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RESEARCH MEMORANDUM

INVESTIGATION OF A GAS TURBINE WITH NATIONAL BUREAU OF STANDARDS BODY 4811 CERAMIC ROTOR BLADES

By John C. Freche and Bob W. Sheflin

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

The feasibility of using ceramic materials for highly stressed turbine components is being investigated. The National Bureau of Standards developed Body 4811, a more promising ceramic than sillimanite, which was previously investigated, for application to turbine blading and a gas turbine utilizing 58 such blades was built. The turbine-wheel design was so altered as to reduce the stress concentrations to a minimum at the blade-supporting shoulders, which were apparently responsible for the blade failures of the earlier ceramic turbine.

Both spin tests and hot-gas tests were made. Spin tests were run with one set of sillimanite blades as well as the several sets of Body 4811 blades to check the effectiveness of the blade-mounting method. Hot-gas tests were essentially endurance runs made to determine the strength characteristics of Body 4811 blades at turbine operating conditions. One hot run was made with sillimanite blades, however, as an additional check on the blade-mounting method.

The set of sillimanite blades was spin-tested to a tip speed of 737 feet per second without the appearance of blade-fracturing stresses. These blades were also operated hot at a turbine-inlet gas temperature of 1400° F and a tip speed of 489 feet per second for 30 minutes without adverse effects from stress concentrations at the blade-supporting shoulders.

All sets of Body 4811 blades were successfully spin-tested to a tip speed of 737 feet per second and were run hot for periods of varying length at high tip speeds. The last set of blades was successfully operated for 50 hours at various tip speeds to 737 feet per second and at a turbine-inlet gas temperature of 1800° F.

The investigation has shown that stress concentrations at the blade-supporting shoulders have been sufficiently eliminated to allow successful operation at least to tip speeds of 737 feet per second. Body 4811 blades have been shown capable of withstanding high temperature at reasonably high tip speeds for long periods of operation. The blades have also been shown capable of withstanding a considerable decreasing-temperature heat shock while centrifugally stressed, however, they will not endure a complete heat shock of such magnitude as that caused by loss of the air supply to the turbine while centrifugally stressed.

INTRODUCTION

As part of the general program to increase turbine-inlet gas temperatures, an investigation of a ceramic-bladed turbine was initiated at the NACA Cleveland laboratory. Several factors indicate the advantages to be gained from such a turbine. The more important of these advantages are: (1) Ceramic-bladed turbines offer a particularly desirable advantage in the attempt to provide ever-increasing turbine-inlet gas temperatures in that no heat loss is incurred at high gas temperatures as in cooled turbines; (2) ceramics in general compare favorably with current heat-resisting alloys on a strength-to-density basis at turbine operating temperatures; and (3) contrary to the action of most metals, ceramics retain their strength characteristics at high temperatures. Specific ceramic properties, which indicate that ceramics may be advantageously applied to gas-turbine blading, are described in references 1 to 3. Because of the foregoing properties, the economy, and the availability of ceramic materials, the application of ceramic blades to a low-cost expendable missile turbine would be desirable.

Although short-time tensile tests showed sillimanite to have a tensile strength of 19,000 pounds per square inch at 1800° F, stress-rupture tests indicated that stress-rupture strength rapidly decreased from temperatures of 1400° to 1800° F (reference 1). In an attempt to obtain a refractory with better long-time strength characteristics at high temperatures, the National Bureau of Standards began a series of investigations as early as 1940. One of the more promising materials developed by these investigations was Body 4811. Experimental results on this material (reference 3) indicated satisfactory resistance to creep as well as rupture at a stress of 13,000 pounds per square inch at 1800° F. The superiority of this material over ordinary metals at 1800° F was indicated on a strength basis alone and particularly on a strength-density-ratio basis.

Accordingly, a turbine was built at the Cleveland laboratory to utilize National Bureau of Standards Body 4811 blades, which were dimensionally the same as the second-design sillimanite blades of reference 2. Design changes were incorporated in the turbine wheel to reduce the stress concentrations at the blade-supporting shoulders, which were apparently responsible for previous failures. These changes resulted in a turbine rig completely altered in its physical aspects from that described in reference 2.

An investigation was made to study the problems involved in the adaptation of ceramic materials to stressed turbine components. Specifically the outstanding problems are: (1) The blades must be attached to the disk in such a manner that they will resist fracturing caused by stresses at the blade-supporting surfaces; (2) the blades must be able to withstand high temperature at high speed; and (3) the blades must withstand a reasonable heat shock while being centrifugally stressed.

Two types of run, spin tests and hot-gas tests were made. The spin tests consisted in operating the turbine in a partial vacuum up to a tip speed of 737 feet per second. The spin tests were first run with a sillimanite blade ring to insure that the blade-mounting method had actually been improved by the redesign. Spin tests were also made prior to every hot-gas run with Body 4811 blades to eliminate any blades with hidden flaws not detected during inspection. The hot-gas tests were endurance runs made at turbine-inlet gas temperatures up to 1800° F and turbine tip speeds up to 737 feet per second to determine the strength characteristics of Body 4811 blades at high-speed and high-temperature conditions.

APPARATUS

The components of the turbine rotor and rig as well as a description of the blade material and the method by which the blades are supported in the rotor are described in the following paragraphs:

Turbine Rotor

Blades. - National Bureau of Standards Body 4811 has a specific gravity of 3.0 and has a satisfactory resistance to creep under a maximum stress of 14,000 pounds per square inch at a temperature of 1800° F. The maximum rate of creep under these conditions is 2.36×10^{-4} percent per hour. A detailed description of the procedures followed in obtaining these and other properties of this material is presented in reference 3.

In order to provide an additional guide in turbine operation, two load-time determinations were made at the Cleveland laboratory on specimens of this ceramic. One specimen withstood a 12,000-pound-per-square-inch tensile loading at 1800° F for 200 hours. A second specimen withstood a 10,000-pound-per-square-inch tensile loading at 2000° F for 160 hours. In both cases, the bars were unbroken at the conclusion of the determinations. These determinations indicated that the maximum permissible material stresses as dictated by reasonable characteristics of life under load were of the same order of magnitude as the stresses expected in the turbine blades upon operation at tip speeds up to 1000 feet per second.

