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EXPERIMENTAL EVALUATION OF CERMET TURBINE STATOR BLADES FOR USE AT ELEVATED GAS TEMPERATURES

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SUMMARY

The suitability of cermets for turbine stator blades of a modified turbojet engine was determined at an average turbine-inlet-gas temperature of 2000° F. Such an increase in temperature would yield a premium in thrust from a service engine. Because the cermet blades require no cooling, all the available compressor bleed air could be used to cool a turbine made from conventional ductile alloys.

Cermet blades were first run in 100-hour endurance tests at normal gas temperatures in order to evaluate two methods for mounting them. The elevated gas-temperature test was then run using the method of support considered best for high-temperature operation.

After 52 hours at 2000° F, one of the group of four cermet blades fractured probably because of end loads resulting from thermal distortion of the spacer band of the nozzle diaphragm. Improved design of a service engine would preclude this cause of premature failure.

INTRODUCTION

A likely application of cermets is for the turbine stator blades of a gas-turbine engine. The outstanding strength and oxidation resistance of some cermets at high temperature suggest that cermet stator blades could withstand gas temperatures appreciably higher than conventional metal-alloy blades. Increasing the turbine-inlet-gas temperature from 1540° to 2000° F could result in an increase in net thrust of about 30 percent for a nonafterburning turbojet engine (ref. 1). At these higher gas temperatures, turbine rotor blades made from conventional ductile alloys would probably be air cooled. The quantity of compressor bleed air required for cooling would be minimized, however, because the cermet stator blades would be uncooled.

The use of cermets for turbine rotor blades has already been reported in reference 2. The current study was concerned with the use of cermets for the stator blades.

Other investigators have studied the use of cermets as stator blades at normal gas temperatures. Several cermet compositions were used in laboratory bench tests as well as in different turbojet engines. Endurance tests in a turbojet engine were published in a classified report for a cermet (K152B) containing titanium carbide and nickel. A test in a turbojet engine of a cermet (K162B) of titanium carbide, nickel, and molybdenum was reported in reference 3. Although the single cermet stator blades were mounted to avoid the hottest gas stream, failure occurred after 4 hours.

The purpose of this investigation was to determine the suitability of cermet turbine stator blades at an average turbine-inlet-gas temperature of 2000° F. This temperature is about 400° F above the normal for the turbojet engine used. Tests were confined to a cermet (K162B) containing titanium carbide, nickel, and molybdenum. Two endurance tests were first run at the NASA Lewis Research Center at normal gas temperature to evaluate two methods of mounting stator blades in a standard nozzle diaphragm. A single test at 2000° F used the method of support considered to be best. Only one group of four cermet stator blades was subjected to the hot gas environment. The test blades were mounted downstream of the center of one combustor. An auxiliary fuel supply to this combustor was used to obtain the desired gas temperature. Because the fuel supply to the other seven combustors was decreased at rated operation, the exhaust gas temperature was maintained at the normal value. Cooling of the standard turbine was therefore unnecessary.

The "hot" test was run essentially at steady-state conditions. The blade temperature was estimated to range from about 1780° to 2200° F during normal test operation, and from about 1640° to 2320° F during one interval of abnormal operation discussed in the RESULTS AND DISCUSSION section.

TEST SPECIMENS AND APPARATUS

Cermet Stator Blades

The composition of the K162B cermet used for the test blades was 64-percent titanium carbide, 6-percent solid solution of columbium, tantalum, and titanium carbides, 25-percent nickel and 5-percent molybdenum by weight. These test blades, which were supplied by Kennametal, Inc., were cold pressed and sintered. The airfoil shapes were similar to the standard metal blades. They differed, as shown in figure 1, in the following ways: (1) no offset was provided at the leading edge near the outer spacer band, (2) the ends were diamond ground to length square with the leading and trailing edges, (3) the core holes were smaller (and the walls correspondingly thicker), and (4) upsets were not provided at the trailing edges at either end.

For the first test, the cermet blades were mounted in the "as-received" condition. Selection of test blades was based on satisfactory surface inspection by post-emulsifying penetrant dye (Penetrex).

For the next two tests both ends of each cermet blade were ground to conform to the curved spacer bands; all sharp edges were removed. Penetrant dye inspection indicated no cracks as a result of this grinding.

Method of Mounting Cermet Blades

Test 1. - The four cermet blades were located near the centerlines of combustors 2, 4, 6, and 8 of a J47-GE-25 turbojet engine. Thus, they were spaced 90° apart and avoided ignition chambers. Each blade was mounted in a slot with a clearance of about 0.015 inch all around, as shown in figure 2. A clearance of about 0.10 inch was provided at the trailing edge to preclude accidental loading of the thin trailing edge. A clearance of about 0.03 inch was allowed between each end of the blade and the flat backing plate.

The cermet blades used in this test were mounted in the as-received condition. No further grinding was done on the ends to avoid the probability of introducing microscopic imperfections (that could not be detected by the surface inspection method used) because such imperfections might cause cracks during exposure to engine operating conditions.

Test 2. - The four cermet blades used in this test were located in the same positions as in test 1, and had the same clearances around the airfoil and at the ends. The ends were ground, however, to conform to the curvatures of the spacer bands. The outer spacer band was cut on either side of the test blades (fig. 3) and the included portion of the ring removed in order to eliminate accidental loading of the cermets as a result of thermal distortion of the outer band during engine operation. A stainless-steel strut within each cermet was welded to the backing plates to support the cut section of the outer band. Some cooling of the strut would be required at high temperature. This rather complex scheme was investigated as a possible method for fabricating a nozzle diaphragm with all cermet blades.

Test 3. - For the hot test, the ends of the cermet blades were ground (as for test 2) and mounted in loose slots without a strut (as for test 1). The four cermet blades were grouped in the middle hot section downstream of the transition liner as shown in figure 4. The two metal blades on either side of the cermets were air cooled to improve their endurance at the elevated gas temperature. The cooling air, which was supplied through a manifold welded to the inner spacer band, flowed radially between the inside wall of the blade and a corrugated insert, then flowed between the outer spacer band and the turbine casing, and exhausted to the gas stream through holes drilled in the outer spacer band between the trailing edges of the cermet vanes (fig. 4). In this way, the air provided some cooling for the outer band as well as for the metal stator blades.

The spacer bands were reinforced in the test section by the 1/8-inch stainless-steel backing plates which also served to position radially the cermet vanes within the slots.

Test Facility

The turbojet engine was operated in a static sea-level test stand. A standard engine was used for tests 1 and 2. For test 3, the following modifications were made: An auxiliary fuel supply system was added, and a manifold was added to the inner spacer band of the nozzle diaphragm to supply cooling air to the two metal blades on each side of the group of four cermets downstream of the hot combustor.

Modifications to fuel supply system. - The fuel system was modified to provide additional fuel flow to the hot combustor and a reduction of normal flow to the other seven combustors. In the standard fuel system (fig. 5(a)), flow to all the fuel nozzles is governed by a single control valve. In order to permit independent control of the hot combustor the standard control valve was replaced with two throttle valves, and a suitable pressure relief valve (fig. 5(b)). Check valves were added to permit the main throttle valve to control the flow to all combustors during starting and acceleration to rated speed.

Modifications to combustor and transition liners. - Previous tests with high temperature in single combustors at the Lewis Research Center indicated that standard combustor and transition liners would probably survive the proposed tests at 2000° F, with some additional cooling to the transition liner. Figure 6(a) shows the standard transition liner and ring assembly used in the outlet of seven combustors. A ring with larger holes was used in the hot combustor to provide additional cooling to the transition liner (fig. 6(b)). The two posts were removed from the transition liner (fig. 6(b)) to reduce the probability of damage to the cermets if the posts burned (as has been occasionally experienced during military service at normal operating conditions). The three slots in the upper surface and holes in the lower surface accommodated the thermocouple rakes.

