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EXPERIMENTAL INVESTIGATION OF TWO-STAGE AIR-COOLED TURBINE SUITABLE FOR FLIGHT AT MACH 2.5

By Harold J. Schum, Donald A. Petrash, and Robert R. Nunamaker

Lewis Research Center
Cleveland, Ohio

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EXPERIMENTAL INVESTIGATION OF TWO-STAGE AIR-COOLED TURBINE SUITABLE FOR FLIGHT AT MACH 2.5*

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SUMMARY

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The over-all component performance characteristics of an experimental two-stage turbine, designed to power a turbojet engine suitable for a flight Mach number of 2.5, were determined for a range of speed and pressure ratio at inlet conditions of 35 inches of mercury absolute and 700° R. Because of the high design turbine-inlet temperature (2500° R), the rotor blades were designed for air-cooling, the air being effused from the blade tips and into the main turbine airstream. A second phase of the experimental program was therefore conducted at the design equivalent speed and over a range of pressure ratio, in which the turbine performance was evaluated with various amounts of cooling air being effused from the first- or second-stage-rotor blade tips, or both.

For the uncooled turbine, the brake internal efficiency at equivalent design speed and work was 0.922. The corresponding equivalent turbine weight flow was 3 percent greater than the design value of 42.88 pounds per second, mainly because the turbine was designed for an additional 4-percent cooling airflow. In general, the turbine yielded high efficiencies over a wide range of equivalent speed and pressure ratio. Turbine limiting loading was not attained, although it was approached at high speeds and high pressure ratios.

When cooling air was employed at the equivalent design speed, the turbine efficiency decreased with increasing amounts of air effusion from either rotor blade row. This decrease was greater when the second stage was individually cooled than when the first stage was cooled, for corresponding coolant-flow ratios, indicating that the second stage extracted some work from that air effused from the first-stage-rotor blade tips. At the rating pressure ratio (3.07) at which design work was obtained at the equivalent design speed, and with the design coolant-flow ratio of 2 percent for each rotor, results indicate that turbine efficiency would be no less than 0.903.

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INTRODUCTION

Considerable research effort has been expended by the NACA and NASA during the past several years on the study of problems arising in turbojet engines for supersonic flight speeds. The basic problem is that of obtaining required engine thrust with minimum weight, drag, and specific fuel consumption at design flight speeds. It is also required that the engine develop required thrust at takeoff conditions. The turbine requirements of one such powerplant have been analyzed for an axial-flow turbojet engine suitable for a flight Mach number of 2.5. A free-stream velocity-diagram study of this turbine is presented in reference 1, and a description of the methods employed in designing the blading for this turbine is presented in reference 2. The turbine evolved for this application was a two-stage turbine operated at an inlet temperature of 2500° R. As discussed in the references, the combination of high turbine-inlet temperature and tip speed requires that the turbine be cooled. The air-cooled-turbine configuration that was considered feasible for this application required 2 percent of the compressor airflow for cooling each turbine rotor stage (ref. 1).

The net effect on multistage-turbine performance of rotor blade coolant effusion is unknown. It is possible that the coolant flow may disturb the main gas stream so that the aerodynamic performance of the blades may be lowered. Conversely, this cooling air may cause an effective reduction in the tip clearances by partially filling the clearance spaces, and hence the turbine performance may be improved. Also, the air effused from the first stage of a multistage turbine provides a potential additional measure of shaft work when permitted to expand to the turbine downstream measuring station. The net effect on the efficiency of an air-cooled turbine must therefore be determined experimentally, and little experimental data are available. Some single-stage cooled-turbine investigations (refs. 3 to 5) have been reported in which the turbine efficiency was found to be not seriously affected by coolant airflows less than about 3 or 4 percent of the main gas stream. A search of the literature, however, indicates that no experimental results on air-cooled multistage turbines have been obtained.

From the analyses presented in references 1 and 2, a full-scale cold-air two-stage model of the air-cooled turbine was fabricated and investigated experimentally. Provisions were incorporated for air-cooling the rotor blades, the coolant flow being effused from the rotor blade tips and into the main gas stream. Blading throat areas were adjusted to accommodate this coolant flow. This report presents the over-all performance of this turbine both with and without blade coolant air.

The performance characteristics of the two-stage research turbine were obtained at a constant inlet stagnation pressure of 35 inches of mercury absolute and an inlet temperature of 700° R over a range of pressure ratios. The performance data with no rotor blade cooling were obtained for a range of equivalent speeds, whereas the data obtained with varying amounts of air effusion from the first- and/or second-stage-rotor blades were limited to the equivalent design speed. A tabulation of pertinent turbine parameters is appended for the convenience of those interested in more detailed analyses.

APPARATUS

The velocity-diagram analysis and the method employed to design the blading for the subject turbine are discussed in references 1 and 2, respectively. Dimensions of the turbine are presented in reference 1, and reference 2 includes tables of blade coordinates for each of the four blade rows. Briefly, the first-stage stator has a constant hub diameter of $19\frac{1}{8}$ inches and a tip diameter of 28 inches. The flow passage then diverges through the subsequent blade rows, as shown in figure 1, to a hub diameter of $17\frac{1}{8}$ inches and a tip diameter of 30 inches. The first stage of the turbine was designed to produce 58 percent of the total turbine work, and the second stage 42 percent. The turbine had 41 first-stage-stator blades, 64 first-stage-rotor blades, 65 second-stage-stator blades, and 50 second-stage-rotor blades.

The sea-level design conditions and the design equivalent conditions for the subject experimental turbine are as follows:

	Turbine design conditions (ref. 1)	Turbine equivalent design conditions
Work, Btu/lb	147.1	31.50
Weight flow, lb/sec	176.5	42.88
Rotational speed, rpm	9375	4338
Inlet temperature, °R	2500	518.7
Inlet pressure, in. Hg abs	278.1	29.92

In order to determine the equivalent design conditions for this turbine, the variation in the ratio of specific heats from the design turbine inlet temperature to standard atmospheric temperature should be considered. An approximate method of determining the equivalent design conditions was used in this particular investigation. This method is based on the critical velocity determined from the turbine-inlet stagnation temperature and an average equilibrium value of γ of the flow through the turbine. Symbols are defined in appendix A, and derivation of the method is presented in appendix B.

[redacted]

A photograph of the turbine rotor is shown in figure 2. A closeup view of the rotor blade tips, showing the slotted blade tip configurations, is presented in figure 3. The slots for the coolant-air effusion were sized to permit a maximum coolant flow of about 8 percent of the equivalent design turbine weight flow. Actually, however, the coolant-flow requirement for each rotor stage was only 2 percent of the compressor airflow.

The turbine test facility is shown in figure 4. The facility was, in general, similar to that used for other full-scale turbine investigations and is described in reference 6. Airflow to the turbine was supplied by the laboratory combustion air system. The air was then throttled by means of butterfly valves to the desired turbine test inlet pressure of 35 inches of mercury absolute. A portion of this air was heated by two commercial jet-engine burners and permitted to reenter the main air supply. By regulating the amount of bypassed air and the fuel flow to the burners, the air temperature to the turbine could be maintained at the desired value of 700° R. This heated air was then directed into two pipes, entering a plenum chamber through two diametrically opposed pipes. Screens were located in this plenum to remove foreign particles from the air and to minimize pressure imbalance. The air was then turned, passing through an annular corrugated-type flow straightener and another screen and through the turbine blading, and was finally discharged into the laboratory exhaust system (see fig. 1).

Coolant air for both the first- and second-stage rotors was similarly supplied by the laboratory combustion-air system through two separate systems that were independent of the main turbine air supply. Each coolant supply line was equipped with its own orifice metering system (see fig. 4). The coolant air then passed through flexible hoses to the turbine tailcone section and into separate toroidal-shaped collectors, from which the air passed through four divided tailcone struts, into hollow turbine rotor shafting, through the turbine rotor disks and blades, and was finally discharged from the blade tips into the main turbine gas stream. The complex path of the coolant airflows through the turbine proper can also be seen in figure 1. The amount of coolant flow to each rotor blade row was regulated by valves located downstream of their respective orifice measuring stations. Labyrinth seals (see fig. 1) were used to minimize air leakage between the tailcone chamber and the hollow turbine shafts. The radial clearance between the blade tips and the turbine casing was approximately 0.040 inch for each stage.

The pressure ratio across the turbine was varied by butterfly throttle valves located in the exhaust ducting. Turbine power output was absorbed by two cradled electrical dynamometers connected in tandem.

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INSTRUMENTATION

The turbine airflow measurement and the two rotor blade coolant airflow measurements were made with ASME flat-plate orifices located in their respective air supply pipes. Each orifice was calibrated against sonic flow nozzles. Fuel flow was metered by a calibrated rotameter located in the fuel supply line, and the turbine airflow was corrected for this fuel addition. Turbine torque output was measured by means of a calibrated NACA-developed balanced-diaphragm thrustmeter. Turbine rotative speed was measured by use of an electric chronometric tachometer.

Measurements of temperature, total pressure, and static pressure were made in the axial locations shown in figure 1. Turbine-inlet temperature was measured with 20 iron-constantan thermocouples, arranged five to a rake, the thermocouples being located on centers of equal annular areas and rakes being spaced 90° apart around the annulus. Three Kiel-type total-pressure probes that were also located at the inlet measuring station were used during the turbine tests to establish the desired turbine-inlet pressure. Six static-pressure taps on both the inner and outer walls were located around the annulus at the inlet measuring station as well as at all the other measuring stations (stations 2 to 6, fig. 1).

The turbine-outlet measuring station (station 6, fig. 1), located about 1 blade chord downstream of the second-stage rotor, was instrumented similarly to station 1. In addition to the thermocouples and the static-pressure taps, five combination total-pressure - flow-angle probes were also installed around the casing circumference.

The precision of the test measurements to determine the performance of the subject research turbine is estimated to be within the following limits:

Temperature, °R	±1.0
Pressure, in. Hg abs	±0.05
Air weight flow, percent	±1.0
Rotor speed, percent	±0.5
Torque, percent	±0.5
Flow angle, deg	±2.0

The cumulative effect on calculated turbine efficiency, from measurements of the foregoing precision, is a maximum error of ±2.0 percent at equivalent design conditions. Because of the lack of scatter in the data obtained, however, it is felt that the error in efficiency is considerably less than 2 percent.

[redacted]

METHODS AND PROCEDURE

The turbine was operated with nominal values of inlet pressure and temperature of 35 inches of mercury absolute and 700° R, respectively. Turbine performance was evaluated on the basis of calculated values of turbine-inlet and -outlet total pressures (measuring stations 1 and 6, fig. 1). The following equation to calculate these total pressures was derived from the energy equation, the continuity equation, the equation of state, and the isentropic relation between pressure and temperature:

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$$P_c = p\left[\frac{1}{2} + \frac{1}{2}\sqrt{1 + \frac{2\left(\frac{w}{A}\right)^2\left(\frac{R}{p}\right)^2 T}{gJc_p \cos^2\beta}}\right]^{\frac{\gamma-1}{\gamma}} \tag{1}$$

The static pressure p used in this equation is the arithmetical average of the 12 hub and tip static pressures measured at either the inlet or outlet measuring station considered. The total temperature T was determined by averaging the 20 corresponding thermocouple readings and correcting these readings for Mach number. The flow area A is the annular area at the particular measuring station considered. The flow direction at the turbine-inlet measuring station is considered axial ($\beta = 0$). At the turbine exit, the flow angle was computed as the numerical average of the five angle readings of the combination total-pressure - angle probes. These angle readings were then plotted and faired against the ratio of measured inlet total pressure to measured outlet total pressure. These faired values of flow angle were used in calculating the turbine-outlet total pressure.

The weight-flow term w in equation (1) is considered to be the actual flow through the turbine proper (w_T) when calculating the inlet total pressure (measuring station 1) for both the uncooled- and the cooled-turbine investigations. The same w_T is used to calculate the turbine-outlet total pressure (measuring station 6) for the uncooled-turbine performance tests. When calculating the outlet total pressure for the cooled turbine, however, the weight-flow term in equation (1) includes the coolant flow ($w = w_T + w_a$).

Turbine performance as presented herein is based on a "rating" total pressure at the turbine outlet (measuring station 6), defined as the static pressure at the outlet measuring station plus the velocity pressure corresponding to the axial component of the absolute velocity leaving the turbine blading. This outlet rating total pressure can be stated in equation form as

$$P_{x,6} = p_6\left\{1 + \frac{\gamma - 1}{2}\left[(\cos\,\beta_6)M_6\right]^2\right\}^{\frac{\gamma}{\gamma-1}} \tag{2}$$

[redacted]

[redacted]

where the Mach number term M_6 is obtained from the ratio of the average static pressure at the outlet measuring station to the total pressure at the same measuring station, the latter being a calculated value as obtained from equation (1), using the tables of reference 7. Turbine rating total-pressure ratio, then, is defined as $P_{c,1}/P_{x,6}$.

The over-all performance of the two-stage turbine with no cooling air was obtained over a range of over-all rating total-pressure ratio $P_{c,1}/P_{x,6}$ from 1.3 to 4.4 and over a speed range from 60 to 120 percent of the equivalent design speed $N/\sqrt{\theta_{cr,T}}$. The ideal turbine equivalent work was based on the outlet rating total pressure, the inlet calculated total pressure, and the inlet total temperature. The actual equivalent work was determined from torque, speed, and turbine weight-flow measurements. Experimental values of equivalent torque Γ/δ_T and equivalent weight flow $w_T\sqrt{\theta_{cr,T}}/\delta_T$ were plotted against the turbine over-all rating total-pressure ratio. Then, for even increments of rating total-pressure ratios, values of torque and weight flow for the various rotor speeds were used to calculate the turbine performance map. Pertinent data for this phase of the investigation are tabulated in table I.

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The investigation to determine the over-all turbine performance with air-cooling was limited to the equivalent design speed. The turbine was operated with a nominal total-pressure ratio imposed across the turbine, and cooling air was admitted to each of the two rotor blade rows independently as well as simultaneously. The coolant-air weight flow was varied from about 3 to 8 percent of the turbine weight flow when cooling of a single rotor row was employed. Two sets of runs were required for each nominal total-pressure ratio, because two different sized orifices were necessary to cover the coolant-flow range. When both rotors used cooling air, the second-stage-rotor coolant flow was at the maximum attainable, and the first-rotor coolant flow was varied within the aforementioned limits. Data were obtained over a range of turbine rating total-pressure ratio for all three different rotor cooling configurations.

The method used to rate the uncooled turbine is to express the adiabatic efficiency of the expansion process of the air through the turbine as a ratio of the useful shaft output to the ideal adiabatic work available, as determined from the change in air state from turbine-inlet to -exit conditions. The introduction of coolant airflow into the turbine main stream adds other work terms, because the shaft output is no longer dependent solely on the turbine-inlet air weight flow. The cooling air for the subject turbine is introduced at or near the centerline of the turbine. Some work is done on this air in going from the rotor axis to the blade tips, and then the cooling air may produce some useful shaft work in expanding from its state at the rotor blade tips to the turbine-outlet measuring station. The coolant flow is herein considered as expanding from the state conditions at (or near) the turbine axis of rotation to the turbine-exit rating conditions.

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The efficiency of the cooled turbine is expressed as the ratio of the shaft output to the ideal work output available for both the turbine weight flow and the coolant-air weight flow in expanding from their respective inlet states to that at the turbine outlet. This expression then includes net work terms of the coolant air that could be either positive or negative and thus represents an over-all or machine efficiency of the turbine, whereas for the uncooled turbine the efficiency is merely that of the expansion process of the primary air w_T. Cooled-turbine efficiency expressions derived in the appendix C for the three cooling configurations utilized, as well as for the uncooled turbine, are summarized as follows:

Uncooled-turbine efficiency:

$$\eta_T = \frac{\frac{2\pi}{60J}\left(\frac{N}{\sqrt{\theta_{cr,T}}}\right)\left(\frac{\Gamma/\delta_T}{w_T\sqrt{\theta_{cr,T}}/\delta_T}\right)}{c_p\ (518.7)\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{C12}$$

Efficiency for first-stage-rotor cooling only:

$$\eta_{T,I} = \frac{\frac{2\pi}{60J}\left(\frac{N}{\sqrt{\theta_{cr,T}}}\right)\left(\frac{\Gamma/\delta_T}{w_T\sqrt{\theta_{cr,T}}/\delta_T}\right)}{c_p\ (518.7)\left\{\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + \frac{w_{a,(1)}}{w_T}\frac{T_{a,(1),℄}}{T_{1,T}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(1),℄}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}} \tag{C13}$$

For second-stage-rotor cooling only:

$$\eta_{T,II} = \frac{\frac{2\pi}{60J}\left(\frac{N}{\sqrt{\theta_{cr,T}}}\right)\left(\frac{\Gamma/\delta_T}{w_T\sqrt{\theta_{cr,T}}/\delta_T}\right)}{c_p\ (518.7)\left\{\left[1 - \left(\frac{P_{x,6}}{P_{x,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + \frac{w_{a,(2)}}{w_T}\frac{T_{a,(2),℄}}{T_{1,T}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(2),℄}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}} \tag{C14}$$

For simultaneous first- and second-stage-rotor cooling:

[redacted]

$$\eta_{T,I,II} = \frac{\frac{2\pi}{60J}\left(\frac{N}{\sqrt{\theta_{cr,T}}}\right)\left(\frac{\Gamma/\delta_T}{w_T\sqrt{\theta_{cr,T}}/\delta_T}\right)}{c_p\ (518.7)\left\{\left[1-\left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right]+\frac{w_{a,(1)}}{w_T}\frac{T_{a,(1),\text{℄}}}{T_{1,T}}\left[1-\left(\frac{P_{x,6}}{P_{a,(1),\text{℄}}}\right)^{\frac{\gamma-1}{\gamma}}\right]+\frac{w_{a,(2)}}{w_T}\frac{T_{a,(2),\text{℄}}}{T_{1,T}}\left[1-\left(\frac{P_{x,6}}{P_{a,(2),\text{℄}}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}} \tag{C15}$$

In the preceding cooled-turbine efficiency equations, $T_{a,(1),\text{℄}}$ and $T_{a,(2),\text{℄}}$ represent the temperature of the cooling air as it enters the rear of the turbine shaft (see figs. 1 and 2) and where the cooling-air inlet state is considered.

The corresponding cooling-air inlet pressure was not measured in the experimental investigations and was therefore calculated as follows. The relation between the cooling-air equivalent weight flow $w_a\sqrt{\theta_{cr,a,t}}/\delta_{a,t}$ and the ratio of static to total pressure across the blade tips was established for each rotor stage from a static flow check prior to the turbine experimental investigations. In the cooled-turbine tests the total temperature inside the rotor tip was obtained from the observed coolant-air supply temperature and the kinetic-energy input of the rotor. This can be expressed in equation form as

$$T_{a,t} = T_{a,\text{℄}} + \frac{U^2}{2gJc_p} \tag{3}$$

The static pressure outside the rotor blade row was obtained for all cooled-turbine data points from the numerical average of the tip wall static pressures before and after the rotor row considered. The total pressure inside the rotor blade tips could then be obtained by iteration so that the cooling-air equivalent weight flow $w_a\sqrt{\theta_{cr,a,t}}/\delta_{a,t}$ and the static- to total-pressure ratio across the blade tips were compatible with the static flow calibration. With the total pressure and temperature of the cooling air known in the rotor blade tip, and with the temperature known at (or near) the cooling-air entry to the turbine rotor shafts, the cooling-air entry pressure $P_{a,\text{℄}}$ was computed by assuming an adiabatic compression efficiency of 0.80. Subsequent calculations have proved that this efficiency does not play an important role in the obtained over-all turbine efficiency, mainly because of the small ratios of coolant to turbine air weight flow (hereinafter called "coolant-flow ratio") used in the tests.

In the aforementioned cooling-air temperature calculations (eq. (3)), no consideration of the effect of heat transfer from the mainstream flow to the cooling airflow is included. It is felt that in these cold-air tests any effect of heat transfer would be insignificant and hence could be neglected.