The blade design was aerodynamically such as to provide a simple, untapered, unshrouded, impulse-type blade. The chord was 0.840 inch and the span was 1.125 inches. Large fillet radii were incorporated at the base of the aerodynamic section to reduce stress concentrations. Dimensionally, their design is the same as the second-design blades used in the ceramic-bladed turbine investigation described in reference 2.

An effort was made to solve the blade-mounting problem by making a careful analysis of the failures of the ceramic-bladed gas turbine described in reference 2. These failures were observed to occur across the blade base originating at the shoulder sections where the blades were supported by the disks. Further analysis revealed the line of fracture to be coincident with compression peaks, which were found to have a magnitude of 185,000 pounds per square inch at a turbine tip speed of 526 feet per second. These points of stress concentration were caused by insufficient allowance for blade and disk deflections, which result from rotational forces, in the design of the turbine-disk contour that mates with the blade-supporting shoulder. Such stress concentrations imposed upon the blades were reduced by building a turbine wheel incorporating several design changes. An asbestos-cloth gasket of 0.032-inch nominal thickness, chosen for its compression-loading characteristics, served as a cushion between the disks and the blade-supporting shoulders.

Because the asbestos cloth supports the blades against centrifugal force, it will be compressed along the blade-supporting shoulders and some radial displacement of the blades will result. The disks were contoured to provide a constant cushion thickness after radial displacement had taken place in order to utilize as large a supporting area as possible and to keep the stresses in the supporting shoulders as low as possible. By such means, excessive blade-supporting-shoulder loadings were reduced to a calculated 12,500 pounds per square inch at a turbine tip speed of 1000 feet per second.

Turbine disks. - The entire turbine assembly is shown in figure 1. The turbine wheel consisted of 58 blades and two disks held together by a lock nut that screwed onto threads cut on the turbine shaft. The ceramic blades were clamped between the disks and were supported against centrifugal force by overhanging lips on the disks. An asbestos-cloth gasket 0.032 inch thick served as a cushion between the disks and the blade bases.

The disks were contoured to distribute the centrifugal load uniformly over as large an area of the blade base as possible. A cross section of the rotor (fig. 1) reveals an overhanging mass on each disk. Such a design allowed the formation of a couple upon rotation that resisted the tendency of the blades to spread the disks. Cooling air was drawn into the open end of the hollow shaft, discharged into the space between the disks, and forced out through eight holes drilled transversely through each disk. Deflector plates clamped between the disks forced the air past the hot sections of the inside disk surfaces prior to being discharged through the disk cooling passages.

Because maintenance of the blades at a uniform temperature was desirable in order to keep thermal stresses within the blades to a minimum, a thin aluminum ring was clamped between the disks at a slightly smaller diameter than the inside diameter of the blade-ring assembly. The ring prevented cooling air from making contact with the bottom of the blades as it passed through the disks.

Blade and disk assembly. - The blades were assembled in a fixture as shown in figure 2 of reference 2. The complete ring had 58 blades. In order to reduce the possibility of damage from motion of the blades relative to each other, a strip of 0.025-inch asbestos cloth was placed around the base of alternate blades (fig. 2). After insertion in the fixture, an asbestos-cloth cushion of 0.032-inch thickness was fastened with a quick-drying cement to the annular ring formed by the exposed blade bases. The disks were assembled on the shaft and with the ring of blades in position, an axial load was applied to the disks by means of a hydraulic press. This procedure served to clamp the blades between the disks by compressing the asbestos cloth around the blade ring an amount predetermined by the thickness of the spacers between the disks.

Turbine Rig

Turbine. - A rigid cylindrical drum provided support for the conical bearing housings (fig. 1). The disks were straddle-mounted between two bearings of the three-bearing turbine shaft.

Both inlet and outlet collectors were of the single-entry scroll type. The entire collector assembly was hung from rigid supports bolted to the outer case. The nozzle-blade ring was a small commercial type. An annular space was provided above the blades to allow the rejection of individual broken blades with a minimum of damage to the rest of the blades. The tip diameter of the turbine was 12.06 inches, the root diameter was 9.81 inches, and the diameter of the disks was 9.40 inches. The power output of the turbine was absorbed by an electric dynamometer coupled to the turbine through an intermediate gear box with a 10:1 gear ratio.

Hot-gas system. - The hot-gas system consisted of a variable size, adjustable orifice for air-flow measurement, an air filter, a combustion chamber, and a sufficient length of ducting to allow adequate mixing of the products of combustion prior to entering the turbine. Turbine exhaust gas was discharged through a scroll-type collector into the laboratory low-pressure exhaust system. The burner was designed for low-flow velocities and could produce temperatures from 150° to 2000° F at air flows from 2 to 200 pounds per minute. This design permitted starting the burner with a small temperature rise and allowed control over a wide range of temperatures.

Instrumentation. - Because the immediate purpose of this investigation was to study the problems involved in the adaptation of ceramic materials to stressed turbine components rather than a turbine-performance investigation, a simplified form of instrumentation was required to provide the necessary data.

The inlet-gas temperature was measured by a standard quadruple-shielded commercial-type thermocouple located 54 inches upstream of the turbine.

Thermocouples were spot-welded to the straight entrance section of the inlet collector to provide wall temperatures that would serve as a guide to indicate the conditions of the duct during periods of high-temperature operation. Additional thermocouples were spot-welded at approximately 90° intervals around the periphery of both the inlet and outlet collectors to provide an indication of temperature distribution throughout the collectors.

Pressure into the turbine was measured by a mercury manometer connected to a static-pressure ring located on the inlet duct 61 inches upstream of the turbine. The outlet pressure was measured in a similar manner; in this case the static-pressure ring was located on the outlet duct 42 inches downstream of the unit.

Fuel flow was measured by a rotameter. Speed was measured with an electric tachometer and checked with a chronometric tachometer.

