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RESEARCH MEMORANDUM

INVESTIGATION OF HIGH-TEMPERATURE OPERATION OF LIQUID-COOLED GAS TURBINES

I - TURBINE WHEEL OF ALUMINUM ALLOY, A HIGH-CONDUCTIVITY NONSTRATEGIC MATERIAL

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SUMMARY

Theoretical analyses showing that turbine operating temperatures can be greatly increased by liquid cooling, particularly if materials of high conductivity are used, were verified by temperature measurements on an aluminum blade at gas temperatures up to 1925° F in a static heat-transfer rig and by operation of a liquid-cooled aluminum-alloy turbine wheel at inlet gas temperatures up to 2100° F and speeds up to 19,000 rpm. The turbine was operated for a total of 92 hours without any measurable deterioration of the blades. Further increase in the maximum operating temperature of the turbine was limited by the temperatures of the uncooled stator vanes, burners, and ducting of the hot-gas system.

The results of this investigation show that a liquid-cooled turbine wheel of a high-conductivity nonstrategic material, such as aluminum alloy, can be satisfactorily operated at gas temperatures of at least 2100° F.

INTRODUCTION

A substantial increase in the power output of both turbojet and turbine-propeller power plants can be obtained by increasing the inlet gas temperature. The fuel economy can also be improved, particularly in the turbine-propeller power plant, if higher compression and expansion ratios accompany the increase in temperature.

Turbine-inlet gas temperature is limited by the strength at high temperature of available materials. This temperature limit has been raised during the last few years by the development of better materials but, considering the past rate of progress, the large increase in turbine operating temperature desired in the immediate future cannot be attained with improvement in materials alone.

Theoretical analyses presented in references 1 to 3 show that liquid cooling permits a large increase in turbine-inlet gas temperature and that the use of high-conductivity material increases the effectiveness of cooling. From these analyses, a combination of liquid cooling with aluminum alloy as the blade material seemed promising. Alloys of aluminum are not particularly heat resistant, but they do have high conductivity, are light in weight, have a low cost, are available, are easily fabricated, and have a characteristic of forming durable oxide coatings at high temperatures.

A turbine with a liquid-cooled aluminum-alloy wheel was designed on the basis of the data presented in references 1 to 3 and supplementary data obtained from a single water-cooled aluminum blade in a static heat-transfer rig. In order to obtain experimental verification of the analysis in the static rig and to investigate the operation of the liquid-cooled turbine wheel made of nonstrategic material at high inlet gas temperatures and normal turbine speeds, an investigation was conducted at the NACA Cleveland laboratory, in which a liquid-cooled aluminum-alloy turbine wheel was operated for the first time on January 16, 1947.

APPARATUS

Static Heat-Transfer Rig

A single water-cooled aluminum blade 2.5 inches high with a chord length of 1.8 inches was placed in the heat-transfer rig shown in figure 5 of reference 4. Thermocouples to measure blade-metal temperature were located at the points shown in the sectional view of the blade in the insert of figure 1 in a plane about midway between the tip and the root of the blade. This rig was suitable for operation at temperatures of about 1900° F.

Turbine Rig

Turbine. - A turbine wheel was built of 14S-T aluminum alloy with a tip diameter of 12.06 inches, a root diameter of 9.75 inches, and having 50 impulse blades to be operated at a tip speed of

1000 feet per second. The blades and the disk were integral and in order to facilitate machining, they were untapered and were cut as a series of planes and cylinders. Into each blade were drilled four radial coolant holes and two transfer holes to make possible a forced flow through the blades. The outside ends of the 300 coolant passages were sealed with screwed-in plugs. The most important dimensions of the turbine wheel and blades are shown in figure 2. Figure 3 is a view of the turbine wheel from the leading edge of the blades after the coolant holes were plugged and figure 4 shows the turbine-wheel and shaft assembly. The path of coolant through the turbine may be traced in figure 5. The cooling water entered the turbine wheel at the center and flowed radially outward in the space between the turbine wheel and the baffle plate, through the two coolant holes nearest the leading edge of the blade, across the tip of the blade through the transfer holes, radially inward through the two holes nearest the trailing edge of the blade, and out of the wheel through the axial-discharge holes. The water was discharged into a collector formed by the inner wall of the exhaust hood from which it was emptied into the gas stream.