[redacted]

For each nominal total-pressure ratio across the turbine, and for each of the three types of cooling employed, the following parameters were calculated (when applicable):

$$\frac{\Gamma}{\delta_T} \qquad \frac{w_T\sqrt{\theta_{cr,T}}}{\delta_T} \qquad \frac{P_{x,6}}{P_{c,1}}$$

$$T_{a,(1)} \qquad \frac{w_{a,(1)}}{w_T} \qquad \frac{P_{x,6}}{P_{a,(1)}}$$

$$T_{a,(2)} \qquad \frac{w_{a,(2)}}{w_T} \qquad \frac{P_{x,6}}{P_{a,(2)}}$$

For each type of rotor cooling, pertinent performance parameters were plotted against the coolant-flow ratio, and the data were faired. Then, for even percentage increments of this coolant-flow ratio, the faired values of these parameters were read and a turbine efficiency was calculated from the appropriate equation from the set defined by equations (C12) to (C14). The cooled-turbine performance is presented herein in terms of turbine efficiency as a function of turbine over-all rating total-pressure ratio.

For the convenience of the reader who may be interested in more detailed analyses of the air-cooled turbine, pertinent cooled-turbine data are presented in table II.

RESULTS AND DISCUSSION

The results of the experimental investigation of the subject two-stage air-cooled turbine, designed for use in a turbojet engine to power an airplane at a cruise Mach number of 2.5, are discussed in two phases. First, the over-all turbine performance of the uncooled turbine is discussed; and secondly, the turbine performance results obtained at the design equivalent speed and with various amounts of cooling-air effusion from the first- and/or second-stage rotors are discussed.

Uncooled-Turbine Performance

The over-all performance of the uncooled turbine is presented in figure 5 as a composite map, in terms of equivalent shaft work $\Delta H/\theta_{cr,T}$ and an equivalent weight-flow - speed parameter $(w_T N/60\delta_T)\epsilon$ for lines of constant rating total-pressure ratio $P_{c,1}/P_{x,6}$ and equivalent rotor speed $N/\sqrt{\theta_{cr,T}}$. Contours of constant brake internal efficiency η, based on the rating total-pressure ratio, are also included. The

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equivalent design work and speed are indicated by point A in figure 5, whereas equivalent design work and weight-flow - speed parameter are indicated by point B. Comparison of the abscissa values at these two points shows that the turbine used 3 percent more than equivalent design weight flow. This excess weight flow can be attributed to the fact that the turbine was designed and fabricated to handle an additional total of 4-percent coolant flow (2 percent through each rotor blade row). The equivalent design operating point (point A) occurred at a pressure ratio of about 3.07, with a corresponding efficiency value of about 0.922. The turbine exhibited high efficiencies over a broad range of both speed and pressure ratio. The maximum efficiency obtained was 0.940, at 120 percent of the equivalent design speed and at a rating total-pressure ratio of about 3.50.

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The variation of equivalent torque $(\Gamma/\delta_T)\epsilon$ and of equivalent weight flow $(w_T\sqrt{\theta_{cr,T}}/\delta_T)\epsilon$ with rating total-pressure ratio for the equivalent speeds investigated is presented in figures 6 and 7, respectively. Data from the faired curves of these two figures were read at selected increments of pressure ratio, and these data were used to calculate the performance map shown in figure 5. The equivalent-torque curves (fig. 6) show that, for the range of conditions investigated, values of torque continually increase with increasing pressure ratio, indicating that limiting blade loading in the last rotor was not reached. Limiting loading is defined as that point where changes in total-pressure ratio result in no additional change in torque output. That limiting loading was being approached, however, can be noted by observing the diminishing slopes of the curves in the high-speed, high-pressure-ratio range. Here, large increases in pressure ratio result in relatively small increase in torque output.

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The equivalent-weight-flow curve (fig. 7) indicates that, above an over-all rating total-pressure ratio of 3.2, the turbine was choked for all values of equivalent speed investigated. However, the choking weight flow decreased with increasing rotor speeds, indicating that at pressure ratios above 3.2 the first-stage stator was not choking. The choking must have occurred, then, in one of the downstream blade rows.

Cooled-Turbine Performance

The performance results of the two-stage air-cooled-turbine investigation are presented in terms of a turbine efficiency as a function of the turbine over-all rating total-pressure ratio for various amounts of coolant-air weight flow and for the equivalent design speed. These results are compared with those obtained from the over-all turbine performance map at the corresponding speed with no air-cooling. Turbine performances with first-stage-rotor coolant flow, with second-stage-rotor coolant flow, and with both rotors cooled, are discussed in order.

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First-stage-rotor cooling. - The efficiency of the turbine with air effusion from the first-stage rotor, as calculated from equation (C13), is presented in figure 8 for various values of coolant-flow ratio ranging from 3 to 8 percent. It is immediately apparent that, over the range of rating total-pressure ratio and coolant-flow ratio investigated, the trends of the curves parallel closely those obtained for the turbine with no cooling airflow. Also, the cooled-turbine efficiency consistently decreased as the coolant-flow ratio was increased. At the rating pressure ratio at which equivalent design work was obtained at the equivalent design speed (about 3.07 as determined from point A of fig. 5), an efficiency decrease of 0.066 occurred as the coolant-flow ratio was increased from 0 to 8 percent (see fig. 8). It will be noted, however, that at this turbine operating point the addition of 3-percent coolant flow resulted in an efficiency decrease of only 0.011.

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Second-stage-rotor cooling. - The effect on over-all turbine efficiency with air effusion from the second-stage-rotor blade tips is presented in figure 9 in the same manner as used for the first-stage cooled-turbine performance presentation. The efficiency shown in figure 9 was computed from equation (C14). The curves in figure 9 exhibit the same characteristics observed for first-stage-rotor cooling (fig. 8). Although the maximum coolant-flow ratio attainable was 7 percent over most of the rating-pressure-ratio range investigated, as compared with 8 percent for the first-stage cooled-turbine study, comparison of corresponding curves for the two types of cooling indicates that a greater decrease in efficiency occurred when the second stage was cooled. This can be explained by the fact that, when first-stage cooling was employed, some work was extracted from this coolant air by the second stage of the turbine. At the design operating point (a rating pressure ratio of about 3.07), and at the minimum coolant-flow ratio investigated (3 percent), a decrease of 0.021 in turbine efficiency occurred as compared with zero coolant flow. This compares with a decrease of 0.011 in turbine efficiency noted for first-stage cooling at corresponding turbine operating conditions.

First- and second-stage-rotor cooling. - Before the results obtained with cooling-air effusion from both the first- and second-stage-rotor blade tips are discussed, it should be reiterated that, in order to facilitate and shorten the experimental test program, the coolant-flow ratio for the second stage was the maximum obtainable (about 7 percent) and the first-stage coolant-flow ratio was varied. Over the range of rating total-pressure ratio investigated, a 7-percent coolant-flow ratio through the first stage was the maximum attainable. When the first stage was independently cooled, the maximum coolant-flow ratio was 8 percent over the same pressure-ratio range. This decrease was probably a result of this coolant flow choking the turbine in the latter blade rows. That the turbine equivalent weight flow decreased as coolant weight flow was increased can be noted from the data tabulation for the cooled-turbine investigation shown in table II.

The efficiency for the turbine with cooling-air effusion from both rotor rows is shown in figure 10, as calculated from equation (C15). Referring to figure 10, the change in efficiency with cooling airflow through both rotors is considerably greater than that observed when cooling air was admitted to the individual rotors. Again, comparison of the efficiency of the uncooled turbine at the design operating point (rating pressure ratio of 3.07) with that obtained with maximum cooling airflow through both rotors (about 7 percent each) shows a loss in efficiency of about 0.087.

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Comparison of cooling-air configurations. - Figure 11 compares the effect of cooling-air effusion on turbine efficiency for the various cooling configurations investigated. Efficiencies obtained at the design operating rating total-pressure ratio (3.07) and shown in figures 8 to 10 are cross-plotted in figure 11 as a function of coolant-flow ratio. Where both stages utilized cooling air, the abscissa of figure 11 represents the total coolant-flow ratio, the second-stage coolant-flow ratio being constant at about 7 percent.

Figure 11 shows that, when either the first stage or the second stage employed air-cooling, the turbine efficiency decreased as the amount of coolant flow, or coolant-flow ratio, was increased. Air-cooling of the second stage resulted in a greater efficiency loss than that of the first stage at corresponding coolant-flow ratios. It is apparent from this figure that the decrease in efficiency of the individual stages is not additive to result in the curve representing the simultaneous cooling of both turbine stages. For a 7-percent coolant-flow ratio individually applied to the first- and second-stage rotors, the corresponding efficiency decreases were 0.054 and 0.071, respectively. When the two stages were simultaneously cooled with 7-percent coolant-flow ratios, representing a total coolant-flow ratio of 14 percent, a net decrease in turbine efficiency of only 0.086 resulted. This, plus the fact that the efficiency decrease for the second stage is greater than that for the first stage at corresponding coolant-flow ratios, indicates that the second stage of the turbine extracted some work output from that air effused from the first stage of the turbine. It is recognized also that some additional shaft work may be extracted by the same rotor blade row from which the cooling air is being effused. No effort was made herein to isolate the second-stage work recovery from the first-stage coolant air, this phase being considered beyond the scope of the report. Only the over-all net work of the turbine, as measured on the test stand as shaft output, was used to rate the subject turbine.

The curve in figure 11 for simultaneous cooling of both stages indicates a consistent decrease in efficiency with increases of total coolant-flow ratio. Remembering that the second stage was operated with a constant coolant-flow ratio of about 7 percent, it is interesting to note that addition of coolant flow to the first-stage rotor actually increased

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the turbine efficiency over a portion of the range of coolant-flow ratio investigated. Consider a 7-percent coolant-flow ratio to the second stage, where the efficiency was 0.851. With addition of a 3-percent coolant-flow ratio to the first-stage rotor, making a total coolant-flow ratio of 10 percent, the turbine efficiency was actually raised to 0.873, an increase of 0.022. In other words, when both turbine rotor stages were cooled, the second stage operating with a 7-percent coolant-flow ratio, there was a range of cooled-turbine operation where added first-stage coolant flow actually improved turbine efficiency. It was only when $5\frac{1}{2}$ percent or more coolant-flow ratio was added to the first stage (representing a total coolant-flow ratio of about 12.5 percent or more) that the efficiency was found to decrease to values less than obtained with a 7-percent coolant-flow ratio to the second stage only. Again, this can be attributed to additional work output of the second stage as affected by the first-stage coolant flow. It should be remembered, however, that the values of coolant-flow ratio discussed are considerably greater than the design values of 2 percent for each rotor row.

Turbine performance with design coolant flow. - Most of the foregoing cooled-turbine discussion has centered about the experimental results obtained with a minimum coolant-flow ratio of 3 percent. Both rotors, however, were designed for only a 2-percent coolant-flow ratio (ref. 2). Reference to figure 11 for an interpolated coolant-flow ratio of 2 percent shows that a loss in efficiency of 0.006 occurred with first-stage cooling, and the corresponding loss with second-stage cooling was 0.013. Although it has been pointed out that the turbine efficiency losses for the individual stages are not additive, it can be expected that, with design coolant flow through each rotor, the net over-all efficiency (as defined herein) would decrease somewhat less than 0.019. In other words, for an uncooled-turbine efficiency of 0.922, as obtained from the performance map at the equivalent design speed and a rating total-pressure ratio of 3.07, the corresponding turbine efficiency with design coolant flow to each rotor would be no less than 0.903. Although the turbine design operating point may shift slightly with these small amounts of coolant flow, it is felt that this effect on turbine efficiency would be small because of the relatively wide range of efficient turbine operation at or near the uncooled-turbine design point.

In conclusion, it can be said that, at the design operating point for the subject two-stage turbine, the turbine efficiency as defined herein was not seriously affected when the unit employed design coolant-air effusion simultaneously from both rotor blade rows. This finding corroborates the results observed in the single-stage air-cooled-turbine investigations reported in references 3 to 5.

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SUMMARY OF RESULTS

An experimental two-stage turbine, designed to power a turbojet engine suitable for a flight Mach number of 2.5, was investigated over a range of equivalent speed and rating total-pressure ratio with inlet conditions of 35 inches of mercury absolute and 700° R. The rotor blades were designed for air-cooling, and a second experimental investigation was conducted at the equivalent design speed and over a range of pressure ratio with varying amounts of air effusion from the first- and/or second-stage-rotor blade tips.

From the turbine performance investigation with no cooling air, the following results were obtained:

1. At equivalent design speed and work, the turbine efficiency was 0.922, occurring at a rating total-pressure ratio of about 3.07. The corresponding turbine equivalent weight flow was 3 percent greater than the design value of 42.88 pounds per second. This excess weight flow could be expected, however, since the turbine was designed for an additional total coolant flow of 4 percent.

2. A maximum efficiency of 0.940 was obtained at 120 percent of equivalent design speed and at a rating total-pressure ratio of about 3.50.

3. The turbine exhibited high efficiency over a wide range of equivalent speed and over-all pressure ratio.

4. Turbine limiting loading was approached but not reached over the range of speed and pressure ratio investigated.

From the cooled-turbine performance investigation, the following results were obtained:

1. Turbine efficiency decreased with increasing amounts of coolant-air effusion from either the first- or second-stage-rotor blade rows and over the range of rating total-pressure ratio investigated.

2. The efficiency decrease was greater when the second stage was individually cooled than when the first stage was individually cooled, indicating that the second stage utilized some of the energy of the air effused from the first-stage rotor.

3. With a 7-percent coolant-flow ratio through the second-stage rotor, an increase in turbine efficiency was noted with additional first-stage-rotor coolant-flow ratios up to about $5\frac{1}{2}$ percent.

4. At the total-pressure ratio corresponding to equivalent design work and speed (3.07), with the design coolant-flow ratio of 2 percent for each rotor, the results indicate that the turbine efficiency would be no less than 0.903, compared with 0.922 for the uncooled turbine.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, July 24, 1959

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APPENDIX A

SYMBOLS

A	annular area, sq ft
c_p	specific heat at constant pressure, Btu/(lb)($^{\circ}$F)
g	gravitational constant, 32.174 ft/sec^2
H	total enthalpy, Btu/lb
h	total enthalpy, Btu/sec
J	mechanical equivalent of heat, 778.16 ft-lb/Btu
M	Mach number
N	rotational speed, rpm
P	total pressure, lb/sq ft unless otherwise specified
P_x	rating total pressure, static pressure plus velocity pressure corresponding to axial component of velocity, in. Hg abs
p	static pressure, lb/sq ft unless otherwise specified
R	gas constant, 53.35 ft-lb/(lb)($^{\circ}$R)
T	total temperature, $^{\circ}$R
t	static temperature, $^{\circ}$R
U	rotor tip speed, ft/sec
V	velocity, ft/sec
w	air weight flow, lb/sec
$\frac{wN}{60\delta}\epsilon$	weight-flow parameter, based on products of equivalent weight flow and equivalent rotor speed
β	airflow angle measured from axis, deg
Γ	torque, ft-lb

[redacted]

γ	ratio of specific heats
δ	ratio of total pressure to NASA standard sea-level pressure of 2116 lb/sq ft
ϵ	function of γ, $\frac{\gamma_{sl}}{\gamma_e}\left[\frac{\left(\frac{\gamma_e + 1}{2}\right)^{\frac{\gamma_e}{\gamma_e - 1}}}{\left(\frac{\gamma_{sl} + 1}{2}\right)^{\frac{\gamma_{sl}}{\gamma_{sl} - 1}}}\right]$
η	brake internal efficiency
θ_{cr}	squared ratio of critical velocity to critical velocity at NASA standard sea-level temperature of 518.7° R, $\frac{\frac{2\gamma}{\gamma + 1} gRT}{\frac{2\gamma_{sl}}{\gamma_{sl} + 1} gRt_{sl}}$
ρ	gas density, lb/cu ft

Subscripts:

a	cooling air
ac	actual
℄	turbine axis of rotation
c	calculated
cr	critical
e	engine operating conditions
hub	hub
id	ideal
n	net
sl	NASA standard sea-level conditions

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[redacted]

T	turbine
t	rotor blade tip
tip	outer casing
1,2,3 4,5,6	turbine axial measuring stations (see fig. 1)
(1)	first stage
(2)	second stage
I	with first-stage cooling-air effusion
II	with second-stage cooling-air effusion

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APPENDIX B

APPROXIMATE METHOD OF DETERMINING EQUIVALENT DESIGN CONDITIONS

Information on the effect of heat-capacity lag in turbine nozzles presented in reference 8 indicates that, for some typical turbines used in turbojet engines, the vibrational energy of the gas molecules is unavailable in the expansion process. This condition corresponds to a constant value of γ of 1.4. For this particular engine, however, examination of the results of reference 8 indicates that the actual flow processes may be more closely approximated by using the equilibrium value of γ because of the high pressure level and increased length of the flow path through the turbine. Consequently, an average equilibrium value of $\gamma = 1.315$ was selected as a representative value. This value of γ was applied in the following methods of determining the turbine equivalent design conditions shown on the performance curves.

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Determination of Equivalent Weight Flow

By writing the equation of continuity in terms of the critical velocity V_{cr}, area A_{cr}, and density ρ_{cr}, and solving for the critical area, the following equation is obtained:

$$A_{cr} = \frac{w_{cr}V_{cr}}{Pg}\,\frac{1}{\gamma}\left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma}{\gamma-1}} \tag{B1}$$

The critical area for turbine operating conditions is equated to the critical area for NASA standard sea-level conditions at the turbine inlet to obtain

$$\frac{w_{cr,e}V_{cr,e}}{P_e}\,\frac{1}{\gamma_e}\left(\frac{\gamma_e + 1}{2}\right)^{\frac{\gamma_e}{\gamma_e-1}} = \frac{w_{cr,sl}V_{cr,sl}}{P_{sl}}\,\frac{1}{\gamma_{sl}}\left(\frac{\gamma_{sl} + 1}{2}\right)^{\frac{\gamma_{sl}}{\gamma_{sl}-1}} \tag{B2}$$

Solving for the critical weight flow at NASA standard sea-level conditions, the following equation may be written:

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$$w_{cr,sl} = \frac{w_{cr,e}\dfrac{V_{cr,e}}{V_{cr,sl}}}{P_e/P_{sl}}\,\frac{\gamma_{sl}}{\gamma_e}\left[\frac{\left(\dfrac{\gamma_e + 1}{2}\right)^{\frac{\gamma_e}{\gamma_e - 1}}}{\left(\dfrac{\gamma_{sl} + 1}{2}\right)^{\frac{\gamma_{sl}}{\gamma_{sl} - 1}}}\right] \tag{B3}$$

Equation (B3) may be written as

$$w_{cr,sl} = \frac{w_{cr,e}\sqrt{\theta_{cr}}}{\delta}\,\epsilon \tag{B4}$$

Figure 12 shows the variation of ϵ as a function of γ.

Determination of Equivalent Work

The work output of a turbine rotor blade row may be expressed by the following equation:

$$H = \eta\,\frac{\gamma}{\gamma - 1}\,\frac{R}{J}\,T_1\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma - 1}{\gamma}}\right] \tag{B5}$$

Dividing equation (B5) by V_{cr}^2 and simplifying yield

$$\frac{H}{V_{cr}^2} = \eta\,\frac{\gamma + 1}{2(\gamma - 1)}\,\frac{1}{gJ}\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma - 1}{\gamma}}\right] \tag{B6}$$

Equating $H_{sl}/V_{cr,sl}^2$ for standard sea-level conditions to $H_e/V_{cr,sl}^2$ for engine operating conditions gives

$$\frac{H_{sl}}{V_{cr,sl}^2} = \frac{H_e}{V_{cr,e}^2} \tag{B7}$$

Combining equation (B7) with equation (B6) produces

[redacted]

$$\eta_{sl}\frac{\gamma_{sl}+1}{2(\gamma_{sl}-1)}\frac{1}{gJ}\left[1-\left(\frac{P_{x,6}}{P_{c,1}}\right)_{sl}^{\frac{\gamma_{sl}-1}{\gamma_{sl}}}\right]=\eta_e\frac{\gamma_e+1}{2(\gamma_e-1)}\frac{1}{gJ}\left[1-\left(\frac{P_{x,6}}{P_{c,1}}\right)_{e}^{\frac{\gamma_{e}-1}{\gamma_{e}}}\right] \tag{B8}$$

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Assuming the turbine efficiency η does not change, then

$$\frac{\gamma_{sl}+1}{\gamma_{sl}-1}\left[1-\left(\frac{P_{x,6}}{P_{c,1}}\right)_{sl}^{\frac{\gamma_{sl}-1}{\gamma_{sl}}}\right]=\frac{\gamma_e+1}{\gamma_e-1}\left[1-\left(\frac{P_{x,6}}{P_{c,1}}\right)_{e}^{\frac{\gamma_{e}-1}{\gamma_{e}}}\right] \tag{B9}$$

To preserve the equality of equation (B9) as γ changes, the pressure ratio must vary. Figure 13 shows the variation of the ratio of the pressure ratio at standard conditions to the pressure ratio at engine operating conditions as a function of γ for various constant values of each pressure ratio.