PROCEDURE

The scope of the runs is shown in the following table:

Blade-ring assembly	Blade material	Inlet gas temperature (°F)	Tip speed (ft/sec)	Turbine speed (rpm)
Spin tests				
1	Sillimanite		737	14,000
2	Body 4811		737	14,000
3	Body 4811		737	14,000
4	Body 4811		737	14,000
Hot-gas tests				
1	Sillimanite	1400	489	9300
2	Body 4811	1000-1800	368-578	7000-11,000
3	Body 4811	1800	400-489	7600-9300
4	Body 4811	1800	484-737	9200-14,000

Spin tests. - Blade-ring assembly 1 consisted of 29 sillimanite blades and 29 sillimanite spacers alternately placed. The spacers were blade bases that had been ground off flush at the root of the aerodynamic section; they were used in this and one other assembly only to conserve the limited supply of blades. The turbine was first operated cold in a partial vacuum up to a tip speed of 737 feet per second. This procedure was repeated three times in this and all subsequent spin tests to determine the suitability of the blade-mounting technique. At this speed the blades are stressed to approximately one-half the loading that would be obtained at a tip speed of 1000 feet per second. Sillimanite blades were used because the strength-to-density ratio of sillimanite at room temperature is considerably less than that of Body 4811 and successful completion of a spin test using this material would present more conclusive evidence of the adequacy of the blade-mounting method than a similar test with Body 4811 blades.

Blade-ring assembly 2 consisted of 29 Body 4811 blades alternately spaced with 29 sillimanite spacers. This blade ring was also spin-tested in the turbine up to a tip speed of 737 feet per second. By means of such a spin test, it was felt that any serious flaw not detected in the original blade inspection would result in the failure of any blades so affected. This method served to limit causes of blade failure during hot runs and thus tended to simplify the analysis of any blade breaks that might occur during such runs. Accordingly, blade-ring assembly 3 and blade-ring assembly 4, each consisting of 58 Body 4811 blades, were also spin-tested in the turbine up to a tip speed of 737 feet per second prior to being operated at temperature.

Hot-gas tests. - The turbine was first operated hot up to 1400° F at a tip speed of 489 feet per second with the sillimanite blade-ring assembly. These conditions of operation closely resembled the maximum conditions imposed upon the ceramic-bladed gas turbine described in reference 2. The pattern of blade breakage obtained with sillimanite blades on the turbine of reference 2 is, of course, known. A comparison was intended between this pattern and any blade breaks occurring when sillimanite blades were mounted in the altered disks used in this investigation. In this way the adequacy of the blade-mounting method could be further evaluated.

The remainder of the runs were essentially periods of endurance operation in which Body 4811 blades were used. Blade-ring assembly 2 was operated at various conditions of temperature and speed up to a maximum turbine-inlet-gas temperature of 1800° F and a turbine tip speed of 578 feet per second.

Blade-ring assembly 3 was operated in the turbine at a turbine-inlet-gas temperature of 1800° F and a turbine tip speed of 489 feet per second for the greater portion of this endurance run.

Blade-ring assembly 4 was continuously operated in the turbine at an inlet-gas temperature of 1800° F and a turbine tip speed of 484 feet per second during the first stage of this run. A turbine tip speed of 536 feet per second was set in the second stage of this run. Before beginning the third stage of operation, the turbine was disassembled and the blade ring inspected. The turbine was then reassembled with the same blade ring unaltered and the entire unit balanced prior to operation with an inlet-gas temperature of 1800° F and at tip speeds of 631, 684, and 737 feet per second.

Method of operation. - Because little information was available concerning the mechanical strength of the ceramic used in this investigation when subjected to high thermal stresses, the turbine operating conditions were cautiously set. The outlet pressure was set to give a low pressure drop (1.5 in. Hg) across the turbine and the burner was started at a fuel flow that gave an inlet-gas temperature not higher than 200° F. The inlet-gas temperature was increased to 500° F at a rate of approximately 100° F per minute and the pressure drop across the turbine was maintained at 1.5 inches of mercury. At this point the turbine was accelerated to a tip speed of approximately 142 feet per second. The pressure drop was then set according to values of inlet and outlet pressure computed to maintain zero angle of attack for an assumed constant value (90 percent) of nozzle efficiency. These values were previously calculated for all combinations of speed and temperature at which the turbine was to be operated. The inlet-gas temperature was varied by changing the fuel flow; speed was controlled by an electric dynamometer. High-temperature operating points were set by increasing the inlet-gas temperature to the desired value while the turbine was rotating at the minimum dynamometer speed. The speed and the pressure ratio were increased to the desired level once the operating temperature had been fixed. Such a procedure was followed so that temporary thermal stresses would not be added to high centrifugal stresses.

RESULTS AND DISCUSSION

Spin tests. - A complete synopsis of the several runs made, showing operating conditions and results is given in table I.

Blade-ring assembly 1 successfully underwent the three spin tests described in the preceding section. The fact that no damage resulted to any of the sillimanite blades indicated that the stress concentrations at the blade base evidenced by the type of failure that occurred with sillimanite blades used in the previous ceramic-turbine investigation (reference 2) had been considerably reduced.

Blade-ring assemblies 2, 3, and 4 successfully underwent similar spin tests without the failure of a single blade.

Hot-gas tests. - Blade-ring assembly 1 was operated for 30 minutes at a turbine-inlet gas temperature of 1400° F and a tip speed of 489 feet per second. No adverse effects were apparent from stress concentrations at the blade base within this period of time, which is somewhat longer than the sillimanite-bladed gas turbine of reference 2 was operated without failure at similar conditions.

Blade-ring assembly 2 was operated for 12 hours and 30 minutes. Included in this period of operation were four starts from the cold condition. Operation with this blade ring was halted by the failure of a sillimanite spacer. One blade directly adjacent to this spacer was broken off slightly above the blade base. Flying fragments chipped 19 of the 29 blades in the ring. The turbine wheel after this failure is shown in figure 3. Because a sillimanite spacer apparently fractured, final conclusions cannot be drawn from this run concerning the number of turbine starts Body 4811 blades can undergo.