For purposes of economy, some existing equipment was used. The rotating parts of the turbine are designed to be used with the inlet collector nozzle ring, bearings, oiling system, and main housing of a small commercial turbosupercharger that had been used for a previous investigation. This unit was assembled on a specially constructed base designed to facilitate and maintain alinement between the turbine (fig. 5) and a water brake to which it is connected with a high-speed coupling. The turbine shaft, a part of the hot-gas system, and most of the instrumentation of the previous setup were used. In order to prevent air or gas flow through the turbine main housing (fig. 5) with a resulting contamination or loss of oil, a pressure seal was added to the coupling end of the turbine and a connection was made to the exhaust duct so that the same pressure would exist at both ends of the main housing.

Hot-gas system. - The induction system with the exception of the burners was also from the previous setup and consisted of an orifice tank to measure air flow, an air filter, two burners, and a straight section of pipe to allow thorough mixing of the products of combustion before they entered the turbine. The two burners were found to be suitable for operation up to about 2300° F, which produced a gas temperature of slightly more than 2100° F at the turbine inlet. The turbine was supplied with room air and the exhaust was discharged through an annular discharge duct into the laboratory low-pressure exhaust system.

Instrumentation. - Extensive instrumentation was not required because the purpose of the investigation was to determine whether a turbine with aluminum blades could, with adequate cooling, be operated at high gas temperatures.

Turbine-inlet pressure was measured by a mercury manometer connected to a static-pressure ring, which was installed on the inlet duct 12 inches ahead of the turbine inlet collector. Turbine-exhaust pressure was measured by a mercury manometer connected to a static-pressure ring, which was installed on the exhaust duct 36 inches downstream of the turbine.

The inlet-air flow was measured with a micromanometer connected across a 10-inch plate orifice in the orifice tank. Fuel flow was measured with rotameters.

Inlet gas temperature was measured at the entrance to the turbine by triple-shielded and by unshielded chromel-alumel thermocouples. Pipe-wall temperature was measured at various points to be sure that the hot-gas ducting was able to support the stresses imposed upon it.

Coolant flow was measured with a rotameter. Inlet and outlet coolant temperature was measured with thermocouples. The thermocouple measuring the discharge temperature of the water was located in a stationary cup (fig. 5) into which a small part of the water leaving the turbine was thrown.

Turbine speed was measured with an electric tachometer and checked with a chronometric tachometer.

A crystal pickup and an amplifier were used to avoid operation at severe vibrating conditions.

For the last few hours of operation, six thermocouples were installed on the turbine blades and temperature was read by means of a potentiometer through a slip-ring and brush system. The accuracy of this system was estimated to be within ±20° F.

OPERATING PROCEDURE

At the beginning of each run, the turbine was brought up to speed for a few minutes with cold burners to check the bearings and the general operating characteristics.

Operating points were set at 8000, 10,000, 12,000, 14,000, 16,000 18,000, and 19,000 rpm with various measured temperatures ranging from 800° to 2100° F. Speeds of approximately 13,000 rpm were avoided because the first critical speed occurred at about this point with no water in the turbine and at points from 500 to 1000 rpm lower with the cooling water flowing. For each combination of speed and temperature, the pressure ratio across the turbine was set and the gas mass flow through the turbine checked to assure a relative gas velocity that would result in flow into the blades at an angle of attack of 0° based on an assumed nozzle efficiency of 90 percent. By this means, it was hoped to keep to a minimum the effect of varying gas flow paths around the blades. At each operating point, the coolant flow through the turbine was varied from 2 to 10 gallons per minute except at points where a low water flow would have resulted in a maximum coolant temperature above 150° F, which, with an appreciable factor of safety, had been estimated to be the maximum safe temperature for water leaving the turbine.