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APPENDIX C

DEVELOPMENT OF AIR-COOLED-TURBINE EFFICIENCY EQUATIONS

The ideal total turbine work output of an uncooled turbine can be expressed as

$$\Delta h_{T,id} = w_T c_p T_{1,T}\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{C1}$$

The ideal work of the first-stage cooling air, herein defined as the state change from the cooling-air entry as measured at (or near) the axis of rotor rotation to the turbine-exit rating conditions, can be written as

$$\Delta h_{a,I,id} = w_{a,(1)} c_p T_{a,(1),\text{℄}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(1),\text{℄}}}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{C2}$$

Similarly, for the second stage,

$$\Delta h_{a,II,id} = w_{a,(2)} c_p T_{a,(2),\text{℄}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(2),\text{℄}}}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{C3}$$

The net ideal turbine work, with first-stage-rotor cooling only, with second-stage-rotor cooling only, and with both rotors cooled, can be expressed by the following three equations, respectively:

$$\Delta h_{n,I,id} = w_T c_p T_{1,T}\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + w_{a,(1)} c_p T_{a,(1),\text{℄}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(1),\text{℄}}}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{C4}$$

$$\Delta h_{n,II,id} = w_T c_p T_{1,T}\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + w_{a,(2)} c_p T_{a,(2),\mathrm{CL}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(2),\mathrm{CL}}}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{C5}$$

$$\Delta h_{n,I,II,id} = w_T c_p T_{1,T}\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + w_{a,(1)} c_p T_{a,(1),\mathrm{CL}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(1),\mathrm{CL}}}\right)^{\frac{\gamma-1}{\gamma}}\right]$$
$$+ w_{a,(2)} c_p T_{a,(2),\mathrm{CL}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(2),\mathrm{CL}}}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{C6}$$

Dividing the four ideal turbine work equations (eqs. (C1), (C4), (C5), and (C6)) by θ_{cr} in order to obtain the turbine work in terms of equivalent conditions, and by the turbine air weight flow w_T in order to obtain the work on a per pound of turbine air weight-flow basis (Btu/lb), and combining terms, give the following ideal turbine work equations:

$$\left(\frac{\Delta H}{\theta_{cr}}\right)_{T,id} = c_p(518.7)\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{C7}$$

$$\left(\frac{\Delta H}{\theta_{cr}}\right)_{T,n,I,id} = c_p(518.7)\left\{\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + \frac{w_{a,(1)}}{w_T}\,\frac{T_{a,(1),\mathrm{CL}}}{T_{1,T}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(1),\mathrm{CL}}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\} \tag{C8}$$

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$$\left(\frac{\Delta H}{\theta_{cr}}\right)_{T,n,II,id} = c_p(518.7)\left\{\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + \frac{w_{a,(2)}}{w_T}\,\frac{T_{a,(2),\text{C}\!\!\!\text{L}}}{T_{1,T}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(2),\text{C}\!\!\!\text{L}}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\} \tag{C9}$$

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$$\left(\frac{\Delta H}{\theta_{cr}}\right)_{T,n,I,II,id} = c_p(518.7)\left\{\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + \frac{w_{a,(1)}}{w_T}\,\frac{T_{a,(1),\text{C}\!\!\!\text{L}}}{T_{1,T}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(1),\text{C}\!\!\!\text{L}}}\right)^{\frac{\gamma-1}{\gamma}}\right] + \frac{w_{a,(2)}}{w_T}\,\frac{T_{a,(2),\text{C}\!\!\!\text{L}}}{T_{1,T}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(2),\text{C}\!\!\!\text{L}}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\} \tag{C10}$$

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The net actual equivalent shaft work output of the turbine $(\Delta H/\theta_{cr})_{T,ac}$ was, for both the uncooled- and the cooled-turbine configurations, calculated in terms of equivalent operating conditions from the expression

$$\left(\frac{\Delta H}{\theta_{cr}}\right)_{T,ac} = \frac{2\pi}{60J}\left(\frac{N}{\sqrt{\theta_{cr,T}}}\right)\left(\frac{\Gamma/\delta_T}{w_T\sqrt{\theta_{cr,T}}/\delta_T}\right) \tag{C11}$$

Turbine efficiency, then, for the various coolant-flow configurations considered, defined as the ratio of actual equivalent turbine work to ideal equivalent turbine work, can be summarized as follows:

For the uncooled turbine,

$$\eta_T = \frac{\dfrac{2\pi}{60J}\left(\dfrac{N}{\sqrt{\theta_{cr,T}}}\right)\left(\dfrac{\Gamma/\delta_T}{w_T\sqrt{\theta_{cr,T}}/\delta_T}\right)}{c_p(518.7)\left[1 - \left(\dfrac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{C12}$$

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For first-stage-rotor cooling only,

$$\eta_{T,I} = \frac{\frac{2\pi}{60J}\left(\frac{N}{\sqrt{\theta_{cr,T}}}\right)\left(\frac{\Gamma/\delta_T}{w_T\sqrt{\theta_{cr,T}}/\delta_T}\right)}{c_p(518.7)\left\{\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + \frac{w_{a,(1)}}{w_T}\,\frac{T_{a,(1),\text{℄}}}{T_{1,T}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(1),\text{℄}}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}} \tag{C13}$$

For second-stage-rotor cooling only,

$$\eta_{T,II} = \frac{\frac{2\pi}{60J}\left(\frac{N}{\sqrt{\theta_{cr,T}}}\right)\left(\frac{\Gamma/\delta_T}{w_T\sqrt{\theta_{cr,T}}/\delta_T}\right)}{c_p(518.7)\left\{\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + \frac{w_{a,(2)}}{w_T}\,\frac{T_{a,(2),\text{℄}}}{T_{1,T}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(2),\text{℄}}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}} \tag{C14}$$

With both the first- and second-stage rotors being cooled simultaneously, the turbine efficiency becomes

$$\eta_{T,I,II} = \frac{\frac{2\pi}{60J}\left(\frac{N}{\sqrt{\theta_{cr,T}}}\right)\left(\frac{\Gamma/\delta_T}{w_T\sqrt{\theta_{cr,T}}/\delta_T}\right)}{c_p\,(518.7)\left\{\left[1 - \left(\frac{P_{x,6}}{P_{c,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + \frac{w_{a,(1)}}{w_T}\,\frac{T_{a,(1),\text{℄}}}{T_{1,T}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(1),\text{℄}}}\right)^{\frac{\gamma-1}{\gamma}}\right] + \frac{w_{a,(2)}}{w_T}\,\frac{T_{a,(2),\text{℄}}}{T_{1,T}}\left[1 - \left(\frac{P_{x,6}}{P_{a,(2),\text{℄}}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}} \tag{C15}$$

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TABLE I. - UNCOOLED-

Equivalent speed, % design	Turbine speed, N, rpm	Rating total-pressure ratio, $P_{c,1}/P_{x,6}$	Turbine weight flow, w_T, lb/sec	Torque, Γ, ft-lb	Total temperatures, °R		Total pressures, in. Hg abs		
					T_1	T_6	$P_{c,1}$	P_3	P_6
60	3027	1.299	35.86	947	699.9	657.0	34.90	28.77	27.08
	3021	1.450	40.25	1498	700.2	639.0	34.93	26.81	24.15
	3023	1.697	43.23	2151	700.4	618.4	34.88	24.68	20.56
	3025	1.935	44.17	2593	699.9	604.0	34.85	23.25	18.04
	3019	2.266	44.51	3048	700.4	588.7	34.96	22.03	15.52
	3022	2.544	44.43	3354	702.7	581.1	34.95	21.43	13.96
	3019	2.883	44.60	3633	700.4	567.4	34.91	21.11	12.56
	3008	3.177	44.68	3861	700.7	558.8	34.95	21.04	11.64
	3021	3.418	44.61	4000	700.4	551.7	34.83	20.94	11.20
	3021	3.714	44.55	4113	700.1	546.3	34.84	20.94	10.58
	3022	3.732	44.58	4130	700.4	546.2	34.89	20.96	10.56
	3019	3.949	44.58	4195	700.4	543.9	34.87	20.98	10.28
	3017	4.110	44.58	4236	700.4	542.6	34.85	20.96	10.12
70	3522	1.302	35.38	792	699.9	656.9	34.83	28.58	27.23
	3531	1.461	39.72	1303	699.9	637.4	34.90	26.45	24.11
	3527	1.697	42.88	1912	700.0	614.5	34.90	24.11	20.63
	3526	1.930	43.91	2351	700.7	598.0	34.87	22.66	18.09
	3524	2.292	44.50	2828	700.4	579.6	34.91	21.33	15.24
	3511	2.567	44.33	3135	702.9	570.5	34.89	20.82	13.72
	3519	2.871	44.65	3369	700.4	556.6	34.97	20.57	12.49
	3526	3.186	44.52	3584	700.1	547.2	34.86	20.38	11.41
	3530	3.449	44.53	3744	700.7	539.4	34.90	20.37	10.66
	3529	3.732	44.55	3865	700.4	533.1	34.86	20.33	10.24
	3527	3.733	44.52	3858	700.4	533.4	34.83	20.29	10.24
	3525	3.956	44.58	3950	700.1	529.4	34.89	20.32	9.92
	3526	4.177	44.56	3989	700.1	527.7	34.92	20.35	9.52
80	4031	1.320	35.09	645	699.6	659.4	34.88	28.52	27.29
	4035	1.474	39.31	1118	700.1	637.5	34.88	26.33	24.14
	4028	1.708	42.53	1702	699.8	612.5	34.87	23.74	20.60
	4041	1.930	43.66	2109	700.7	595.6	34.87	22.13	18.18
	4030	2.298	44.37	2597	700.4	573.1	34.95	20.78	15.27
	4037	2.607	44.34	2918	702.9	561.4	34.93	20.25	13.49
	4031	2.847	44.45	3100	700.4	549.6	34.90	19.91	12.47
	4032	3.184	44.51	3331	700.4	537.9	34.87	19.71	11.28
	4037	3.467	44.48	3494	700.4	530.0	34.88	19.62	10.52
	4030	3.766	44.45	3626	700.4	521.9	34.84	19.60	9.68
	4031	3.987	44.54	3702	700.1	517.7	34.93	19.64	9.41
	4026	4.252	44.52	3744	700.4	517.4	34.87	19.63	8.96
90	4542	1.326	34.62	503	699.9	663.4	34.80	28.45	27.41
	4531	1.490	38.97	955	700.3	639.5	34.93	26.29	24.25
	4546	1.723	42.18	1493	700.2	612.1	34.94	23.74	20.68
	4536	1.949	43.41	1895	699.9	592.5	34.90	21.95	18.15
	4538	2.272	44.09	2325	699.9	571.1	34.87	20.16	15.45
	4535	2.631	44.18	2691	702.4	555.2	34.92	19.31	13.33
	4534	2.855	44.42	2869	700.4	542.7	34.94	19.09	12.35
	4537	3.176	44.41	3086	700.4	531.6	34.87	18.89	11.15
	4539	3.469	44.40	3250	700.4	520.8	34.90	18.84	10.43
	4539	3.753	44.39	3368	699.9	514.2	34.87	18.79	9.86
	4543	4.024	44.51	3457	700.4	508.9	34.93	18.77	9.20
	4534	4.337	44.45	3510	700.1	505.8	34.91	18.81	8.80
100	5038	1.500	38.55	781	700.0	643.5	34.93	26.35	24.47
	5039	1.733	41.85	1308	700.2	613.7	34.87	23.63	20.80
	5040	1.960	43.12	1686	700.3	593.0	34.87	21.94	18.19
	5036	2.287	43.93	2113	699.9	569.0	34.85	20.12	15.41
	5040	2.631	44.10	2466	703.4	552.5	34.94	19.07	13.12
	5039	2.853	44.28	2624	700.1	539.1	34.89	18.67	12.14
	5041	3.201	44.22	2850	699.9	525.2	34.83	18.41	11.01
	5040	3.478	44.30	3016	700.4	516.5	34.88	18.35	10.24
	5040	3.763	44.31	3142	700.4	507.1	34.88	18.30	9.49
	5041	4.045	44.37	3242	700.1	501.6	34.91	18.33	9.12
	5036	4.416	44.29	3271	700.4	499.8	34.84	18.29	8.55
110	5539	1.498	38.22	626	699.5	650.2	34.88	26.30	24.95
	5539	1.756	41.59	1129	699.9	616.7	34.90	23.66	20.94
	5545	1.971	42.98	1488	700.3	595.0	34.88	21.85	18.42
	5543	2.301	43.72	1904	700.4	569.4	34.93	20.29	15.54
	5551	2.643	44.07	2221	700.4	548.5	34.94	19.15	13.16
	5547	2.841	44.05	2380	700.4	538.9	34.89	18.74	12.27
	5536	3.217	44.14	2638	700.4	522.0	34.90	18.38	11.04
	5541	3.507	44.18	2801	700.4	511.6	34.89	18.29	10.09
	5541	3.788	44.19	2919	700.4	505.0	34.89	18.30	9.43
	5544	4.030	44.17	2995	700.4	499.1	34.94	18.27	8.92
	5532	4.544	44.21	3051	700.4	496.9	34.94	18.28	8.40
120	6042	1.500	37.90	488	699.5	657.2	34.98	26.15	25.30
	6045	1.760	41.20	955	700.2	623.0	34.87	23.69	21.29
	6050	1.985	42.68	1303	700.3	598.8	34.89	21.92	18.69
	6042	2.304	43.52	1705	700.4	571.5	34.91	20.14	15.74
	6052	2.653	43.97	2021	700.4	550.2	34.99	19.16	13.16
	6049	2.828	43.96	2167	700.4	539.2	34.93	18.81	12.36
	6046	3.212	44.03	2412	700.1	522.6	34.91	18.49	11.16
	6048	3.521	44.01	2580	700.4	509.2	34.86	18.40	9.92
	6046	3.786	44.32	2710	700.4	499.5	34.91	18.35	9.31
	6044	4.043	44.06	2778	700.4	496.3	34.93	18.37	8.82
	6049	4.743	43.99	2831	700.7	493.5	34.91	18.37	8.17

E-222

[redacted]

E-222

Casing static pressures, in. Hg abs											
$p_{1,hub}$	$p_{1,tip}$	$p_{2,hub}$	$p_{2,tip}$	$p_{3,hub}$	$p_{3,tip}$	$p_{4,hub}$	$p_{4,tip}$	$p_{5,hub}$	$p_{5,tip}$	$p_{6,hub}$	$p_{6,tip}$
34.09	34.04	26.43	30.05	27.85	27.69	26.50	27.05	26.32	26.59	26.32	26.59
33.91	33.80	22.70	28.04	25.25	25.10	23.48	24.31	23.44	23.51	23.46	23.63
33.70	33.57	18.26	25.45	21.75	21.75	19.67	20.82	19.68	19.63	19.77	19.85
33.69	33.57	15.74	23.85	19.35	19.37	17.00	18.43	17.08	17.00	17.17	17.20
33.72	33.58	12.75	22.43	17.10	17.20	14.10	15.97	14.26	14.20	14.35	14.45
33.71	33.57	12.07	21.87	15.93	16.05	12.10	14.49	12.24	12.27	12.50	12.65
33.65	33.51	11.81	21.56	15.33	15.31	10.27	13.39	10.50	10.58	10.65	10.90
33.69	33.56	11.67	21.52	15.15	15.05	9.02	12.68	9.10	9.12	9.34	9.68
33.58	33.42	11.64	21.46	15.09	14.91	8.32	12.33	8.17	8.15	8.31	9.70
33.59	33.43	11.58	21.46	15.03	14.79	8.11	12.16	7.31	7.22	7.34	7.95
33.64	33.47	11.61	21.46	15.08	14.88	8.18	12.20	7.32	7.29	7.27	7.81
33.61	33.47	11.58	21.46	15.01	14.80	8.10	12.11	6.69	6.59	6.67	7.22
33.60	33.44	11.58	21.43	15.01	14.76	8.07	12.06	5.90	5.18	6.09	6.62
34.02	34.00	26.67	30.06	27.64	27.43	26.22	26.86	25.87	26.26	26.11	26.61
33.91	33.82	23.28	28.24	25.23	24.96	23.32	24.10	23.09	23.32	23.18	23.51
33.74	33.62	19.17	25.87	22.12	21.84	19.77	20.82	19.66	19.70	19.75	19.95
33.66	33.49	16.71	24.25	19.73	19.38	17.04	18.36	17.00	16.93	17.17	17.28
33.67	33.51	13.27	22.81	17.36	17.04	13.95	15.74	14.06	13.94	14.18	14.23
33.65	33.52	12.42	22.18	16.27	15.78	12.05	14.33	12.16	12.09	12.41	12.48
33.72	33.55	12.22	22.05	15.86	15.13	10.42	13.35	10.60	10.53	10.82	10.93
33.62	33.47	12.09	21.90	15.61	14.77	9.03	12.63	9.24	9.04	9.40	9.56
33.65	33.51	12.06	21.85	15.54	14.65	8.35	12.32	8.28	8.00	8.40	8.65
33.59	33.47	11.97	21.81	15.43	14.51	8.05	12.09	7.39	7.05	7.41	7.75
33.56	33.45	12.00	21.85	15.45	14.59	8.05	12.11	7.32	6.97	7.41	7.73
33.62	33.48	11.99	21.84	15.41	14.51	8.08	12.09	6.73	6.41	6.72	7.09
33.71	33.49	12.04	21.88	15.44	14.55	8.02	12.05	5.66	4.37	6.04	6.46
34.11	34.06	27.02	30.22	27.61	27.48	26.20	26.89	25.65	26.26	25.68	26.38
33.89	33.84	23.76	28.42	25.14	24.77	23.14	23.98	22.74	23.19	22.67	23.38
33.71	33.62	19.86	26.20	22.20	21.73	19.67	20.72	19.46	19.63	19.55	19.84
33.68	33.54	17.51	24.72	20.06	19.57	17.17	18.39	16.99	17.03	17.15	17.34
33.74	33.55	14.19	23.26	17.78	16.95	14.06	15.78	14.03	13.90	14.17	14.24
33.69	33.54	12.93	22.63	16.71	15.60	11.97	14.22	11.97	11.86	12.23	12.27
33.66	33.52	12.67	22.38	16.23	15.07	10.65	13.35	10.71	10.51	10.98	11.03
33.63	33.47	12.47	22.27	15.95	14.65	9.16	12.61	9.22	8.93	9.49	9.56
33.64	33.49	12.48	22.25	15.88	14.54	8.39	12.26	8.25	7.83	8.42	8.56
33.59	33.46	12.39	22.16	15.82	14.43	8.07	12.09	7.40	6.84	7.42	7.58
33.68	33.56	12.42	22.21	15.82	14.45	8.05	12.08	6.71	6.11	6.76	6.97
33.62	33.46	12.40	22.20	15.84	14.47	8.01	12.01	5.34	3.77	5.88	6.19
34.07	33.98	27.23	30.30	27.47	27.41	26.10	26.91	25.30	26.26	25.42	26.32
33.95	33.88	24.19	28.57	25.10	24.85	23.07	23.98	22.47	23.08	22.55	23.30
33.79	33.72	20.61	26.52	22.23	21.67	19.55	20.62	19.12	19.55	19.34	19.82
33.72	33.58	18.20	25.09	20.23	19.63	17.11	18.35	16.77	16.96	16.93	17.24
33.63	33.53	15.80	23.73	18.09	17.27	14.27	15.84	14.03	14.00	14.29	14.45
33.67	33.55	13.61	22.93	16.88	15.82	12.03	14.14	11.90	11.74	12.08	12.16
33.68	33.58	13.38	22.80	16.47	15.28	10.78	13.30	10.72	10.50	10.98	11.02
33.62	33.49	13.13	22.66	16.17	14.80	9.35	12.60	9.25	8.89	9.59	9.56
33.66	33.50	13.12	22.65	16.16	14.73	8.51	12.20	8.21	7.66	8.48	8.56
33.61	33.51	13.06	22.61	16.06	14.55	8.13	12.03	7.45	6.51	7.56	7.62
33.70	33.54	13.15	22.64	16.08	14.57	8.07	12.04	6.09	6.12	6.74	6.82
33.68	33.52	13.13	22.64	16.11	14.62	8.05	12.02	4.76	3.35	5.72	6.02
33.99	33.91	24.52	28.70	25.02	24.81	22.97	23.99	22.20	23.06	22.28	23.24
33.77	33.64	21.12	26.67	22.16	21.68	19.41	20.57	18.82	19.42	19.04	19.79
33.70	33.56	18.85	25.38	20.22	19.49	16.98	18.25	16.54	16.98	16.69	17.22
33.62	33.50	16.93	24.08	18.25	17.41	14.27	15.83	13.96	14.07	14.11	14.41
33.71	33.57	15.15	23.46	17.08	15.84	12.10	14.14	11.77	11.69	12.09	12.24
33.65	33.51	14.47	23.21	16.65	15.24	10.97	13.32	10.72	10.52	10.98	11.04
33.59	33.44	13.97	23.07	16.38	14.78	9.47	12.55	9.16	8.80	9.48	9.52
33.65	33.49	13.93	23.06	16.34	14.73	8.74	12.24	8.23	7.67	8.51	8.50
33.63	33.51	13.88	23.03	16.27	14.62	8.30	12.05	7.45	6.52	7.60	7.58
33.67	33.52	13.91	23.05	16.27	14.64	8.26	12.06	6.68	5.47	6.76	6.76
33.60	33.46	13.84	22.97	16.19	14.55	8.19	12.02	4.15	3.22	5.54	5.77
33.96	33.89	24.67	28.89	24.97	24.93	23.06	24.17	22.05	23.27	22.16	23.36
33.81	33.69	21.57	26.88	22.13	21.77	19.37	20.60	18.58	19.36	18.70	19.68
33.71	33.59	19.47	25.61	20.21	19.62	16.91	18.30	16.33	16.96	16.49	17.26
33.72	33.59	17.71	24.52	18.42	17.40	14.32	15.88	13.85	14.14	13.97	14.45
33.72	33.58	16.38	23.86	17.22	16.06	12.20	14.11	11.76	11.73	11.96	12.24
33.66	33.54	15.92	23.61	16.82	15.54	11.17	13.37	10.77	10.64	11.00	11.16
33.67	33.54	15.52	23.48	16.49	15.09	9.58	12.49	9.19	8.81	9.47	9.50
33.65	33.50	15.45	23.40	16.44	14.95	8.90	12.18	8.16	7.42	8.45	8.41
33.66	33.50	15.41	23.41	16.35	14.85	8.54	12.04	7.40	6.39	7.58	7.45
33.70	33.56	15.43	23.45	16.41	14.96	8.46	12.01	6.79	5.42	6.88	6.79
33.71	33.57	15.39	23.41	16.36	14.83	8.45	12.03	3.72	3.29	5.29	5.25
33.96	33.90	25.08	29.01	24.86	25.01	23.09	24.31	21.84	23.39	22.02	23.45
33.81	33.69	21.99	27.07	22.07	21.78	19.38	20.68	18.39	19.44	18.54	19.70
33.73	33.61	19.96	25.58	20.25	19.72	16.92	19.33	16.02	16.84	16.26	17.26
33.73	33.60	18.17	24.70	18.41	17.56	14.24	15.87	13.60	14.15	13.84	14.51
33.77	33.63	17.37	24.19	17.36	16.07	12.23	14.13	11.64	11.85	11.56	12.28
33.71	33.57	16.97	23.96	16.93	15.53	11.30	13.43	10.75	10.72	11.03	11.30
33.72	33.52	16.55	23.79	16.65	15.06	9.80	12.51	9.16	8.53	9.44	9.55
33.63	33.49	16.45	23.72	16.52	14.93	9.11	12.15	8.12	7.25	8.40	8.38
33.67	33.53	16.38	23.73	16.48	14.81	8.80	12.02	7.33	6.27	7.59	7.50
33.69	33.56	16.41	23.76	16.46	14.83	8.77	12.03	6.83	5.45	6.66	6.78
33.67	33.56	16.41	23.72	16.49	14.95	8.72	12.00	3.58	3.43	4.91	4.45