Blade-ring assembly 3, the first complete ring consisting entirely of Body 4811 blades used in this investigation, contained the 10 blades that were undamaged in the preceding run. After 23 hours of continuous endurance operation at an inlet-gas temperature of 1800° F and a turbine tip speed of 489 feet per second, failure of the electric system supplying power to the dynamometer caused an emergency shutdown in which the fuel was automatically shut off. Before the air supply could be manually shut off, however, the inlet gas temperature decreased immediately to 500° F. The sudden decrease in temperature imposed a severe thermal shock on the blades that might more properly be referred to as "a decreasing-temperature heat shock." Failure of ceramic blades by heat shock even while not under centrifugal stress has always been somewhat of a problem. Heat-shock tests on sillimanite blades (reference 2) showed that these blades could withstand heating cycles with an 1100° F temperature change from 400° to 1500° F at the rate of 24,000° F per minute. During the cooling cycle, however, two out of three sillimanite blades failed with the same degree and rate of temperature change. The conditions of this particular shutdown resemble those of such a cooling cycle with the important exception that a centrifugal stress as well as a thermal stress was present. The fact that only one blade was broken off halfway between its tip and base and two blades were slightly chipped at the top corners of their leading edges while the blades were subjected to a combined thermal and centrifugal stress gives an indication of their strength characteristics. The entire blade ring as it appeared upon removal from the turbine after this shutdown is shown in figure 4.

The three damaged blades were replaced to form blade-ring assembly 4. This blade ring was operated continuously for 45 hours without damage to any of the blades at an inlet gas temperature of 1800° F and a turbine tip speed of 484 feet per second. The tip speed was increased to 536 feet per second during the second stage of the run and the turbine operated for 3 additional hours. Close examination of figure 5, which shows the turbine wheel after the second stage of this run, shows that several blades were chipped. The chipping did not occur during this run but is present because the limited supply of blades available made it necessary to use some blades that were slightly damaged in order to obtain the full complement of 58 blades required for a complete ring. During the third stage of this run while the turbine was being operated for periods of 1 hour at the various conditions described in the preceding section, the air supply to the turbine failed. This failure occurred at an inlet-gas temperature of 1800° F and a turbine tip speed of 737 feet per second, which subjected the blades to a tremendous heat shock at a time when they were already under high centrifugal stress and resulted in the failure of all blades. The loss of combustion air caused the temperature to first increase and then decrease as the sudden condition of excess fuel created an excessive temperature and then actually acted as a coolant, which finally extinguished burning. Whereas the shutdown that occurred while blade-ring assembly 3 was being run resulted in only decreasing-temperature heat shock to the blades, the sudden temperature increase followed immediately by a temperature decrease due to the loss of air subjected the blades to a complete heat-shock cycle. Figure 6 shows the turbine wheel after this shutdown.

SUMMARY OF RESULTS

The following results were obtained from an investigation conducted on a ceramic-bladed gas turbine with National Bureau of Standards Body 4811 blades as part of a program to determine the feasibility of using ceramic materials for highly stressed turbine components:

1. The turbine was operated cold with both sillimanite and Body 4811 blades without blade failure up to tip speeds of 737 feet per second.

2. The sillimanite blade ring was also operated without the appearance of blade fracturing stresses for 30 minutes at a turbine-inlet gas temperature of 1400° F and a tip speed of 489 feet per second, which is considerably longer than the sillimanite-bladed gas turbine of the previous investigation was operated at similar conditions.

3. The turbine was run hot with Body 4811 blades for 50 hours at a turbine-inlet gas temperature of 1800° F at tip speeds ranging from 484 to 737 feet per second (9200 and 14,000 rpm), which greatly exceeds the maximum tip speed of 457 feet per second and the maximum inlet gas temperature of 1725° F as well as the length of operation achieved with the sillimanite-bladed turbine of a previous investigation.

4. The strength characteristics of Body 4811 blades insofar as resistance to heat shock while undergoing centrifugal stress were demonstrated. The blades were capable of withstanding a considerable decreasing-temperature heat shock while undergoing centrifugal stress; however, they did not stand up under a complete heat-shock cycle of such magnitude as that caused by loss of the air supply to the turbine while centrifugally stressed.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, July 20, 1948.

REFERENCES

1. Kunen, Alfred E., Hartwig, Frederick J., and Bressman, Joseph R.: Tensile Properties of a Sillimanite Refractory at Elevated Temperatures. NACA TN No. 1165, 1946.

2. Hartwig, Frederick J., Sheflin, Bob W., and Jones, Robert J.: Preliminary Investigation of a Gas Turbine with Sillimanite Ceramic Rotor Blades. NACA TN No. 1399, 1947.

3. Geller, R. F., and Burdick, M. D.: Progress Report on Strength and Creep of Special Ceramic Bodies in Tension at Elevated Temperatures. NACA ARR No. 6D24, 1946.

TABLE I - RESULTS OF INVESTIGATION OF CERAMIC-BLADED GAS TURBINE

Blade-ring assembly	Blade material	Running time (hr)	Running time (min)	Inlet gas temperature ($^{\circ}$F)[1]	Turbine tip speed (ft/sec)	Turbine speed (rpm)	Remarks
1	29 sillimanite blades with 29 sillimanite spacers				737	14,000	Spin test. Unit operated cold and brought up to speed three times. Blades undamaged.
			30	1400	489	9300	No blades broken from stress concentrations at blade-supporting shoulder.
2	29 Body 4811 blades and 29 sillimanite spacers				737	14,000	Spin test satisfactory.
			15	1000	368	7000	
			45	1400	368	7000	
			30	1400	484	9200	
		7		1400	578	11,000	
		4		1800	578	11,000	One sillimanite spacer failed and flying fragments chipped 19 blades.
	TOTAL	12	30				
3	Complete ring of 58 Body 4811 blades				737	14,000	Spin test satisfactory.
		3	45	1800	400	7600	
		23		1800	489	9300	Electric power failure to dynamometer resulted in decreasing-temperature heat shock to blades, breaking one and chipping two.
	TOTAL	26	45				
4	Complete ring of 58 Body 4811 blades				737	14,000	Spin test satisfactory.
		45		1800	484	9200	Turbine disassembled and blades undamaged after run. Turbine reassembled with same blade ring and rebalanced.
		3		1800	536	10,200	
		1		1800	631	12,000	Air supply to turbine failed after tip speed of 737 ft/sec was reached, thus subjecting blades to complete heat-shock cycle, which resulted in failure of all blades.
		1		1800	684	13,000	
				1800	737	14,000	
	TOTAL	50					

[1] Temperature measured by quadruple-shielded commercial-type thermocouple.