After each 10-hour period of operation, the turbine-exhaust hood was removed and the turbine blades examined for evidence of oxidation, erosion, or other types of deterioration. On most of these occasions, the disk was removed from the shaft and the coolant passages were checked for accumulations of solids from the cooling water.

RESULTS AND DISCUSSION

Static Heat-Transfer Rig

The variation of blade-metal temperature with inlet gas temperature at four points on the blade for a cooling-water flow rate of 0.30 gallon per minute is shown in figure 1. The highest blade-metal temperature reached was about 360° F with an inlet gas temperature of 1925° F. The maximum temperature occurred on the concave side of the blade even though the gas flow was directed over the convex side of the blade as shown.

Reasonable agreement exists between the calculated blade-metal temperatures reported in reference 3 and those obtained in the static heat-transfer tests when differences in the arrangement of cooling passages, blade size and shape, and gas density and velocity are considered.

Turbine Rig

The various speeds and temperatures over which the turbine was operated are listed in table I. The temperatures listed are as read from a triple-shielded chromel-alumel thermocouple. These temperatures were not allowed to exceed 2100° F because parts of the hot-gas system - stator vanes, burners, and inlet ducts - were inadequate for higher temperatures and not because the turbine wheel imposed any limitation.

The coolant left the turbine with a high velocity; therefore, the coolant discharge temperature as measured included the velocity energy-recovery factor and the actual coolant temperature in the turbine wheel was always less than the measured discharge temperature, which was kept below 150° F. Because a factor of safety had been included in the calculation that set 150° F as the maximum water outlet temperature and because the water in the turbine never actually reached this temperature, it is probable that an excessive coolant flow was used at all the points at which this turbine has been operated. At no operating point were more than 5 gallons of water per minute required to cool the turbine.

Owing to the tendency of all metals to yield slowly under load at high temperatures, it is possible from dimensional inspection plus a knowledge of material properties to show that the turbine-blade temperatures did not exceed 350° F over any appreciable area. Further substantiation in the last few runs was obtained by the installation of six thermocouples on the blades. With a turbine speed of 5000 rpm and an inlet gas temperature of 2100° F, the maximum blade-metal temperature indicated was 284° F at the blade leading edge and all the blade-metal temperatures indicated were between this temperature and 180° F. The blade-metal temperatures measured on the turbine blades are essentially in agreement with those measured in the static heat-transfer rig in that they are of about the same magnitude.

Even though this turbine was operated for a total of 92 hours and for more than 30 hours at temperatures between 1600° F and 2100° F, no evidence of oxidation, erosion, or blade elongation indicated that any more than a small part of the turbine's useful life was consumed. The only apparent effect of hot gases on the turbine blades was the accumulation of a light coating of carbon on the blade surfaces. The carbon deposit was similar to soot and tended to burn off at high gas temperatures.

From the cooling-water flow rates required, the blade-metal temperatures obtained, and the condition of the blades after completion of the present operating program, it appears probable that the turbine wheel could be operated at higher inlet gas temperatures than 2100° F.

The mechanical method of sealing the ends of the coolant holes with screwed-in plugs appears to be practical inasmuch as no leaks developed around any of the 300 plugs even though calculated pressures of 3400 pounds per square inch were indicated at the plugged surfaces.

There was little evidence of any tendency by the turbine to centrifuge solids out of the cooling water and no trouble was encountered in operation from this cause even though the water was not recirculated and contained over 200 parts per million of total solids, at least 4 percent of which was undissolved.

At low speeds and temperatures, a small doughnut-like ring of dirt was deposited around each radial hole in the annulus into which the holes in the trailing edge of the blade discharged. At high speeds and temperatures, small rings of dirt formed around all the radial holes. Water leaving the radial holes would lose most of its velocity and would tend to deposit any suspended dirt around the holes. Thus it appears that convection currents were superimposed upon the forced-flow pattern at high speeds and temperatures.