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TABLE II. - COOLED-

(a) Cooling in

Turbine speed, N, rpm	Rating total-pressure ratio, $p_{c,1}/p_{x,6}$	Turbine weight flow, w_T, lb/sec	Torque, Γ, ft-lb	Total temperatures, °R		Total pressures, in. Hg abs			Coolant-flow ratio, $\frac{w_{a,(1)}}{w_T}$, %	Coolant inlet temperature, $T_{a,(1),t}$, °R
				T_1	T_6	$p_{c,1}$	p_3	p_6		
5041	2.906	44.59	2867	700.1	536.2	34.96	18.61	12.16	-----	-----
5035	2.875	43.71	2823	700.4	537.6	34.57	19.15	12.27	3.294	[illegible]
5036	2.847	43.51	[illegible]	699.9	538.3	34.87	19.27	12.39	4.294	537.7
5037	2.847	[illegible]	2794	700.1	538.4	34.91	19.43	12.38	5.093	537.7
5045	3.185	44.35	2844	700.1	525.5	34.97	18.48	11.09	-----	-----
5038	3.135	43.90	2812	699.9	527.0	34.89	19.00	11.23	3.280	536.7
5031	3.113	43.74	2790	700.1	527.6	34.87	19.18	11.33	4.252	535.7
5033	3.105	43.60	2776	699.6	527.6	34.87	19.23	11.36	5.046	536.7
5037	3.502	44.46	[illegible]	699.7	513.9	34.95	18.39	[illegible]	-----	-----
5034	3.468	43.82	2995	700.4	516.1	34.85	18.94	10.21	3.309	534.1
5041	3.443	43.73	2985	700.9	516.3	34.88	19.11	10.30	4.322	533.7
5047	3.436	43.53	2958	700.4	517.0	34.88	19.17	10.30	5.077	532.7
5037	3.749	44.28	3132	700.4	506.8	34.94	18.36	9.53	-----	-----
5038	3.704	43.83	[illegible]	700.4	[illegible]	34.89	18.93	9.66	3.285	532.3
5041	3.690	43.69	[illegible]	700.4	[illegible]	34.87	19.06	[illegible]	4.250	532.7
5032	3.672	43.52	3073	700.7	[illegible]	34.92	19.18	9.74	5.078	533.7
5033	4.416	44.30	3258	700.4	499.4	34.89	18.31	8.55	-----	-----
5035	4.321	43.94	3214	699.9	501.1	34.91	18.91	8.78	3.277	531.3
5039	4.303	43.68	3198	700.1	502.5	34.94	19.05	8.81	4.304	531.7
5028	4.275	43.57	3184	700.4	502.7	34.93	19.19	8.87	5.049	532.7
5033	1.761	41.76	1343	699.7	611.7	35.00	23.52	20.57	-----	-----
5035	1.720	40.53	1231	699.6	613.3	34.92	24.10	21.05	5.450	550.3
5035	1.717	40.19	1199	699.4	613.2	34.92	24.19	21.04	6.743	549.3
5037	1.706	39.88	1180	699.6	613.2	34.91	24.12	21.20	7.836	548.3
5036	1.702	39.73	1166	700.1	613.7	34.90	24.28	21.24	8.636	547.7
5035	2.026	43.63	1787	700.4	587.2	34.81	21.57	17.55	-----	-----
5038	1.972	42.32	1667	699.8	589.7	34.83	22.22	18.06	5.069	550.1
5043	1.966	42.24	1638	699.8	590.7	34.97	22.34	18.17	6.148	549.1
5041	1.960	41.90	1622	700.2	590.7	34.93	22.53	18.21	6.998	548.3
5038	1.947	41.69	1611	700.7	591.6	34.86	22.50	18.26	7.707	548.7
5038	2.277	44.01	2096	700.4	570.2	34.91	20.37	15.54	-----	-----
5032	2.209	43.26	1987	700.4	572.8	34.94	21.12	16.06	4.972	548.3
5041	2.182	42.88	1960	700.3	573.8	34.92	21.14	16.24	5.975	548.3
5038	2.182	42.67	1938	699.8	573.8	34.93	21.20	16.24	6.855	548.3
5036	2.180	42.53	1922	699.7	574.8	34.93	21.40	16.27	7.585	547.3
5042	2.606	44.18	2430	700.7	550.8	34.89	19.19	13.65	-----	-----
5039	2.574	43.57	2384	700.2	550.9	34.88	19.86	13.66	4.916	542.7
5039	2.562	43.31	2344	700.2	552.5	34.84	20.05	13.69	6.022	543.7
5032	2.555	43.17	2331	699.8	552.5	34.88	20.14	13.73	6.778	545.1
5031	2.528	42.99	2314	700.8	554.0	34.84	20.19	13.88	7.462	546.7
5034	2.899	44.37	2650	700.4	536.9	34.92	18.65	12.16	-----	-----
5032	2.852	43.68	2602	699.8	537.8	34.93	19.41	12.37	4.986	537.7
5037	2.828	43.43	2572	700.3	539.7	34.89	19.59	12.44	6.132	536.7
5036	2.801	43.07	2542	700.3	540.8	34.78	19.66	12.55	7.047	536.7
5035	2.795	43.11	2523	699.8	540.7	34.87	19.80	12.56	7.641	536.7
5044	3.200	44.36	2851	700.4	525.5	34.91	18.43	11.01	-----	-----
5036	3.088	43.62	2752	700.4	528.6	34.92	19.41	11.45	5.135	530.0
5040	3.056	43.47	2722	700.0	529.2	34.90	19.51	11.54	6.142	529.1
5038	3.047	43.29	2710	700.4	530.1	34.86	19.62	11.57	6.953	530.2
5036	3.071	43.26	2707	700.3	529.3	34.92	19.70	11.48	7.675	530.5
5037	3.542	44.28	3048	700.4	513.3	34.85	18.47	10.02	-----	-----
5039	3.480	43.62	2975	700.0	515.6	34.87	19.30	10.19	5.089	530.8
5036	3.464	43.47	2958	700.0	516.1	34.88	19.39	10.23	6.036	531.1
5037	3.444	43.39	2947	700.3	516.6	34.89	19.60	10.28	6.960	530.9
5036	3.444	43.22	2931	700.6	516.8	34.92	19.58	10.28	7.635	531.5
5037	3.761	44.35	3143	700.1	506.9	34.90	18.31	9.47	-----	-----
5036	3.679	43.70	3067	700.4	510.1	34.88	19.27	9.71	4.966	530.1
5032	3.647	43.52	3046	700.4	510.9	34.94	19.42	9.84	6.066	529.6
5029	3.639	43.40	3027	700.1	511.3	34.89	19.47	9.84	6.935	529.8
5036	3.606	43.25	3007	700.4	511.6	34.87	19.62	9.91	7.630	529.5
5036	4.040	44.38	3225	699.9	501.4	34.95	18.36	9.11	-----	-----
5044	4.016	44.32	3216	700.4	502.0	34.90	18.39	9.12	-----	-----
5034	3.932	43.60	3143	700.1	504.9	34.88	19.17	9.33	5.092	527.9
5040	3.936	43.69	3141	700.9	505.2	34.91	19.23	9.32	5.237	532.7
5035	3.918	43.57	3125	700.3	505.7	34.91	19.34	9.39	6.236	533.1
5031	3.876	43.57	3103	[illegible]	506.2	34.88	19.44	9.46	7.047	536.1
5039	3.820	43.25	3085	699.8	507.1	34.88	19.58	9.28	[illegible]	[illegible]
5046	4.431	44.37	3268	700.4	499.1	34.96	18.30	8.53	-----	-----
5038	4.294	43.77	3188	699.9	501.7	34.95	19.18	8.81	5.077	533.7
5034	4.244	43.61	3164	699.9	502.7	34.93	19.33	8.93	6.251	535.1
5042	4.224	43.36	3139	700.4	503.7	34.89	19.48	8.94	7.106	535.7
5035	4.197	43.21	3129	700.3	504.7	34.98	19.53	9.01	7.975	535.7

[redacted]

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TURBINE PERFORMANCE DATA

first rotor only

Coolant pressure, $p_{a,(1),t}$, in. Hg abs	Casing static pressures, in. Hg abs											
	$p_{1,hub}$	$p_{1,tip}$	$p_{2,hub}$	$p_{2,tip}$	$p_{3,hub}$	$p_{3,tip}$	$p_{4,hub}$	$p_{4,tip}$	$p_{5,hub}$	$p_{5,tip}$	$p_{6,hub}$	$p_{6,tip}$
-----	33.73	33.57	14.56	23.27	16.59	15.14	10.63	13.16	10.35	10.16	10.74	10.83
32.38	33.69	33.54	16.78	24.36	17.25	15.41	10.73	13.44	10.57	10.38	10.80	10.87
38.33	33.69	33.57	17.30	24.59	17.42	15.43	10.62	13.44	10.50	10.33	10.92	11.00
44.32	33.73	33.59	17.59	24.94	17.64	15.46	10.63	13.50	10.55	10.44	10.90	10.98
-----	33.75	33.56	14.26	23.15	16.47	14.86	9.56	12.57	9.23	[illegible]	9.57	9.65
32.24	33.72	33.56	16.54	24.27	17.13	15.14	9.52	12.82	9.30	8.98	9.69	9.70
38.64	33.69	33.55	17.18	24.56	17.30	15.15	9.53	12.91	9.35	9.04	9.74	9.78
44.07	33.67	33.56	17.45	24.83	17.44	15.17	9.47	12.91	9.32	8.97	9.77	9.80
-----	33.70	33.57	14.09	23.12	16.37	14.74	8.58	12.16	8.04	7.40	8.44	8.42
32.30	33.69	33.50	16.37	24.15	16.99	14.94	8.61	12.46	8.16	7.53	8.44	8.43
38.97	33.71	33.55	17.15	24.52	17.25	15.00	8.61	12.55	8.19	7.55	8.52	8.51
44.12	33.73	33.53	17.45	24.84	17.36	15.04	8.56	12.55	8.12	7.51	8.52	8.53
-----	33.69	33.57	14.07	23.11	16.37	14.75	8.25	12.04	7.37	6.42	7.67	7.67
[illegible]	33.72	33.55	16.42	24.22	16.96	14.94	8.36	12.36	7.51	6.59	7.64	7.68
[illegible]	33.69	33.58	17.09	24.50	17.15	14.95	8.40	12.48	7.53	6.63	7.71	7.69
41.14	33.74	33.60	17.48	24.65	17.31	15.07	8.40	12.52	7.51	6.61	7.76	7.74
-----	33.67	33.49	14.03	23.09	16.29	14.69	8.13	11.98	4.11	2.90	5.53	5.81
[illegible]	33.67	33.53	16.59	24.18	16.97	14.95	8.29	12.32	4.22	2.99	5.65	5.92
[illegible]	33.75	33.63	17.21	24.62	17.21	14.99	8.31	12.40	4.10	3.03	5.67	5.95
44.31	33.76	33.59	17.44	24.84	17.37	15.00	8.35	12.48	4.18	3.18	5.71	5.96
-----	33.90	33.80	21.01	26.70	22.14	21.58	19.32	20.42	18.76	19.32	18.82	19.53
46.91	33.86	33.81	22.47	27.89	22.69	21.83	19.59	20.69	19.05	19.57	19.23	19.93
58.18	33.89	33.81	22.85	28.16	22.90	21.94	19.70	20.81	19.19	19.79	19.27	19.96
63.23	33.90	33.82	23.06	28.33	22.95	21.86	19.77	20.87	19.25	19.81	19.37	20.10
69.39	33.91	33.87	23.21	28.41	23.10	21.84	19.77	20.91	19.18	19.80	19.41	20.14
-----	33.61	33.50	18.38	25.08	19.78	19.04	16.38	17.68	16.02	16.33	16.10	16.53
45.00	33.70	33.58	20.13	26.50	20.55	19.40	16.72	18.09	16.35	16.74	16.57	17.00
52.59	33.85	33.74	20.65	26.97	20.76	19.50	16.86	18.21	16.50	16.90	16.68	17.13
58.34	33.81	33.71	20.84	27.12	21.04	19.54	16.91	18.25	16.55	16.95	16.71	17.16
65.03	33.78	33.64	20.98	27.16	20.96	19.43	16.86	18.26	16.54	16.96	16.79	17.23
-----	33.69	33.55	17.12	24.22	18.44	17.57	14.44	15.91	14.04	14.16	14.21	14.49
44.55	33.77	33.62	18.87	25.90	19.47	17.93	14.76	16.34	14.55	14.68	14.67	14.95
51.86	33.76	33.64	19.19	26.10	19.43	17.77	14.82	16.46	14.58	14.76	14.84	15.16
59.17	33.77	33.66	19.51	26.31	19.56	17.76	14.85	16.50	14.62	14.79	14.85	15.15
65.20	33.80	33.67	19.79	26.60	19.80	17.85	14.89	16.54	14.73	14.88	14.85	15.16
-----	33.66	33.52	15.35	23.42	17.09	15.84	12.10	14.04	11.97	11.70	12.21	12.36
43.69	33.69	33.56	17.74	25.12	17.99	16.04	12.08	14.29	11.97	11.88	12.28	12.43
51.57	33.66	33.52	18.10	25.44	18.20	16.09	12.17	14.45	12.13	12.05	12.32	12.48
59.04	33.71	33.56	18.40	25.68	18.32	16.11	12.25	14.52	12.24	12.09	12.37	12.51
64.82	33.66	33.55	18.67	25.90	18.50	16.13	12.28	14.57	12.30	12.18	12.51	12.65
-----	33.70	33.52	14.47	23.22	16.61	15.17	10.85	13.27	10.64	10.41	10.75	10.85
43.67	33.72	33.60	17.55	24.93	17.59	15.45	10.56	13.52	10.56	10.41	10.89	10.94
53.35	33.73	33.55	17.92	25.25	17.82	15.47	10.58	13.60	10.66	10.48	10.96	11.04
60.80	33.62	33.47	18.19	25.50	17.94	15.46	10.61	13.63	10.65	10.49	11.07	11.13
65.99	33.72	33.56	18.44	25.70	18.07	15.53	10.65	13.70	10.77	10.62	11.12	11.17
-----	33.70	33.51	14.06	23.07	16.39	14.79	9.44	12.52	9.18	8.80	9.51	9.53
44.60	33.72	33.58	17.51	24.96	17.57	15.22	9.65	13.06	9.56	9.30	9.86	9.87
53.14	33.69	33.59	17.83	25.28	17.74	15.23	9.60	13.05	9.56	9.25	9.96	9.98
59.98	33.69	33.54	18.05	25.49	17.83	15.20	9.59	13.11	9.54	9.36	9.98	9.99
66.14	33.74	33.62	18.34	25.74	17.98	15.27	9.54	13.16	9.51	9.27	9.86	9.89
-----	33.60	33.49	13.97	23.08	16.41	14.75	8.56	12.16	8.07	7.35	8.31	8.26
44.24	33.69	33.53	17.42	24.91	17.45	15.06	8.57	12.54	8.11	7.43	8.39	8.35
52.82	33.69	33.56	17.73	25.13	17.64	15.04	8.57	12.61	8.15	7.46	8.43	8.38
60.19	33.69	33.59	17.98	25.44	17.78	15.06	8.62	12.71	8.19	7.52	8.47	8.41
65.79	33.75	33.61	18.26	25.77	17.90	15.19	8.67	12.75	8.25	7.57	8.45	8.44
-----	33.67	33.51	13.98	23.07	16.29	14.68	8.29	12.05	7.44	6.47	7.62	7.59
43.21	33.69	33.55	17.36	24.83	17.42	14.99	8.39	12.47	7.63	6.67	7.71	7.69
52.55	33.74	33.60	17.73	25.18	17.63	15.06	8.47	12.56	7.70	6.80	7.80	7.78
59.94	33.72	33.56	17.95	25.40	17.76	15.05	8.50	12.55	7.67	6.79	7.78	7.76
65.68	33.71	33.55	18.23	25.68	17.94	15.13	8.59	12.69	7.82	6.94	7.88	7.65
-----	33.71	33.56	13.97	23.09	16.31	14.69	8.19	12.01	6.71	5.38	6.78	6.77
-----	33.66	33.52	13.96	23.08	16.38	14.68	8.19	12.03	6.69	5.35	6.83	6.84
44.12	33.69	33.55	17.40	24.84	17.41	14.99	8.38	12.36	6.66	5.46	6.91	6.91
45.69	33.70	33.57	17.47	24.90	17.46	15.01	8.33	12.39	6.74	5.44	6.85	6.89
54.25	33.70	33.59	17.60	25.18	17.61	15.02	8.42	12.50	6.73	5.54	6.91	6.88
61.10	33.70	33.56	18.02	25.41	17.73	15.01	8.46	12.56	6.94	5.76	7.00	6.99
69.99	33.70	33.58	18.31	25.70	17.85	15.03	8.54	12.65	7.04	5.94	7.15	7.15
-----	33.71	33.59	13.96	23.09	16.26	14.60	8.13	11.98	4.18	3.41	5.52	5.78
44.39	33.76	33.61	17.45	24.79	17.37	14.98	8.38	12.46	4.18	3.22	5.64	5.90
54.54	33.73	33.60	17.81	25.18	17.60	14.98	8.44	12.52	4.21	3.59	5.71	5.99
62.44	33.68	33.61	18.11	25.50	17.71	15.01	8.53	12.62	4.17	3.32	5.75	5.99
68.97	33.70	33.57	18.34	25.68	17.82	15.02	8.55	12.62	4.15	3.20	5.78	6.06

