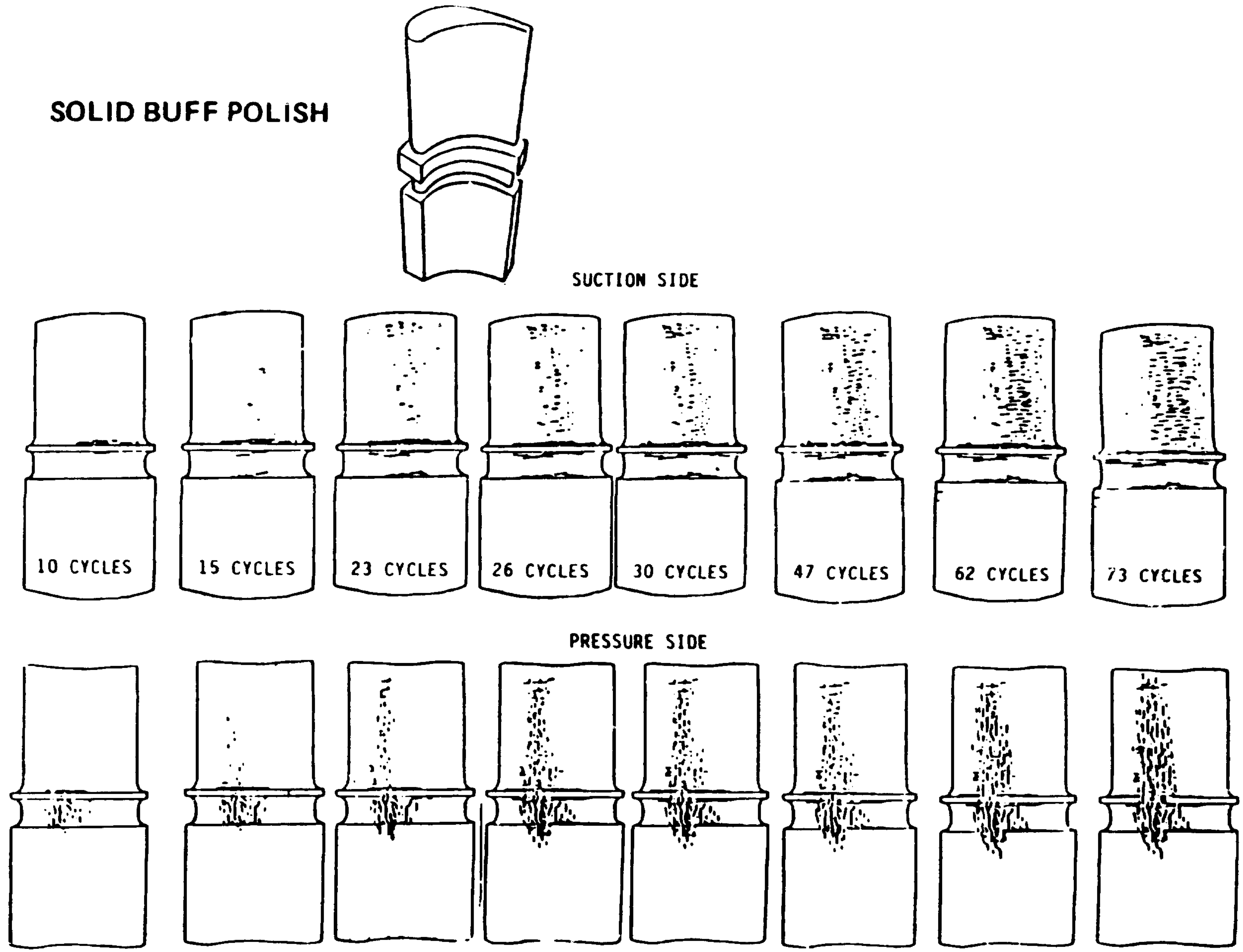

Figure 8. Set 2, solid blade crack maps.