Instrumentation. - The exhaust gas temperature was measured with 14 Chromel-Alumel thermocouples. All temperatures were recorded on electronic potentiometers.

The turbine-inlet-gas temperature profile upstream of the cermet blades was initially measured with Chromel-Alumel thermocouples mounted in three rakes of five couples each (fig. 7). Each rake was installed radially and located in the middle of equal areas of the annular end of the transition liner. These thermocouples were not usable after only about 6 hours at hot conditions. Because the gas-temperature profile could be adequately defined by only nine of the fifteen thermocouples, new rakes of three thermocouples each were used. Cooling air was circulated through the fairing around the thermocouple conduits and exhausted to the test cell. This cooling improved the endurance of the Chromel-Alumel thermocouples to about 20 hours. In order to attain still greater durability, platinum - platinum-13-percent-rhodium thermocouples were substituted and the supply of cooling air to these rakes was increased. The effect of the cooling air on the indicated gas temperature was determined and appropriate corrections were made.

PROCEDURE

Tests 1 and 2 at Normal Gas Temperature

After a normal start, the engine speed was held at idle for 3 minutes and then increased slowly to the "takeoff rated" conditions (engine speed, 7950 rpm and exhaust gas temperature, 1260 $^{\circ}$F). These rated conditions were maintained for a nominal 100 hours except for inspections which were made from about 8 to 13 hours apart. The same procedure was used following each inspection.

Test 3 at Elevated Gas Temperature

The flow of cooling air to the metal blades in the hot section was started. Then, a normal start was made and the speed brought up to idle. After 3 minutes at idle, the speed was slowly increased to rated, the exhaust gas temperature was set as before at 1260° F, and the cooling-air supply to the blades was adjusted to 0.22 pound per second. The speed was then reduced about 5 percent and fuel was added to the hot combustor until the desired combination was attained of an average turbine-inlet-gas temperature of 2000° F, engine speed of 7950 rpm, and exhaust gas temperature of 1260° F. These conditions were maintained except for shutdowns for inspection of the hot parts, after 12 hours, or following engine malfunction.

The turbine-inlet-gas temperature profile was recorded at 1-hour intervals. The turbine-disk temperatures were monitored at 1/2-hour intervals, as was the engine performance.

RESULTS AND DISCUSSION

Tests at Normal Temperature

Test 1. - After 9 hours at rated operating conditions, the corner at the trailing edge of one cermet blade at the outer spacer band was chipped about 1/8 inch. The test was completed without further damage to this corner. After 88 hours and 40 minutes, the trailing-edge corner at the inner band of this same blade was also chipped about 1/4 inch (fig. 8). This damage did not progress further during the remainder of the test. The test was completed with 101 hours and 40 minutes at rated. A total of 12 engine starts was made. Except for the broken corners, the four cermet blades showed no visible signs of deterioration, nor did penetrant-dye inspection indicate any further damage.

During interim inspections, the damaged blade was tight in the end slots. After the test, this blade could be moved in the slots until the trailing edge hit the ends of the slots. The chipping of the sharp corners could have been caused by either pinching between the spacer bands or repeated blows of the thin trailing edge against the ends of the slots. More care was taken in the following installations to prevent such damage.

Test 2. - There was no visible damage to the four cermet blades after 100 hours and 15 minutes at rated nor did penetrant-dye inspection reveal any damage. Figure 9 shows a typical blade after the test. Nine engine starts were made. Except for the third inspection (after 36 hr and 30 min) when one blade was tight between the spacer bands, all cermet blades were loose in the slots during all of the inspections. Both the increased care that was taken during fabrication to prevent contact between the thin trailing edge and the slot, and the somewhat more complex method of mounting the blades in the segmented outer spacer band apparently contributed to the success of this test.

Test 3 at Elevated Temperature

Before the start of test 3, three of the cermet blades had the desired looseness in the slots, but blade 6 (fig. 7) was snug between the spacer bands. No attempt was made to remedy this condition. During the fourth inspection (after 37 hr and 35 min) the trailing edges of all cermet blades were found to be buckled. The depth of buckle was the greatest in blade 3 and decreased to be the least in blade 6. Comparison between the turbine-inlet-gas temperature profile for this fourth test interval (fig. 10(a)) and the typical profile for a previous interval (fig. 10(b)) indicated an abnormal condition. There was a spread of about 800° F in the gas temperatures as compared with 500° F obtained during normal operation even though the exhaust gas temperature was maintained at 1260° F. The fuel nozzle in the hot combustor was found to leak at the upstream end, because the O-ring made a poor seal. The resulting excess fuel supplied to this combustor probably caused hot gas streaks that might have contributed to the buckling of the trailing edges. Because the buckle in the trailing edge of blade 3 was downstream of the highest gas temperature measured (fig. 10(a)), it is reasonable to expect it to be the deepest - measuring about 3/16 inch. Likewise, blade 6 was downstream of the lowest temperatures measured and it buckled the least.

Blade 6, which was originally snug, was tight in the slots during the second and subsequent inspections until the fifth (after 46 hr and 45 min), when it was loose. During the next inspection after 52 hours and 15 minutes at rated speed, (including 11 engine starts) this blade was found to have fractured chordwise about 1/4 of the height from the inner band. No localized deformation was noted at the fracture. Figure 11 shows the fracture and the buckling of the trailing edges mentioned in the previous paragraph. There was no conclusive evidence that blade 6 was the most highly loaded cermet. It is likely, however, that this blade was subjected to end bending moments resulting from thermal distortion of the outer spacer band. Such loading is suggested because blade 6 was usually tight in the end slots during inspections, while the other three were not. End compression was unlikely because of the end clearance provided. Furthermore, this blade had the least capacity to deform because it was exposed to relatively cool gas. The resulting combination of high loading and low temperature, and the relatively rapid oxidation of the surfaces possibly caused the failure. Oxidation is discussed in the next section.

Fortunately, both pieces of the fractured blade 6 jammed against the adjacent blade 5. If one of these pieces had come loose, damage would most likely have spread to the turbine rotor blades and then to the other stator blades - expecially the remaining three cermets. In order to prevent such catastrophic damage to a service engine, some internal strut should be used.

Penetrant-dye inspection of the cermet blades revealed one additional crack at the inner end of blade 4. This crack started at the trailing edge of the core hole on the suction side and extended for about 1/2 inch in an approximately spanwise direction.

Oxidation of Cermets

After termination of test 3, the surfaces of the fractured blade were found to be oxidized. Figure 12 shows this oxidation on the surfaces of the core hole as well as the outer surfaces of the blade. Spalling and erosion of this coating was evident on the leading edges of blade 3 (at about midheight) and blade 6 (adjoining the fracture). For blades 3 and 6, photomicrographs showed the oxidized coating on the outside to be approximately 0.015-inch thick and uniform chordwise. The coating on the inside was about half as thick and also uniform. The photomicrograph of the suction surface at midchord (fig. 13) shows the typical structure of the coating. Three distinct layers of oxidation are evident. Although the coating was adherent, the outermost layer contained striations that suggest excessive scale volume and a tendency to spalling. The small dark areas closest to the oxide-cermet interface are probably voids left by the more rapid oxidation of the metal binder.

The oxide coating that formed on the cermets after exposure to 100 hours at normal gas temperature is shown in figure 14. The total thickness was about 0.002 inch, or about 1/7 of the thickness formed during 52 hours at 2000° F.

