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RESEARCH MEMORANDUM

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ALTITUDE INVESTIGATION OF GAS TEMPERATURE DISTRIBUTION
AT TURBINE OF THREE SIMILAR AXIAL-FLOW
TURBOJET ENGINES

By W. R. Prince and F. W. Schulze

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RESEARCH MEMORANDUMALTITUDE INVESTIGATION OF GAS TEMPERATURE DISTRIBUTION AT TURBINE
OF THREE SIMILAR AXIAL-FLOW TURBOJET ENGINES

By W. R. Prince and F. W. Schulze

SUMMARY

An investigation of the effect of inlet pressure, corrected engine speed, and turbine temperature level on turbine-inlet gas temperature distributions was conducted on a J40-WE-6, interim J40-WE-6, and prototype J40-WE-8 turbojet engine in the altitude wind tunnel at the NACA Lewis laboratory. The engines were investigated over a range of simulated pressure altitudes from 15,000 to 55,000 feet, flight Mach numbers from 0.12 to 0.64, and corrected engine speeds from 7198 to 8026 rpm.

The gas temperature distribution at the turbine of the three engines over the range of operating conditions investigated was considered satisfactory from the standpoint of desired temperature distribution with one exception - the distribution for the J40-WE-6 engine indicated a trend with decreasing engine-inlet pressure for the temperature to exceed the desired in the region of the blade hub. Installation of a compressor-outlet mixer vane assembly remedied this undesirable temperature distribution.

The experimental data have shown that turbine-inlet temperature distributions are influenced in the expected manner by changes in compressor-outlet pressure or mass-flow distribution and by changes in combustor hole-area distribution.

The similarity between turbine-inlet and turbine-outlet temperature distribution indicated only a small shift in temperature distribution imposed by the turbine rotors.

The attainable jet thrusts of the three engines were influenced in different degrees and directions by changes in temperature distributions with change in engine-inlet pressure. Inability to match the desired temperature distribution resulted, for the J40-WE-6 engine, in an 11-percent thrust loss based on an average turbine-inlet temperature of 1500° F at an engine-inlet pressure of 500 pounds per square foot absolute. Departure from the desired temperature distribution in the blade tip region results, for the prototype J40-WE-8 engine, in an attainable thrust increase of 3 to 4 percent as compared with that obtained if tip-region temperature limitations were observed.

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INTRODUCTION

During previous investigations of the effect of turbojet operating conditions on turbine-inlet gas temperature distributions (references 1 and 2), radial turbine temperature distributions were encountered that were detrimental to turbine blade life. For these engines, increases in corrected engine speed and altitude increased the turbine-inlet temperature in the region of the blade roots or hub and reduced the temperature at the blade tips. This trend is directly opposite to the desired distribution for maximum turbine blade life based on blade-stress considerations. The average turbine-inlet temperature, for these cases of maldistribution, must be reduced in order to avoid excessive hub temperatures. The reduction in average temperature results, of course, in a loss in maximum engine thrust. The maldistribution of turbine temperatures, primarily attributed to adverse radial-velocity gradients at the compressor outlet and to characteristics of the combustor, was corrected by the installation of a mixer vane assembly at the compressor outlet (reference 2).

As part of a program to investigate the altitude performance of the J40-WE-6 engine in the altitude wind tunnel at the NACA Lewis laboratory, the effect of inlet pressure, corrected engine speed, and turbine temperature level on turbine-inlet temperature distribution was investigated. During this initial phase of the investigation, an undesirable compressor stall characteristic was encountered that, until remedied, limited further performance investigation (reference 3). The engine was altered by installation of a compressor-outlet mixer vane assembly and a modified engine combustor (interim J40-WE-6 engine). Temperature distributions were investigated in this modified engine. Further modifications to the compressor to improve stall characteristics resulted in a final engine configuration (prototype J40-WE-8 engine) in which temperature distributions were also investigated.

In all investigations, the radial turbine temperature distributions were measured by traversing sonic-flow thermocouple probes at the turbine inlet and by conventional thermocouple rakes at the turbine outlet. With a turbine-inlet temperature survey an accurate indication of turbine blade temperature was obtained, and, by comparison with a turbine-outlet survey, the amount of shift in temperature distribution imposed by the turbine rotors was determined. The reliability and accuracy of the temperature probes at the turbine inlet were also determined.

