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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF HOLLOW-BLADED TURBINES HAVING CLOSED AND OPEN BLADE TIPS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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PRELIMINARY INVESTIGATION OF HOLLOW-BLADED TURBINES HAVING CLOSED AND OPEN BLADE TIPS

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SUMMARY

The effect of closed or open rotor blade tips on the performance of a turbine having hollow rotor blades was investigated in a 4000-pound-thrust turbojet engine over a range of equivalent turbine speeds from about 80 to 97 percent of rated equivalent turbine speed at several values of turbine rotor tip clearance. This investigation indicated that the open tips did not reduce the turbine efficiency and may have been responsible for a small increase in efficiency over the turbine having closed-tip rotor blades. Generalization of these results suggesting that open-tip blades will usually give a turbine performance superior to closed-tip blades is not warranted because of the limited scope of the investigation. Reducing the rotor blade tip clearance from about 0.120 to about 0.075 inch resulted in a slight improvement in turbine efficiency for each turbine blade type.

INTRODUCTION

Hollow turbine rotor blades are being considered for use in both lightweight and air-cooled turbines. The effect on turbine efficiency of leaving the tips of these blades open has not been fully investigated. For lightweight, uncooled turbines, the blade tips may be either open or closed (by capping, e.g.). Air-cooled blades will generally have open tips for radial discharge of cooling air, but at cruise conditions with reduced turbine-inlet temperatures, even such cooled blades may have no cooling-air flow.

In order to acquire some preliminary information about the comparative effect of open- and closed-tip rotor blades on turbine performance, turbines having open- and closed-tip blades were investigated at the NACA Lewis laboratory in a 4000-pound-thrust turbojet engine. A set of hollow blades with open tips was investigated to obtain the turbine operating characteristics of this blade configuration. The tips of the blades were then closed by capping the blades, and the operating characteristics of the turbine were obtained. The operating characteristics of each turbine were compared at three values of turbine blade tip clearance that approximately cover the tip-clearance range characteristics of current unshrouded turbines. The turbine performance parameters were compared over a range of equivalent turbine speeds from about 80 percent to approximately 97 percent of rated equivalent turbine speed.

SYMBOLS

The following symbols are used in this report:

f	fuel-air ratio
H	total enthalpy, Btu/lb
ΔH_T	actual drop of total enthalpy across turbine, Btu/lb
N	engine speed, rpm
P	total pressure, lb/sq ft
T	total temperature, ^{o}R
η_T	adiabatic turbine efficiency
θ	ratio of total temperature to NACA standard sea-level temperature of 518.7° R

Subscripts:

0	test cell
1	compressor inlet
2	compressor discharge
3	turbine inlet
4	engine tail pipe

APPARATUS AND INSTRUMENTATION

The engine used in this investigation was a 4000-pound-thrust production engine with a centrifugal, double-faced compressor. The single-stage axial-flow turbine had 54 unshrouded turbine blades, which differed from the blades of the standard production turbine as described in the following paragraphs.

Turbine Blade Modifications

Blade geometry. - The cross-sectional areas of the blades of this investigation were greater than those of the standard uncooled engine rotor blades at all spanwise positions above the blade base. The profiles and cross-sectional areas at the hub of the research blades were the same as those of the standard blades. These larger cross-sectional areas were intended to accommodate relatively large quantities of cooling air necessary for more general air-cooled turbine investigations. The outside profiles of the research blade and of a standard blade are compared in figure 1 for the hub, midspan, and tip sections of the blades.

The increase in the cross-sectional blade thickness resulted in a reduced turbine rotor-exit area which alone would have altered the matched operation of the compressor and turbine units. In order to obtain the original, uncooled-rotor-exit area, the amount of twist in the modified blades was maintained the same as for the standard blades, and the entire airfoil section of the blade was rotated 4° with respect to the axis of the turbine rotor. This rotation resulted in a slightly different distribution of the exit area along the blade span for the modified blades as compared with that for the standard blades. The standard stator was not modified.

Performance characteristics of modified blades. - The turbine rotor blade modifications just discussed were detrimental to the turbine efficiency, which was found to be from 2 to $3\frac{1}{2}$ points lower than the efficiency of the standard rotor. The thicker average cross sections and altered blade angles appear to be responsible for the reduced efficiency.

Comparison of open- and closed-tip rotor blades. - The turbine rotor blades, with the profile modifications just discussed, were cast of HS-21 high-temperature alloy and investigated with and without blade tip caps. Photographs of the standard blade, the open-tip blade, and the closed-tip blade are shown in figure 2. The struts visible at the top of the open-tip blade (fig. 2(b)), which were installed for structural reasons, were not primarily intended as internal cooling-air fins. These struts, extending radially inward from the blade tip about $1\frac{1}{2}$ inches, were necessary to prevent transverse vibration (oil canning) of the blade tip cross section. Such vibration led to early failure of the blade tip region when these struts were not used.

The closed-tip blades were identical with the open-tip blades except that the tip was closed with an 0.018-inch-thick HS-21 alloy cap welded to the periphery of the blade tip. After welding, the tip caps were dressed with a hand grinder to ensure a smooth, flat blade tip surface as shown in figure 2(c). The nominal length of the open- and closed-tip blades was the same.

Engine Instrumentation

Instruments were installed at the measuring stations shown in figure 3 to establish the performance characteristics of the turbine. The instrumentation is discussed in detail in the following sections.

Temperature measurements. - Total temperatures of the compressor-inlet air T_1 were measured by 11 iron-constantan thermocouples on the front and rear compressor-inlet air screens. The compressor-discharge total temperatures T_2 were determined by three iron-constantan thermocouples each located on the centerline of a combustion-chamber-inlet unit. The engine tail-pipe total temperatures T_4 were measured by 25 shielded chromel-alumel thermocouples located in the engine tail pipe about 8 feet downstream of the turbine rotor exit.