Of the titanium-carbide-base cermets, K162B is one of the best in its ability to resist oxidation. The action of the columbium in the triple carbide solid solution is to aid the formation of an impervious oxide which retards further oxidation. Although the adherent nature of the coating provides a somewhat protective coating to extreme corrosion, there seems to be a reduction in the effectiveness of this protection at the experimental conditions of test 3, that is, at an estimated blade temperature above 2000° F.

SUMMARY OF RESULTS

The results of experience with K162B cermet stator blades in a J47-GE-25 turbojet engine are summarized as follows:

Operation at Normal Gas Temperature

1. Four cermet blades mounted at 90° spacing in slots survived 100 hours of takeoff rated operation. The only damage that occurred was chipping of both corners at the trailing edge of one blade. This blade was tight between the end supports during interim inspections.

2. Four other cermet blades mounted with more care in loose slots and spaced at 90° suffered no damage after 100 hours at takeoff rated conditions.

Operation at Elevated Gas Temperature

3. Four cermet blades mounted loosely in adjacent slots were subjected to an average gas temperature of 2000° F and survived 52 hours, with steady-state conditions prevailing throughout the test.

4. Permanent distortion of the trailing edges of the four cermet blades was observed; the greatest distortion was in the hottest blade. Although cermets are brittle at room temperature, considerable capacity for permanent deformation at a temperature of about 2300° F was indicated.

5. One of the four cermet blades fractured. This blade was the only one that was tight in its supports and was exposed to relatively cool gas, with correspondingly small gain in capacity for permanent deformation.

6. Cermet blades must be mounted so as to prevent restraints to loads that result from thermal distortions of the hot engine parts.

7. Oxidation of the surfaces of the cermets occurred. The coating was impervious and adherent; however, the degree of protection against extreme corrosion decreased markedly at the higher test temperature.

CONCLUDING REMARKS

This study demonstrated that under carefully controlled operating conditions the life of cermet turbine stator blades would probably be acceptable at temperatures that would yield substantial increases in thrust.

As was the case for cermet turbine rotor blades, the method of support is an important problem. The results of this investigation indicate that this problem is readily solvable.

The results of this very preliminary study were encouraging. It can be anticipated on the basis of previous research on cermets for turbine rotor blades, however, that the use of cermets for turbine stator blades will still be prohibited by the deficiencies in impact resistance, short-time ductility, and inspection methods. It appears desirable to direct future research towards a better understanding of why cermets behave as they do. Such an understanding should lead to better cermets.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, November 19, 1958

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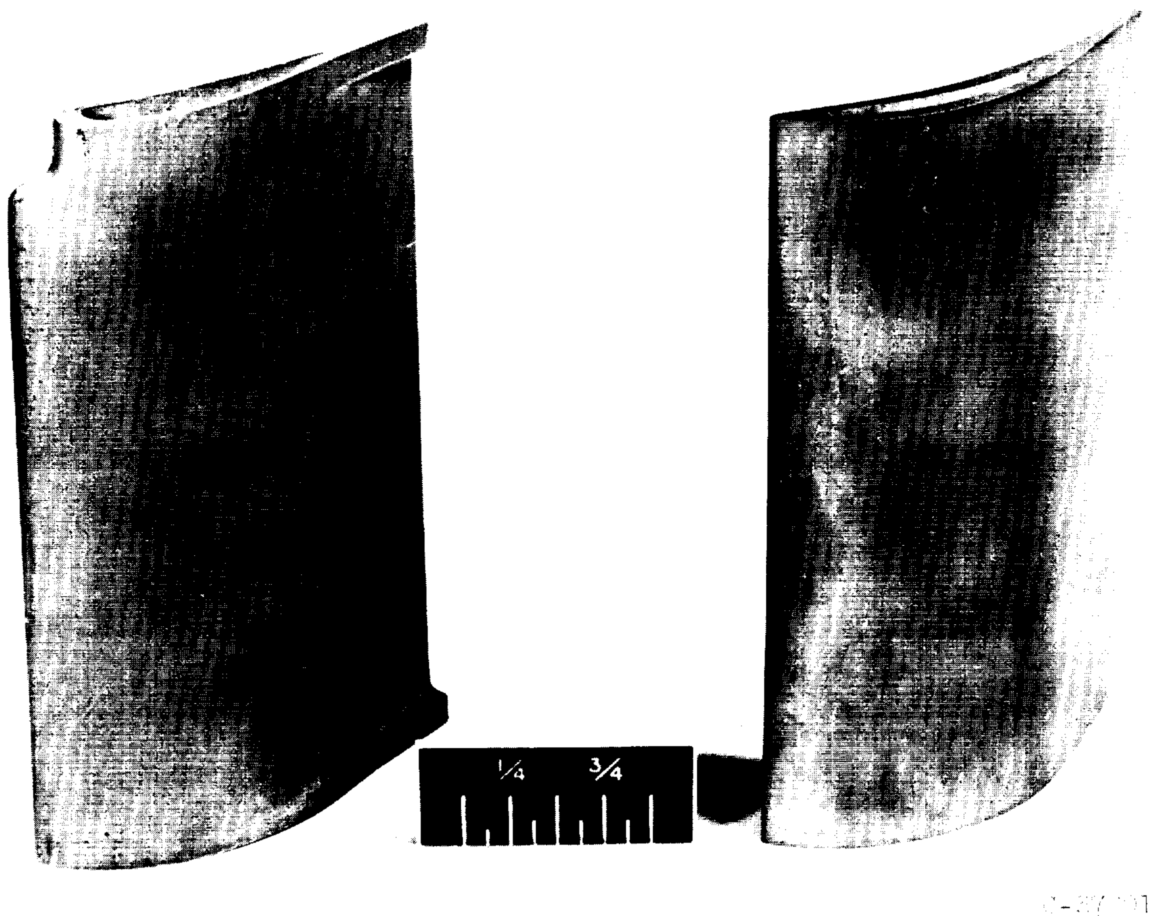
2. Deutsch, G. C., Meyer, A. J., Jr., and Ault, G. M.: A Review of the Development of Cermets. Rep. 185, AGARD, Mar.-Apr., 1958.

3. Zimmerman, W. F., and Sayre, E. D.: Engine Test of Cermet Nozzle Diaphragm Partitions - Test No. 1. R54AGT167, General Electric Co., Apr. 1954.



Metal blade

Cermet (K162B) blade

Figure 1. - Difference between standard metal turbine stator blade and cermet blade used in tests.

Figure 2. - Method of supporting cermet blades for test 1.

Figure 3. - Method of supporting cermet blades for test 2.