APPARATUS

Installation

The engines were mounted on a wing section that spanned the 20-foot-diameter test section of the altitude wind tunnel (fig. 1). Dry

refrigerated air throttled from atmospheric to the desired inlet pressure is ducted into the engine through the inlet air duct. Engine thrust measurements by the tunnel balance scales were made possible by a frictionless slip joint located in the duct upstream of the engine.

Engines

The J40-WE-6 axial-flow turbojet engine used in the altitude-wind-tunnel investigation has a sea-level static rating of 7500 pounds thrust at an engine speed of 7260 rpm and a turbine-inlet temperature of 1425° F. At this rating, the engine air flow is approximately 142 pounds per second. Main components of the engine include an 11-stage axial-flow compressor with a pressure ratio of approximately 5.0 at rated engine speed, a single-annulus basket-type combustor with a liner hole area of 809 square inches, a two-stage turbine, and a clamshell-type variable-area exhaust nozzle. Over-all length of the engine is approximately 186 inches, maximum height is $45\frac{1}{2}$ inches, maximum width is $42\frac{1}{4}$ inches, and the total dry weight is approximately 3000 pounds. The engine is equipped with an electronic control that varies engine fuel flow and exhaust-nozzle area to maintain a schedule of turbine-outlet temperature and engine speed. Nine chromel-alumel thermocouples connected in parallel and located $2\frac{1}{4}$ inches from the outer wall and 11 inches downstream of the trailing edge of the second-stage turbine rotor constitute the temperature-sensing device for the electronic control.

The interim J40-WE-6 engine is a J40-WE-6 engine in which the two-stage compressor-outlet straightening vane assembly was replaced by a two-element mixer vane assembly of similar envelope and the combustor was replaced with one having a total liner-hole area of 877 square inches. The mixer-vane-assembly blading is shown schematically in figure 2. The first-row outlet guide vanes are the same as those originally used in the J40-WE-6 engine and consist of 108 straightening vanes with a chord of 1.18 inches and a span of 2.68 inches fixed at an angle of 39° 45' with the axis of the engine, while the mixer vane section consists of two sets of 54 vanes each with a mean chord of 1.70 inches and a span of 2.95 inches. Both sets of vanes were fixed at the mean diameter at an angle of 14° 20' with the axis of the engine (same as original second-stage straightening vane), while the hub and tip sections of adjacent vanes were twisted in opposite directions. Variation in the blade form of alternate vanes produces a turbulent mixing action.

The prototype J40-WE-8 engine, which will have an afterburner as part of the standard engine, is a J40-WE-6 engine with a modified compressor, a mixer vane assembly at the compressor outlet, and a combustor with a total liner-hole area of 795 square inches. Side, front, and rear views of this combustor are shown in figure 3. The combustors of each of the three engines were similar with the exception of the hole geometry in the outer and inner liners.

Instrumentation

Temperature and pressure measuring stations throughout the engine and detailed location of the instrumentation at the compressor outlet, turbine inlet, and turbine outlet are shown in figure 4.

Aspiration-type thermocouples were used to minimize the effects of radiation on the measured turbine-inlet temperature. The probes, designed and fabricated by the engine manufacturer, maintained sonic gas velocity (high rate of heat transfer) at all operating conditions over a chromel-alumel thermocouple element. The design and development of the sonic-flow temperature probe is discussed in reference 4. A view of the turbine-inlet temperature traverse mechanism and motor drive, the device which produces radial movement of the temperature probes in the annular passage, is shown in figure 5. An individual temperature probe is shown in figure 6. These probes were used during this investigation without failure for over 200 hours of engine operation.

A view of the instrumentation installed at the turbine outlet is presented in figure 7. The temperatures were measured and recorded by self-balancing potentiometers. Pressures throughout the engine were measured by water, alkazine, and mercury manometers and were photographically recorded.

PROCEDURE

The three engines were investigated over a range of inlet pressures from 236 to 1534 pounds per square foot absolute (simulated pressure altitudes from 15,000 to 55,000 ft and flight Mach numbers from 0.12 to 0.64) and over a range of inlet air temperatures from 68° to -35° F. All tests were run at rated engine speed of 7260 rpm. Corrected engine speeds $N/\sqrt{\theta}$ ranged from 7198 to 8026 rpm. Variations in turbine temperature level were obtained by controlling fuel flow and exhaust-nozzle area. The effect of compressor-outlet total-pressure distribution (obtained by compressor modifications) on temperature distribution in a modified interim J40-WE-6 engine and the effect of combustor-hole area and location on temperature distribution in the prototype J40-WE-8 engine were also investigated.