SUMMARY OF RESULTS

From an investigation of a single liquid-cooled aluminum-alloy blade in a static heat-transfer rig and an investigation of a liquid-cooled turbine with aluminum-alloy blades and disk, the following results were obtained:

1. A reasonable verification of previous theoretical analyses was obtained from the investigation of the single aluminum-alloy blade.

2. Although the turbine was operated for a total of 92 hours with inlet gas temperatures as high as 2100° F, at a speed of 19,000 rpm there was no appreciable oxidation or erosion of the blade surfaces. It was estimated that the blade-metal temperature did not exceed 350° F over any appreciable cross-sectional area of the blade as indicated by the absence of blade elongation during the period of operation and by later operation with thermocouples on the turbine blades.

3. The turbine wheel could not be operated with inlet gas temperatures higher than 2100° F because of the danger of damaging the uncooled stator vanes, burners, and inlet ducts.

4. The distribution of a moderate amount of sediment indicated the existence of convection currents in the coolant superimposed on the forced-flow pattern. Dirt was not centrifuged out of the coolant to an extent sufficient to interfere with the cooling process even though the cooling water was not recirculated.

CONCLUSION

The results of this investigation show that nonstrategic material such as aluminum alloy can be used in liquid-cooled turbine wheels operating at high gas temperatures.

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4. 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.

TABLE I. - OPERATING CONDITIONS FOR LIQUID-COOLED TURBINE

Inlet gas temperature ($^{\circ}F$)	Turbine speed (rpm)	Running time (hr)	Running time (min)	Total running time (hr)	Total running time (min)
800	8,000	1	50	1	50
1000	8,000	3	15		
	10,000	2	50		
	12,000	2	30		
	13,000		55		
	14,000	1	35		
				11	5
1200	8,000	1	25		
	10,000	1	30		
	12,000		40		
	13,000	1	5		
	14,000	2	35		
	16,000	1	5		
				8	20
1400	8,000		15		
	10,000		50		
	12,000	1	5		
	13,000		20		
	14,000		35		
	16,000		45		
	18,000	2	5		
				5	55
1600	12,000	1	5		
	14,000		45		
	16,000	2	40		
	18,000	3	45		
	19,000	1	5		
				9	20
1800	8,000	9	30		
	14,000	5			
	16,000	1	20		
	18,000	1	10		
	19,000		30		
				17	30
2000	5,000	1	30		
	18,000		40		
	19,000		20		
				2	30
2100	5,000	1		1	
[a]800-1600	5,000-19,000	34	30	34	30
Total time of operation at inlet gas temperatures above 800° F				92	

[a] Operation while checking associated equipment and instruments.