Pressure measurements. - The total pressure at the inlet to the turbine stator P_3 was measured by total-pressure probes located on the centerlines of three combustion-chamber-exit sections. The total pressure in the engine tail pipe P_4 was determined at the same axial position as the tail-pipe total temperatures. The total pressures were measured by 30 total-pressure probes equally divided among five rakes.

The turbine-exit total pressure was measured downstream of the turbine in the engine tail pipe. The measured total-pressure drop across the turbine, therefore, included all the total-pressure losses between the turbine rotor exit and the tail-pipe rake. Unpublished data obtained at the NACA Lewis laboratory indicate that the total-pressure losses in the engine tail-cone - tail-pipe unit utilized in this investigation caused a 2- to 5-point reduction in turbine efficiency relative to efficiency values obtained from instrumentation located immediately downstream of the turbine rotor exit.

Variations of the total-pressure losses just discussed would, of course, affect the performance comparisons between the closed- and open-tip blades. Since the same tail-cone - tail-pipe configuration was utilized with both the closed- and open-tip turbine rotors and each was operated over the same range of engine conditions, the mass-flow rates and pressure levels in the tail cone were the same. Convergent-area configurations like this particular tail-cone - tail-pipe configuration have loss coefficients that are generally insensitive to inlet conditions. For this reason, the difference in turbine-exit conditions caused by the change in turbine blade tip configuration would not be expected to materially affect the total-pressure loss between the turbine exit and the tail-pipe measuring station. Therefore, comparisons of turbine efficiency with closed- and open-tip rotor blades should be essentially unaffected by the tail-cone total-pressure losses.

General instrumentation. - The air weight flow to the sealed engine test cell was determined by pressures and temperatures measured in two 18-inch venturi tubes located in ducts supplying air to the test cell. The ambient-air pressure within the quiescent zone of the sealed test cell was determined from the static-pressure measurement at station 0 (fig. 3). The engine speed was measured by a chronometric tachometer, and the fuel flow was determined with a calibrated rotameter.

PROCEDURES

Experimental Procedure

The engine was operated with a single tail-pipe-nozzle area and blade tip-clearance setting over a range of equivalent turbine speeds $N/\sqrt{\theta_3}$ from about 80 to 97 percent of design value of 5856 rpm.

In order to determine whether blade tip clearance had a significant effect on turbine efficiency for the blade tip shapes investigated, the turbine performance was obtained for the following values of tip clearance: 0.122, 0.079, and 0.075 inch for the open-tip blade; and 0.119, 0.106, and 0.077 inch for the closed-tip blade. These clearance values, which were obtained at room-temperature conditions, are within the allowable limits specified for the standard turbine blades of the engine used in this investigation. Furthermore, this range of clearance values is similar to that normally specified for other engines of similar size and power.

A summary of turbine operating information is presented in table I. Each series number indicates a separate operational sequence, which is depicted in figures 4 and 5 by the symbols indicated in the table. The engine was disassembled to permit removal of the turbine rotor and alteration of the turbine blades before the runs of series 2 and 5. During these disassemblies all important engine clearances were measured, and an effort was made to duplicate these clearances when the engine was reassembled.

The turbine tip clearances shown in table I were averaged from 16 individual measurements, eight at the blade leading edges and eight at the trailing edges. The turbine tip clearances averaging less than 0.080 inch were designated small; and those that averaged more than 0.100 inch, large. With the exception of series 6, the data range for each series was duplicated on a separate day of engine operation. The runs of series 1 and 6 constitute data checks with different engine assemblies, with about 20 hours of engine operation occurring between runs. The data of series 2 and 3 also represent a similar check, but the engine was not disassembled between these runs.

Calculation Procedure

Turbine performance characteristics are presented in terms of the following turbine parameters: equivalent work $(H_3 - H_4)/\theta_3$, equivalent speed $N/\sqrt{\theta_3}$, and turbine adiabatic efficiency η_T. The following conditions were assumed: (1) The power extracted from the hot gas by the turbine rotor blades was equal to the power input of the compressor blades to the incoming air, and (2) heat losses and gas leakage from the engine were negligible. Changes in gas properties and ideal turbine work were determined from charts I and II of reference 1; variations in the fuel hydrogen-carbon ratio from the value of 0.167 used in chart II resulted in negligible errors.

Turbine-inlet temperature was indirectly determined in the following way: From assumptions (1) and (2),

$$H_2 - H_1 = (1 + f)(H_3 - H_4)$$

where the enthalpies H_1, H_2, and H_4 were determined from the measured temperatures and the fuel-air ratio. The temperature T_3 was then established from the enthalpy H_3 and the fuel-air ratio.

RESULTS AND DISCUSSION

During this investigation the turbine pressure ratio was always high enough to prevent the turbine equivalent weight flow from varying a significant amount. For this reason, the turbine performance as presented herein shows only the relations of equivalent work and efficiency to equivalent turbine speed.

Basis of Comparison of Closed- and Open-Tip Blades

The operating characteristics of each turbine are compared first for the range of blade tip clearances investigated. After the sensitivity of the turbine operating parameters with respect to tip clearance is established, the performances of the closed- and open-tip blades are compared. Because of the manner in which the investigation was made, comparisons between the closed- and open-tip turbine blade operating parameters are not entirely free of blade tip-clearance effects. A more significant comparison between the performance of closed- and open-tip blades can be made if the effects of tip clearance are first established for each turbine.

The turbine performance data of equivalent work and efficiency are presented in the following sections as functions of the equivalent turbine speed. Efficiencies of closed- and open-tip blades are compared at common values of equivalent turbine speed.