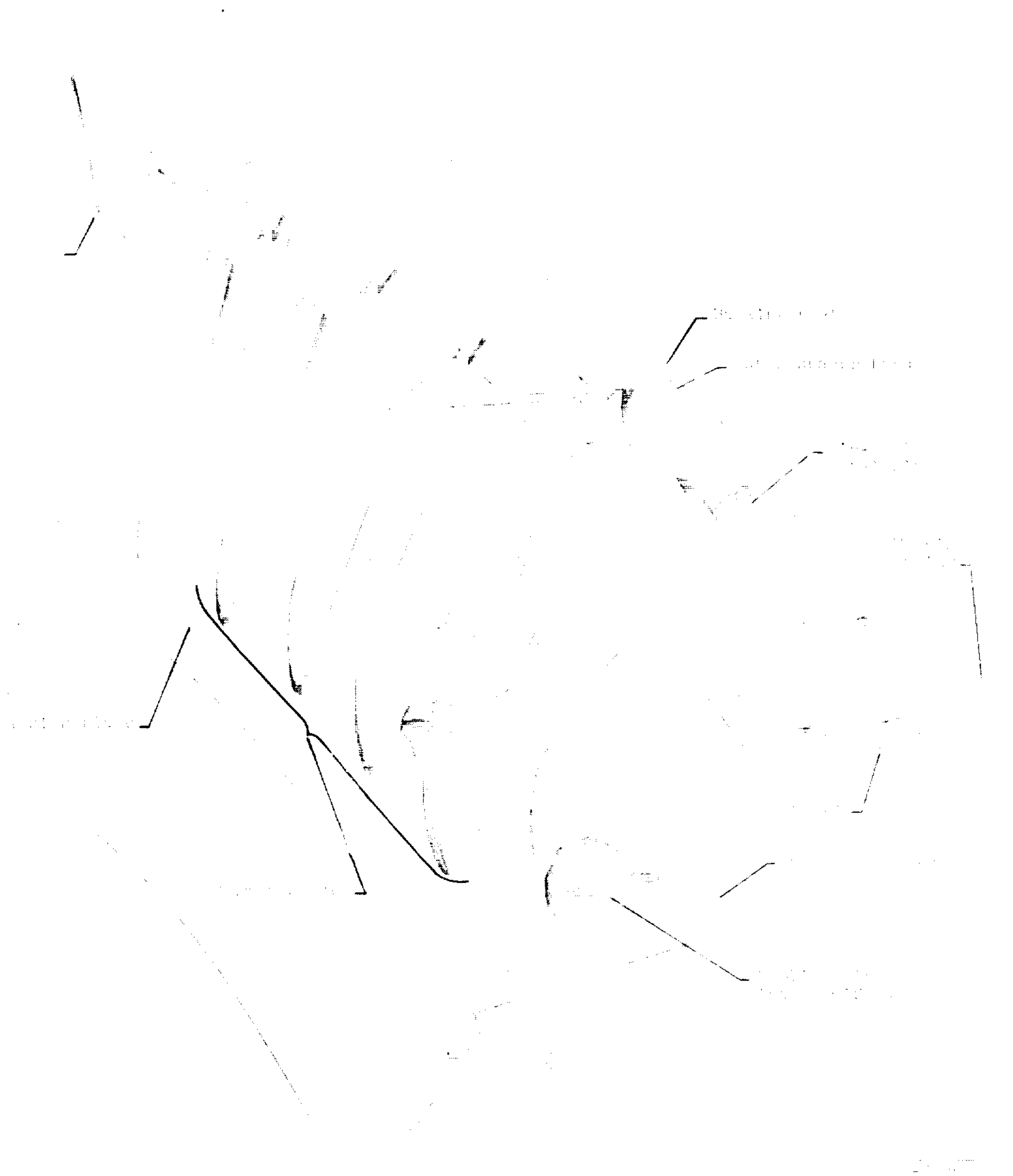
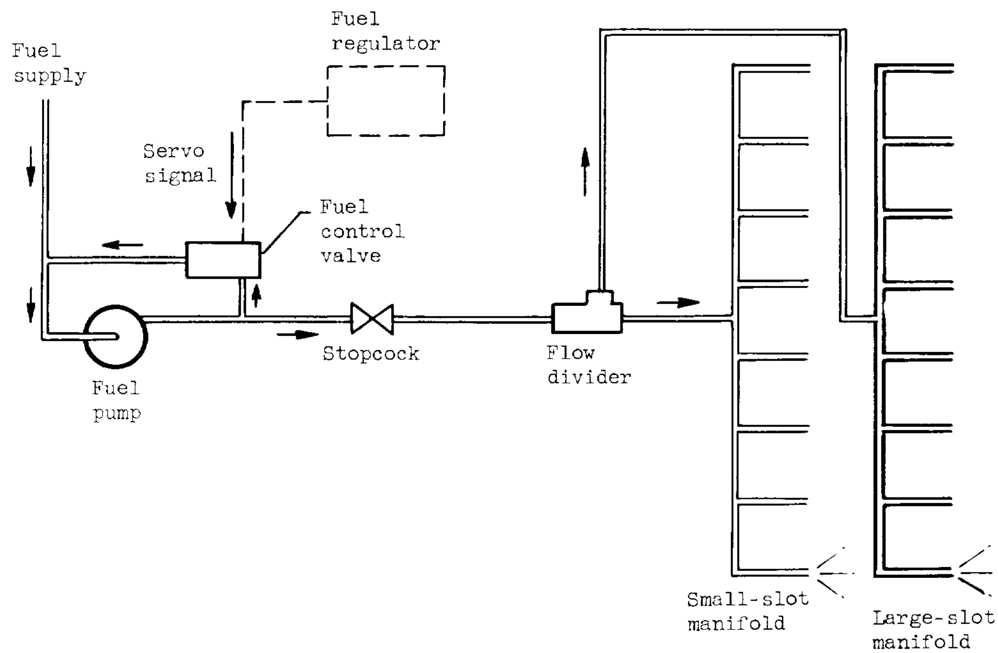
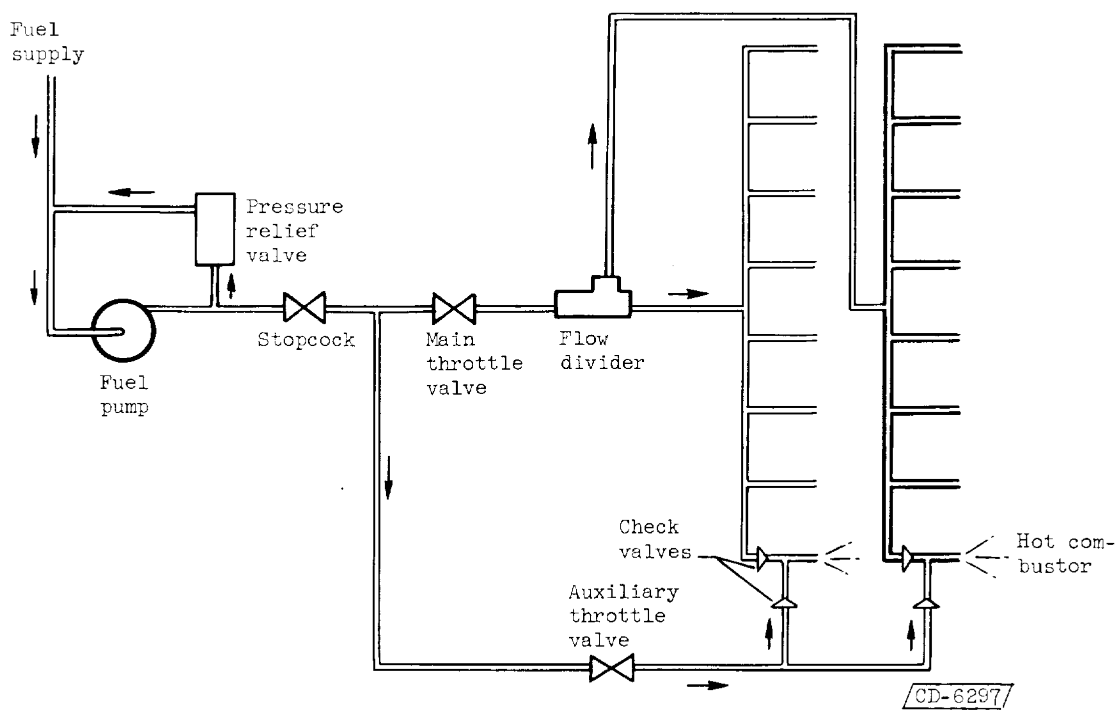


Figure 4. - Method of supporting cermet blades for test 3 at 2000° F.