Temperatures at the turbine inlet were measured at seven radial positions across the annulus by ten individual traversing probes. A full set of engine performance data was obtained at the start and finish of each survey to establish steady-state conditions.

The radial total-pressure distribution at the compressor outlet was obtained by averaging pressures at each radial position from three circumferentially located rakes. The radial temperature distribution at the turbine-outlet annulus was obtained by averaging temperatures at each radial position from four circumferentially located rakes.

Fuel conforming to the specification MIL-F-5624A grade JP-3 with a lower heating value of 18,700 Btu per pound and a hydrogen-carbon ratio of 0.171 was used throughout the investigation.

RESULTS AND DISCUSSION

Limitations on Turbine-Inlet Gas Temperature

The manufacturer's desired distribution (fig. 8) increases from a maximum average radial temperature of 1290° F at the hub to a peak of 1635° F at a blade height of $4\frac{1}{8}$ inches and decreases to 1475° F at the blade tip ($5\frac{5}{8}$ in.). The local radial temperature may vary $\pm 200^{\circ}$ F from the average temperature. The curve is established as a guide for limiting turbine-inlet temperature distribution based on the stress limitations of both the stationary and rotating blading. Because the tip temperature limitation is associated with the stator blades, which are less highly stressed than the rotor blades, limits in the tip region are not considered as rigorous as the limits near the hub.

Turbine-Inlet Temperature Distribution

Radial turbine-inlet temperature distributions obtained from the ten individual traverse probes are shown in figure 9. Average radial temperature distribution is indicated by solid symbols. The individual temperature distributions are similar in shape to the average radial temperature distribution. Therefore, all temperature distributions presented hereinafter are average radial distributions. The maximum and minimum local temperatures are acceptable except at the less critical tip regions where the temperatures are conservative.

The validity of the average indicated turbine-inlet temperature is supported by a comparison with calculated values (fig. 10) for the J40-WE-6 engine operating over a range of flight conditions. The good agreement of the indicated and calculated temperatures (see appendix B) indicates that radiation and other errors in the indicated temperatures are negligible. Indicated temperatures are therefore used without correction.

Effects of inlet pressure, turbine temperature level, and corrected engine speed. - The effects of engine inlet pressure, temperature level, and corrected engine speed on the average radial turbine-inlet indicated temperature distribution in the J40-WE-6, interim J40-WE-6, and prototype J40-WE-8 engines are shown in figures 11 to 13, respectively.

For the J40-WE-6 engine a decrease in inlet pressure (fig. 11(a)) caused the turbine-inlet temperature distribution to shift to the degree that the maximum permissible average temperature near the hub was exceeded by 130° F for an over-all average temperature of 1425° F at the lowest inlet pressure of 482 pounds per square foot absolute. Changes in temperature level and corrected engine speed (figs. 11(b) and 11(c)), however, had no appreciable effect on temperature distribution. In all cases, average temperature in the tip region was considerably lower than the maximum permissible average temperature, thereby reducing blade loading below the maximum potential loading.

For the interim J40-WE-6 engine, inlet pressure, temperature level, and corrected engine speed had no significant effect on temperature distribution (fig. 12), and the distribution closely approximated the desired curve in all regions of the blade.

For the prototype J40-WE-8 engine at the high inlet pressure (figs. 13(a) and 13(b)) the hub temperatures were approximately 150° lower than desired and the tip-region temperatures were 100° greater than desired for an over-all average temperature of 1425° F. A decrease in inlet pressure produced a more favorable distribution. At low inlet pressure, an increase in temperature level (fig. 13(c)) and an increase in corrected engine speed (fig. 13(e)) resulted in a slight reduction of temperature at the hub region and an increase at the tip region. At high inlet pressures a change in either temperature level (fig. 13(d)) or corrected engine speed (fig. 13(f)) had no effect on temperature distribution. For all conditions investigated, the critical average hub-region temperatures for the prototype J40-WE-8 engine were not exceeded. Rated military over-all average temperature (1425° F) could be reached if the tip-region temperatures were allowed to exceed the desired maximum by about 100° F. Because the less critical stresses in the tip region permit some departure from the desired temperature distribution, the temperature distributions for the prototype J40-WE-8 engine are considered acceptable by the engine manufacturer.