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TABLE II. - Continued. COOLED-

(b) Cooling in second

Turbine speed, N, rpm	Rating total-pressure ratio, $P_{c,1}/P_{x,6}$	Turbine weight flow, w_T, lb/sec	Torque, Γ, ft-lb	Total temperatures, °R		Total pressures, in. Hg abs			Coolant-flow ratio, $\frac{w_{a,(2)}}{w_T}$, %	Coolant inlet temperature, $T_{a,(2),t}$, °R
				T_1	T_6	$P_{c,1}$	P_3	P_6		
5042	2.926	44.17	2656	700.1	536.2	34.85	18.66	12.07	-----	-----
5035	2.852	44.07	2585	700.1	540.1	34.91	18.91	12.46	3.184	530.7
5033	2.829	44.10	2557	700.4	541.0	34.91	19.01	12.52	4.079	528.2
5038	2.801	44.07	2527	700.4	542.8	34.87	19.06	12.63	4.806	524.7
5033	3.206	44.11	2859	700.4	525.5	34.91	18.49	11.04	-----	-----
5034	3.143	44.14	2785	699.9	529.0	34.89	18.69	11.20	3.115	525.7
5037	3.127	44.12	2769	700.1	529.6	34.83	18.71	11.25	4.057	522.7
5033	3.118	44.18	2741	700.9	531.2	34.89	18.79	11.31	4.871	519.7
5034	3.530	44.35	3041	700.4	514.5	34.95	18.51	10.09	-----	-----
5038	3.461	44.14	2970	700.7	517.1	34.89	18.55	10.26	3.147	519.7
5038	3.435	44.12	2943	700.9	519.2	34.83	18.59	10.32	4.096	519.7
5038	3.407	44.16	2921	700.9	520.6	34.89	18.74	10.41	4.805	519.7
5037	3.745	44.39	3133	700.1	507.3	35.05	18.45	9.57	-----	-----
5034	3.655	44.24	3052	699.9	511.7	34.87	18.58	9.91	3.339	520.7
5034	3.623	44.26	3033	700.4	513.1	34.93	18.60	9.98	4.270	529.7
5034	3.597	44.19	3013	700.4	515.2	34.96	18.72	10.09	4.958	534.7
5033	4.429	44.35	3260	699.9	499.6	34.99	18.45	8.56	-----	-----
5039	4.286	44.37	3200	700.9	504.7	35.02	18.63	8.86	3.315	530.7
5036	4.243	44.26	3173	700.9	506.2	34.96	18.64	8.92	4.234	525.7
5027	4.210	44.25	3148	700.1	507.2	34.94	18.65	9.00	5.006	524.7
5039	1.750	41.93	1340	699.9	612.3	35.00	23.65	20.74	-----	-----
5037	1.690	41.00	1167	699.2	616.8	34.82	24.29	21.40	5.673	550.1
5033	1.679	40.76	1139	699.7	618.2	34.85	24.47	21.49	7.036	548.1
5038	1.669	40.72	1107	700.2	619.3	34.90	24.63	21.67	8.141	546.9
5036	1.999	43.20	1754	700.9	589.9	34.90	21.76	17.84	-----	-----
5036	1.936	42.66	1600	700.3	595.3	34.86	22.44	18.50	5.319	545.5
5034	1.917	42.53	1569	700.6	596.7	34.79	22.56	18.59	6.685	544.5
5035	1.907	42.50	1536	700.7	598.1	34.86	22.70	18.75	7.664	543.9
5035	2.296	43.99	2129	700.7	569.2	35.03	20.21	15.43	-----	-----
5038	2.203	43.55	1972	699.9	574.8	34.88	20.91	16.09	5.300	542.9
5033	2.189	43.52	1946	699.9	576.8	34.88	21.00	16.20	6.510	541.9
5033	2.178	43.44	1918	699.9	577.6	34.91	21.08	16.36	7.449	540.5
5038	2.571	44.30	2413	699.9	552.3	34.91	19.26	13.76	-----	-----
5033	2.468	44.00	2255	700.9	560.5	34.91	19.73	14.33	5.412	540.5
5029	2.439	43.96	2228	700.4	561.6	34.82	20.00	14.41	6.449	539.5
5033	2.426	43.94	2206	699.4	562.0	34.98	20.11	14.61	7.349	539.5
5035	2.880	44.42	2663	700.1	537.9	34.95	18.69	12.28	-----	-----
5036	2.759	44.17	2514	700.4	546.3	34.90	19.20	12.79	5.151	538.5
5036	2.727	44.19	2463	700.1	548.6	34.95	19.33	12.97	6.427	538.1
5036	2.683	44.11	2430	700.7	550.2	34.90	19.45	13.12	7.338	538.5
5040	3.189	44.38	2909	700.4	525.9	34.95	18.47	11.03	-----	-----
5046	3.223	44.53	2884	700.4	525.0	34.97	18.45	10.91	-----	-----
5033	3.091	44.27	2753	700.1	531.6	34.96	18.81	11.41	5.261	532.3
5032	3.048	44.21	2713	699.7	533.7	34.87	18.87	11.59	6.460	530.1
5038	2.994	44.18	2664	699.9	536.2	34.85	18.93	11.78	7.374	529.7
5039	3.467	44.34	3032	700.1	515.9	34.95	18.42	10.27	-----	-----
5036	3.354	44.19	2896	699.7	522.6	34.81	18.65	10.53	5.175	529.5
5031	3.332	44.18	2876	700.1	524.6	34.89	18.75	10.61	6.474	527.7
5038	3.314	44.24	2851	700.1	525.6	34.93	18.80	10.70	7.396	527.5
5036	3.727	44.28	3138	700.1	507.8	34.96	18.39	9.58	-----	-----
5030	3.592	44.21	3013	700.7	515.3	34.84	18.61	10.01	5.245	526.5
5024	3.577	44.20	2990	700.4	517.5	34.91	18.76	10.12	6.500	524.5
5046	3.519	44.28	2955	700.4	518.7	34.91	18.81	10.27	7.364	523.5
5038	4.076	44.45	3237	700.1	501.6	34.97	18.38	9.03	-----	-----
5030	3.931	44.23	3123	700.1	509.1	34.91	18.69	9.40	5.250	524.5
5036	3.874	44.27	3074	700.1	510.9	34.87	18.75	9.50	6.501	522.7
5032	3.859	44.22	3058	700.9	512.9	34.92	18.80	9.51	7.440	522.5
5036	4.433	44.50	3281	700.7	500.1	34.98	18.40	8.51	-----	-----
5026	4.215	44.13	3156	700.9	507.7	34.90	18.65	8.96	5.255	522.7
5037	4.150	44.13	3115	700.4	509.5	34.86	18.69	9.10	6.535	521.5
5026	4.090	44.18	3101	700.4	510.5	34.89	18.76	9.24	7.474	520.7

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CD-5

TURBINE PERFORMANCE DATA

rotor only

Coolant pressure, $p_{a,(2),t}$, in. Hg abs	Casing static pressures, in. Hg abs											
	$p_{1,hub}$	$p_{1,tip}$	$p_{2,hub}$	$p_{2,tip}$	$p_{3,hub}$	$p_{3,tip}$	$p_{4,hub}$	$p_{4,tip}$	$p_{5,hub}$	$p_{5,tip}$	$p_{6,hub}$	$p_{6,tip}$
-----	33.61	33.46	14.58	23.22	16.61	15.17	10.56	13.13	10.38	10.16	10.63	10.68
28.88	33.71	33.53	15.24	23.44	16.92	15.54	11.29	13.83	10.61	10.41	10.93	10.94
36.96	33.70	33.54	15.43	23.49	17.01	15.70	11.58	14.03	10.60	10.43	11.04	11.00
43.38	33.67	33.49	15.58	23.54	17.08	15.79	11.85	14.21	10.70	10.54	11.14	11.10
-----	33.70	33.55	14.30	23.16	16.47	14.90	9.46	12.56	9.14	8.70	9.51	9.54
28.19	33.67	33.51	14.78	23.30	16.66	15.16	10.09	13.21	9.29	8.90	9.68	9.61
36.60	33.61	33.45	14.91	23.33	16.71	15.25	10.39	13.42	9.29	8.97	9.73	9.61
43.87	33.66	33.51	15.06	23.39	16.78	15.35	10.68	13.58	9.28	9.05	9.76	9.61
-----	33.73	33.55	14.24	23.19	16.45	14.87	8.66	12.28	8.08	7.38	8.35	8.32
28.32	33.67	33.51	14.58	23.23	16.55	15.00	9.43	12.91	8.14	7.48	8.51	8.39
36.84	33.60	33.44	14.69	23.24	16.60	15.06	9.71	13.10	8.11	7.59	8.57	8.41
43.26	33.68	33.50	14.86	23.35	16.73	15.22	9.98	13.31	8.18	7.78	8.67	8.49
-----	33.82	33.65	14.24	23.24	16.47	14.85	8.33	12.15	7.45	6.47	7.71	7.69
30.14	33.61	33.51	14.56	23.24	16.56	15.00	9.21	12.83	7.52	6.73	7.85	7.72
38.87	33.71	33.54	14.70	23.32	16.58	15.07	9.62	13.09	7.63	6.88	7.95	7.77
45.27	33.72	33.59	14.87	23.41	16.69	15.17	9.89	13.31	7.55	6.98	8.06	7.80
-----	33.78	33.60	14.25	23.22	16.47	14.84	8.18	12.08	4.35	3.02	5.57	5.76
30.27	33.82	33.63	14.63	23.36	16.61	15.04	9.10	12.83	4.73	3.22	5.82	5.84
38.41	33.76	33.57	14.71	23.35	16.64	15.09	9.46	13.05	4.71	3.01	5.89	5.86
45.35	33.71	33.57	14.82	23.35	16.65	15.17	9.75	13.24	4.77	3.25	5.96	5.87
-----	33.91	33.76	21.08	26.74	22.15	21.60	19.36	20.46	18.79	19.34	18.94	19.65
48.74	33.75	33.65	22.04	27.25	22.90	22.53	20.59	21.55	19.30	20.07	19.53	20.21
59.98	33.81	33.69	22.28	27.39	23.09	22.70	20.95	21.82	19.43	20.13	19.67	20.36
69.20	33.87	33.74	22.58	27.60	23.26	22.98	21.31	22.06	19.57	20.24	19.82	20.49
-----	33.72	33.59	18.59	25.24	20.01	19.23	16.65	17.94	16.12	16.52	16.38	16.85
47.30	33.71	33.57	19.52	25.82	20.82	20.07	17.84	18.99	16.65	17.10	16.92	17.32
59.23	33.66	33.52	19.70	25.88	20.89	20.19	18.22	19.24	16.68	17.13	17.08	17.42
67.66	33.75	33.59	19.93	26.06	21.13	20.40	18.53	19.48	16.75	17.17	17.20	17.54
-----	33.84	33.66	17.08	24.32	18.46	17.55	14.33	15.85	13.94	14.04	14.14	14.43
48.03	33.70	33.54	17.77	24.70	19.16	18.23	15.54	16.95	14.33	14.54	14.71	14.88
58.91	33.68	33.55	17.90	24.78	19.21	18.32	15.85	17.18	14.32	14.53	14.80	14.97
67.23	33.73	33.58	18.02	24.86	19.30	18.45	16.13	17.38	14.37	14.65	14.91	15.02
-----	33.67	33.53	15.52	23.48	17.25	16.02	12.34	14.23	12.10	12.06	12.38	12.56
49.91	33.70	33.54	16.49	24.00	17.69	16.90	13.79	15.52	12.43	12.56	12.95	12.97
58.83	33.64	33.49	16.77	24.11	18.12	17.16	14.05	15.70	12.47	12.60	13.09	13.07
67.01	33.78	33.62	17.05	24.29	18.27	17.32	14.40	15.97	12.57	12.83	13.22	13.21
-----	33.71	33.58	14.50	23.24	16.62	15.16	10.77	13.18	10.57	10.39	10.86	10.93
47.17	33.70	33.49	15.63	23.63	17.17	15.90	12.24	14.42	10.79	10.83	11.33	11.30
58.83	33.75	33.57	15.79	23.71	17.39	16.17	12.63	14.72	10.98	11.02	11.53	11.41
67.11	33.69	33.53	15.95	23.79	17.48	16.36	12.95	14.96	10.99	11.03	11.72	11.59
-----	33.73	33.55	14.18	23.16	16.41	14.84	9.39	12.48	9.10	8.76	9.54	9.61
-----	33.72	33.60	14.21	23.16	16.39	14.83	9.37	12.50	9.04	8.64	9.42	9.47
48.01	33.74	33.59	15.07	23.41	16.77	15.34	10.89	13.69	9.32	9.18	9.89	9.71
58.78	33.62	33.49	15.22	23.39	16.78	15.45	11.22	13.92	9.29	9.21	10.02	9.80
67.01	33.63	33.44	15.45	23.48	16.91	15.63	11.54	14.12	9.38	9.35	10.23	9.99
-----	33.71	33.58	14.13	23.10	16.32	14.72	8.62	12.17	8.09	7.55	8.56	8.55
47.03	33.58	33.42	14.81	23.27	16.60	15.10	10.10	13.33	8.21	7.89	8.85	8.61
58.72	33.66	33.52	15.04	23.31	16.65	15.27	10.48	13.63	8.18	7.99	8.92	8.64
67.17	33.70	33.56	15.20	23.43	16.79	15.40	10.85	13.84	8.19	8.06	8.98	8.66
-----	33.76	33.55	14.11	23.12	16.31	14.71	8.32	12.07	7.42	6.53	7.75	7.74
47.56	33.62	33.44	14.72	23.29	16.56	15.06	9.84	13.25	7.42	6.96	8.01	7.74
58.82	33.68	33.54	14.93	23.36	16.74	15.26	10.26	13.56	7.44	7.10	8.07	7.74
66.74	33.68	33.52	15.20	23.43	16.79	15.34	10.53	13.73	7.41	7.13	8.23	7.89
-----	33.74	33.58	14.08	23.12	16.28	14.70	8.17	12.02	6.55	5.21	6.68	6.69
47.54	33.67	33.53	14.71	23.26	16.59	15.06	9.74	13.21	6.48	5.76	6.94	6.67
58.83	33.64	33.49	14.92	23.31	16.68	15.20	10.16	13.51	6.40	5.76	7.05	6.70
67.23	33.69	33.54	15.08	23.40	16.77	15.34	10.44	13.71	6.31	5.72	7.08	6.70
-----	33.76	33.58	14.05	23.12	16.32	14.70	8.19	12.01	4.35	3.00	5.49	5.75
47.38	33.67	33.53	14.71	23.27	16.60	15.08	9.72	13.19	4.66	2.94	5.90	5.84
58.91	33.62	33.49	14.94	23.32	16.69	15.21	10.04	13.43	4.47	2.80	6.05	5.88
67.37	33.65	33.50	15.10	23.36	16.75	15.30	10.39	13.67	4.47	2.84	6.17	6.01

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TABLE II. - Concluded. COOLED-

(c) Cooling

Turbine speed, N, rpm	Rating total-pressure ratio, $P_{c,1}/P_{x,6}$	Turbine weight flow, w_T, lb/sec	Torque, Γ, ft-lb	Total temperatures, °R		Total pressures, in. Hg abs			Coolant-flow ratio, %		Coolant inlet temperature, °R	
				T_1	T_6	$P_{c,1}$	P_3	P_5	$\frac{w_{a,(1)}}{w_T}$	$\frac{w_{a,(2)}}{w_T}$	$T_{a,(1),t}$	$T_{a,(2),t}$
5030	2.935	44.28	2670	700.1	536.6	34.84	18.62	12.01	-----	-----	-----	-----
5031	2.668	43.68	2394	700.0	549.0	34.84	19.83	13.19	3.143	7.415	538.7	539.3
5041	2.630	43.53	2359	700.9	551.6	34.92	19.94	13.41	4.068	7.137	538.7	539.5
5038	2.621	43.20	2343	699.9	551.3	34.86	20.02	13.45	4.801	7.137	538.7	539.7
5029	3.206	44.35	2861	700.4	525.5	34.85	18.42	10.97	-----	-----	-----	-----
5034	2.954	43.53	2605	699.9	538.8	34.89	19.44	12.03	3.147	7.340	538.7	539.7
5027	2.935	43.58	2600	700.7	539.3	34.95	19.64	12.10	4.078	7.166	539.7	540.7
5044	2.925	43.32	2584	699.9	539.3	34.90	19.68	12.13	4.797	7.084	539.7	541.7
5038	3.521	44.27	3042	700.9	515.0	34.93	18.38	10.12	-----	-----	-----	-----
5025	3.269	43.71	2810	700.1	527.7	34.88	19.34	10.83	3.130	7.294	539.7	541.7
5030	3.255	43.52	2802	700.4	527.5	34.86	19.44	10.86	4.060	7.171	540.7	542.7
5040	3.247	43.48	2791	700.4	527.9	34.94	19.57	10.93	4.726	7.072	541.7	542.7
5040	3.713	44.20	3113	699.9	507.8	34.83	18.33	9.56	-----	-----	-----	-----
5039	3.447	43.64	2892	700.9	521.7	34.88	19.28	10.44	3.171	7.289	540.7	542.7
5033	3.427	43.63	2884	699.9	521.6	34.92	19.44	10.50	4.057	7.140	540.7	542.7
5060	3.414	43.47	2865	700.4	522.0	34.93	19.55	10.58	4.757	7.067	540.7	541.7
5036	4.433	44.15	3260	700.4	499.5	34.93	18.34	8.53	-----	-----	-----	-----
5043	4.069	43.81	3058	699.9	512.1	34.95	19.32	9.27	3.143	7.268	538.7	540.7
5044	4.036	43.54	3042	700.1	512.0	34.95	19.44	9.36	4.068	7.159	538.7	540.7
5034	4.014	43.39	3028	700.4	512.8	34.92	19.53	9.42	4.768	7.075	538.7	539.7
5043	2.880	44.20	2639	700.9	538.5	34.90	18.66	12.20	-----	-----	-----	-----
5040	2.659	43.38	2365	699.8	548.8	34.89	20.07	13.20	5.000	7.008	529.7	530.7
5036	2.645	43.20	2344	700.3	549.7	34.94	20.15	13.26	5.736	6.926	528.7	529.7
5033	2.640	43.03	2338	700.8	549.7	34.87	20.18	13.28	6.298	6.853	528.7	529.7
5037	2.634	42.81	2327	700.6	549.8	34.90	20.28	13.36	6.851	6.788	528.7	529.7
5042	3.205	44.39	2871	700.4	525.1	34.93	18.43	10.92	-----	-----	-----	-----
5034	2.925	43.27	2573	700.3	538.0	34.87	19.72	12.09	5.015	7.065	527.7	528.7
5038	2.948	43.30	2589	700.4	536.7	34.96	19.85	12.02	5.702	6.935	527.7	528.7
5036	2.911	43.14	2561	700.4	538.3	34.90	19.89	12.16	6.310	6.824	527.7	528.7
5033	2.903	43.14	2550	700.8	538.8	34.90	19.96	12.21	6.815	6.713	527.7	528.7
5034	3.462	44.44	3020	700.4	516.2	34.97	18.41	10.20	-----	-----	-----	-----
5036	3.199	43.53	2752	700.3	528.0	34.93	19.57	10.95	4.948	7.009	527.2	528.7
5031	2.172	43.33	2733	700.4	528.3	34.80	19.67	11.03	5.758	6.903	526.7	527.7
5035	3.171	43.35	2725	700.6	528.5	34.94	19.80	11.07	6.263	6.828	526.7	527.7
5036	3.162	43.17	2719	700.9	529.0	34.94	19.89	11.11	6.794	6.718	526.7	527.7
5041	3.729	44.44	3133	700.4	507.3	34.90	18.40	9.52	-----	-----	-----	-----
5037	3.440	44.49	2887	700.1	519.0	34.92	19.54	10.37	4.878	6.855	526.7	528.7
5034	3.439	43.36	2874	700.6	519.8	34.87	19.66	10.49	5.743	6.896	526.7	527.7
5033	3.455	43.19	2877	700.6	519.5	34.96	19.72	10.50	6.251	6.830	526.7	527.7
5039	3.439	43.16	2866	700.6	519.8	34.94	19.79	10.53	6.789	6.719	526.7	527.7
5039	4.342	44.45	3262	700.7	501.5	34.95	18.42	8.57	-----	-----	-----	-----
5036	3.979	43.50	3012	700.3	512.8	34.86	19.51	9.37	4.989	7.011	526.7	527.7
5035	3.945	43.51	3009	700.6	513.2	34.95	19.71	9.52	5.723	6.964	525.7	526.7
5044	3.952	43.26	2995	700.8	512.4	34.90	19.72	9.45	6.264	6.889	525.7	526.7
5036	3.919	43.18	2985	700.3	513.6	34.88	19.81	9.56	6.832	6.786	525.7	526.7