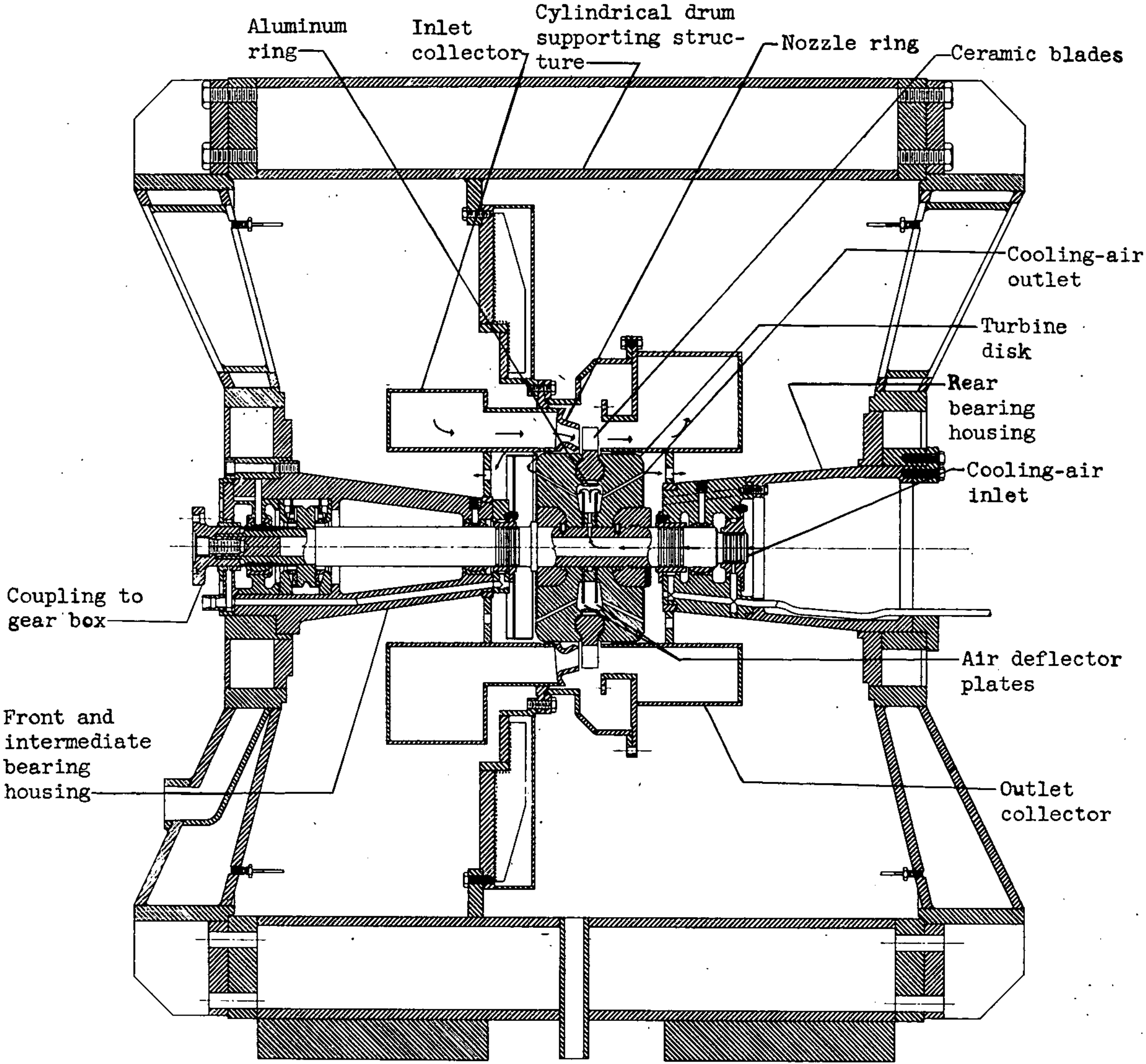

Figure 1. - Ceramic-bladed turbine assembly and supporting structure.