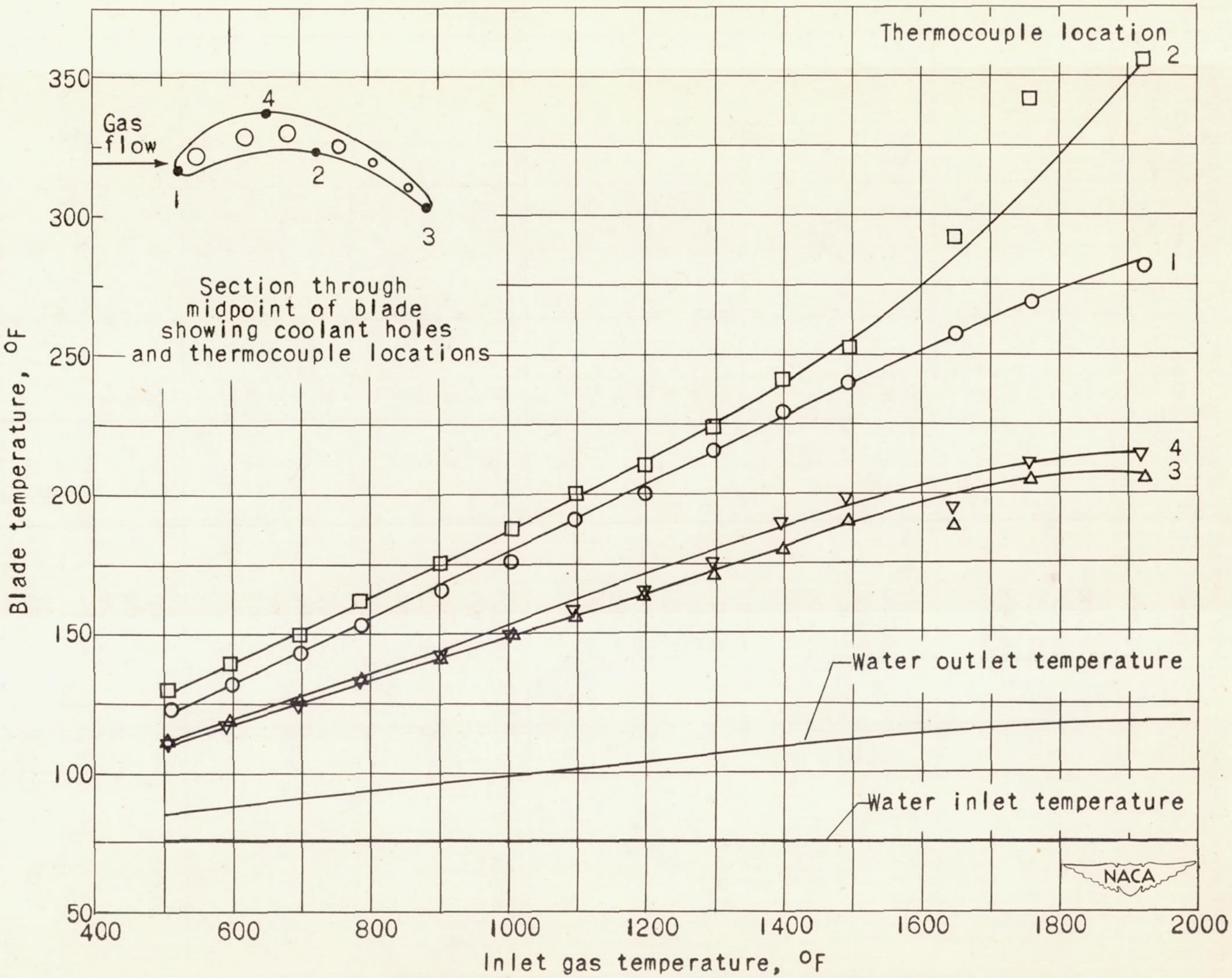

Figure 1. - Temperature distribution of water-cooled aluminum turbine blade installed in static heat-transfer rig. Coolant flow, 0.30 gallon per minute.