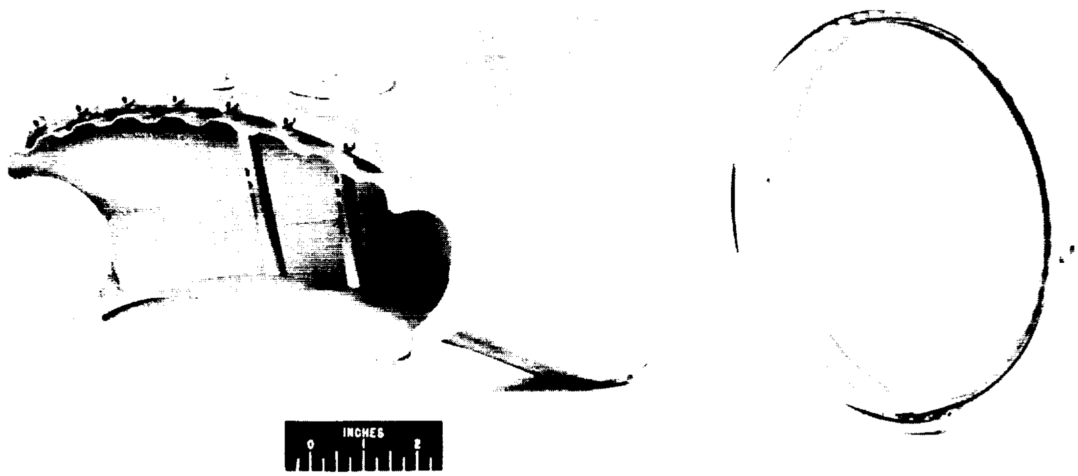


(a) Standard fuel system.

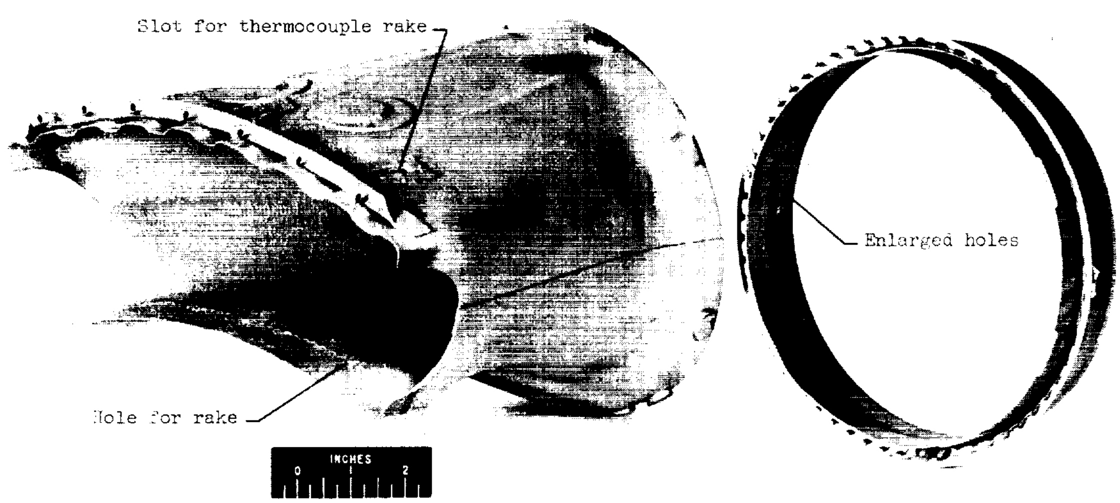


(b) Fuel system modified for independent control of one combustor.

Figure 5. - Modifications to fuel supply system to permit test at elevated gas temperatures.



(a) Standard transition liner and ring assembly used in seven combustors.



(b) Transition liner with posts removed and r.ng assembly with enlarged holes used in hot combustor.

Figure 6. Transition liners and r.ng assemblies.

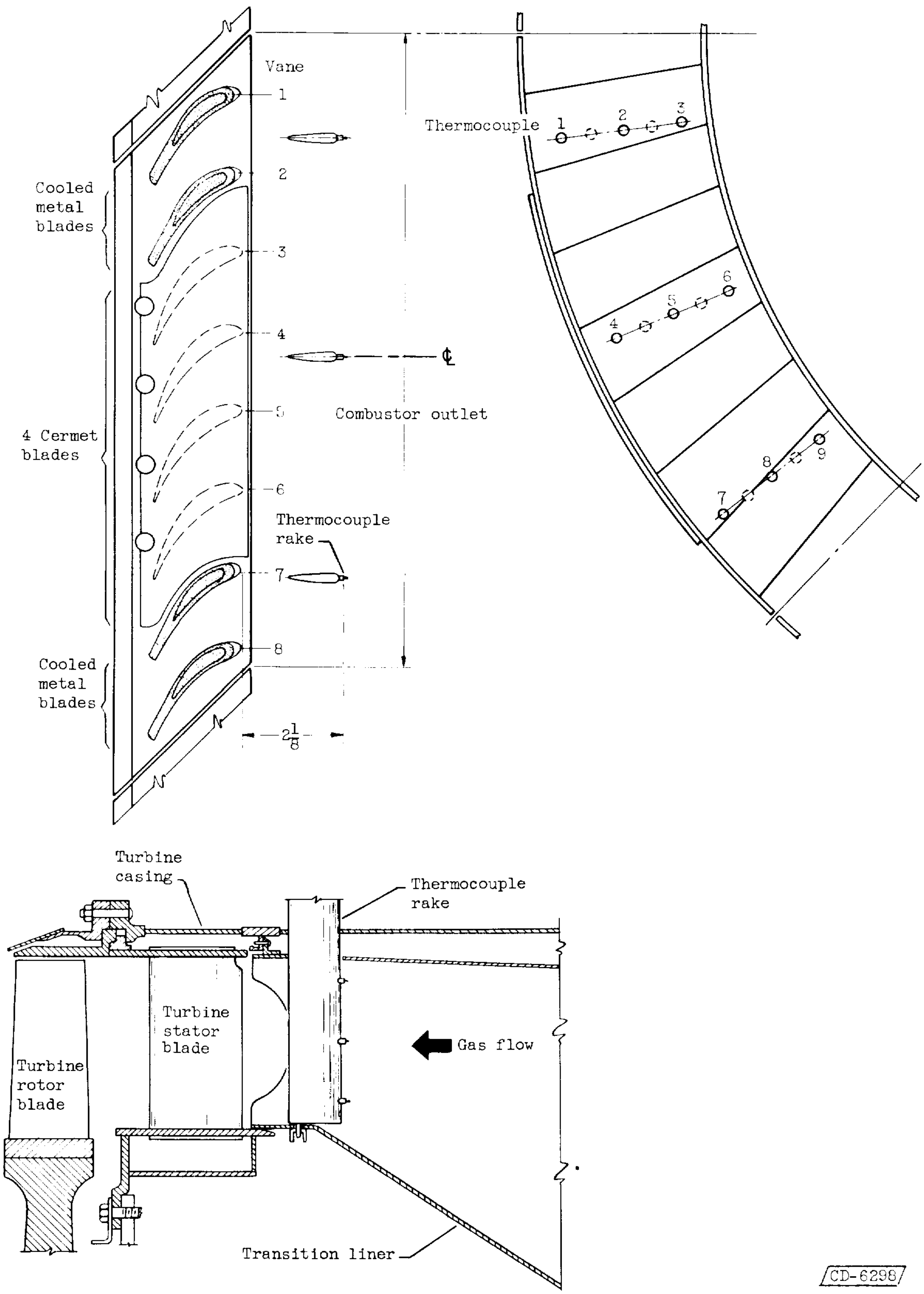


Figure 7. - Locations of thermocouples used to measure elevated turbine-inlet-gas temperature profile at test section.