Effect of tip clearance on equivalent turbine work. - Figure 4(a) indicates the effect of tip clearance on the location of the turbine operating lines for both the closed- and open-tip blades. The data for the closed-tip rotor blades show no consistent separation that can be attributed to tip clearance, since the lower line appears to correlate both a set of large- and small-tip-clearance data. The separation of the two operating lines apparently indicates the degree of reproducibility of the data during separate tests. In fact, the principal separation indicated by the two operating lines is between two sets of large-tip-clearance data rather than between the large- and small-tip-clearance data.

For the open-tip rotor blades, no distinct difference existed between locations of the large- and small-tip-clearance data; and, as before, the principal separation of the operating lines was between the common tip-clearance data (small tip clearances in this case) rather than between the large- and small-tip-clearance data. These results indicate that, within the accuracy and procedures of this investigation, tip clearance generally has a small effect on the location of the turbine operating lines.

Effect of tip clearance on turbine efficiency. - Comparisons of the turbine efficiency between the large- and small-tip-clearance runs are shown for both the closed- and open-tip blades in figure 4(b). The previous comparisons of the positions of the turbine operating lines showed no separation that could be attributed to the turbine rotor tip clearance. Furthermore, the degree of separation that exists between the operating lines is so small that no significant change in turbine efficiency could be expected from a change in turbine operating point, if the comparisons are made at a constant value of equivalent turbine speed. The foregoing is equivalent to saying that, for purposes of comparing turbine-efficiency values, a comparison at any particular value of equivalent turbine speed corresponds to a comparison at a common point on a turbine map.

For the closed-tip blades (fig. 4(b)), the effect of reducing the tip clearance from 0.119 to 0.077 inch was to increase the turbine efficiency 1 to 2 points in the range of corrected turbine speeds from 5300 to 5600 rpm. For the open-tip blades, reducing the tip clearance again had the effect of increasing the turbine efficiency about 1 to 2 points over the range of equivalent turbine speeds investigated. The data indicate no progressive change in turbine performance that can be attributed to accumulation of operational time.

Effect of Tip Shape on Turbine Performance

In this section, the turbine performance characteristics of the closed- and open-tip blades are compared for each of the two tip-clearance ranges investigated. Comparisons are first made between data for the 0.077-inch clearance closed-tip blade and the 0.075 and 0.079-inch open-tip blade. The second comparison is between data for the 0.122-inch clearance open-tip blade and the 0.119- and 0.106-inch clearance open-tip blade.

The comparisons made in the previous section showed no effect on the position of the turbine operating lines attributable to turbine rotor tip clearance. The effect of about a 0.040- to 0.050-inch change in tip clearance for both the closed- and open-tip blades resulted in, at most, a 2-point change in turbine efficiency. It is reasonable to expect, therefore, that comparisons among both the small- and the large-tip-clearance data will be essentially independent of effects resulting from changing tip clearance and should give a reasonable indication of the performance of the open-tip blades relative to the closed-tip blades.

Comparisons of small-tip-clearance data. - The turbine performance characteristics obtained within the small-tip-clearance range are presented in figure 5(a). Both sets of open-tip blade data fall above the operating line of the closed-tip blade data. The difference between the 0.075-inch operating line of the open-tip data and the operating line of the 0.077-inch closed-tip data was 0.1 to 0.2 Btu per pound, while the separation of the two open-tip operating lines was approximately twice this amount. Since reasonably good agreement was obtained between the efficiency values of the open-tip, small-tip-clearance data (lower part of fig. 4(a)), it seems reasonable to assume the slight downward displacement of the closed-tip operating line will not materially affect the efficiency comparisons between the closed- and open-tip turbine efficiencies. As in the case of the tip-clearance comparisons, this is equivalent to assuming that comparisons made at a particular value of equivalent turbine speed are being made at identical map points for both turbine rotors.

Efficiencies for the closed- and open-tip turbine rotors obtained with the small tip clearances are also shown in figure 5(a). The downward displacement of the closed-tip line from the mean line of the open-tip data is from $1\frac{1}{2}$ to 2 points over the entire range of equivalent turbine speeds investigated. For reasons discussed previously, the improved efficiency of the open-tip turbine rotor blades cannot be explained by either tip-clearance differences or changes in turbine operating points. The superior performance of the open-tip blades, therefore, appears to be caused by the characteristic open-tip configuration.

Comparison of large-tip-clearance data. - Figure 5(b) presents the relative locations of the turbine operating lines obtained with the large-tip-clearance data. As was the case with the small-tip-clearance data, the open-tip data line falls somewhat above the operating line for the closed-tip data. In this case, there is a good correlation between the two sets of closed-tip large-tip-clearance data. The separation of the two operating lines of figure 5(b) is approximately the same as the displacement noted between the 0.077-inch closed-tip blade data and the 0.079-inch open-tip data of figure 5(a).

The efficiency data obtained for the large-tip-clearance runs are shown in the lower part of figure 5(b). The open-tip data, again, were from $1\frac{1}{2}$ to 2 points higher than the closed-tip data over the entire range of equivalent turbine speeds investigated.

Comparisons of the turbine-efficiency characteristics for both tip-clearance ranges investigated show the open-tip blades to be from $1\frac{1}{2}$ to 2 points more efficient than the closed-tip blades. Although some increase in turbine efficiency might be attributed to the open-tip blades, generalization of these data suggesting that open-tip blades will usually give a superior turbine performance relative to closed-tip blades is not warranted because of the restricted scope of this investigation.

SUMMARY OF RESULTS

The results of a preliminary engine investigation to determine the performance characteristics of open-tip turbine rotor blades are summarized as follows:

1. Turbine efficiency was not reduced by use of open-tip turbine rotor blades compared with closed-tip blades of the same configuration. On the contrary, use of open-tip rotor blades appeared to improve turbine efficiencies slightly over those obtained with closed, smooth-tip rotor blades.