The improvement in turbine-inlet temperature distribution for the interim J40-WE-6 engine is presumed to result from the installation of the mixer vane assembly and its interaction with the characteristics of the combustor. The satisfactory temperature distributions for the engine with the mixer installed are attributed to the action of the mixer on the compressor-outlet pressure distribution coupled with possible introduction of turbulence into the air stream entering the combustor. This solution to the temperature inversion problem appears to be similar to that previously discussed in reference 2. Although the temperature distributions for the interim J40-WE-6 engine matched the desired distribution, improvement in the engine stall characteristics was still desired. The temperature distribution of the final engine configuration (prototype J40-WE-8), which had satisfactory stall characteristics, was not as desirable as the interim engine; however, it was considered satisfactory by the engine manufacturer.

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The turbine-inlet temperature distribution for the three engines investigated is, to any appreciable extent, only affected by engine inlet pressure and the effect varies from one engine to another. The installation of a mixer vane assembly (interim J40-WE-6 and prototype J40-WE-8 engines) remedied the above mentioned effect. The differences in the temperature distributions of the three engines are due to the differences in the individual compressor and combustor configurations; however, the effects of engine operating conditions on each engine may be due to changes in either the compressor-outlet pressure distribution or changes in combustor characteristics with change in operating conditions, as was discussed in reference 2. The separate effects of compressor-outlet pressure distribution and combustor design on turbine-inlet temperature distribution as well as the effect of operating conditions on compressor-outlet pressure distributions will be discussed in the following paragraphs.

Effect of compressor-outlet total-pressure distribution. - A correlation of average radial turbine-inlet temperature distribution with compressor-outlet total-pressure distribution for two compressor configurations in a modified interim J40-WE-6 engine is shown in figure 14. Compressor modifications A and B (fig. 14(a)) resulted in opposite compressor-outlet total-pressure distributions (that is, A - low inner (hub), high outer (tip); B - high inner (hub), low outer (tip)). As would be expected the turbine-inlet temperature distribution (fig. 14(b)) was high in the hub region and low in the tip region for configuration A, while configuration B produced the reverse distribution for the same engine combustor. High local total pressure (high mass flow) thus reduces the turbine-inlet temperature; low local total pressure increases the turbine-inlet temperature.

Effect of engine combustor design. - The effect of engine combustor modifications on average radial turbine-inlet temperature distribution is presented in figure 15. Three combustors used in the three subject engines were run in the prototype J40-WE-8 engine. The three combustors differed in hole area and hole location, but the differences were small and the tests therefore did not constitute a comprehensive combustor program. Variations in the compressor-outlet total-pressure distribution encountered during operation of the three combustors were negligible (fig. 15(a)), indicating that any change in turbine-inlet temperature distribution between the three combustor configurations could be attributed entirely to the

combustor change. Installation of combustor A (J40-WE-6) and combustor B (interim J40-WE-6) in the prototype engine as compared with combustor C (prototype J40-WE-8) produced only slight changes in the average turbine-inlet temperature distributions (fig. 15(b)). At 75-percent passage height, temperatures for combustor A were approximately 5 percent higher than temperatures for combustor C, while temperatures for combustor B were 5 percent lower than for combustor C, with only slight changes in the hub region. The table (fig. 15) of the hole description for the three combustors shows that the design differences consisted of variations in the seven rows of holes. For combustor A the outer-liner hole area was 26 percent less than the inner-liner hole area with resulting higher temperatures at 75-percent passage height. For combustor B the outer-liner hole area was 7 percent greater than the inner-liner hole area with resulting lower temperatures at 75-percent passage height.

Thus, turbine-inlet temperature distribution is influenced by the combustor-hole-area distribution, as well as the compressor-outlet total-pressure distribution, and the effects are generally in the direction to be expected.