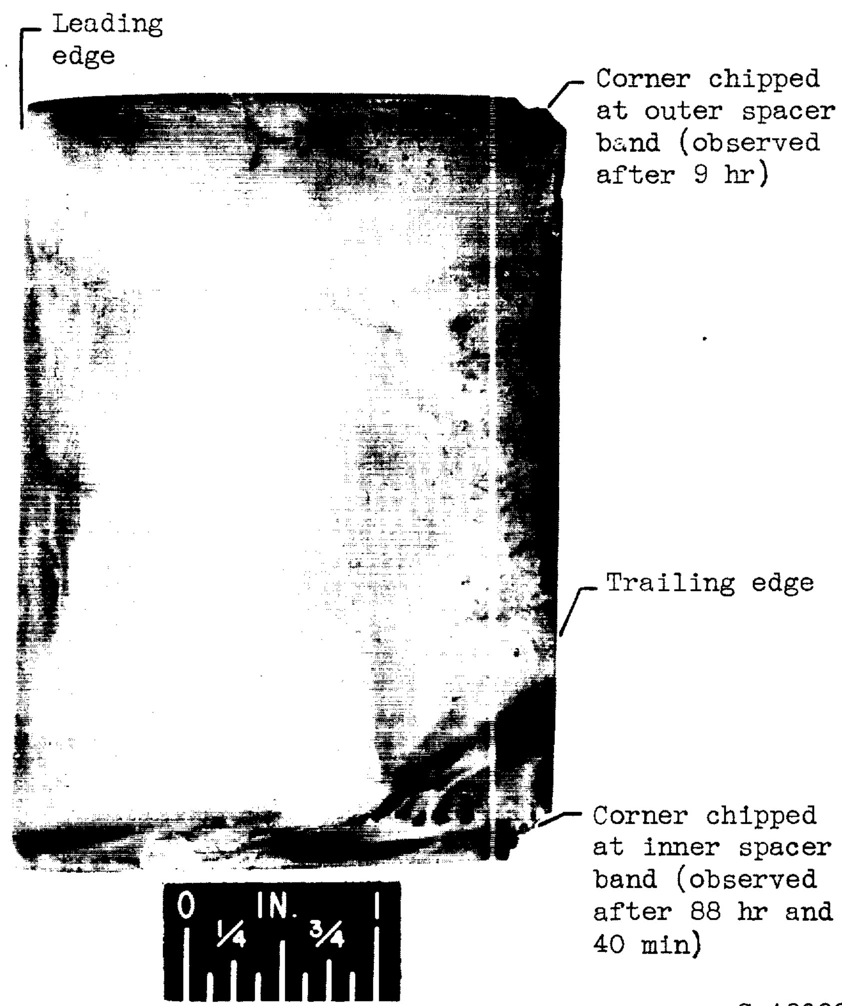


Figure 8. - Cermet blade after 101 hours and 40 minutes at takeoff rated conditions (test 1).