2. Reducing the turbine rotor tip clearance from about 0.120 to about 0.075 inch resulted in a slight increase in turbine efficiency for both the closed- and open-tip blade configurations.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 29, 1955

REFERENCE

1. English, Robert E., and Wachtl, William W.: Charts of Thermodynamic Properties of Air and Combustion Products from 300° to 3500° R. NACA TN 2071, 1950.

TABLE I. - SUMMARY OF TURBINE OPERATION

Series	Blade type	Symbols (figs. 4 and 5)	Average tip clearance, in.	Equivalent turbine speed range, rpm	Operation time, hr
1	Open-tip	◺	0.075	4610 - 5674	8.4
2	Closed-tip	□	.106	4602 - 5652	7.1
3	Closed-tip	○	.119	4696 - 5642	4.1
4	Closed-tip	△	.077	4677 - 5651	3.6
5	Open-tip	▽	.122	4724 - 5922	4.9
6	Open-tip	◇	.079	4742 - 5860	4.5

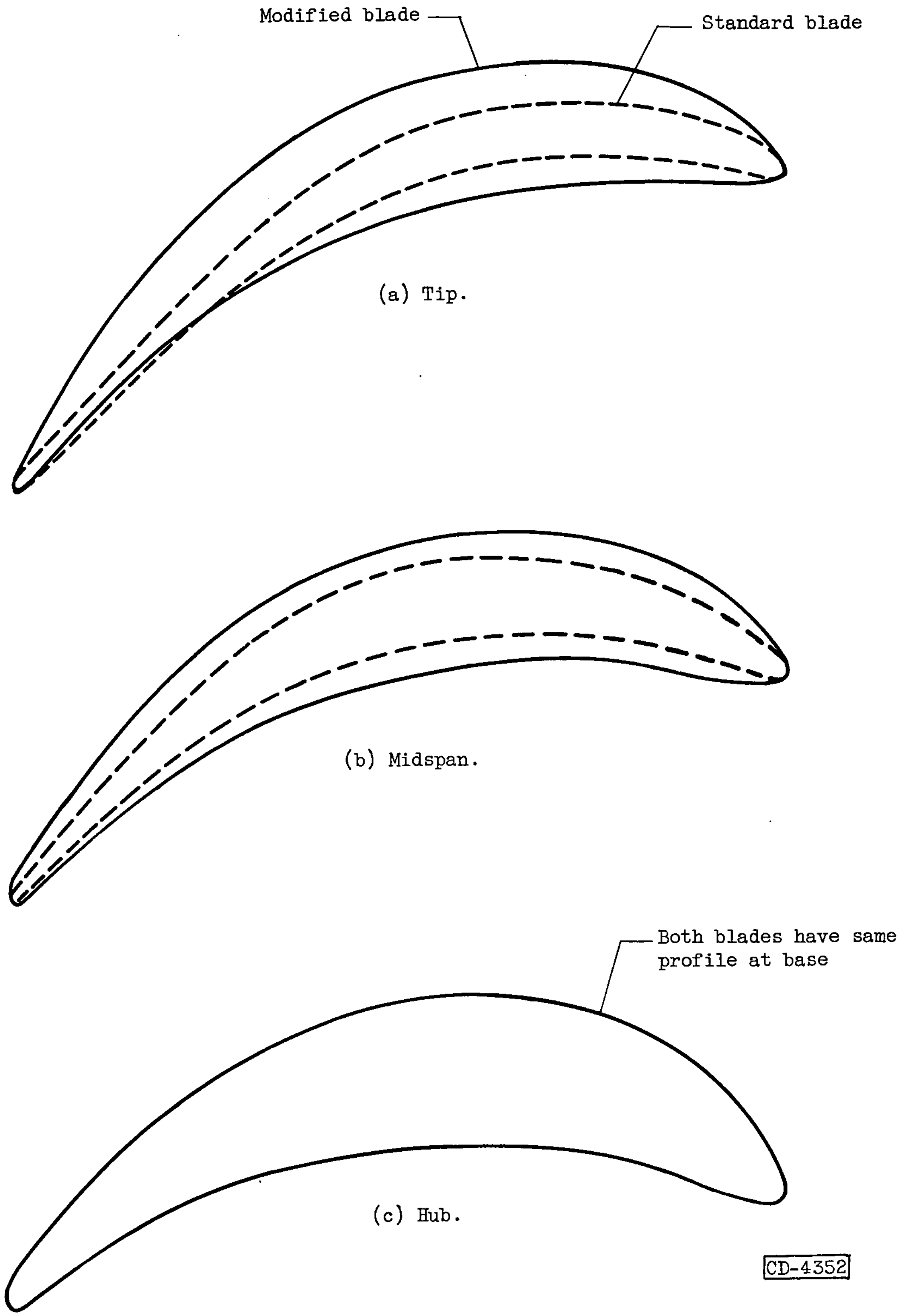
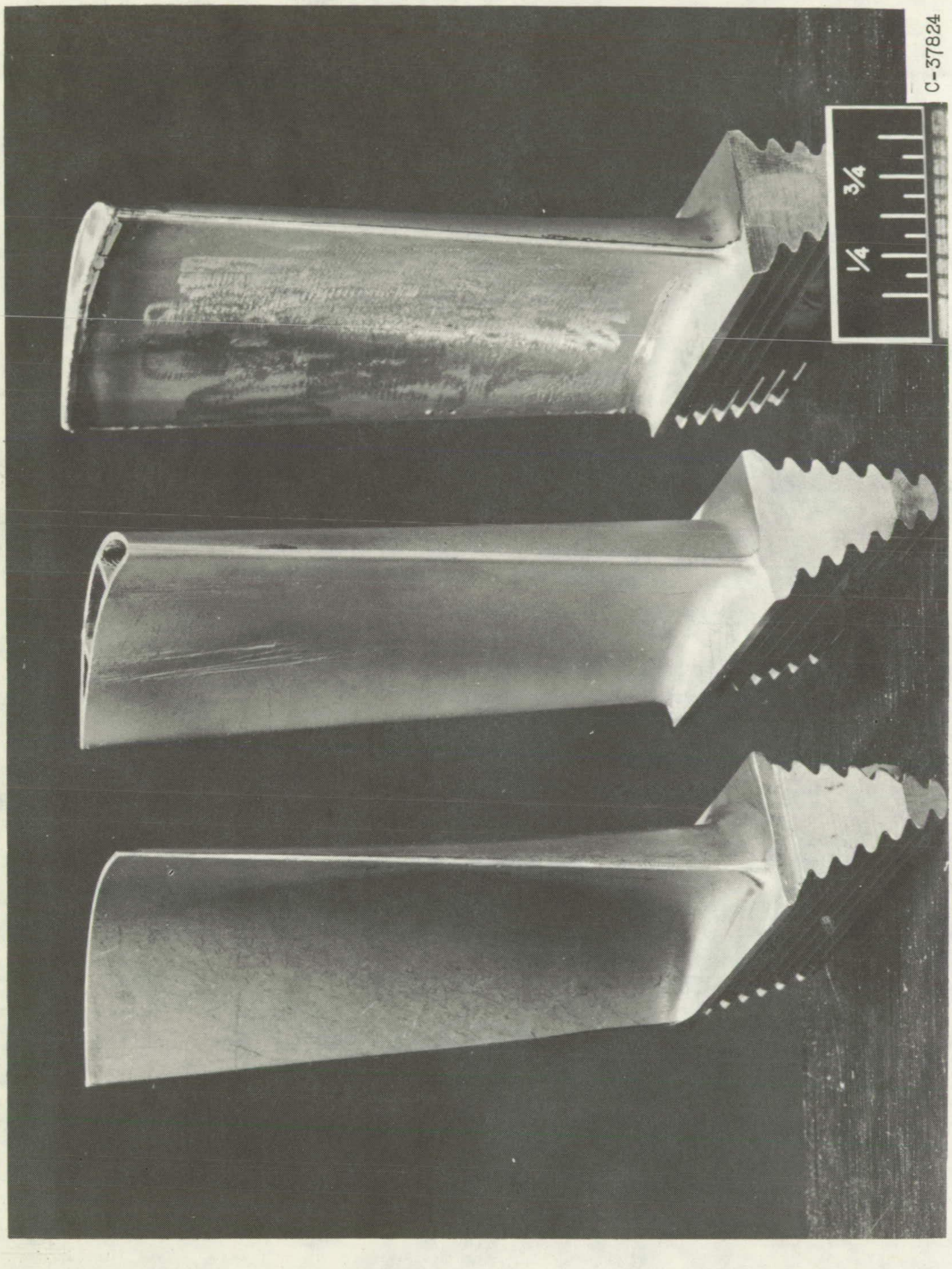
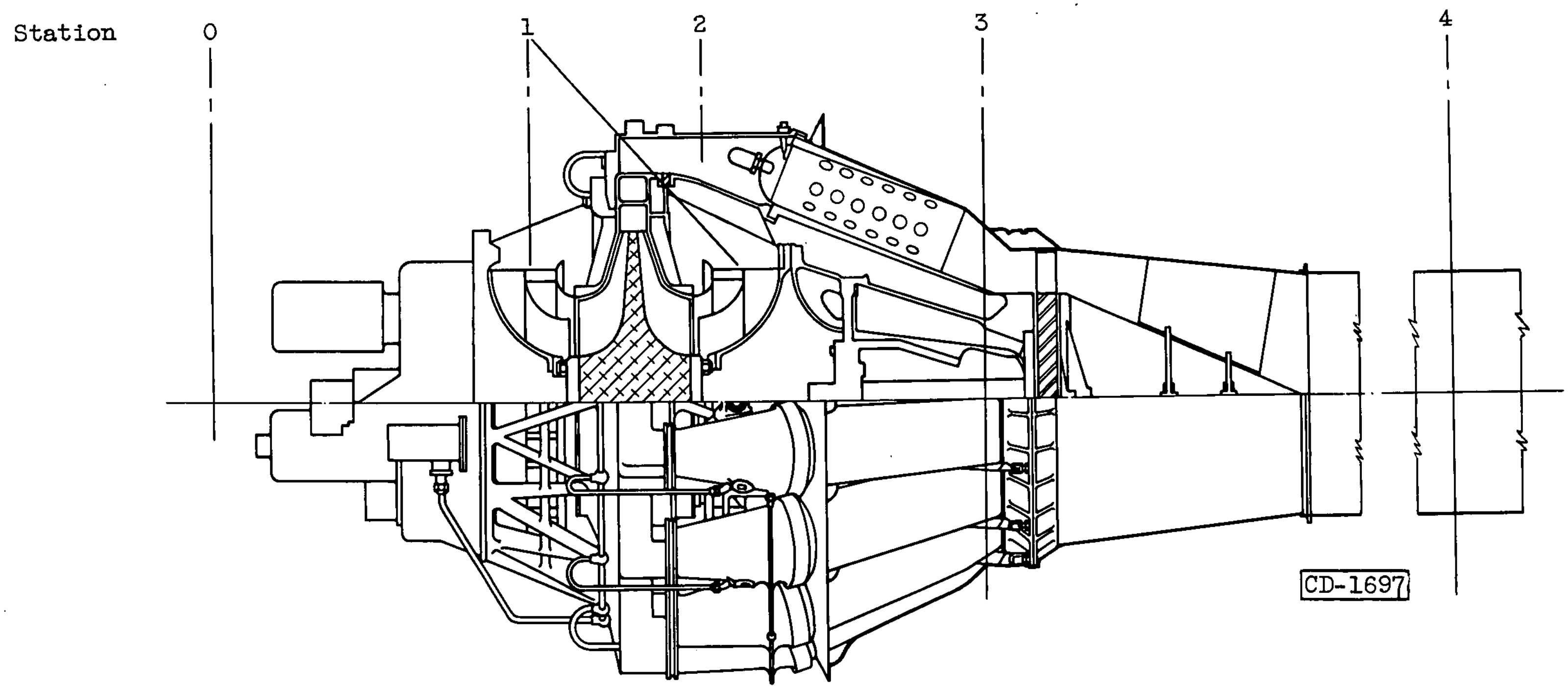


Figure 1. - Comparison of modified blade profile with that of standard uncooled production blade.



