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RESEARCH MEMORANDUM

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

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

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SUMMARY

National Bureau of Standards Body 4811C ceramic blades were used in a continuation of the investigation of the problems involved in the adaption of ceramic materials to stressed turbine components.

Preliminary spin tests to tip speeds of 737 feet per second (14,000 rpm) were made of all blade assemblies to check the blades for flaws not revealed by visual inspection. Rotating heat-shock runs were made with blades used in a previous endurance operation and with new blades. The used blades withstood complete heat-shock cycles in which the gas temperature was varied from 300° to 1800° to 300° F at centrifugal blade loads up to one-half the design load. The new blades withstood similar complete heat-shock cycles at blade loads up to approximately three-fourths the design load. These blades also successfully withstood a decreasing-temperature heat shock in which the gas temperature was decreased from 1700° to 400° F in 4 seconds under a centrifugal load approximately three-fourths of the design value. These results indicated that a starting and shutdown procedure more nearly like that of a conventional metal-blade turbine can be followed with Body 4811C blades.

Limited endurance operation was conducted at an inlet-gas temperature of 1800° F and a tip speed of 842 feet per second (16,000 rpm) and at an inlet-gas temperature of 2000° F with a tip speed of 631 feet per second (12,000 rpm) without damage to the blades. These conditions considerably exceed those achieved with Body 4811C blades during the previous investigation.

The investigation also showed that the method of reducing stress concentrations at the blade supporting shoulders introduced in the previous investigation was satisfactory up to tip speeds of 842 feet per second.

INTRODUCTION

An investigation of ceramic turbine blades is being conducted at the NACA Lewis laboratory as part of a general program to increase turbine-inlet gas temperatures. Several characteristics that make the use of ceramics for gas-turbine blades particularly desirable are: (1) considerable reduction in heat loss as compared with cooled turbines, (2) favorable strength-to-density ratio, and (3) strength at high temperatures.

The first ceramic turbine blades were made of sillimanite (reference 1). Two blade designs were used; the second design was developed for increased strength to correct the cause of failure of the first design. The turbine was operated at inlet-gas temperatures up to 1725° F and at turbine tip speeds up to 526 feet per second (10,000 rpm) with these blades. Another ceramic-blade turbine was operated with National Bureau of Standards Body 4811C blades of the same design as the second-type sillimanite blades (reference 2). The turbine-disk design and the method of blade attachment were altered to permit turbine operation up to tip speeds of 737 feet per second (14,000 rpm) and an inlet-gas temperature of 1800° F. At that operating point, blade breakage occurred because of a complete heat-shock cycle.

Although the specific problems involved in the adaption of ceramic materials to stressed turbine components are still basically the same, the emphasis on certain aspects has changed. Because the blade-mounting problem has been solved for tip speeds up to 737 feet per second (14,000 rpm) at high inlet-gas temperatures and the failure of Body 4811C blades was caused primarily by heat shock, the problems for the investigation reported herein are in the order of importance:

(1) The blades must withstand a reasonable heat shock while being centrifugally stressed.

(2) The blades must be able to withstand high temperature and the stresses of high-speed operation.

(3) The blades must be attached to the disk in such a manner that stress concentrations at the blade-supporting surfaces will be minimized to prevent fracture and insure continued operation at higher speeds and temperatures.

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Because the limiting-strength conditions of Body 4811C blades were not reached in the investigation described in reference 2, the work with these blades was continued. No design changes were made in the apparatus except for a few mechanical adjustments in the disk and shaft assembly. Because the blade breakage with Body 4811C blades (reference 2) resulted primarily from heat shock, a test was designed to determine the heat-shock characteristics of these blades under centrifugal load. No measurements of blade temperatures were made; all temperatures given are inlet-gas temperatures.

Spin, rotating heat-shock, and endurance tests were made. The spin tests consisted in operating the turbine in a partial vacuum up to a turbine tip speed of 737 feet per second (14,000 rpm) and were made with all blade assemblies prior to any other type of run in order to eliminate blades with hidden flaws undetected by visual inspection. The rotating heat-shock runs consisted in varying the inlet-gas temperature over a definite range while the turbine was being operated at each of several tip speeds up to 842 feet per second (16,000 rpm). The resulting centrifugal stress is approximately three-fourths the design value of 6790 pounds per square inch at a tip speed of 1000 feet per second (19,000 rpm) at the root of the aerodynamic section of the blade. The minimum complete cycle of gas-temperature variation was 2 minutes and the maximum temperature range was from 300° to 1800° F. These runs were intended to determine the heat-shock resistance of Body 4811C blades under centrifugal stress so that a safer and faster operating procedure could be evolved. The endurance runs were made at turbine inlet-gas temperatures up to 2000° F and turbine tip speeds up to 842 feet per second (16,000 rpm) to determine the limiting strength characteristics of Body 4811C blades under turbine operating conditions.

APPARATUS

The components of the turbine rotor and rig and the method of supporting the blades in the rotor are described in reference 2.