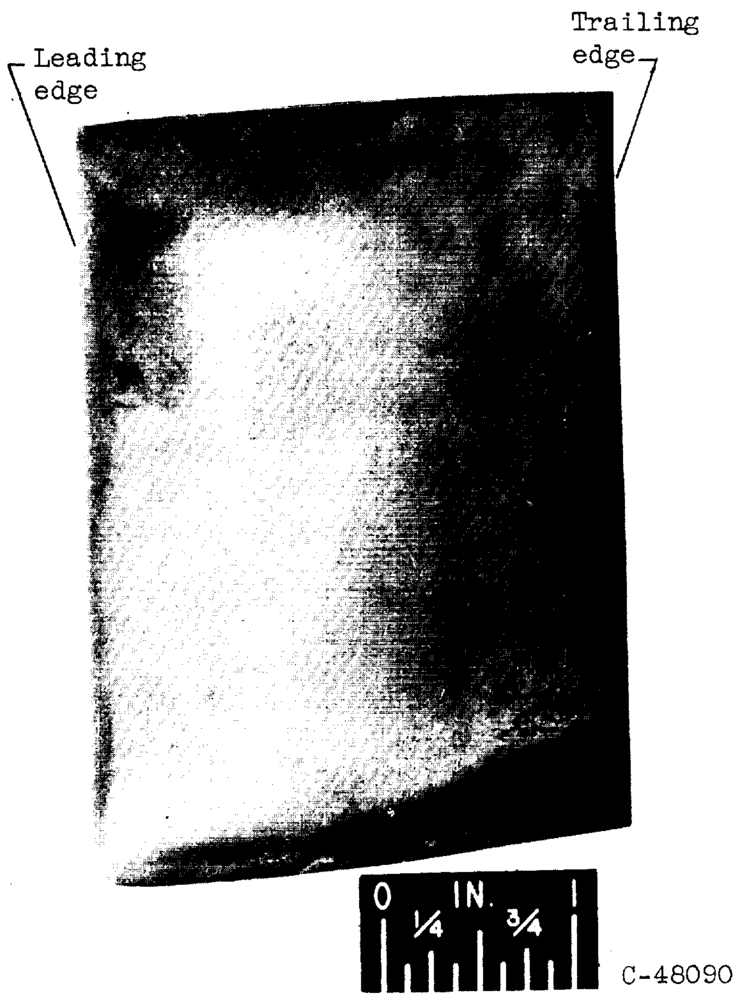
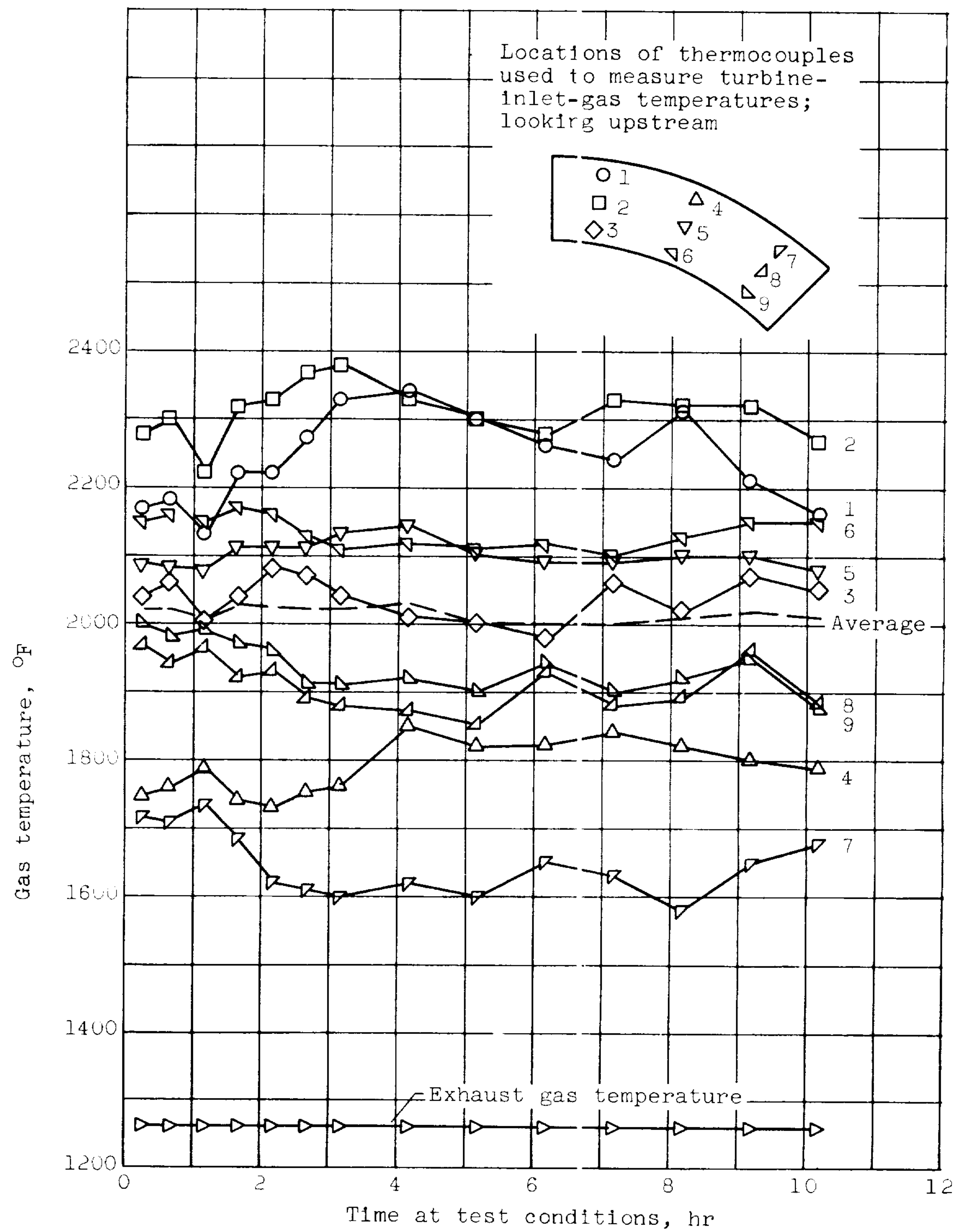
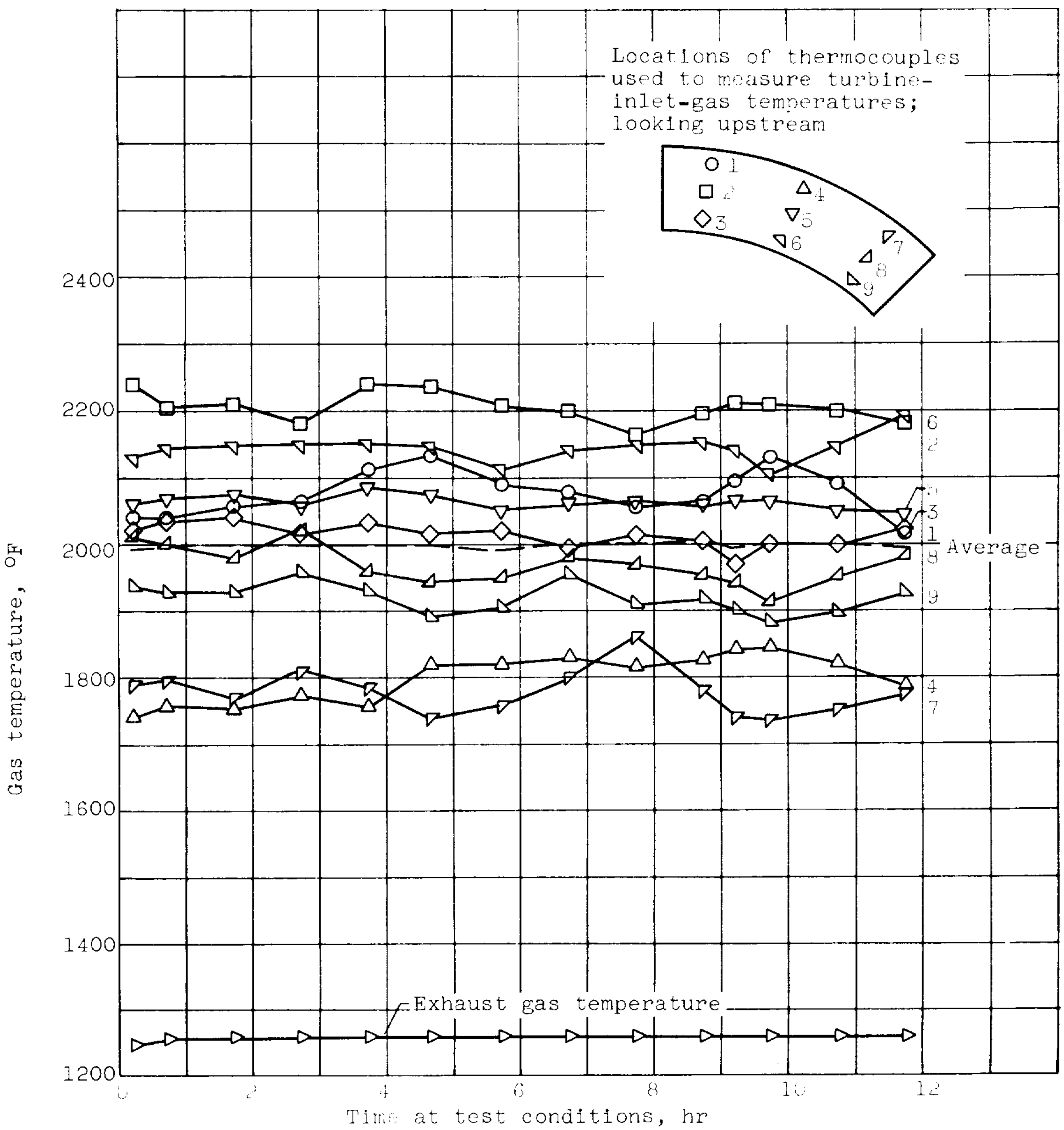


Figure 9. - Cermet blade after 100 hours and 15 minutes at takeoff rated conditions (test 2).



(a) Abnormal engine operating conditions; platinum - platinum-13-percent-rhodium thermocouples.

Figure 10. - Turbine-inlet and exhaust gas temperatures measured during hot test.



(b) Normal engine operating conditions; Chromel-Alumel thermocouples.

Figure 10. - Concluded. Turbine-inlet and exhaust gas temperatures measured during hot test.

Figure 11. - Cermet blades after 52 hours and 15 minutes at an average gas temperature of 2000° F.

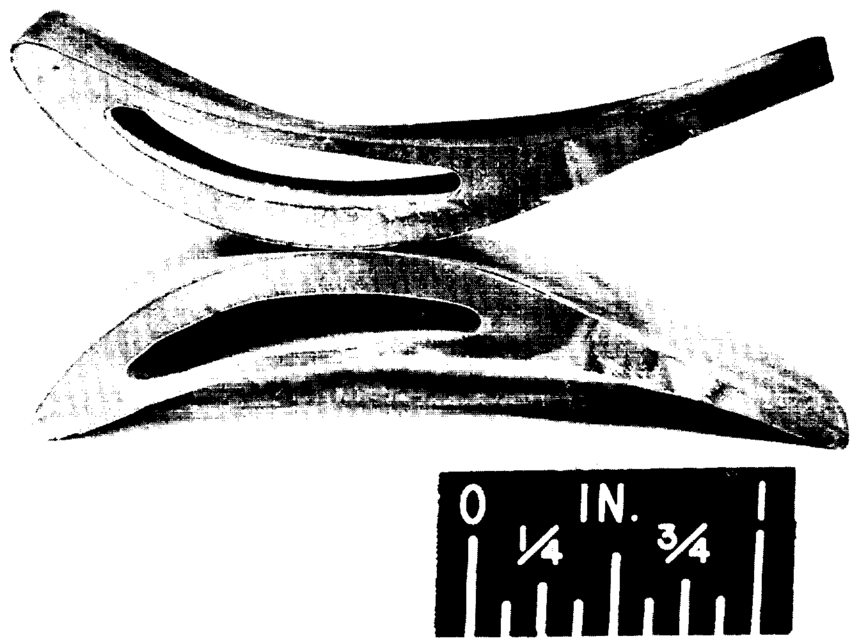


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Figure 12. - Oxidation of surfaces of blade 6 at the fracture.