[redacted]

TURBINE PERFORMANCE DATA

in both rotors

Coolant pressure, in. Hg abs		Casing static pressures, in. Hg abs											
$P_{a,(1),t}$	$P_{a,(2),t}$	$p_{1,hub}$	$p_{1,tip}$	$p_{2,hub}$	$p_{2,tip}$	$p_{3,hub}$	$p_{3,tip}$	$p_{4,hub}$	$p_{4,tip}$	$p_{5,hub}$	$p_{5,tip}$	$p_{6,hub}$	$p_{6,tip}$
-----	-----	33.64	33.41	14.52	23.15	16.58	15.10	10.62	13.15	10.40	10.18	10.56	10.64
31.87	66.30	33.67	33.49	17.52	24.72	17.96	16.42	12.95	15.16	11.14	11.24	11.73	11.58
37.79	65.02	33.73	33.57	17.91	25.12	18.18	16.51	13.01	15.23	11.28	11.36	11.95	11.83
42.59	63.98	33.69	33.56	18.09	25.30	18.24	16.44	12.97	15.22	11.29	11.39	12.00	11.85
-----	-----	33.62	33.45	14.20	23.13	16.40	14.89	9.49	12.54	9.17	8.82	9.46	9.49
31.62	66.30	33.70	33.56	17.32	24.64	17.57	15.86	11.62	14.39	9.63	9.61	10.37	10.13
37.72	64.89	33.76	33.61	17.61	24.99	17.83	15.97	11.63	14.49	9.69	9.72	10.45	10.21
42.56	63.82	33.73	33.57	17.88	25.22	17.95	15.94	11.53	14.64	9.69	9.71	10.48	10.24
-----	-----	33.70	33.54	14.15	23.16	16.36	14.78	8.61	12.19	8.03	7.41	8.38	8.37
31.51	66.28	33.69	33.55	17.17	24.55	17.44	15.63	10.74	14.06	8.28	8.16	9.07	8.74
37.48	64.91	33.66	33.54	17.50	24.84	17.64	15.63	10.69	14.07	8.29	8.18	9.09	8.78
42.19	63.94	33.76	33.62	17.79	25.14	17.82	15.71	10.67	14.10	8.26	8.17	9.14	8.83
-----	-----	33.60	33.44	14.09	23.07	16.31	14.71	8.30	12.05	7.45	6.62	7.76	7.72
31.75	66.15	33.68	33.56	17.20	24.55	17.39	15.60	10.50	13.96	7.55	7.36	6.40	8.09
37.53	64.77	33.72	33.58	17.54	24.87	17.64	15.63	10.50	14.01	7.65	7.42	8.45	8.14
42.30	63.88	33.76	33.60	17.79	25.12	17.77	15.66	10.52	14.05	7.69	7.47	8.49	8.19
-----	-----	33.75	33.54	14.07	23.11	16.32	14.78	8.15	12.00	4.10	3.05	5.54	5.80
31.63	66.15	33.74	33.62	17.23	24.61	17.44	15.55	10.37	13.91	4.42	2.94	6.11	5.94
37.48	64.75	33.74	33.62	17.59	24.90	17.60	15.62	10.35	13.95	4.45	2.91	6.21	6.05
42.24	63.72	33.72	33.62	17.79	25.12	17.76	15.59	10.28	13.95	4.45	2.90	6.25	6.10
-----	-----	33.68	33.51	14.59	23.16	16.73	15.18	10.72	13.21	10.59	10.32	10.84	10.92
43.19	62.58	33.69	33.58	18.12	25.38	18.30	16.41	12.76	15.12	11.19	11.18	11.78	11.63
49.29	61.53	33.76	33.65	18.40	25.66	18.41	16.44	12.79	15.14	11.25	11.25	11.85	11.74
53.91	60.67	33.71	33.58	18.54	25.76	18.50	16.36	12.69	15.11	11.13	11.26	11.84	11.75
58.35	59.78	33.74	33.61	18.72	25.91	18.61	16.38	12.68	15.08	11.16	11.32	11.91	11.80
-----	-----	33.70	33.54	14.19	23.13	16.41	14.84	9.46	12.54	9.17	8.78	9.50	9.52
43.13	62.82	33.69	33.57	17.91	25.19	17.96	15.88	11.45	14.44	9.63	9.60	10.46	10.25
49.08	61.71	33.78	33.65	18.16	25.46	18.10	15.91	11.33	14.41	9.58	9.56	10.39	10.17
54.10	60.49	33.72	33.59	18.33	25.66	18.23	15.92	11.40	14.49	9.76	9.70	10.52	10.29
58.44	59.50	33.71	33.60	18.46	25.73	18.26	15.90	11.38	14.49	9.79	9.73	10.57	10.36
-----	-----	33.74	33.57	14.14	23.18	16.41	14.82	8.64	12.20	8.20	7.46	8.55	8.54
42.78	62.70	33.72	33.60	17.87	25.19	17.86	15.69	10.73	14.12	8.56	8.35	9.30	9.01
49.54	61.40	33.62	33.47	18.03	25.35	17.95	15.63	10.68	14.13	8.57	8.36	9.36	9.07
53.91	60.77	33.75	33.66	18.28	25.60	18.10	15.73	10.73	14.18	8.59	8.47	9.40	9.12
58.23	59.54	33.77	33.62	18.42	25.75	18.22	15.74	10.69	14.19	8.60	8.49	9.43	9.18
-----	-----	33.68	33.48	14.12	23.12	16.41	14.79	8.31	12.09	7.39	6.42	7.72	7.68
43.09	62.68	33.69	33.51	17.82	25.13	17.80	15.62	10.43	14.03	7.59	7.21	8.28	7.97
49.45	61.38	33.68	33.55	18.00	25.40	17.94	15.58	10.38	14.01	7.52	7.18	8.35	8.05
53.62	60.57	33.82	33.63	18.20	25.55	18.02	15.61	10.32	14.05	7.50	7.22	8.33	8.03
58.18	59.54	33.76	33.63	18.39	25.73	18.14	15.66	10.28	14.02	7.53	7.22	8.38	8.07
-----	-----	33.72	33.55	14.08	23.13	16.39	14.78	8.16	12.09	5.21	3.34	5.79	5.97
43.09	62.62	33.66	33.53	17.79	25.09	17.79	15.58	10.22	13.95	5.18	3.38	6.35	6.13
49.39	62.15	33.77	33.63	18.06	25.43	17.96	15.65	10.23	14.00	5.14	3.28	6.47	6.24
53.75	61.16	33.73	33.58	18.20	25.53	18.02	15.60	10.19	14.01	5.06	3.31	6.42	6.24
58.52	60.10	33.70	33.58	18.37	25.66	18.11	15.68	10.19	14.02	5.06	3.30	6.52	6.31

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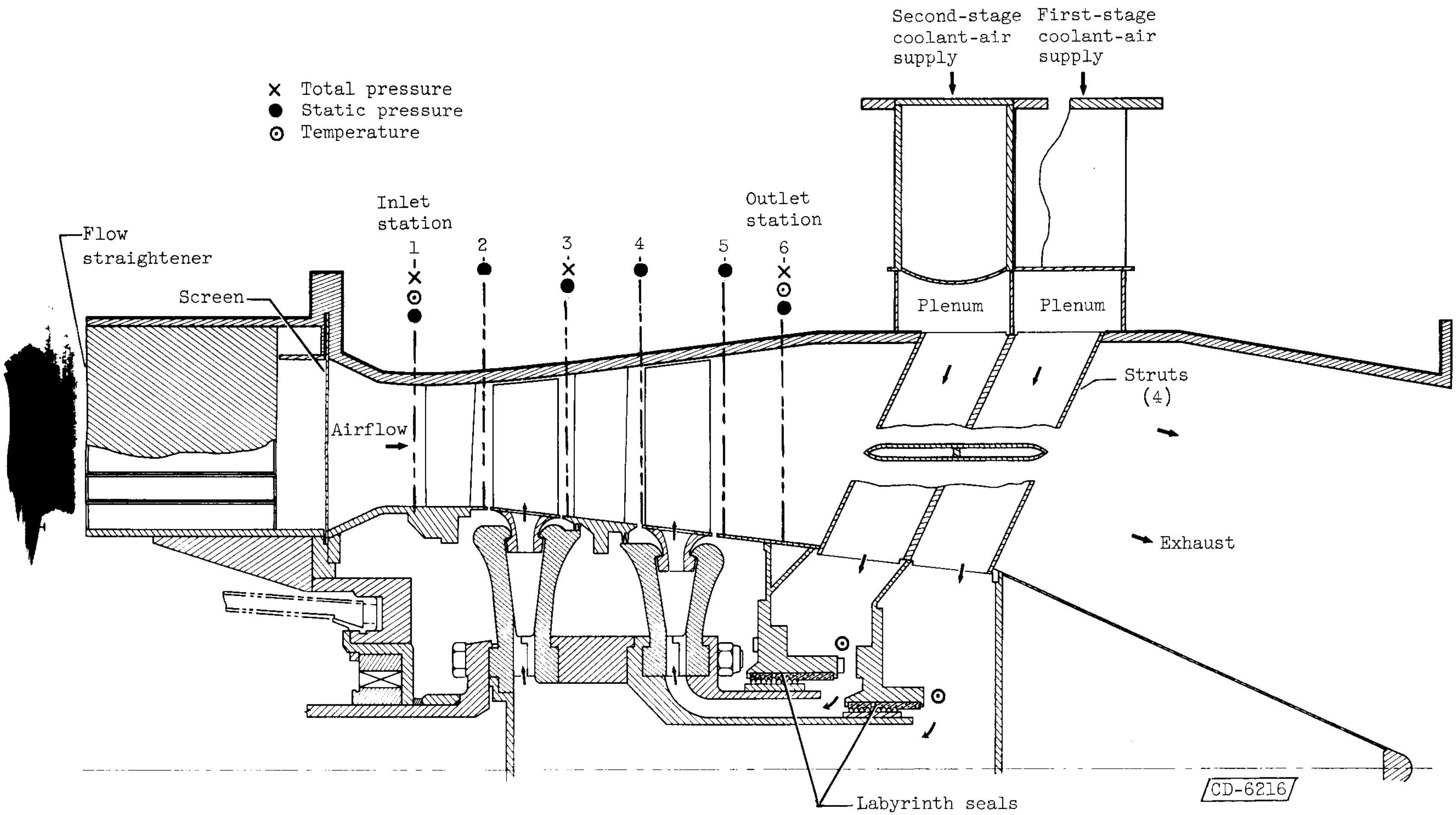

Figure 1. - Schematic diagram of turbine assembly and instrumentation.

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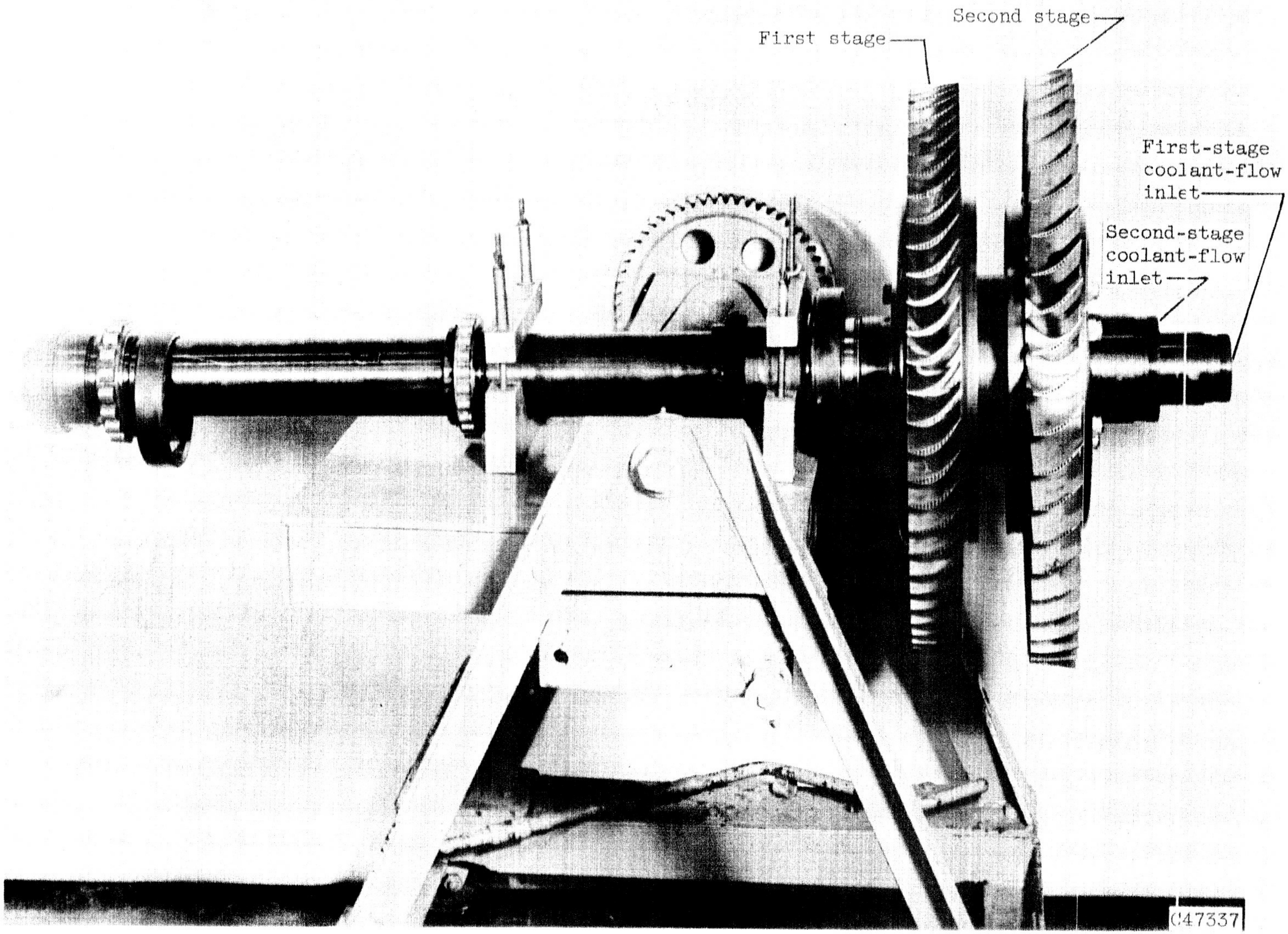
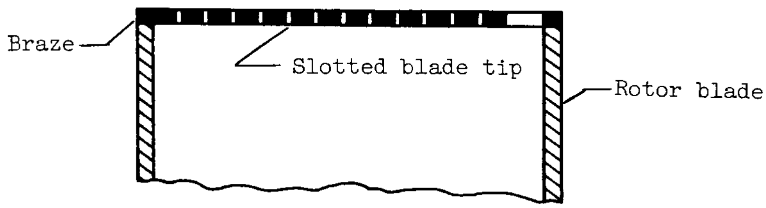


Figure 2. - Turbine rotor assembly.



Cutaway of rotor blade tip

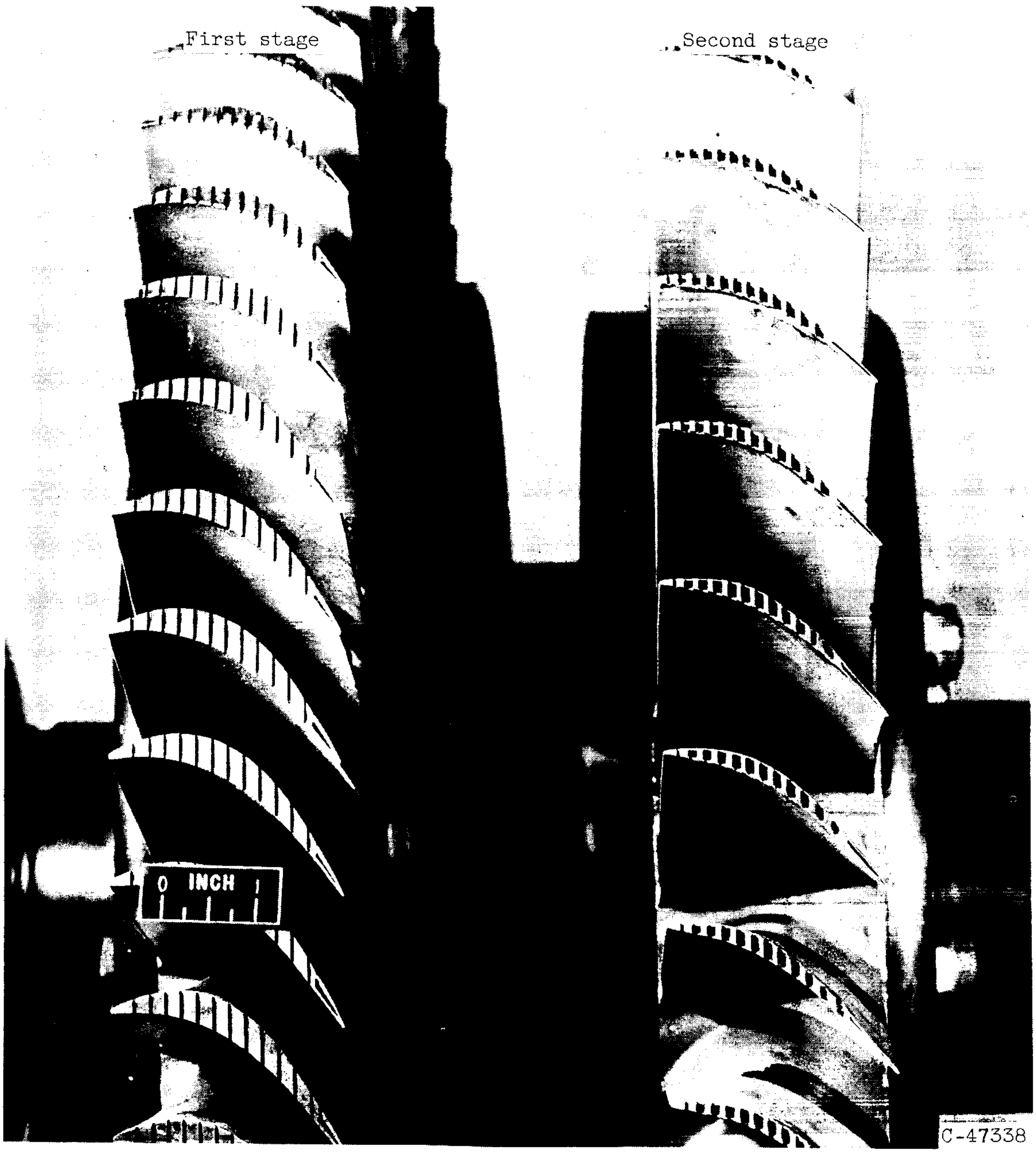


Figure 3. - Closeup of rotor blade tips.