Blade material. - The blade material used in this investigation and in reference 2 was National Bureau of Standards Body 4811C. In reference 2 the material is designated National Bureau of Standards Body 4811 similar to the Bureau of Standards usage in reference 3. The designation in reference 4 is "Body 4811C, 48BeO, Al_2O_3, ZrO_2 (mole) plus 2 percent CaO by weight." The nominal composition of this material in percent by weight is

CaO	BeO	Al_2O_3	ZrO_2
2.0	84.2	7.2	8.6

In accordance with the usage of reference 4, the material will be designated herein Body 4811C.

Turbine disks. - Minor mechanical changes were made in the experimental apparatus to provide a better method of fastening the disks together and to the shaft. These changes resulted in a simplified method of assembly and added to the mechanical stability of the rig. The disk bore was increased and a sleeve was provided upon which the disks were placed and so pinned that no relative motion between sleeve and disks could occur (fig. 1). This disk-and-sleeve assembly was slipped over the shaft and held in place by another nut that locked the sleeve to the shaft. The intermediary sleeve was placed between the disks and the shaft to absorb possible bending loads imposed on the shaft from a slight misalinement of the heavy disks. Four through bolts were installed at a radius slightly less than the inner radius of the blade-ring assembly as an additional means of uniformly clamping the disks together (fig. 1). 1228

In assembling the disks and the blade ring, an axial load was applied to the disks by a hydraulic press while the lock nut was tightened on the sleeve and the distance across the disks at the outermost radius was measured at 90° intervals where the through bolts were located. These bolts were tightened as required to maintain a constant measured distance across the disks around the entire disk circumference until the center lock nut was completely drawn up. The bolts were then locked to the disks.

Blade assembly. - The method of assembling the blade ring for the endurance runs was the same as that in reference 2. For the rotating heat-shock cycles, however, the assembly consisted of four blades and four metal spacers. This blade ring did not require use of the assembly fixture described in reference 1. A strip of 0.025-inch asbestos cloth was fastened with a quick-drying cement around the base of the blades to reduce the possibility of damage from motion of the blades relative to the metal spacers. A 0.032-inch asbestos-cloth cushion was fastened around the sides and shoulders of the blade bases in contact with the disk-clamping surfaces. The four blades were then separated by four metal spacers contoured to match the rotor-clamping surfaces and clamped between the two disks. The rotor assembled with four blades and four metal spacers is shown in figure 2.

Instrumentation. - The instrumentation was the same as that described in reference 2. A high-speed recording potentiometer was added for the heat-shock runs to record changes in gas temperature.

PROCEDURE

The scope of the investigation is given in table I.

Spin tests. - The spin runs are described in reference 2. Briefly, they consisted in operating the turbine cold in a partial vacuum up to a tip speed of 737 feet per second (14,000 rpm), which is equivalent to approximately one-half design load on the blade supporting shoulder. This procedure was followed three times with each blade assembly prior to any hot-gas runs. By this means, any undetected flaws that might cause blade failure would probably be eliminated and thus simplify the analysis of any blade breaks occurring in the hot runs.

Rotating heat-shock runs. - A series of runs was made to determine the effect of superimposing thermal stresses on the centrifugal stresses present in Body 4811C blades during turbine operation. During these runs, the turbine was operated at constant speed to provide centrifugal blade loading. The inlet-gas temperature was increased from a minimum to a maximum value and then decreased to the original temperature during a specified period of time. Each period of time or cycle was divided as far as possible into equal increments. For example, in a 3-minute cycle, 1 minute was required to increase the gas temperature from the minimum to the maximum value. The temperature was held at this maximum value for 1 minute and 1 minute was required to decrease the temperature to the minimum value.

The temperature variation with time for one complete series of heat-shock cycles is presented in figure 3. The gas temperature was varied by manual adjustments of the valve controlling the fuel supply to the burner. A constant rate of temperature increase or decrease was not always maintained, which explains the absence of parallelism in some of the curves.

Blade assembly 1 consisted of four slightly chipped Body 4811C blades (remaining from the endurance operation of reference 2) separated by four metal spacers. Such an assembly was used to conserve blades and to lessen the possibility of any blades being damaged by flying chips from an adjacent blade breakage. Cycles of 5, 4, 3, and 2 minutes were run during which the inlet-gas temperature was varied from 300° to 1200° to 300° F at each of three tip speeds, 263, 526, and 737 feet per second (5000, 10,000, and 14,000 rpm, respectively). Similar cycles were run during which the inlet-gas temperature was varied from 300° to 1800° to 300° F at each of the three tip speeds.