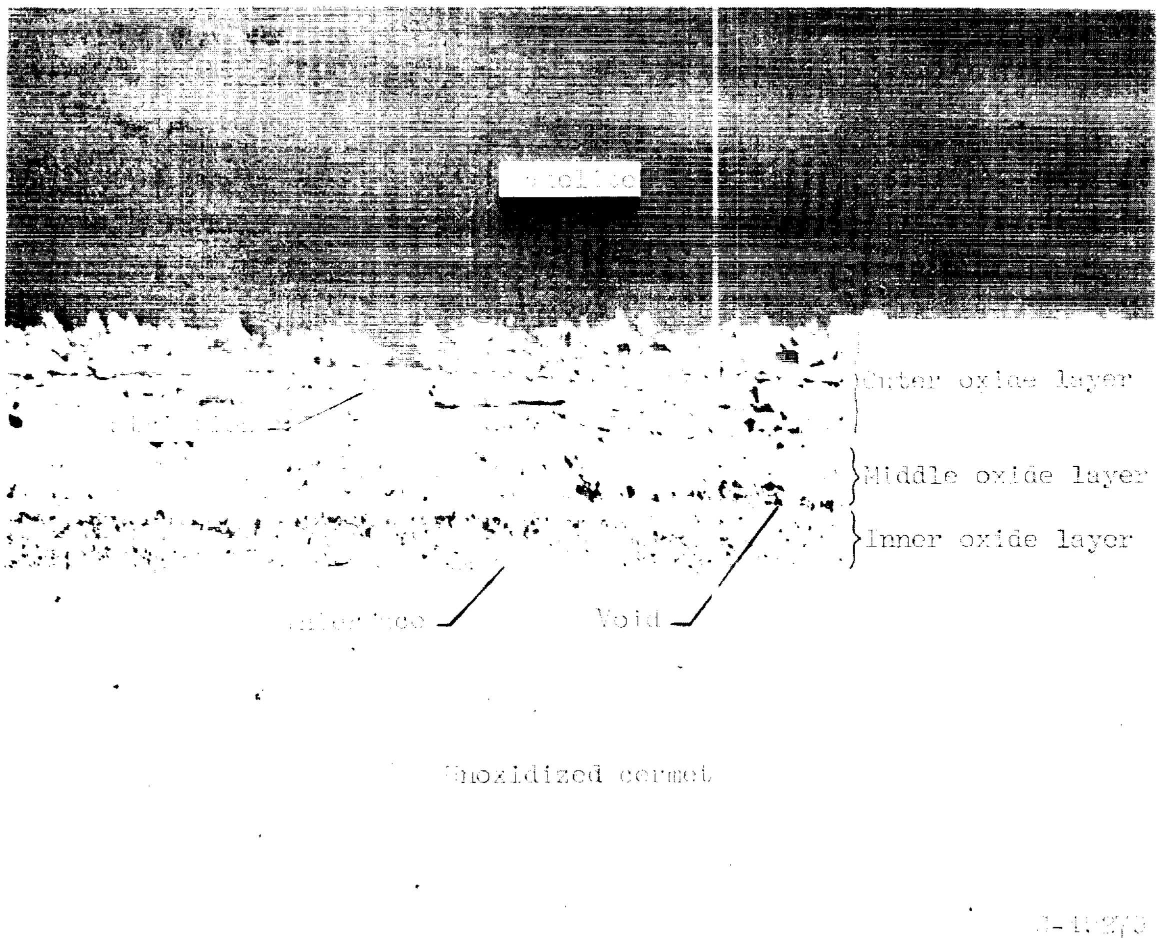

Figure 13. - Photomicrograph of oxidized coating on blade 3 after 52 hours and 15 minutes at an average gas temperature of 2000° F. Unetched. X100.

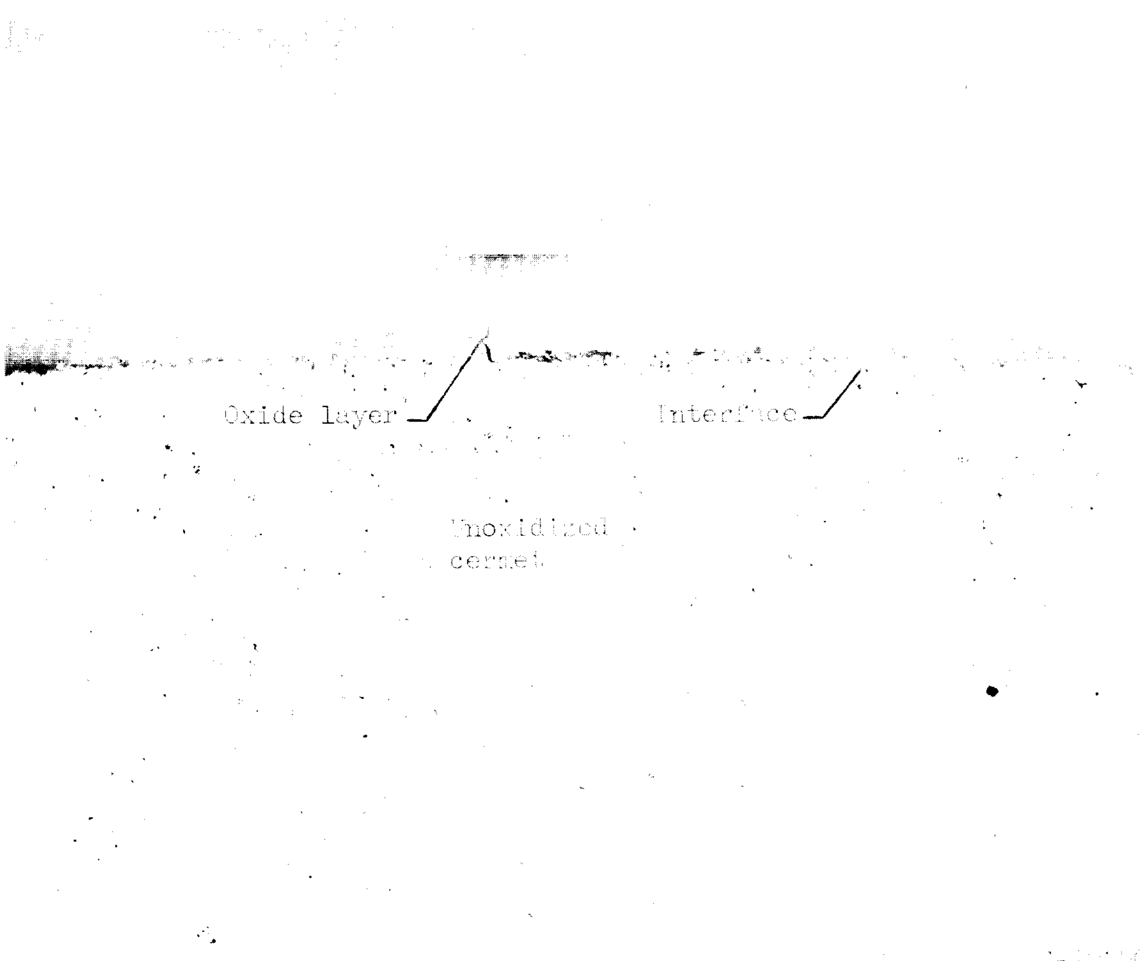

Figure 14. - Photomicrograph of typical oxidized coating on cermet after 100 hours at normal gas temperature. Unetched. X100.