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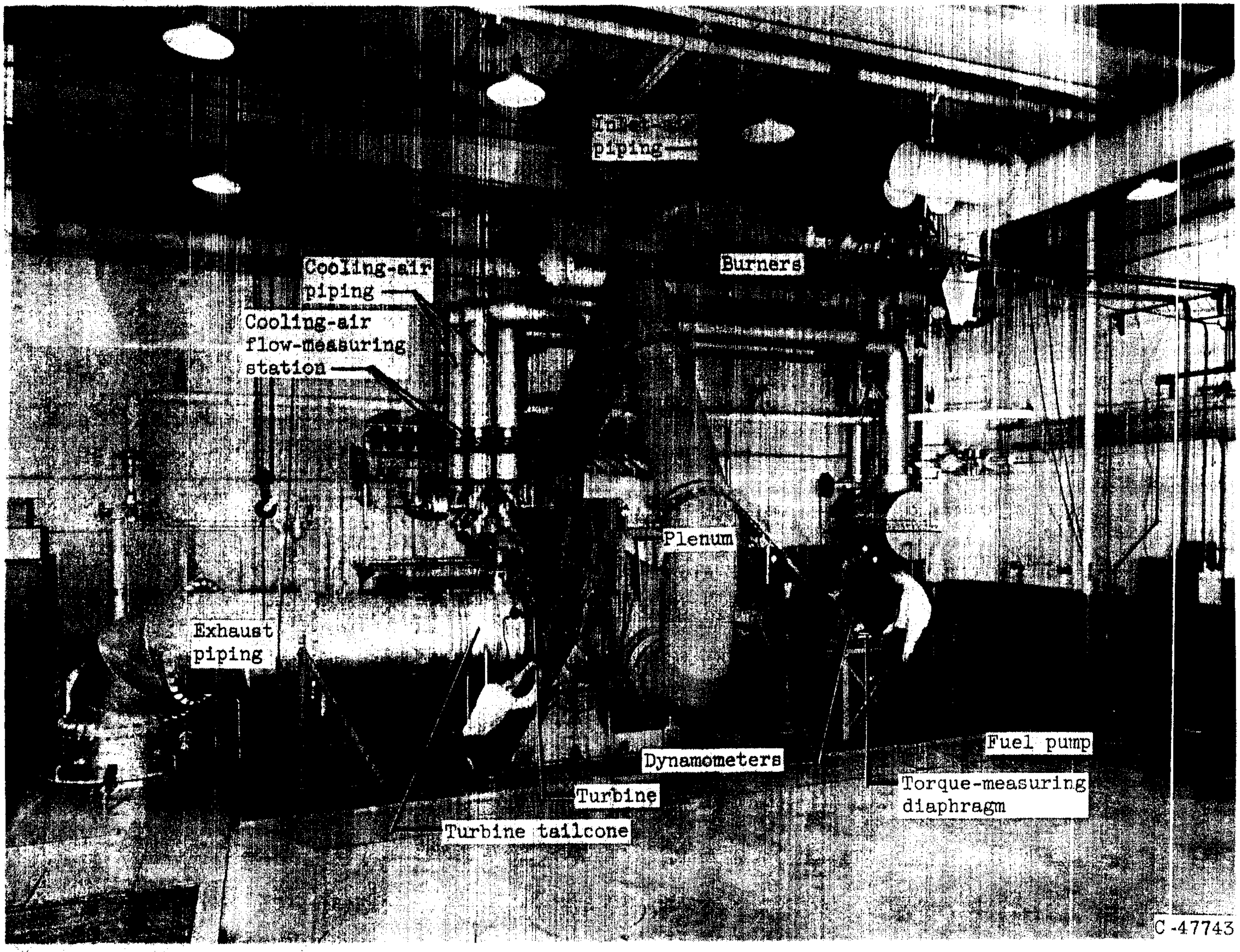

Figure 4. - Turbine test facility.

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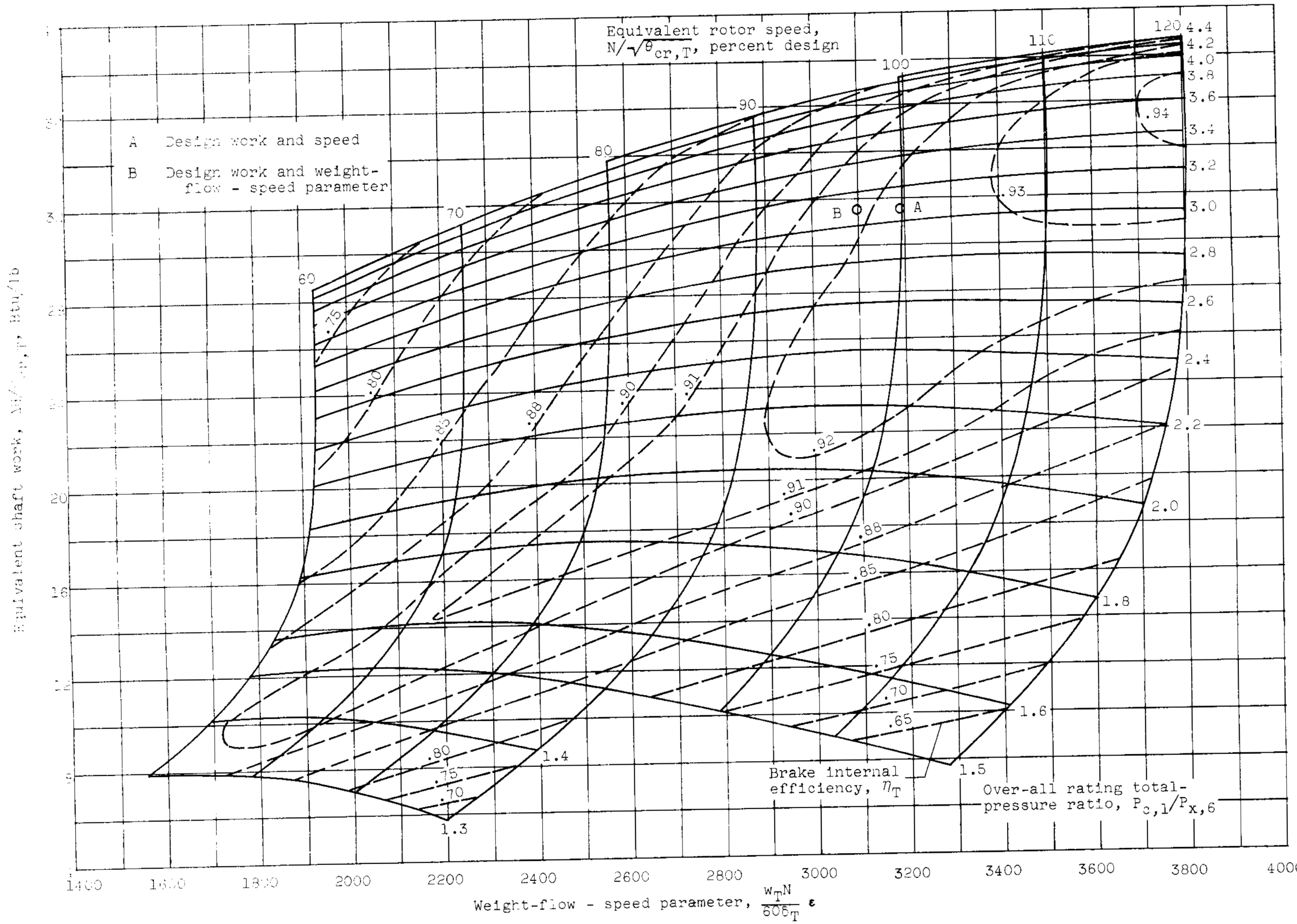

Figure 5. - Over-all performance of turbine without cooling. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R.

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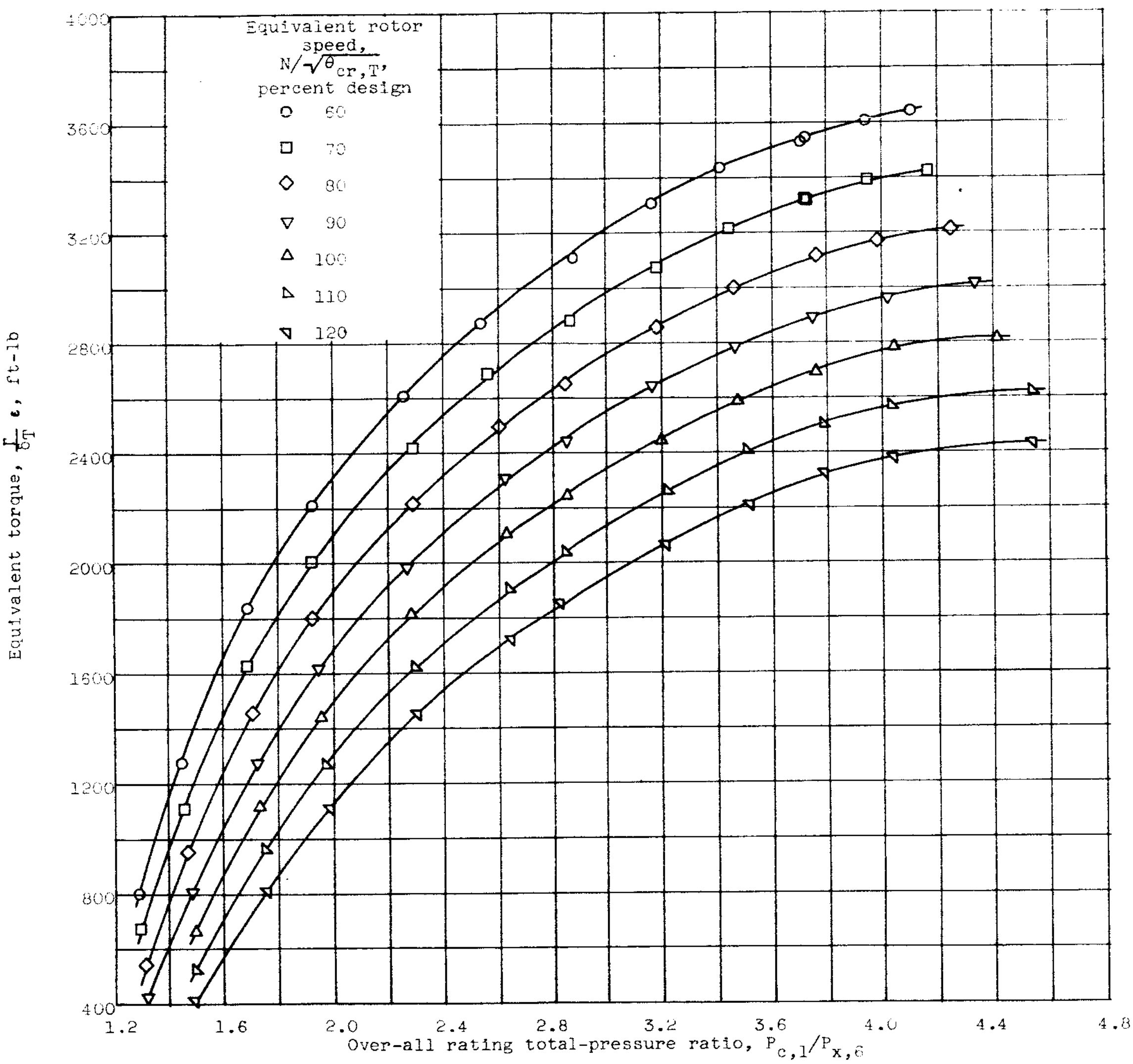

Figure 6. - Variation of equivalent torque with over-all rating total-pressure ratio for constant values of equivalent rotor speed and no coolant flow. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R.

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[redacted]

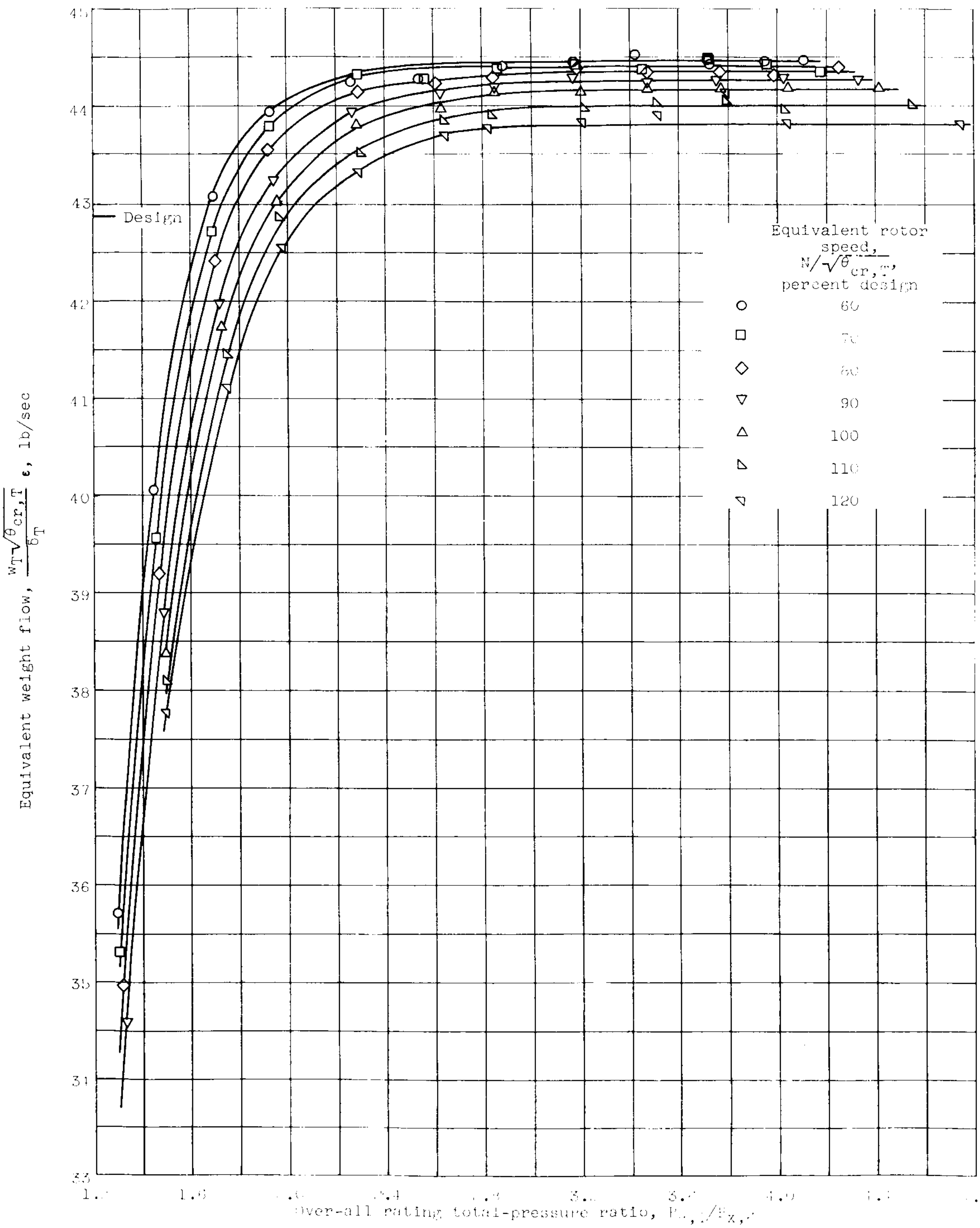

Figure [illegible]. - Variation of equivalent weight flow with over-all rating total-pressure ratio [illegible] constant values of equivalent rotor speed and no coolant flow. Turbine-inlet pressure, [illegible] inches of mercury absolute; turbine-inlet temperature, [illegible] R.

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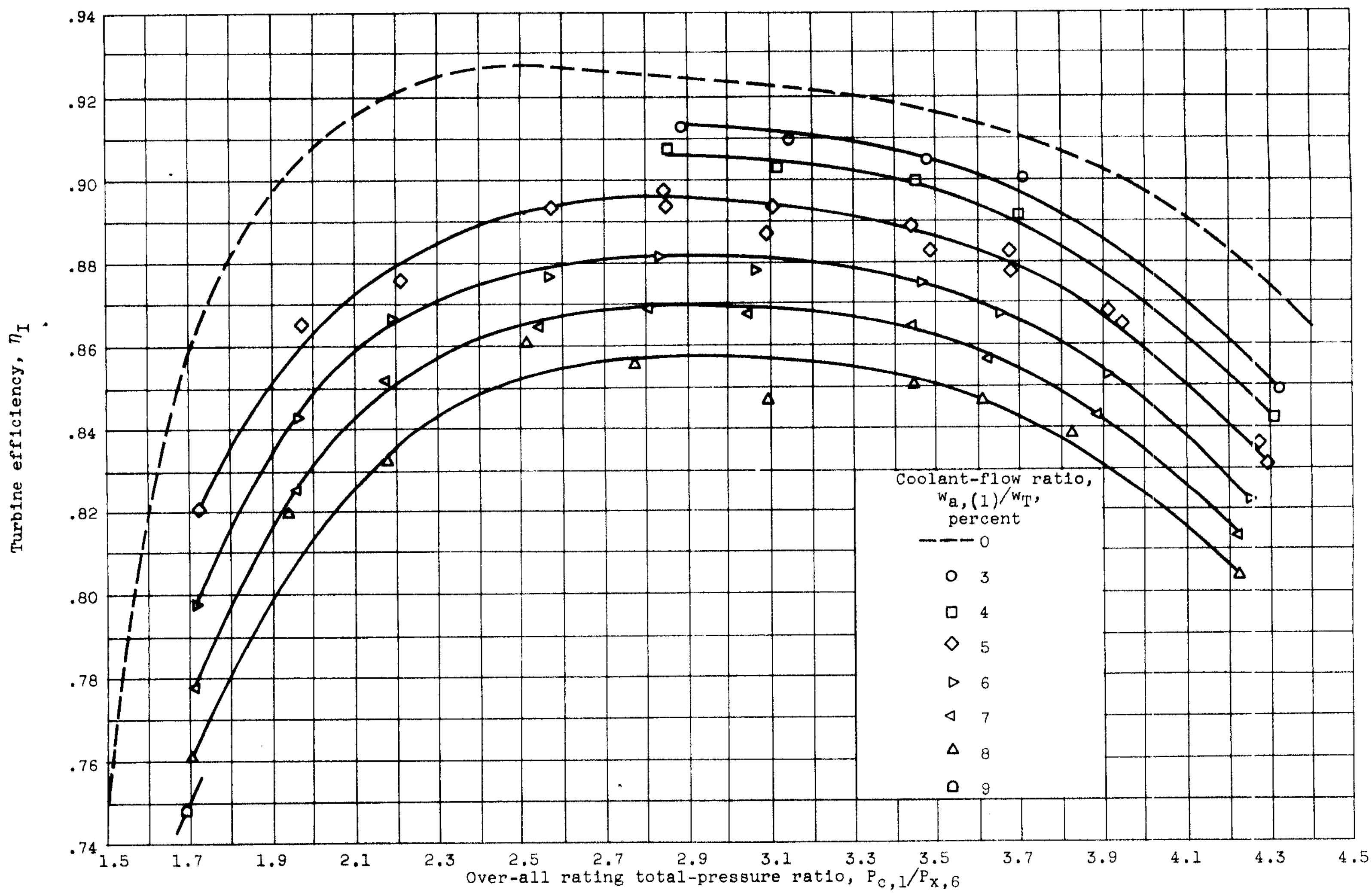

Figure 8. - Effect of first-stage-rotor cooling on turbine efficiency at equivalent design speed. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R.