Blade assembly 2 consisted of new Body 4811C blades separated by four metal spacers. Cycles of 5, 4, 3, and 2 minutes were run during which the inlet-gas temperature was varied from 300° to 1200° to 300° F at each of three tip speeds, 263, 526, and 737 feet per second. 1228

Blade assembly 3 also consisted of four new Body 4811C blades separated by four metal spacers. Time cycles of 2, 3, 4, and 5 minutes were run at a turbine tip speed of 737 feet per second, during which the inlet-gas temperature was varied from 300° to 1800° to 300° F. The cycles were run in this order, the shortest first, in order to subject the blades immediately to the severest conditions of all the previous cycles. Cycles of 5, 4, 3, and 2 minutes were also run at a tip speed of 842 feet per second (16,000 rpm) during each of which the inlet-gas temperature was varied over the same range. This blade assembly was also subjected to a blow-out cycle in which the inlet-gas temperature was decreased from 1700° to 400° F in 4 seconds while the turbine was running at a tip speed of 842 feet per second.

Blade assembly 4 consisted of a complete set of 58 new Body 4811C blades. Runs with blade assembly 4 consisted essentially of periods of endurance operation at ever-increasing conditions of inlet-gas temperature and turbine tip speed. The turbine was operated at an inlet-gas temperature of 1800° F and tip speeds of 737, 789, and 842 feet per second (14,000, 15,000, and 16,000 rpm). The turbine was also operated at an inlet-gas temperature of 2000° F and a tip speed of 631 feet per second (12,000 rpm).

Method of operation. - A detailed description of the method of turbine operation is given in reference 2. Some changes have been incorporated, however, particularly in the rotating heat-shock cycles. In making these runs, the outlet pressure was set to give a low pressure drop (1.5 in. Hg) across the turbine and the burner started at a fuel flow that gave an inlet-gas temperature of approximately 300° F. At this point the turbine was accelerated to a tip speed corresponding to that at which a particular series of cycles was to be run. 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 for the combination of speed and maximum cycle temperature to be run. The fuel flow was adjusted to vary the inlet-gas temperatures over a definite range in equal increments in each of several time cycles. In running the blow-out cycle, the gas temperature was reduced as quickly as possible by completely shutting off the fuel supply.

The operating procedure for the endurance runs was similar to that of reference 2 except for the rate at which the inlet-gas temperature was increased in setting an operating point. Such temperature change was accomplished at a rate approximately five times as fast as in the previous running, about a 500° F increase per minute.

RESULTS AND DISCUSSION

A summary of operating conditions and results is given in table II.

Spin tests. - Blade assemblies 1, 2, 3, and 4 successfully withstood the spin tests previously described.

Rotating heat-shock runs. - Blade assembly 1 was subjected to a series of heat-shock cycles at tip speeds up to 737 feet per second. The minimum-shock cycle was a change in gas temperature from 300° to 1200° to 300° F in 5 minutes. The rate of inlet-gas temperature increase was equal to approximately 9° F per second and the rate of inlet-gas temperature decrease was equal to approximately 9° F per second. The maximum-shock cycle was a change in inlet-gas temperature from 300° to 1800° to 300° F in 2 minutes. The rate of inlet-gas temperature increase was equal to approximately $37\frac{1}{2}^\circ$ F per second and the rate of inlet-gas temperature decrease was equivalent to approximately $37\frac{1}{2}^\circ$ F per second. The blades successfully withstood the complete series of heat-shock cycles except for a small part of the leading edge of one blade. Inspection of the turbine after the first series of cycles at a turbine tip speed of 263 feet per second revealed that a small part of the leading edge of one blade had chipped off. A close-up of this blade still assembled in the turbine wheel after the entire series of runs had been completed is shown in figure 4. All four blades used in this series of heat-shock cycles had already been chipped during previous endurance runs, but the rough edges had been honed prior to assembly in the turbine. It is possible that the chip lost during the heat-shock tests was the result of a previously undetected crack. Because no other breakage occurred Body 4811C blades evidently have a greater heat-shock resistance under load than was indicated by operation in reference 2.

Blade assembly 2 with four new Body 4811C blades was subjected to a series of heat-shock cycles under load that were intended to duplicate the conditions of the runs to which blade assembly 1 had been subjected. A beneficial heat-treating effect may possibly have occurred during the previous endurance operation of the blades used in assembly 1 enabling them to withstand the heat-shock cycles (reference 4). Additional runs under the same conditions were made with new Body 4811C blades to indicate whether such blades were equally resistant to heat shock under load. Approximately one-half of the intended cycles had been completed when a broken blade resulted during the 3-minute, 300° to 1200° to 300° F cycle at 737 feet per second. At the time of breakage, the blades had successfully withstood temperature changes from 300° to 1200° to 300° F at 263 and 526 feet per second for each cycle run with blade assembly 1. In view of subsequent results with blade assembly 3, the broken blade probably resulted from an internal flaw that was insufficiently developed to fail in the spin tests.