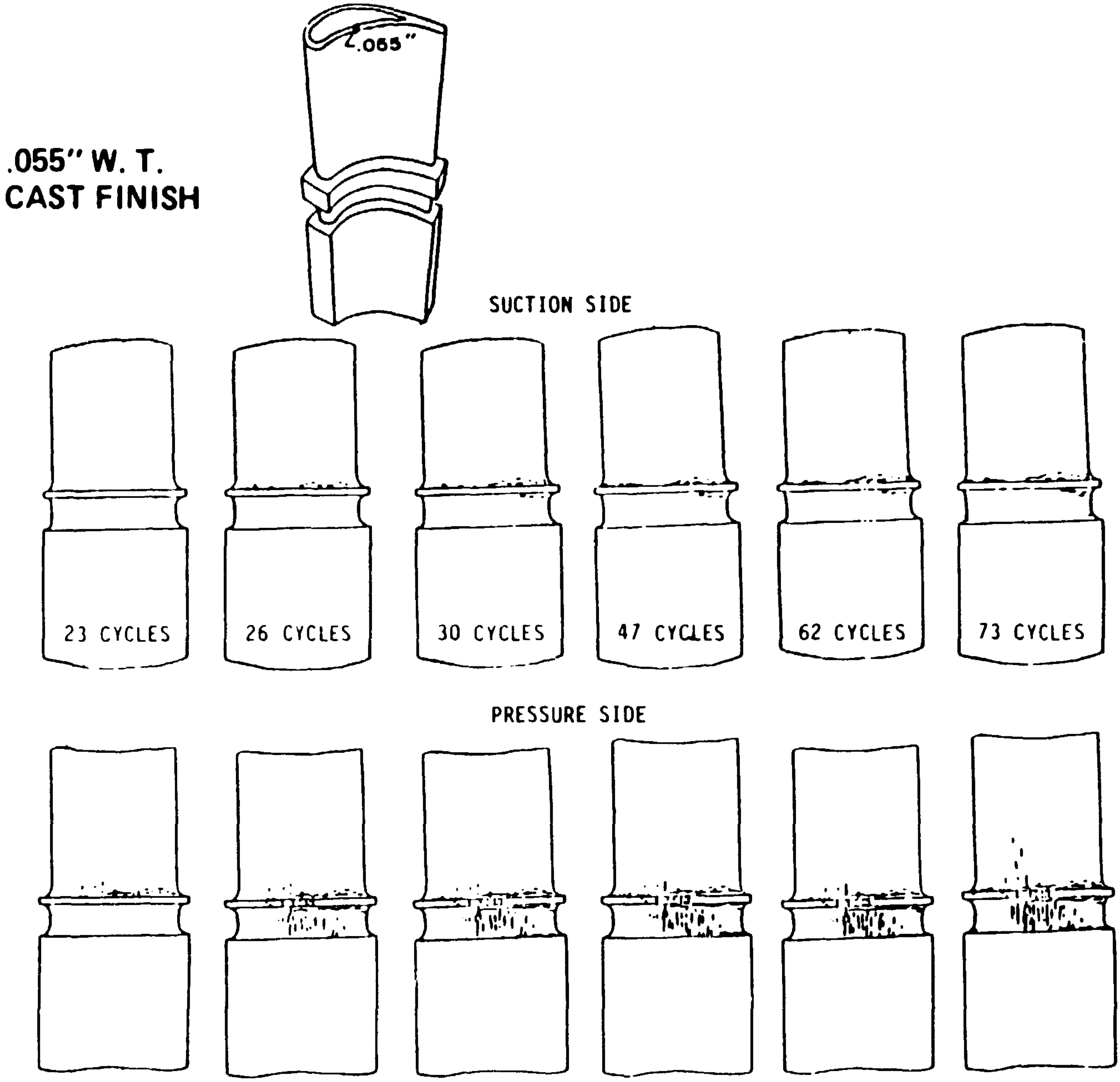

Figure 9. Set 2, thick wall hollow blade crack maps.

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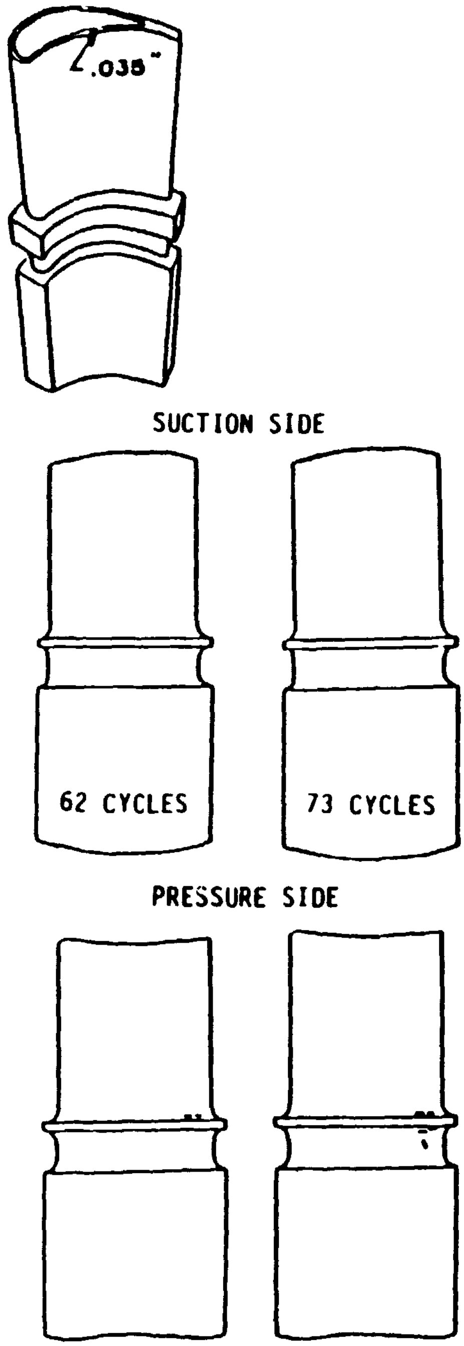

Figure 10. Set 2, thin wall hollow blade crack maps.