Variation of Compressor-Outlet Pressure Distribution

In the Three Engines

Inasmuch as compressor-outlet total-pressure distribution has an effect on turbine-inlet temperature distribution, the degree to which shifts in temperature distribution for the three engines (as shown in figs. 11 to 13) were caused by changes in compressor-outlet total-pressure distribution will be examined. The effect of inlet pressure on the variation of average compressor-outlet total-pressure distribution in J40-WE-6, interim J40-WE-6, and prototype J40-WE-8 engines is shown in figure 16. Inlet pressure had little effect on the average compressor-outlet total-pressure distribution in the three engines. Temperature level and corrected engine speed (curves not shown) also had little effect on compressor-outlet total-pressure distribution. In all cases, the variation was not over ± 1 percent, which was considered insignificant.

Inasmuch as engine operating conditions had little or no effect on the compressor-outlet total-pressure distribution, it is concluded that, for each engine, any change in turbine-inlet temperature distribution with operating conditions is probably due to a characteristic of the engine combustor.

Turbine Temperatures

Typical turbine-inlet and turbine-outlet indicated radial temperature distributions in the three engines are compared in figure 17. In general, as shown by comparison of figures 17(a) and 17(b), turbine-

outlet temperature distribution is similar in shape to the temperature distribution at the turbine inlet, indicating only a small shift in temperature distribution imposed by the turbine rotors.

For a turbine-inlet temperature distribution closely matching the desired distribution (interim J40-WE-6 engine), the radial distribution of temperature drop across the turbine (blade loading) is approximately uniform and equal to the average temperature drop (fig. 17(c)). For a distribution with high tip-region temperatures (prototype J40-WE-8 engine) variation in temperature drop is nonuniform with the temperature drop increasing from 30 percent below average at hub to 40 percent above average at 0.80 passage height and then decreasing to 50 percent below average at the tip. For a distribution with high hub-region temperatures (J40-WE-6 engine), radial temperature drop is 20 percent above average from hub to 0.80 passage height and decreases to 100 percent below average at the tip.

Effect of Temperature Distribution on Engine Performance

If maximum thrust is to be obtained from a turbojet engine, the gas temperature distribution at the turbine inlet should be matched to the maximum temperature distribution that can be tolerated by the various turbine parts. The ratios of jet thrust obtainable with the distributions experimentally obtained from the three engines (figs. 11(a), 12(a), and 13(b)) to the ideal jet thrust have been calculated (see appendix B) and are presented as a function of engine-inlet total pressure in figure 18. Attainable jet thrust was calculated with an average turbine-inlet temperature obtained from the measured temperature distributions, and in all cases the levels of the measured distributions were shifted so that radial temperatures did not exceed the desired radial value. The ideal jet thrust is based on an average turbine-inlet temperature of 1500° F calculated from the maximum average temperature curve (fig. 8). Two examples of the ratios of attainable jet thrust to ideal jet thrust are discussed: (1) The ratio in which the measured temperature distribution is limited to the maximum average temperature curve over the entire blade height (fig. 18(a)), and (2) the ratio in which the measured temperature distribution is only limited to the maximum average temperature curve from the blade hub to a blade height of 4 inches (fig. 18(b)). The latter example, because of the less critical stresses in the tip region, defines a thrust ratio based on a maximum allowable temperature distribution that departs from the desired distribution by not observing the tip-region temperature limitations. This departure from the desired temperature curve allowing approximately 100° overtemperaturing in the tip region, has, during more than 500 hours of engine operating time, resulted in no apparent sacrifice of turbine life.

For the J40-WE-6 engine, the thrust ratio (fig. 18(a)) is constant at about 93 percent as inlet pressure is reduced from 1200 to 800 pounds per square foot absolute and decreases to 89 percent at an inlet pressure

of 500 pounds per square foot absolute. The decrease in thrust ratio for the J40-WE-6 engine as inlet pressure is decreased below 800 pounds per square foot absolute is a result of the inversion of the hub-region temperatures at low inlet pressure. Inasmuch as the tip-region temperatures for the J40-WE-6 engine were, in all cases, lower than the desired temperature curve, the thrust ratio (fig. 18(b)) was the same as shown in figure 18(a).

The thrust ratio for the interim J40-WE-6 engine remains approximately constant at 96 percent (fig. 18(a)) over the range of inlet pressure because of the fact that the temperature distributions were not affected by operating conditions. The thrust ratios (fig. 18(b)) do not differ appreciably from those in figure 18(a) for the interim engine since the temperature in the tip region, as was the case with the original engine, is not the limiting temperature.