Blade assembly 3 also contained four new Body 4811C blades. This assembly was subjected to similar heat-shock cycles insofar as the temperature range and duration of each cycle is concerned; however, the turbine was operated at tip speeds of 737 and 842 feet per second and a maximum temperature of 1800° F. In addition, a blow-out cycle was run at 842 feet per second. The blades successfully withstood all heat-shock tests and were not chipped or damaged in any way. In these runs, the blades were subjected to greater combined centrifugal and thermal stress loads than blade assembly 2 had undergone. The blow-out cycle was run to simulate as nearly as possible the blade stresses encountered in an actual flight installation when the fuel supply is suddenly lost. Such a cycle is similar to a decreasing-temperature heat shock such as occurred with an entire blade ring of Body 4811C blades in previous running (reference 2). In the investigation reported herein, however, the centrifugal load on the blades was three times as great as in the emergency shutdown described in reference 2. Even in the emergency shutdown, only one blade broke after 23 hours of high-temperature endurance operation; Body 4811C blades demonstrated good decreasing-temperature heat-shock resistant properties. These properties are even further demonstrated by the blow-out cycle described herein.

Blade assembly 4 consisting of 58 new Body 4811C blades was operated for 60-minute intervals at 1800° F and various tip speeds up to 842 feet per second and at 2000° F at a tip speed of 631 feet per second without any damage to the blades. The turbine rotor and blade assembly after this period of operation is shown in figure 5. These runs were essentially endurance tests to determine the limiting conditions attainable with Body 4811C blades. The minimum operating conditions set for this run were the same as the maximum operating conditions attained in the earlier investigation (reference 2). When the turbine was disassembled for inspection, it was found that the metal disks had become distorted.

SUMMARY OF RESULTS

The following results were obtained from the continued investigation of a gas turbine with National Bureau of Standards Body 4811C ceramic rotor blades:

1. The turbine was run cold without blade failure up to a tip speed of 737 feet per second with each blade assembly prior to the hot-gas tests.

2. Blade assembly 1, which contained blades subjected to previous endurance operation at 1800° F, withstood complete heat-shock cycles in which the gas temperature was varied from 300° to 1800° to 300° F at various tip speeds up to 737 feet per second, which is equivalent to centrifugal blade loads of one-half design value. Only the leading edge of one blade was chipped during these runs.

3. Blade assembly 3 containing new blades also withstood similar heat-shock cycles at tip speeds of 737 and 832 feet per second, which are equivalent to blade centrifugal loads of approximately one-half and three-fourths design value, without damage. These blades also withstood without damage a decreasing-temperature heat-shock cycle in which the inlet-gas temperature was decreased from 1700° to 400° F in 4 seconds under centrifugal blade load three-fourths of design value.

4. The turbine was operated with a complete set of 58 new blades at 1800° F and a tip speed of 842 feet per second (16,000 rpm) and at 2000° F with a tip speed of 631 feet per second (12,000 rpm) without damage to the blades. These conditions considerably exceed the maximum operating conditions attained with Body 4811C blades during the previous investigation.

5. The method of reducing stress concentrations at the blade supporting shoulders introduced in a previous investigation was satisfactory up to tip speeds of 842 feet per second (16,000 rpm).

6. Body 4811C blades demonstrated the ability to withstand thermal-shock conditions under centrifugal loading in the turbine used. As a result, a turbine starting and shutdown procedure more nearly like that of conventional metal-blade turbines than has been used heretofore can be followed with Body 4811C blades.

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National Advisory Committee for Aeronautics,
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TABLE I - SUMMARY OF PROCEDURE FOR ROTOR-BLADE INVESTIGATION

Type of test	Blade-ring assembly	Inlet-gas temperature (°F)	Turbine tip speed (ft/sec)	Cycle (min)[1]
Spin	1 2 3 4	Room temperature	737	
Rotating heat shock	1	300-1200-300	263,526,737	5 4 3 2
		300-1800-300	263,526,737	5 4 3 2
	2	300-1200-300	263,526,737	5 4 3 2
	3	300-1800-300	737	2 3 4 5
			842	5 4 3 2
Blow-out		1700-400	842	4 (sec)
Endurance	4	1800	737,789,842	
		2000	631	

[1] Each cycle was divided, as far as possible, into equal increments.

TABLE II - CERAMIC-BLADE TURBINE INVESTIGATION

[All blade assemblies successfully underwent spin tests at turbine tip speed of 737 ft/sec (14,000 rpm); cold unit was brought up to speed three times]