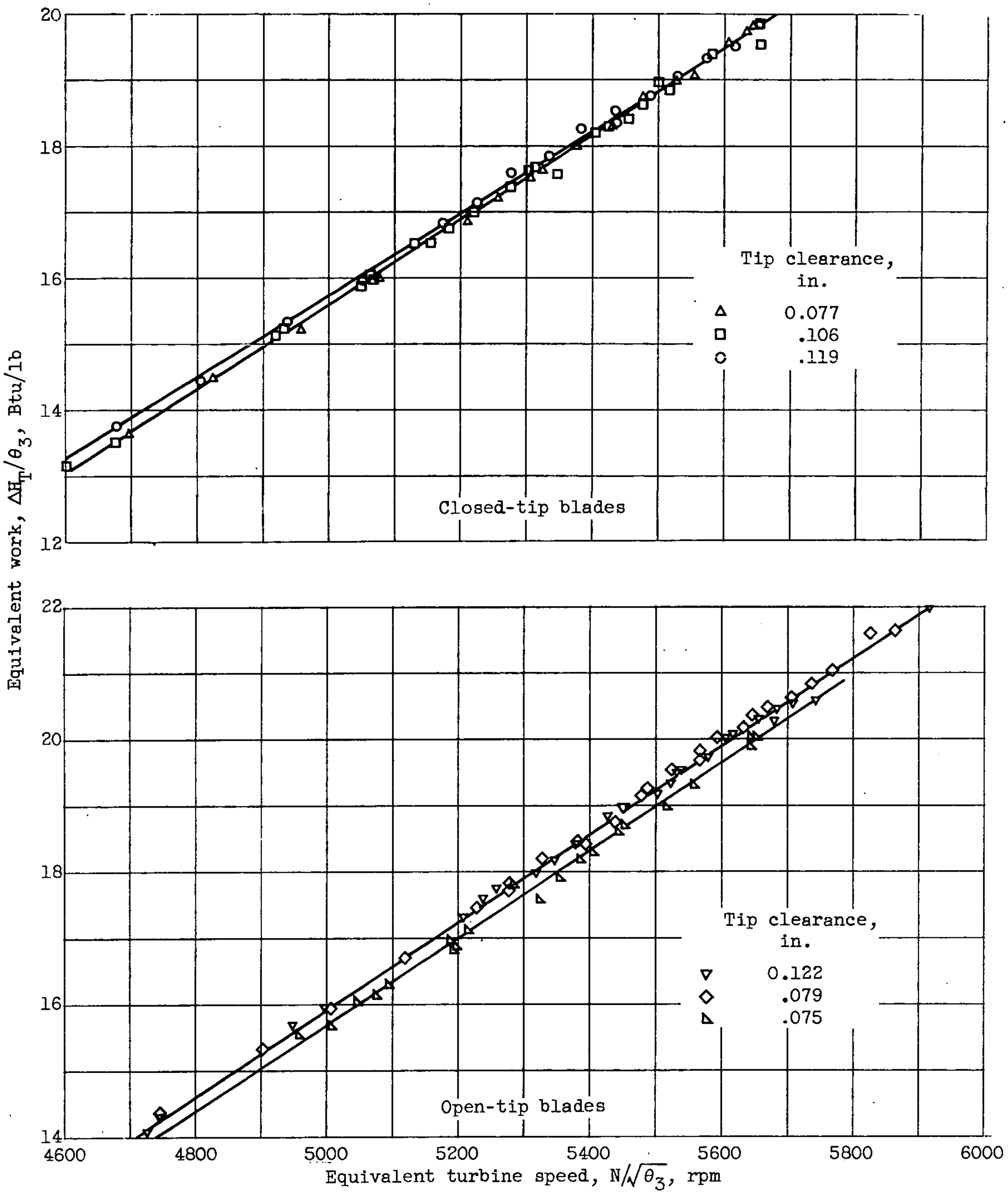
(a) Standard blade. (b) Open-tip. (c) Closed-tip.

Figure 2. - Comparison of standard blade with open-tip and closed-tip modified blades.