For the prototype J40-WE-8 engine that experienced a more favorable temperature distribution, with decrease in inlet pressure, the thrust ratio (fig. 18(a)) increases from about 90 percent at an inlet pressure of 1100 pounds per square foot absolute to about 93 percent at an inlet pressure of 400 pounds per square foot absolute. The thrust ratios for the prototype J40-WE-8 engine (fig. 18(b)) are similar in trend to those presented in figure 18(a), but the temperature distribution for the prototype engine is such that the tip-region temperatures constitute the limiting blade region, and consequently a thrust increase of 3 to 4 percent results at all inlet pressures if tip-region temperature limitations are not observed.

If the ideal thrust were based on the rated turbine-inlet temperature of 1425°F instead of 1500°F , the thrust ratios presented in figure 18 would be approximately 4 percent higher.

CONCLUDING REMARKS

The gas temperature distribution at the turbine of the three engines, over the range of operating conditions investigated, was considered satisfactory from the standpoint of desired temperature distribution with one exception - the distribution for the J40-WE-6 engine indicated a trend with decreasing engine-inlet pressure for the temperature to exceed the desired in the region of the blade hub. Installation of a compressor-outlet mixer vane assembly remedied this undesirable temperature distribution.

The differences in the turbine-inlet temperature distributions of the three engines were due to the differences in the respective compressor and combustor configurations; however, the varying effects of engine operating conditions on each engine were due to changes in either compressor-outlet pressure distribution or combustor characteristics.

The experimental data have shown that turbine-inlet temperature distributions are influenced in the expected manner by changes in compressor-outlet pressure or mass-flow distribution and by changes in combustor-hole-area distribution. Examination of the compressor-outlet-pressure-distribution data of the three engines showed that the effects of engine operating conditions on temperature distribution could not be attributed to changes in combustor-inlet pressure distribution but were probably the result of unexplained combustor characteristics.

The similarity between turbine-inlet and turbine-outlet temperature distribution indicated only a small shift in temperature distribution imposed by the turbine rotors.

Mismatching of turbine-inlet temperature distribution with the desired distribution results in only partial attainment of ideal jet thrust. The attainable jet thrusts³ of the three engines were influenced in different degrees and directions by changes in temperature distributions with change in engine-inlet pressure. Inability to match the desired temperature distribution resulted, for the J40-WE-6 engine, in an 11-percent thrust loss based on an average turbine-inlet temperature of 1500° F at an engine-inlet pressure of 500 pounds per square foot absolute. Departure from the desired temperature distribution in the blade tip region results, for the prototype J40-WE-8 engine, in an attainable thrust increase of 3 to 4 percent as compared with that obtained if tip-region temperature limitations were observed.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 17, 1952

APPENDIX A

SYMBOLS

The following symbols are used in this report:

A	cross-sectional area, sq ft
c_p	specific heat at constant pressure, Btu/(lb)(°F)
F	thrust, lb
g	acceleration due to gravity, 32.2 ft/sec ²
M	Mach number
N	engine speed, rpm
P	total pressure, lb/sq ft abs
p	static pressure, lb/sq ft abs
R	gas constant, 53.4 ft-lb/(lb)(°R)
T	total temperature, °R
W_a	air flow, lb/sec
W_f	fuel flow, lb/hr
W_g	gas flow, lb/sec
γ	ratio of specific heat at constant pressure to specific heat at constant volume
θ	ratio of absolute total temperature at engine inlet to absolute static temperature at NACA standard atmosphere sea-level conditions

Subscripts:

a	air
e	engine
f	fuel
g	gas
i	indicated

- j jet
- 0 free-stream conditions
- 1 cowl inlet
- 2 engine inlet
- 4 compressor outlet
- 5 turbine inlet
- 6 turbine outlet

APPENDIX B

METHODS OF CALCULATION

Temperatures. - Total temperatures were determined from indicated temperatures with the following relation:

$$T = \frac{T_i \left(\frac{P}{p} \right)^{\frac{\gamma-1}{\gamma}}}{1 + 0.85 \left[\left(\frac{P}{p} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]} \quad (1)$$

where 0.85 is the impact recovery factor for the NACA type thermocouple used.