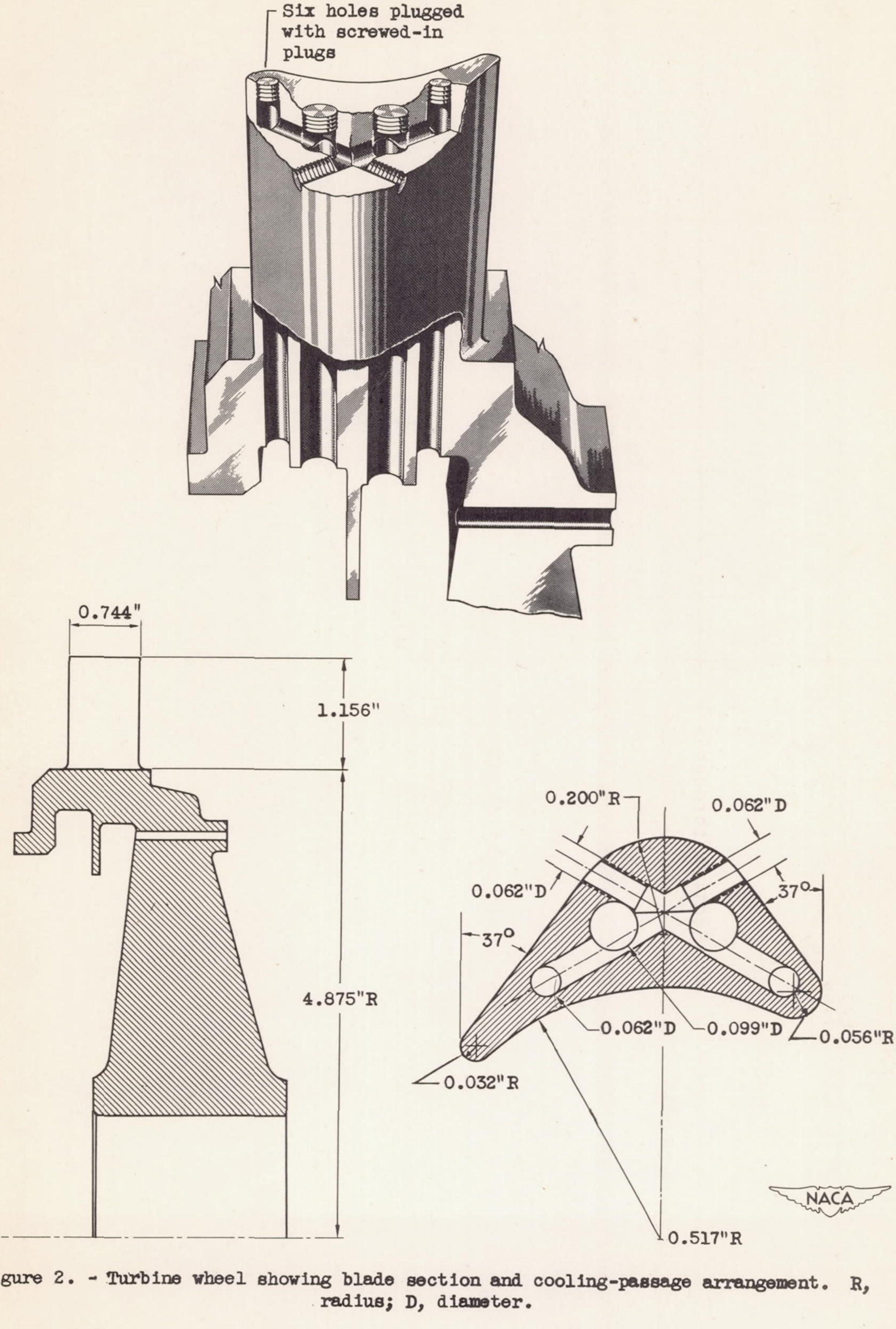

Figure 2. - Turbine wheel showing blade section and cooling-passage arrangement. R, radius; D, diameter.