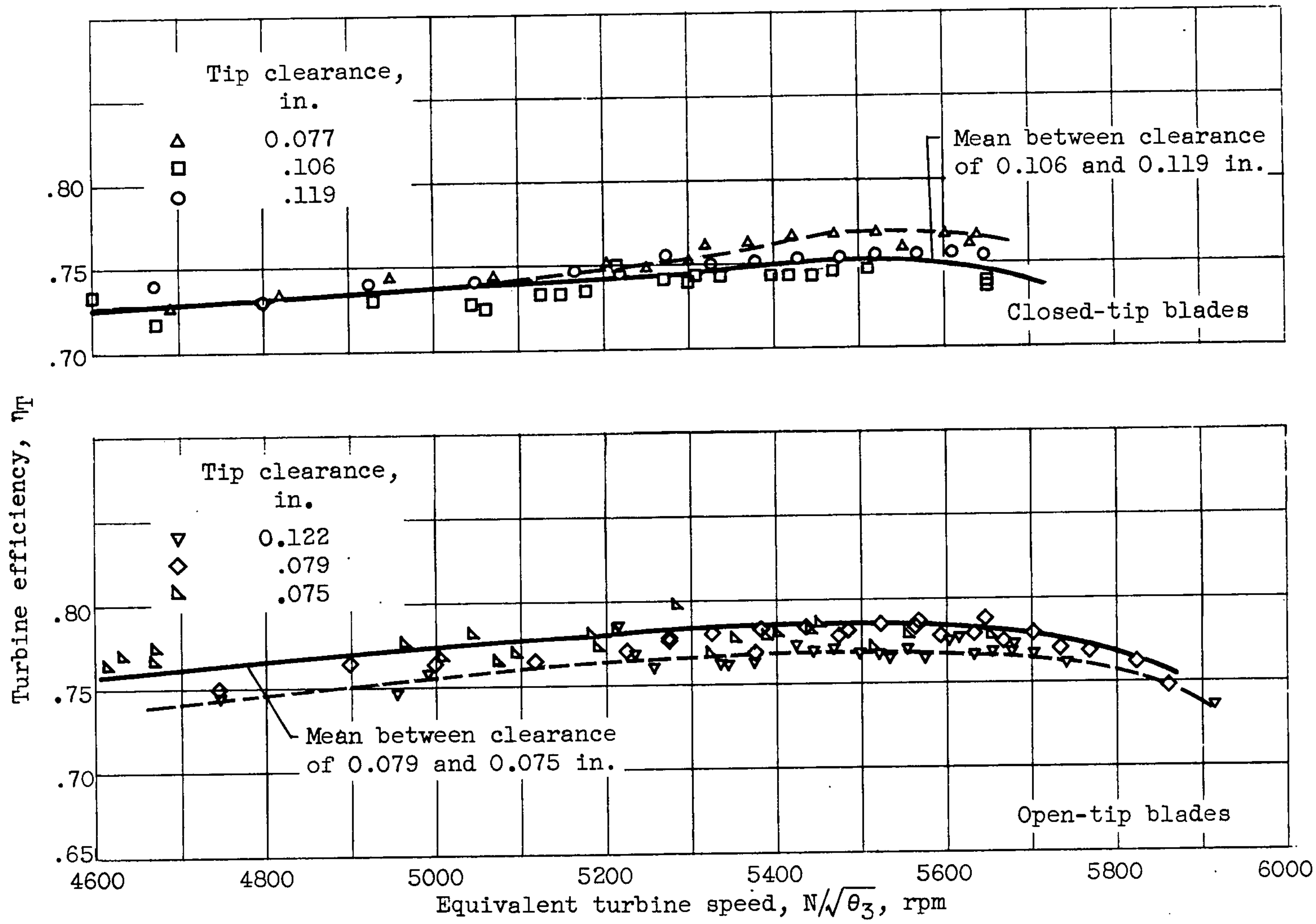
Station	Description	Static-pressure taps	Total-pressure probes	Total-temp. thermocouples
0	Engine test cell	1		1 Iron-constantan
1	Compressor inlet			11 Iron-constantan
2	Compressor discharge			3 Iron-constantan
3	Turbine inlet		3 on burner centerlines	
4	Engine tail pipe		30 (5 rakes)	25 Chromel-alumel

Figure 3. - Schematic sketch of engine showing instrumentation stations.



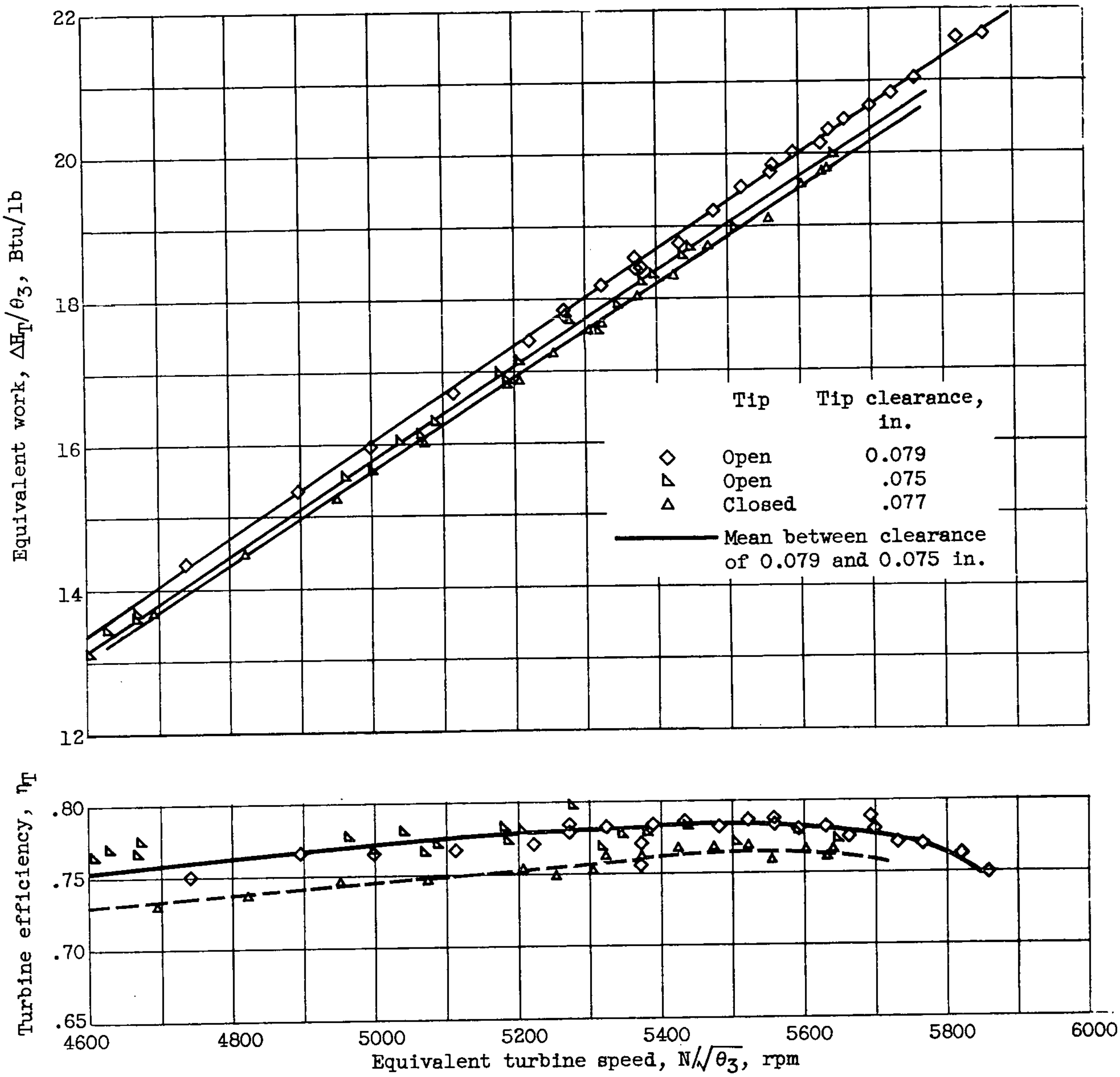
(a) Turbine operating lines.