Air flow. - Air flow was determined from pressure and temperature measurements in the cowl inlet by the equation

$$W_{a,1} = p_1 A_1 \sqrt{\frac{2\gamma g}{(\gamma - 1)RT_1} \left(\frac{P_1}{p_1} \right)^{\frac{\gamma-1}{\gamma}} \left[\left(\frac{P_1}{p_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]} \quad (2)$$

Gas flow. - The total weight flow through the engine was calculated as follows:

$$W_{g,6} = W_{a,1} + \frac{W_{f,e}}{3600} \quad (3)$$

Turbine-inlet total temperature. - Turbine-inlet total temperature was calculated on the assumption that the enthalpy drop across the turbine is equal to the enthalpy rise in the compressor. From this assumption the temperature drop across the turbine ΔT_t may be computed from

$$\Delta T_t = \frac{W_{a,1} c_{p,a} \Delta T_c}{W_{g,6} c_{p,g}} \quad (4)$$

where ΔT_c is the temperature rise across the compressor.

Then, with turbine-outlet temperature known,

$$T_5 = \Delta T_5 + T_6 \quad (5)$$

Ratio of attainable jet thrust to ideal jet thrust. - Ideal jet thrust of an engine can be calculated from the following relation:

$$F_j = \frac{W_g}{g} \sqrt{\frac{2\gamma}{\gamma-1} gRT_6 \left[1 - \left(\frac{P_0}{P_6} \right)^{\frac{\gamma-1}{\gamma}} \right]} \quad (6)$$

The pressure ratio P_0/P_6 also equals $1/(P_6/P_2)(P_2/P_0)$, where P_6/P_2 is the engine pumping ratio and P_2/P_0 is the engine ram-pressure ratio.

With a γ of a constant value of 1.34 and no change in W_g with engine operating conditions, the jet-thrust ratio can be calculated in the following manner:

$$\text{Jet-thrust ratio} = \frac{\sqrt{T_{5,\text{attainable}} \left(\frac{T_6}{T_5} \right) \left\{ 1 - \left[\left(\frac{P_6}{P_2} \right) \left(\frac{P_2}{P_0} \right) \right]^{\frac{1-\gamma}{\gamma}} \right\}}}{\sqrt{T_{5,\text{ideal}} \left(\frac{T_6}{T_5} \right) \left\{ 1 - \left[\left(\frac{P_6}{P_2} \right) \left(\frac{P_2}{P_0} \right) \right]^{\frac{1-\gamma}{\gamma}} \right\}}} \quad (7)$$

The ideal T_5 of 1500°F is based on the integration of the desired temperature distribution curve; the attainable T_5 is based on the integration of the measured temperature distribution. Characteristics of the prototype J40-WE-8 engine were used in all cases to determine values of engine pressure ratio and turbine temperature ratio.