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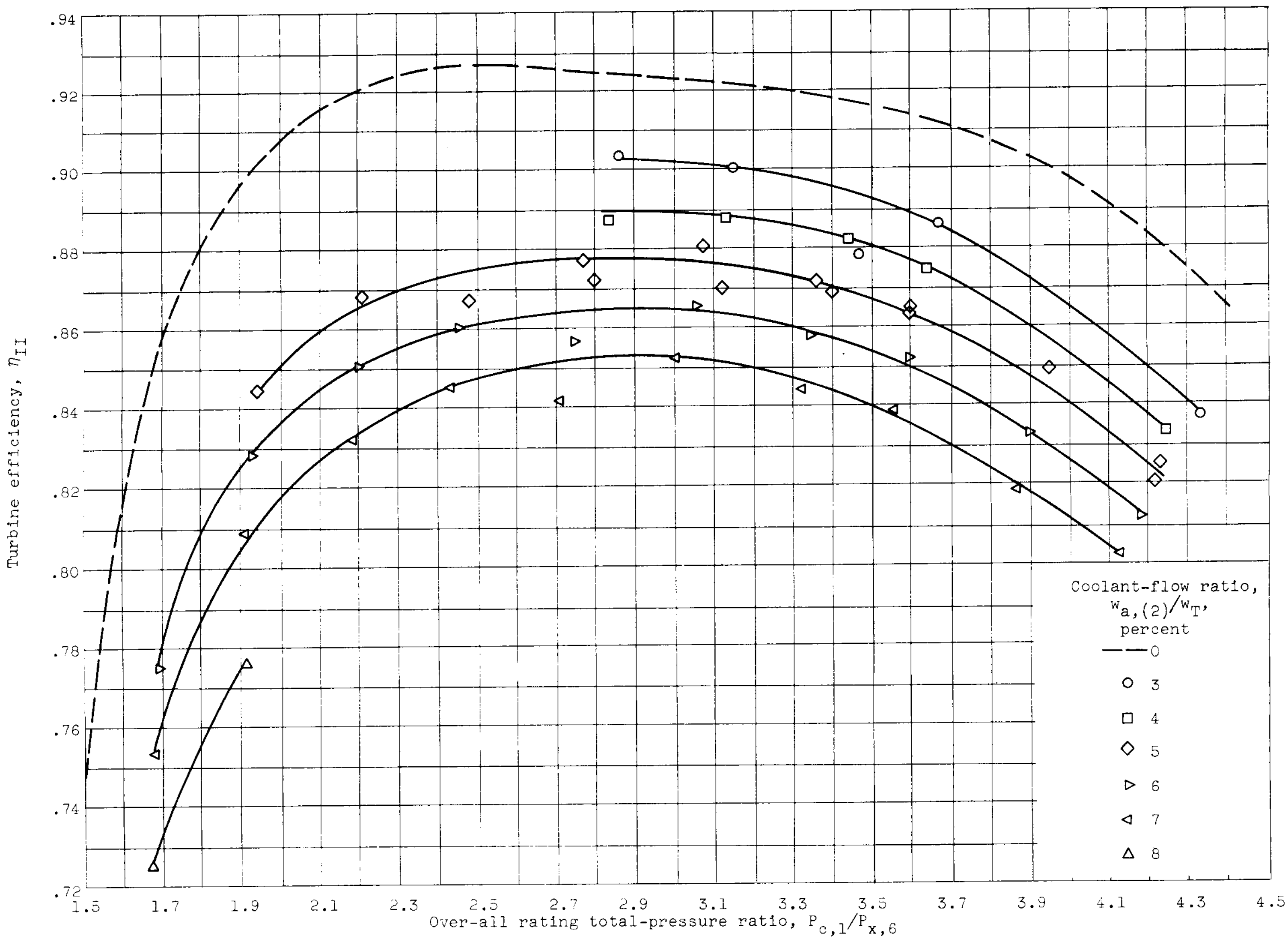

Figure 9. - Effect of second-stage-rotor cooling on turbine efficiency at equivalent design speed. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R.

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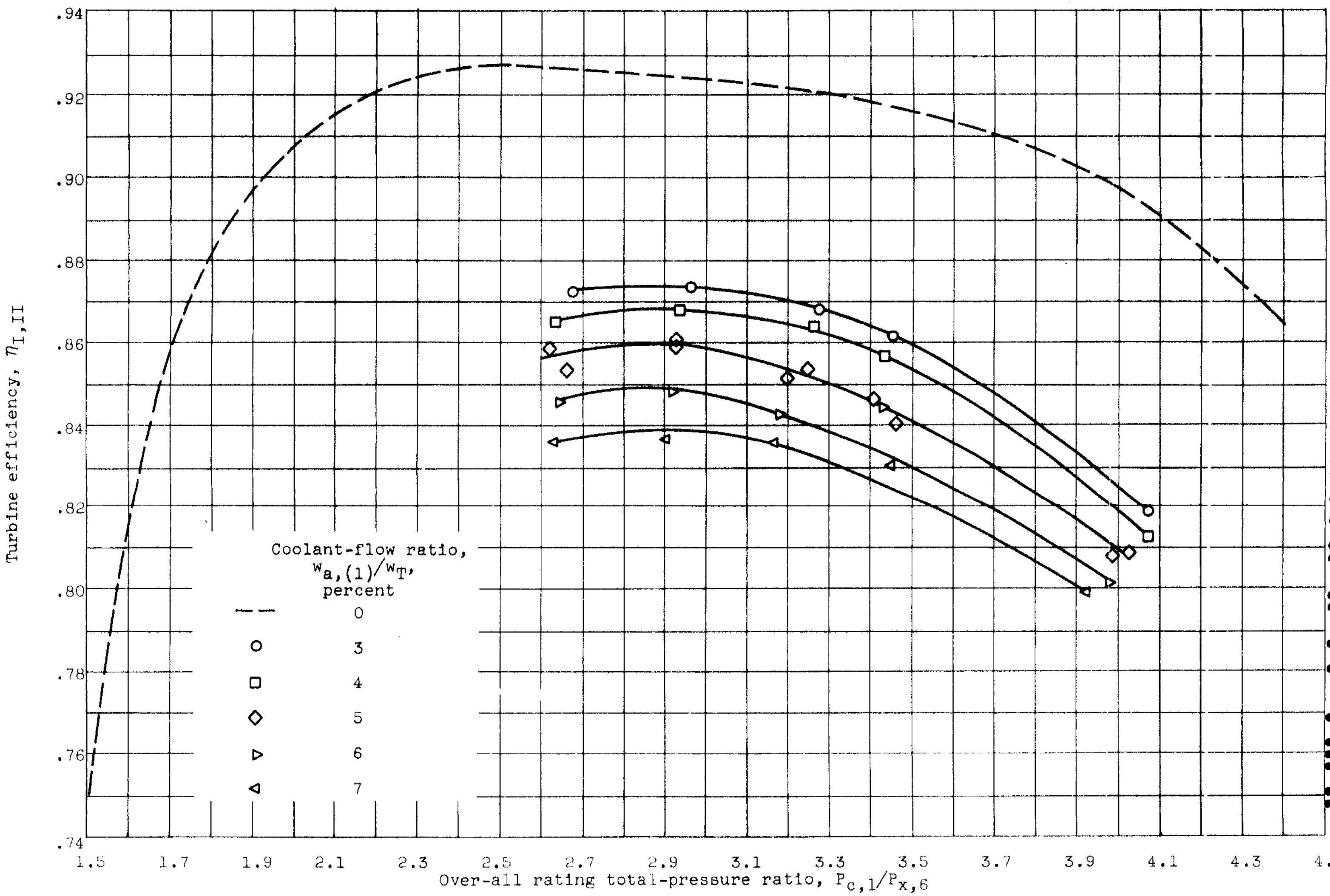

Figure 10. - Effect of first- and second-stage-rotor cooling on turbine efficiency. Second-stage cooling airflow, maximum obtainable. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R.

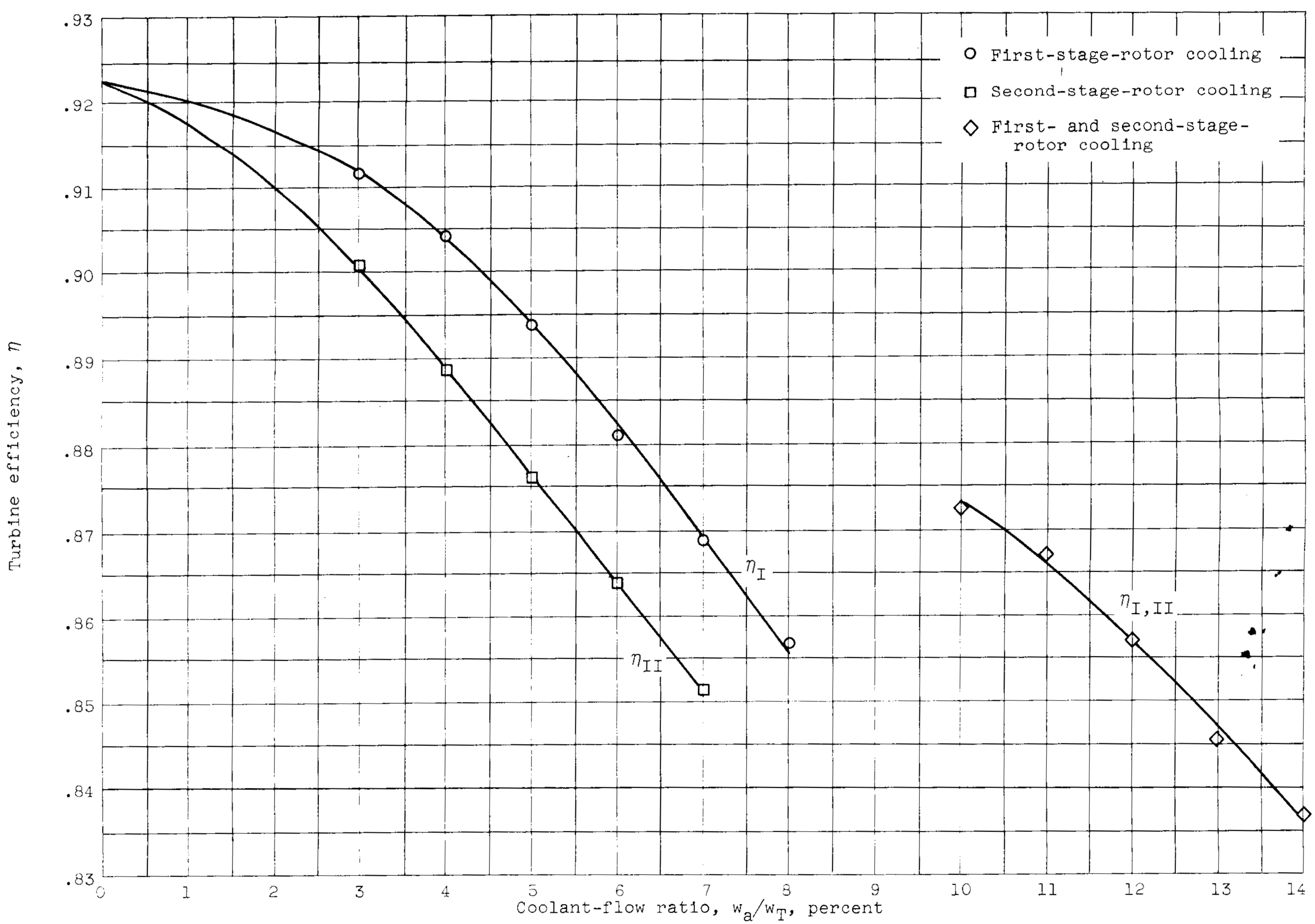

Figure 11. - Effect of cooling air on turbine efficiency at rating pressure ratio of 3.07.

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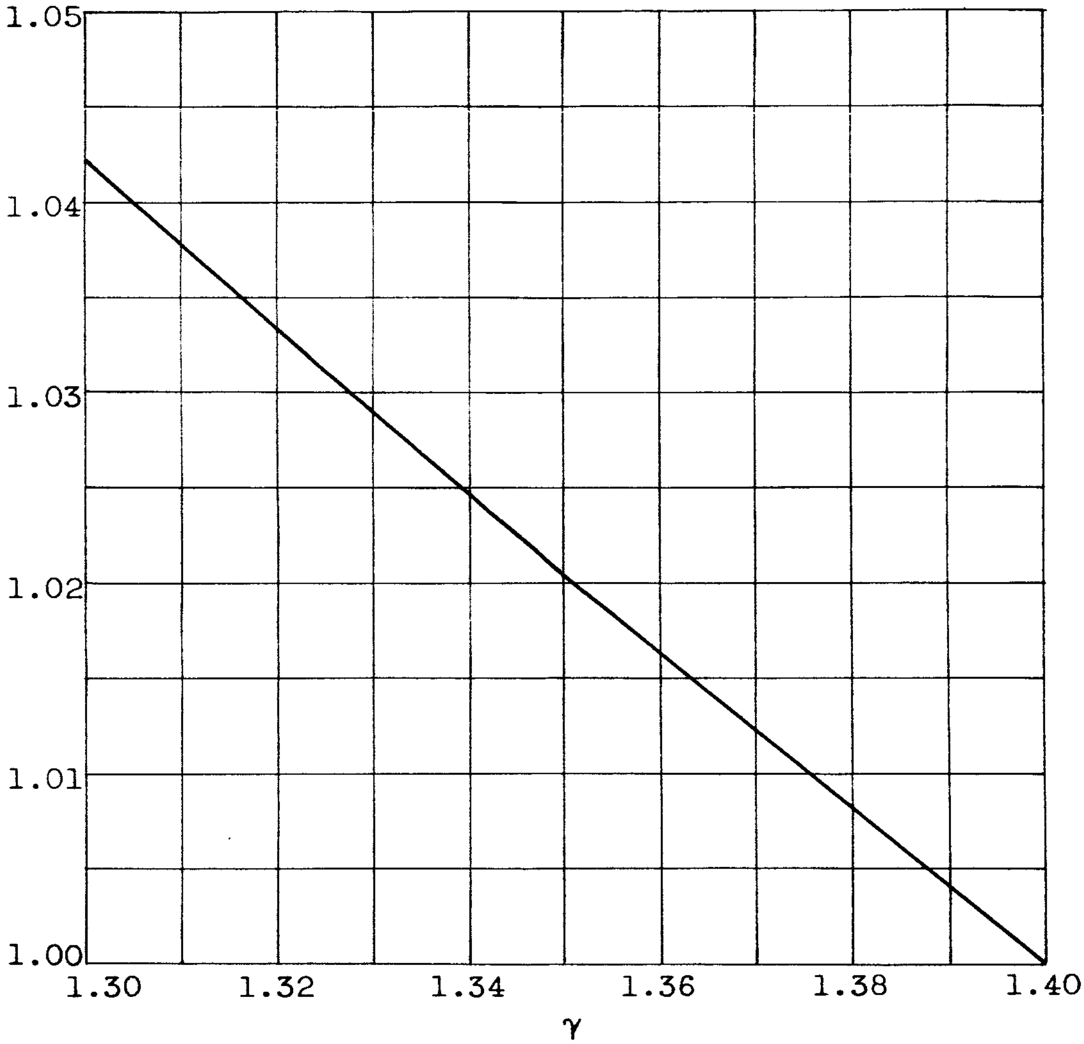

Figure 12. - Variation of ε as a function of γ.

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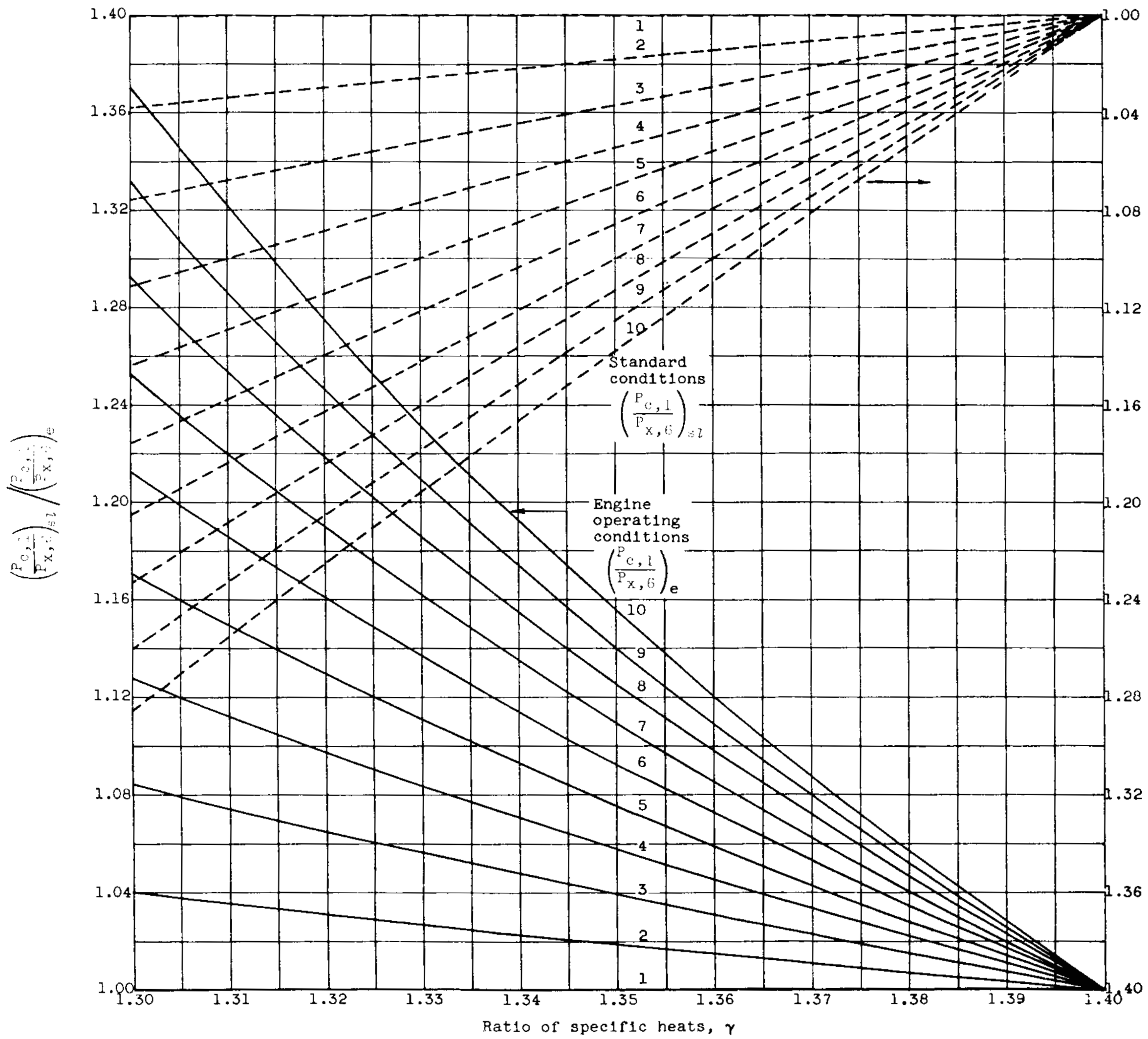

Figure 13. - Variation of the ratio of pressure ratio at standard conditions to pressure ratio at engine conditions with ratio of specific heats.

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