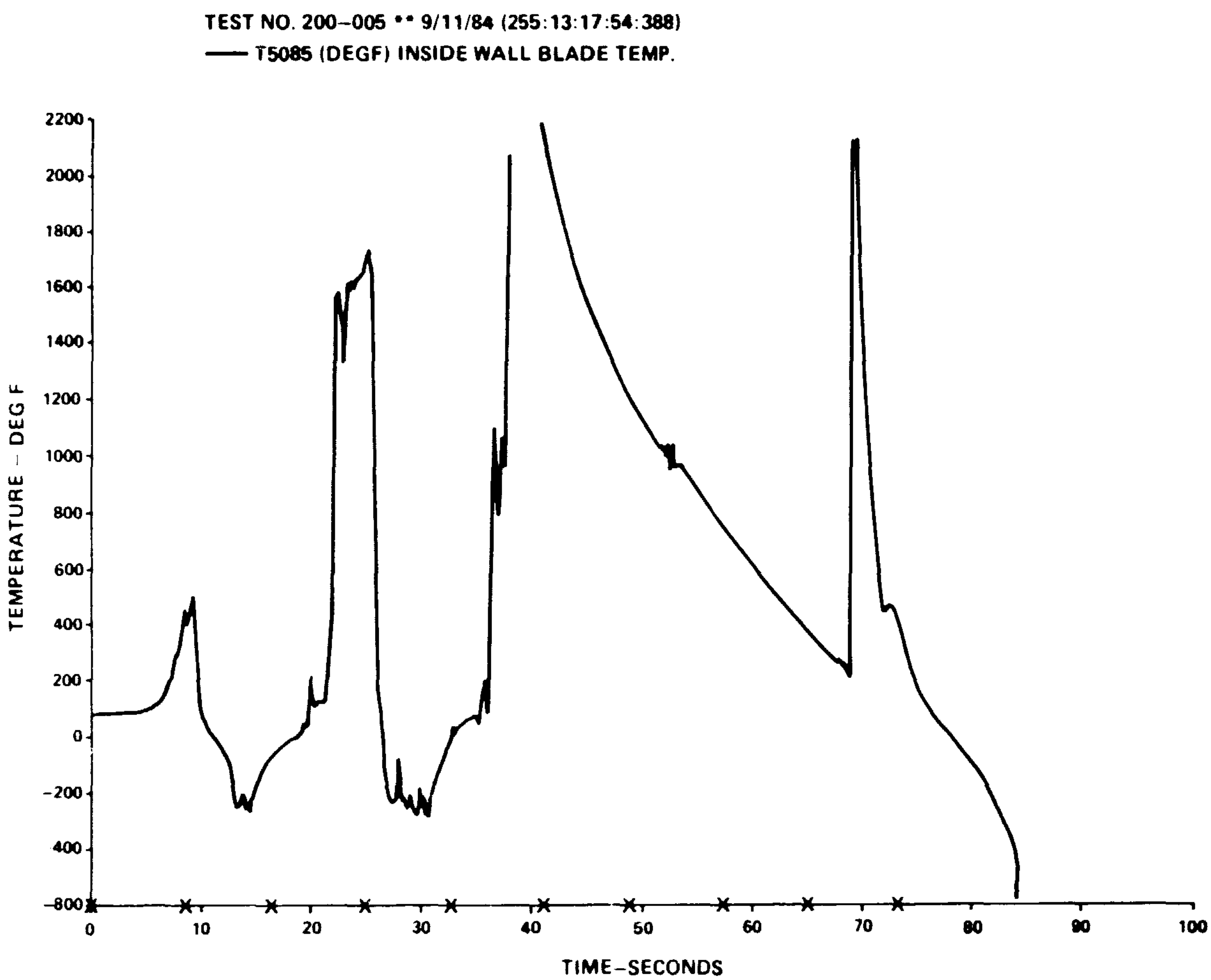

Figure 11. Hollow blade, inside wall temperature.

APPROVAL

TURBINE BLADE THERMAL FATIGUE TESTING PRATT AND WHITNEY AIRCRAFT HOLLOW CORE BLADES

By Jeff Ingram and Loren Gross

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

A. A. McCOOL
Director, Structures and Propulsion
Laboratory

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