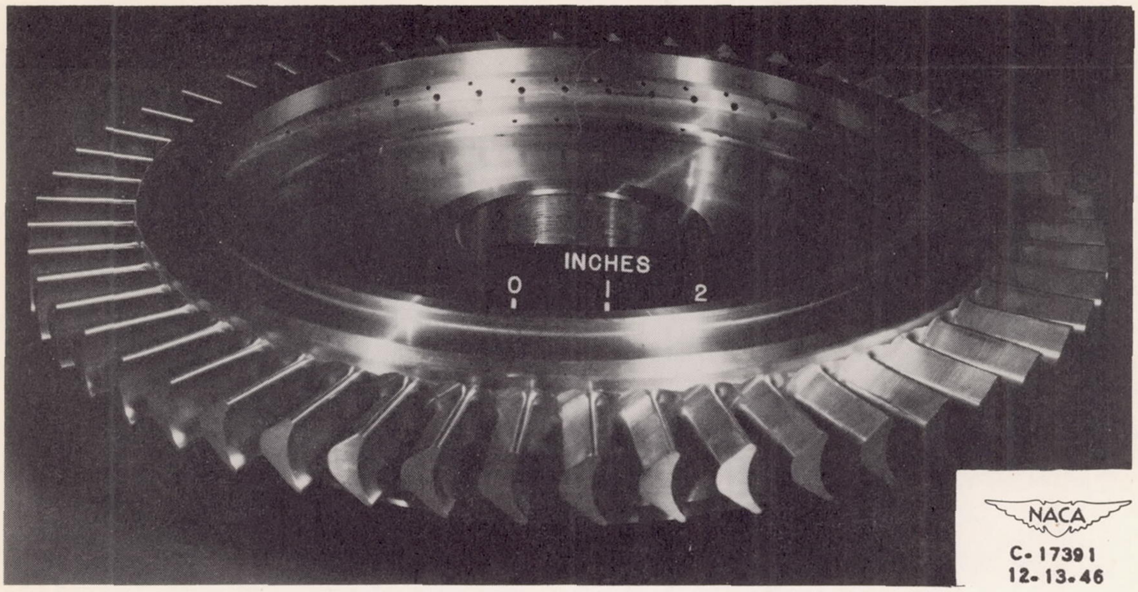

Figure 3. - Turbine wheel with integral blades.

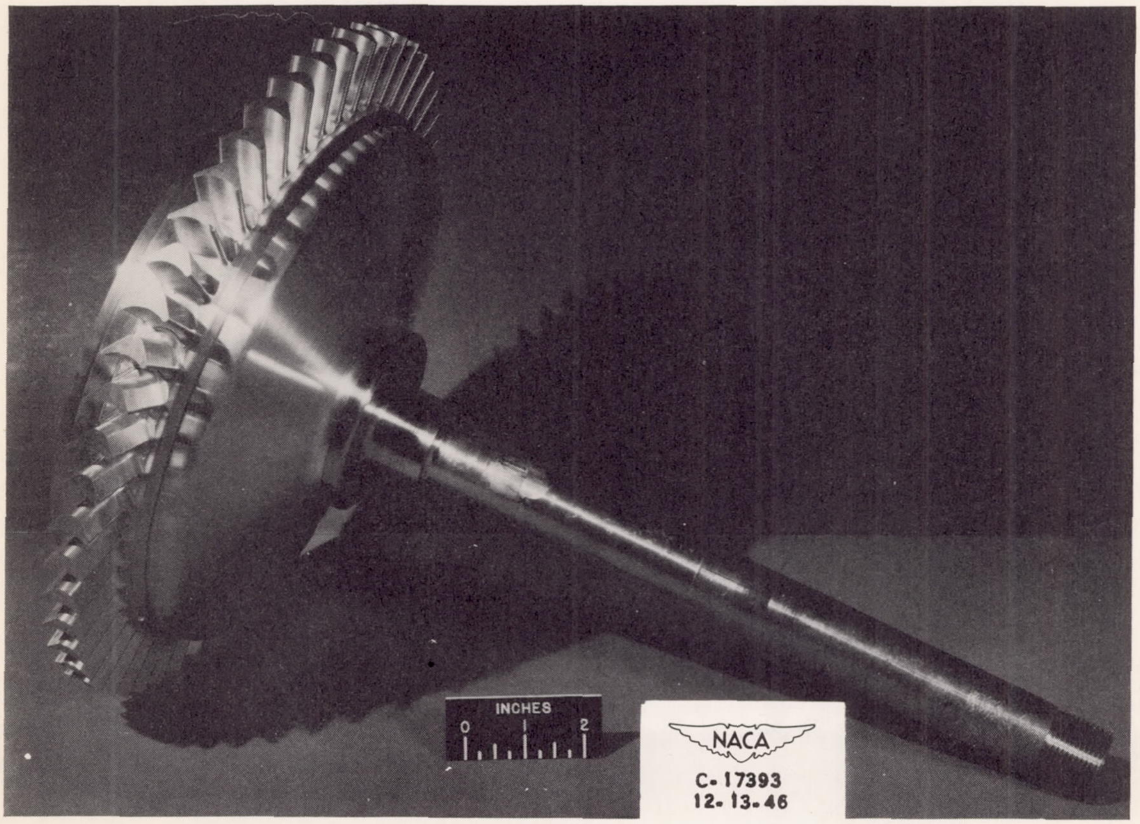

Figure 4. - Turbine-wheel and shaft assembly.