Figure 4. - Effect of turbine rotor tip clearance.



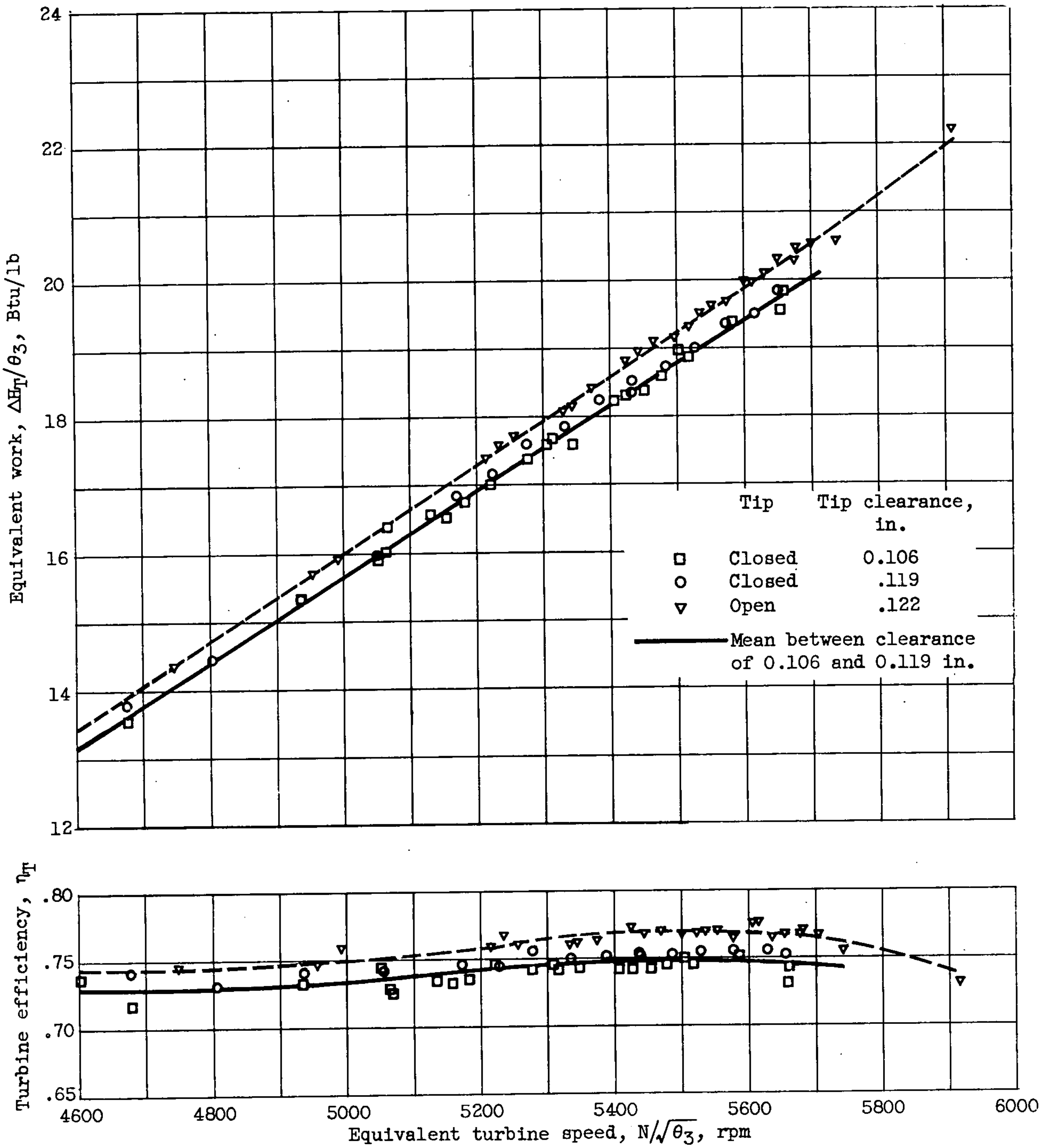
(b) Turbine efficiency.

Figure 4. - Concluded. Effect of turbine rotor tip clearance.



(a) Small tip clearances.

Figure 5. - Effect of turbine rotor blade tip shape on turbine performance.



(b) Large tip clearances.

Figure 5. - Concluded. Effect of turbine rotor blade tip shape on turbine performance.