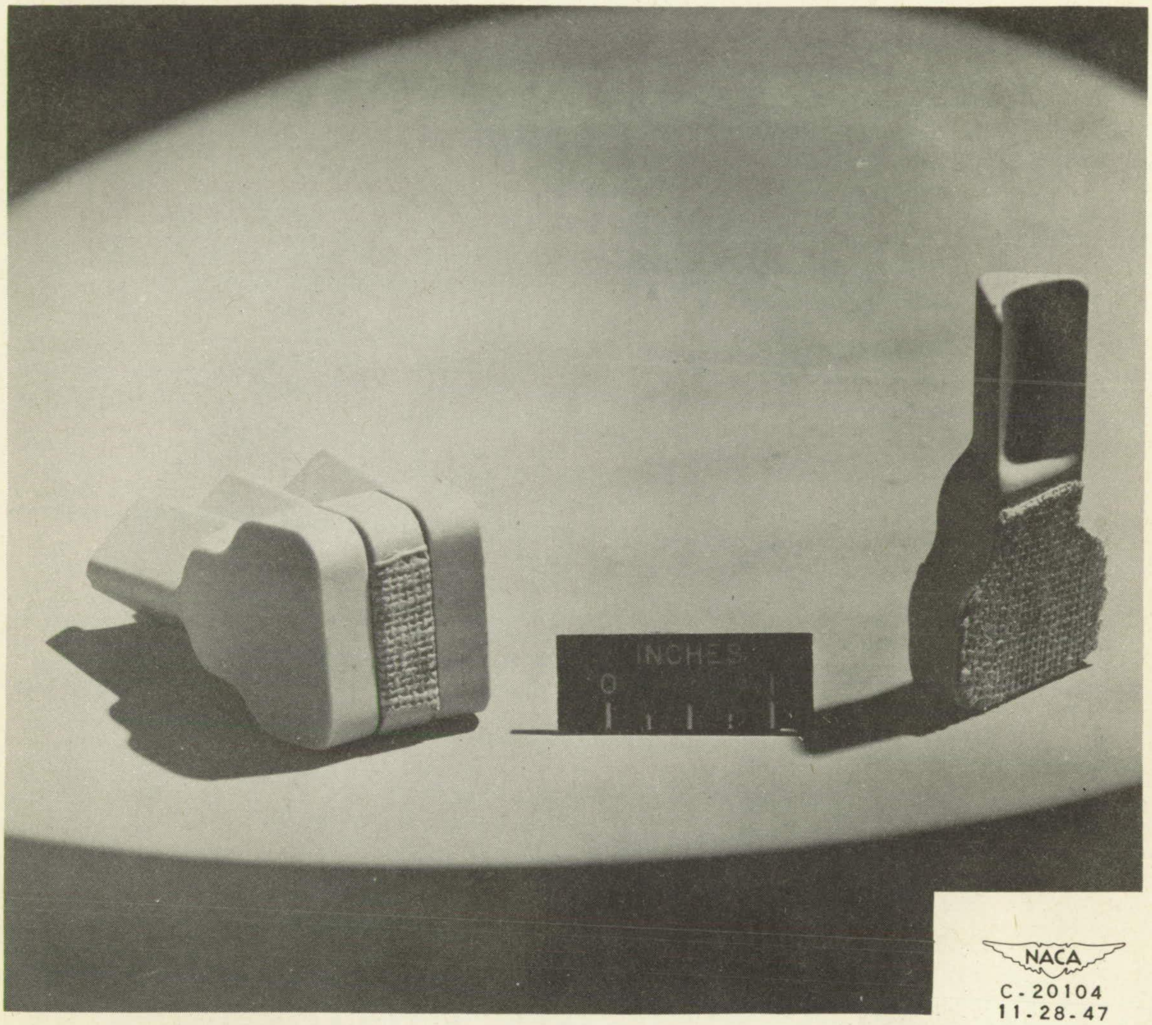

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Figure 2. - View of individual ceramic blades showing asbestos cloth wrapped around base of alternate blades.

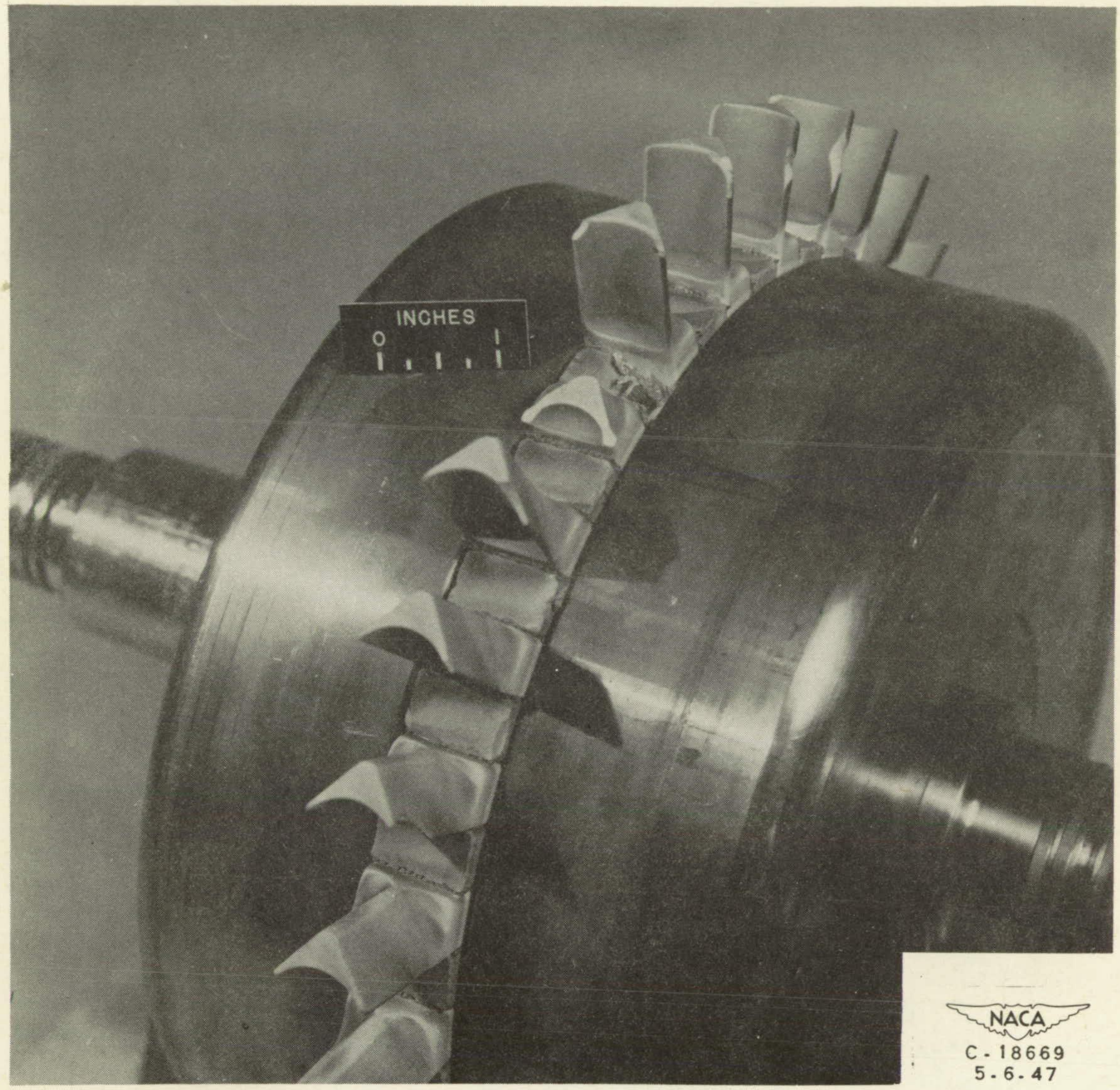

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Figure 3. - View from exhaust side of ceramic-bladed turbine after shutdown caused by broken spacer. Blade-ring assembly 2.