Blade assembly	Type of assembly	Cycle time (min)	Approximate rate of inlet-gas-temperature increase ($^{\circ}F$/sec)	Approximate rate of inlet-gas-temperature decrease ($^{\circ}F$/sec)	Inlet-gas temperature ($^{\circ}F$)	Turbine tip speed (ft/sec)	Turbine speed (rpm)	Remarks
1	Four previously used Body 4811C blades and four metal spacers	5 4 3 2	9 $11\frac{1}{4}$ 15 $22\frac{1}{2}$	9 $11\frac{1}{4}$ 15 $22\frac{1}{2}$	300-1200-300	263,526,737	5000, 10,000, 14,000	Rotating heat-shock test. Only leading edge of one blade chipped during run.
		5 4 3 2	15 $18\frac{3}{4}$ 25 $37\frac{1}{2}$	15 $18\frac{3}{4}$ 25 $37\frac{1}{2}$	300-1800-300	263,526,737	5000, 10,000, 14,000	
2	Four new Body 4811C blades and four metal spacers	5 4 3 2	9 $11\frac{1}{4}$ 15 $22\frac{1}{2}$	9 $11\frac{1}{4}$ 15 $22\frac{1}{2}$	300-1200-300	263,526,737	5000, 10,000, 14,000	Rotating heat-shock test. Blade failed during 3-minute cycle at turbine tip speed of 737 feet per second (14,000 rpm).
3	Four new Body 4811C blades and four metal spacers	2 3 4 5	$37\frac{1}{2}$ 25 $18\frac{3}{4}$ 15	$37\frac{1}{2}$ 25 $18\frac{3}{4}$ 15	300-1800-300	737	14,000	Rotating heat-shock test. Completed test with no damage to blades.
		5 4 3 2	15 $18\frac{3}{4}$ 25 $37\frac{1}{2}$	15 $18\frac{3}{4}$ 25 $37\frac{1}{2}$	300-1800-300	842	16,000	
		4(sec)		325	1700-400	842	16,000	Blow-out cycle.
4	Complete ring of 58 Body 4811C blades	60 60 60 60			1800 1800 1800 2000	737 789 842 631	14,000 15,000 16,000 12,000	Blades undamaged. Further operation halted because of distortion of disks.

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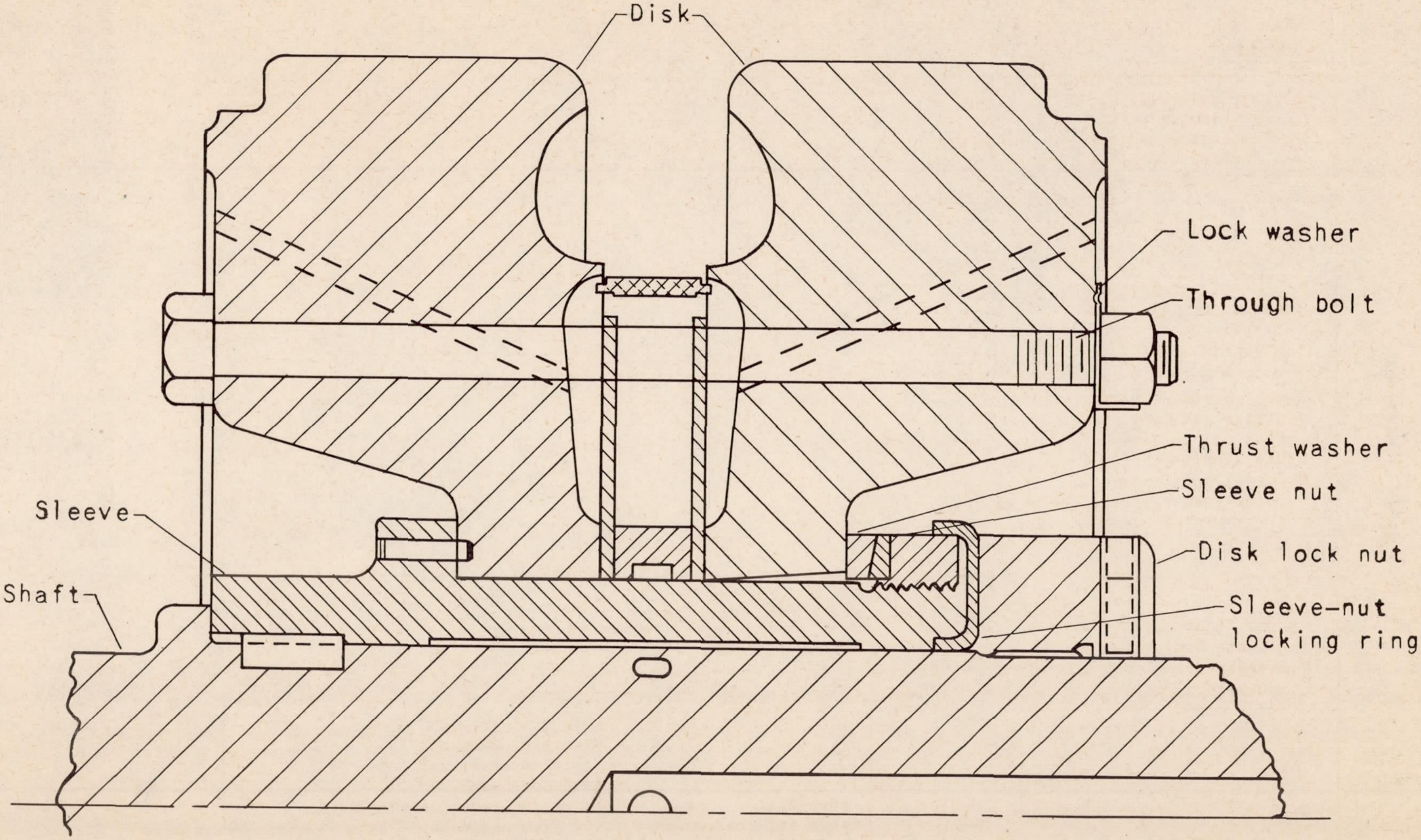

Figure 1. - Assembly of disk, shaft, and sleeve.