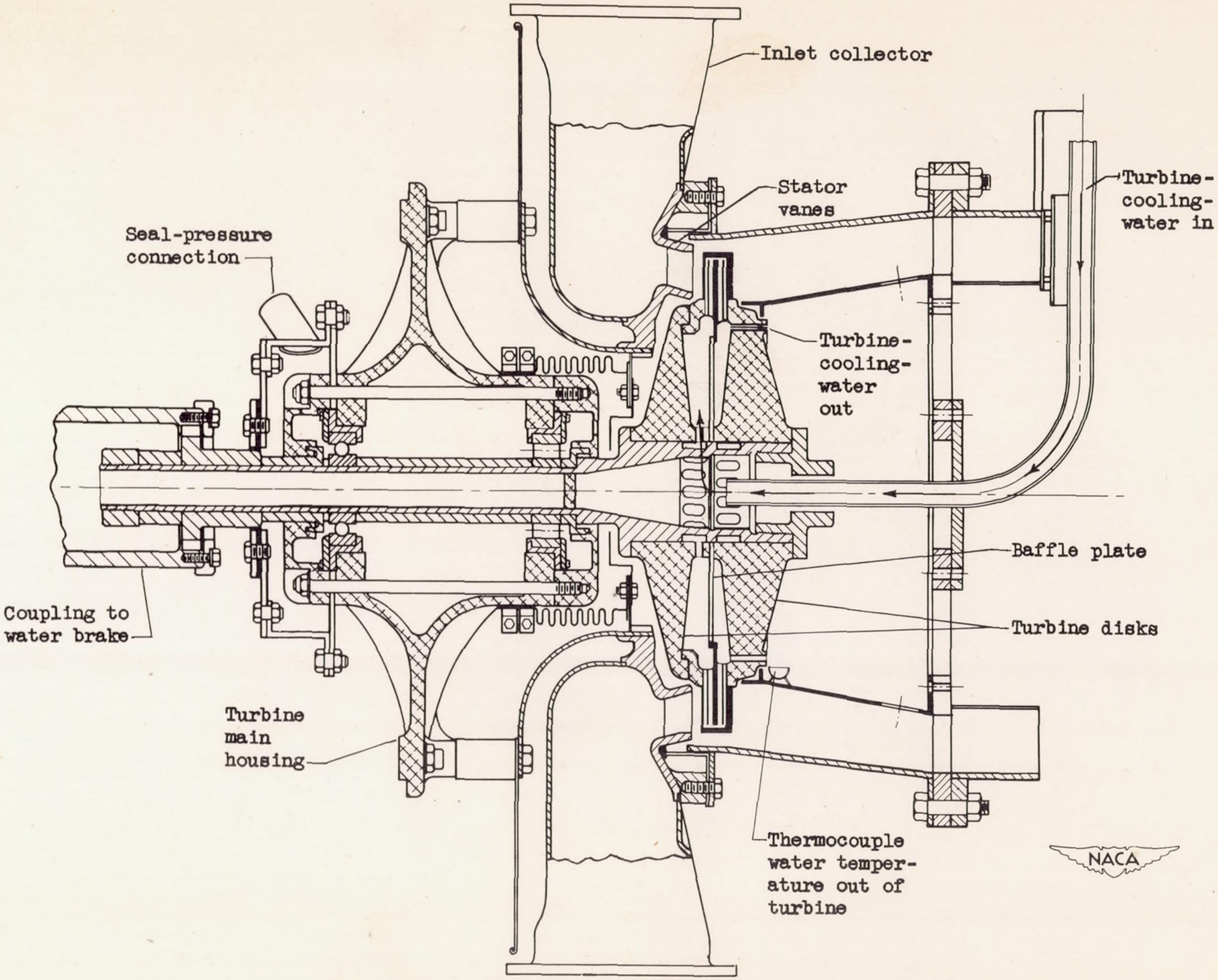

Figure 5. - Cross section of liquid-cooled turbine unit.