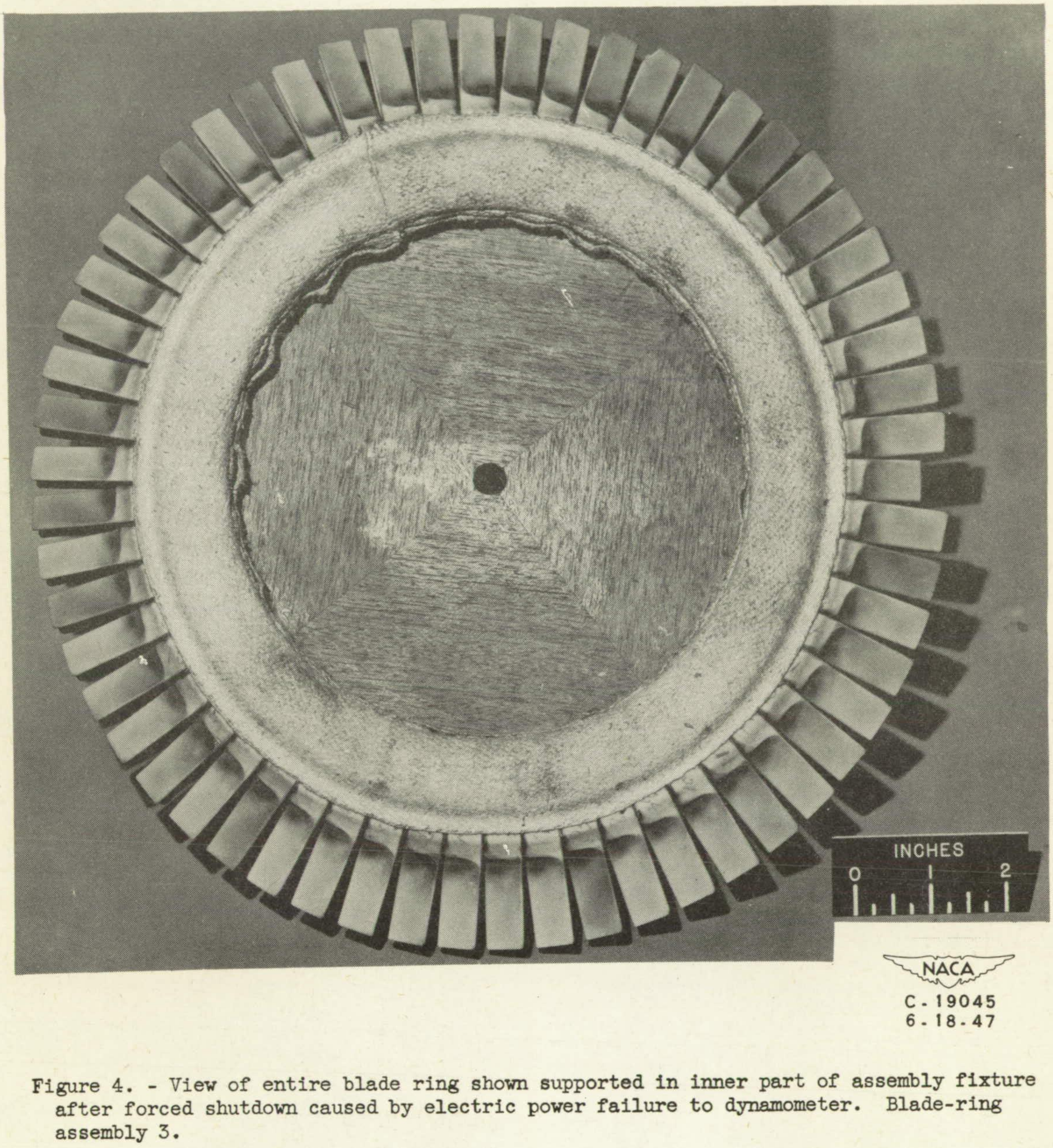

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Figure 4. - View of entire blade ring shown supported in inner part of assembly fixture after forced shutdown caused by electric power failure to dynamometer. Blade-ring assembly 3.