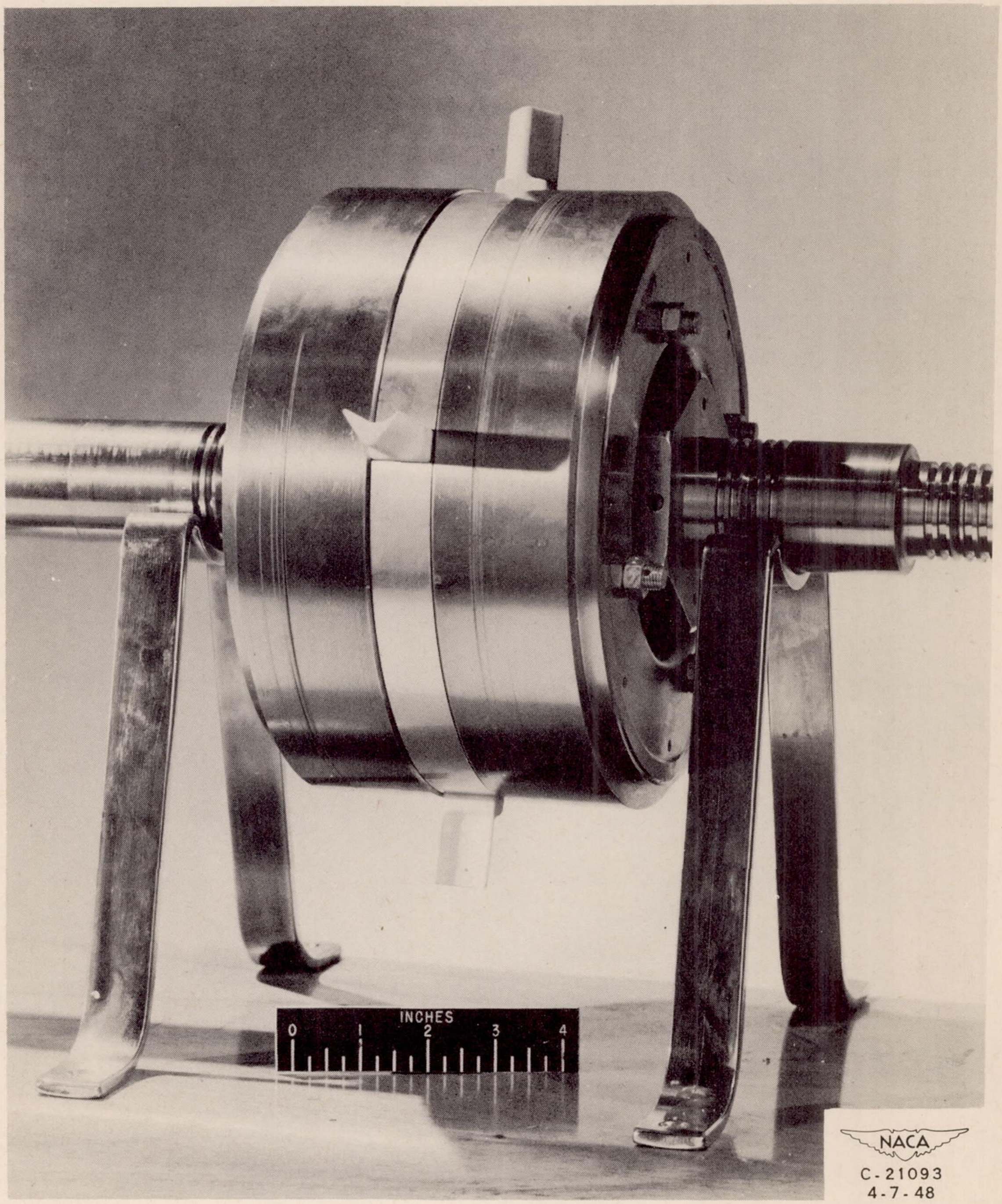

Figure 2. - Turbine wheel assembled with four Body 4811C blades and four metal spacers for rotating heat-shock runs.

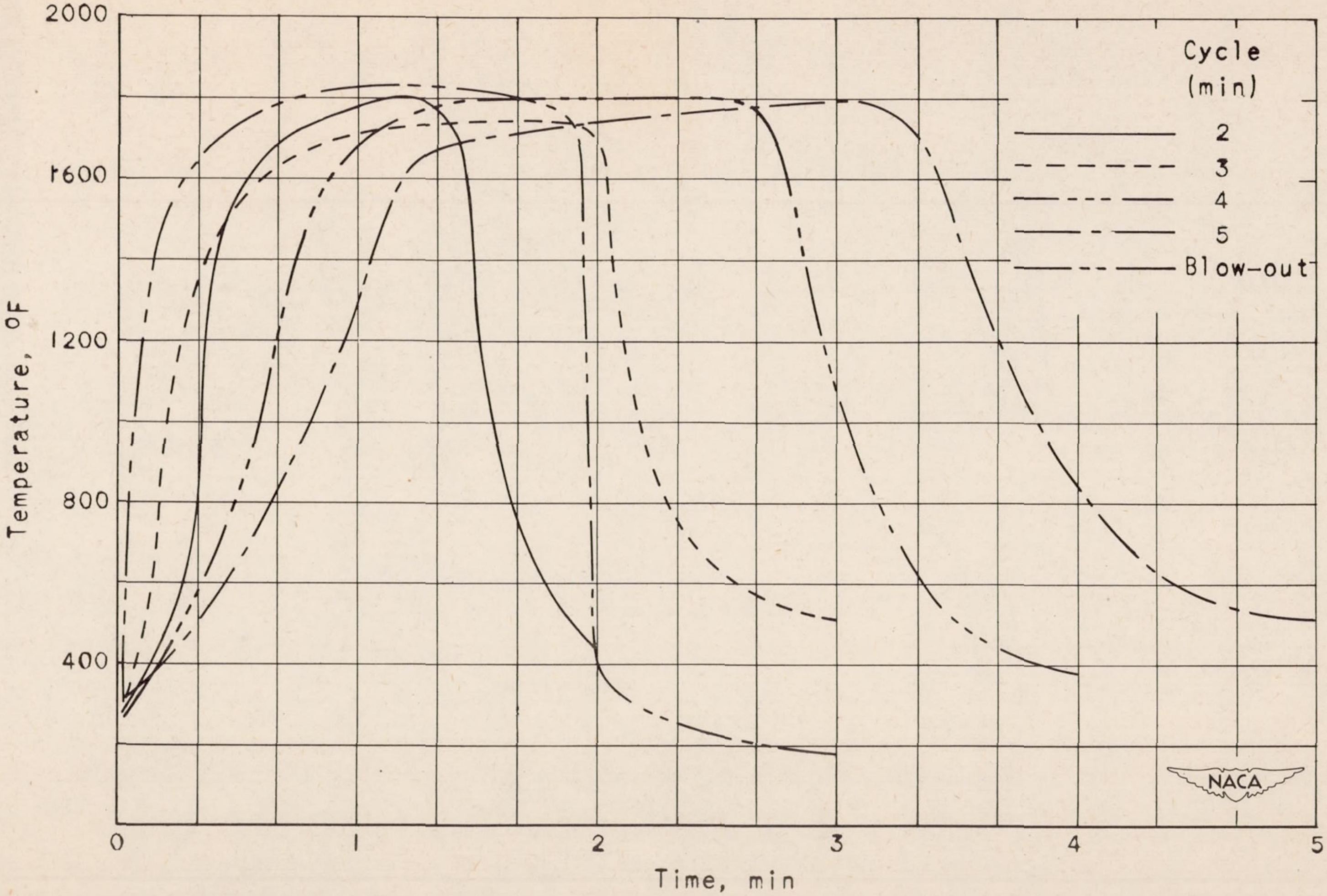

Figure 3. - Rotating heat-shock cycles with blade assembly 3. Blade centrifugal load, three-fourths of design value; turbine tip speed, 842 feet per second (16,000 rpm).