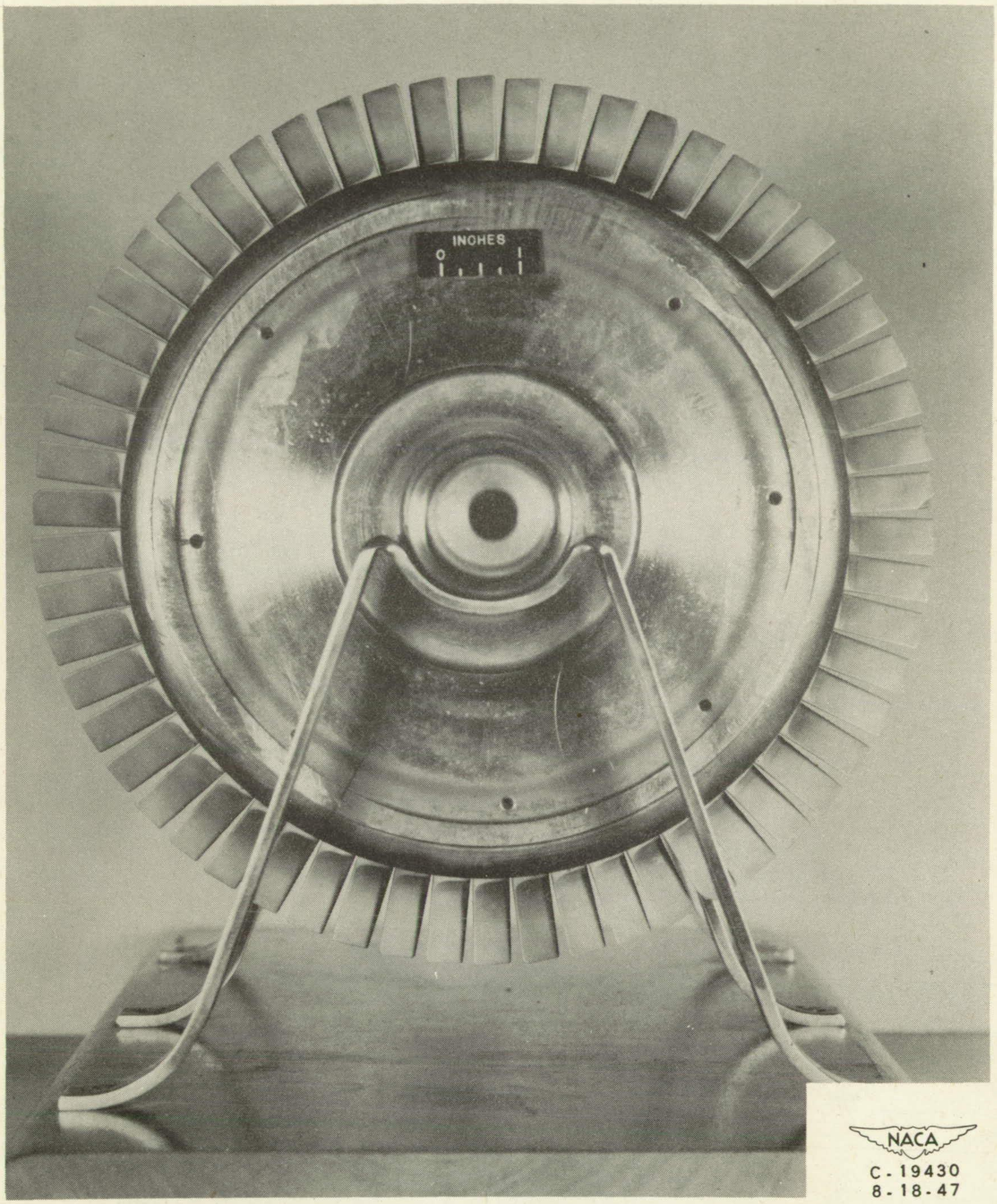

Figure 5. - End view of ceramic-bladed turbine disk, shaft, and blade-ring assembly from exhaust side after 48-hour endurance run. Blade-ring assembly 4.

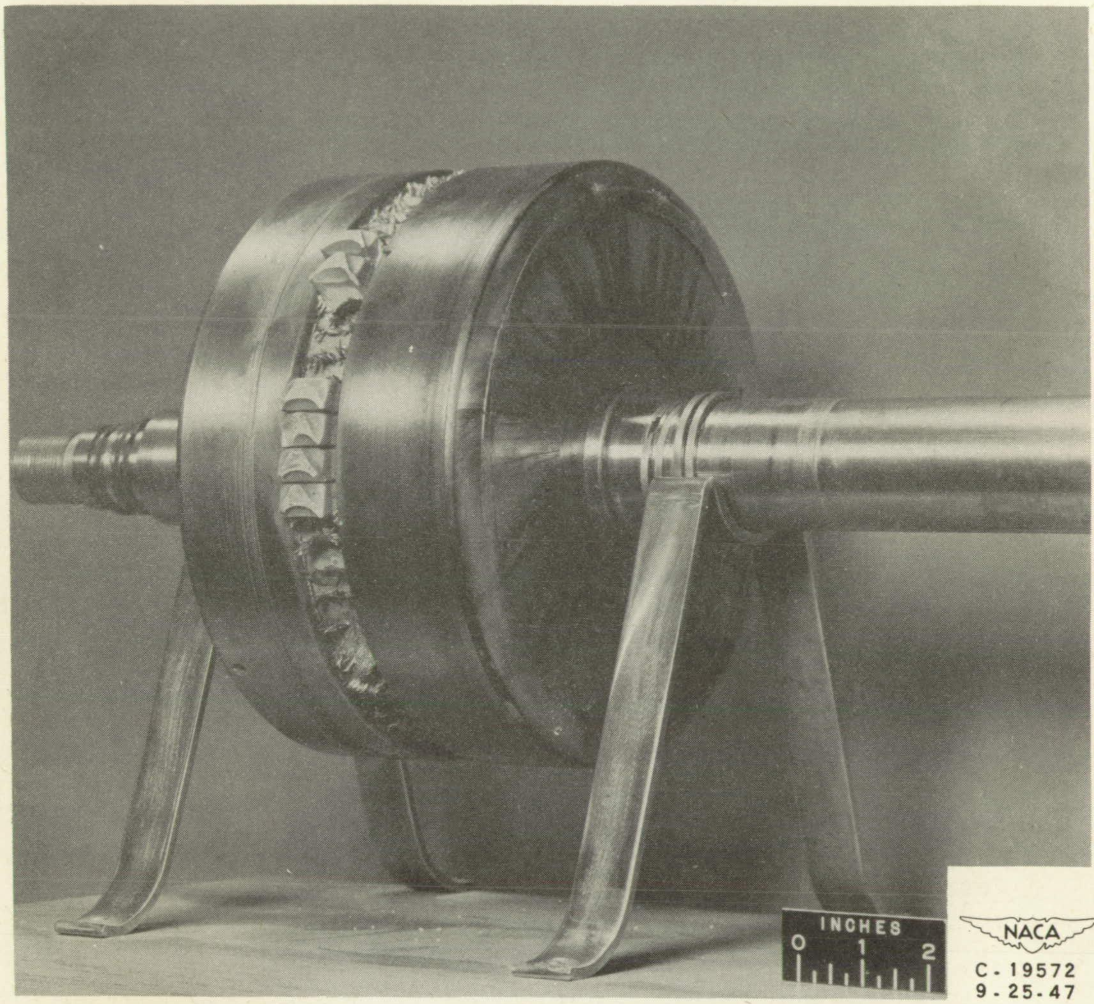

Figure 6. - View of ceramic-bladed turbine disk, shaft, and blade-ring assembly from inlet side after forced shutdown caused by loss of air supply to turbine. Blade-ring assembly 4.