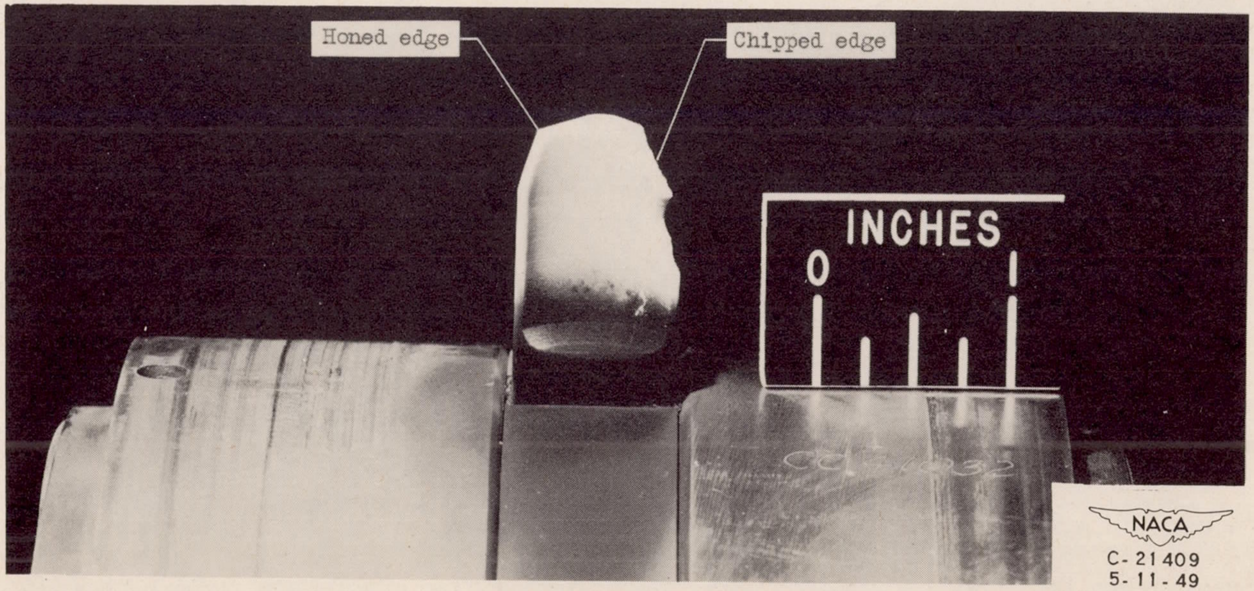

Figure 4. - Close-up of turbine blade showing leading edge chipped during rotating heat-shock runs with blade assembly 1.

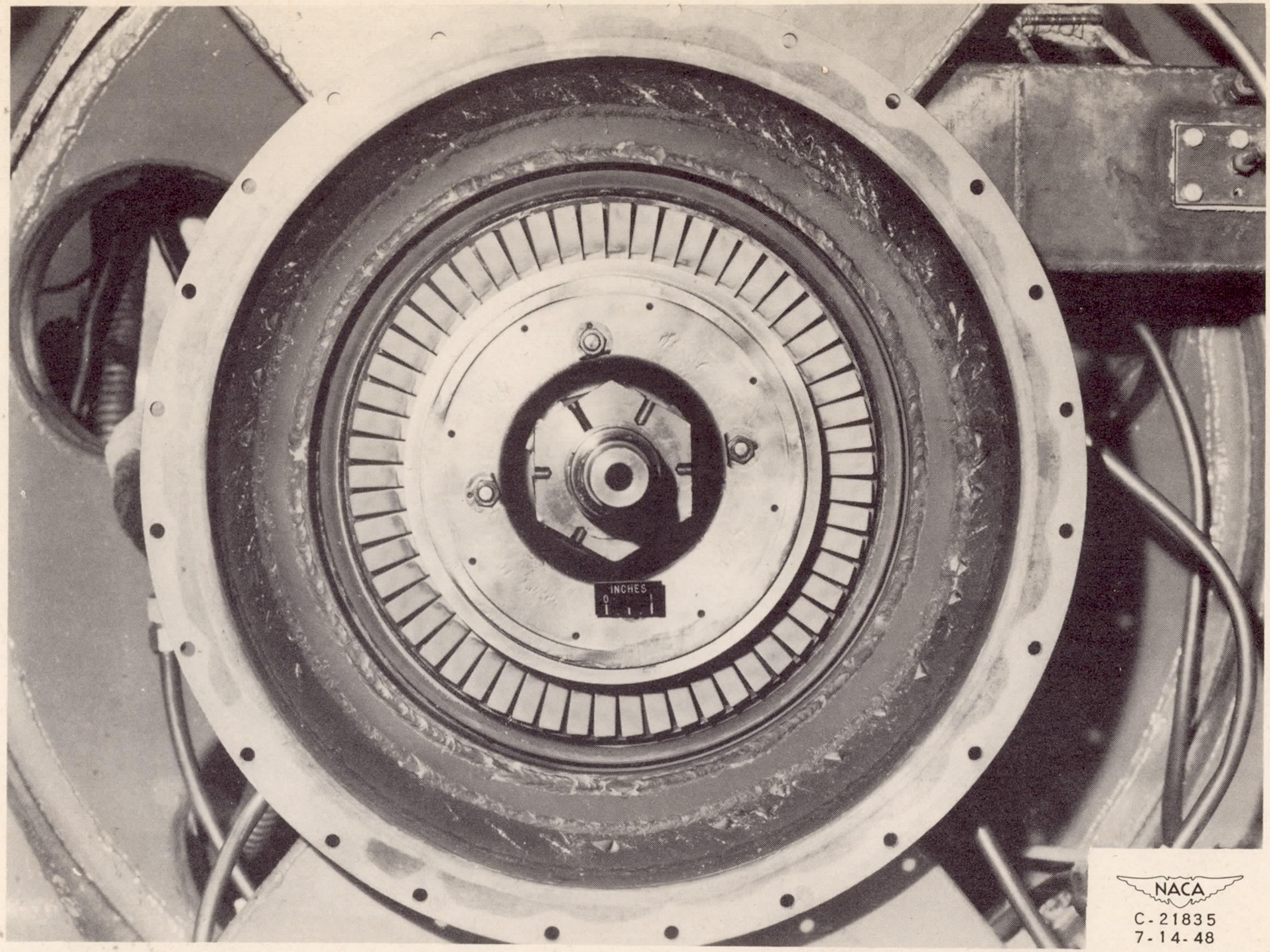

Figure 5. - Turbine rotor with Body 4811C blades in rig supporting structure after operation at turbine tip speed of 842 feet per second (16,000 rpm) and inlet-gas temperature of 1800° F.

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