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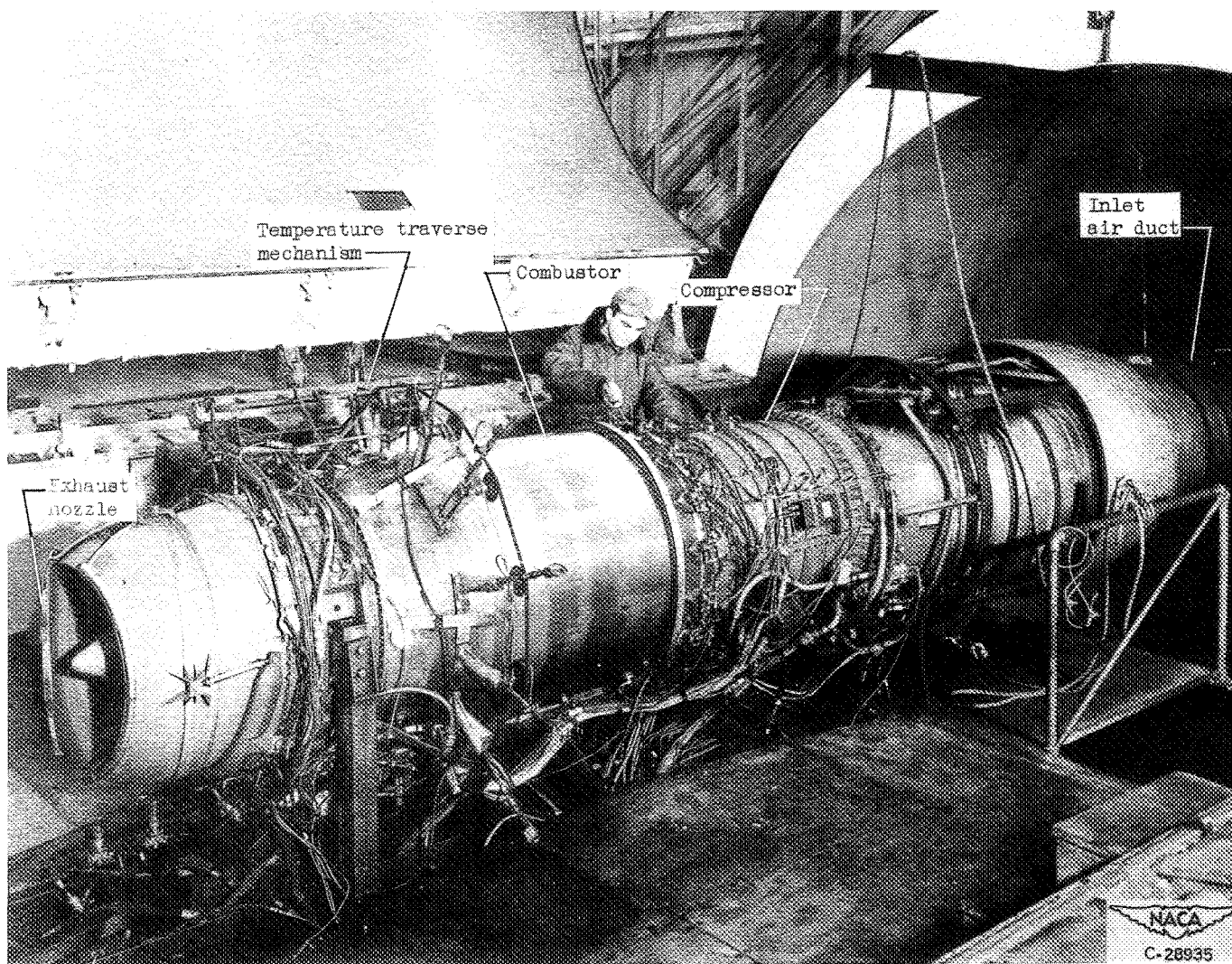
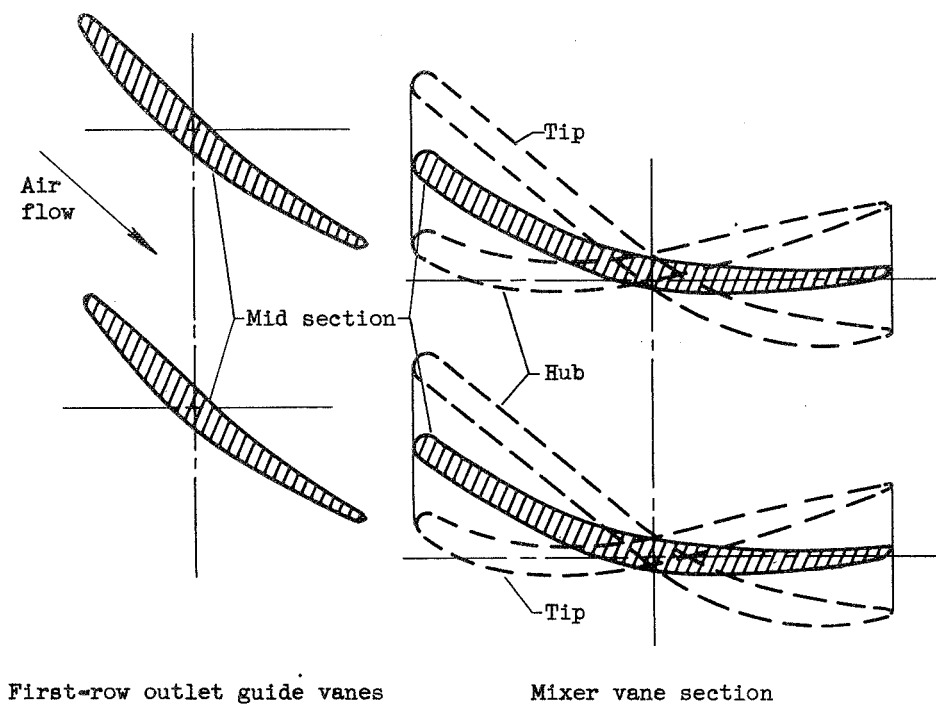
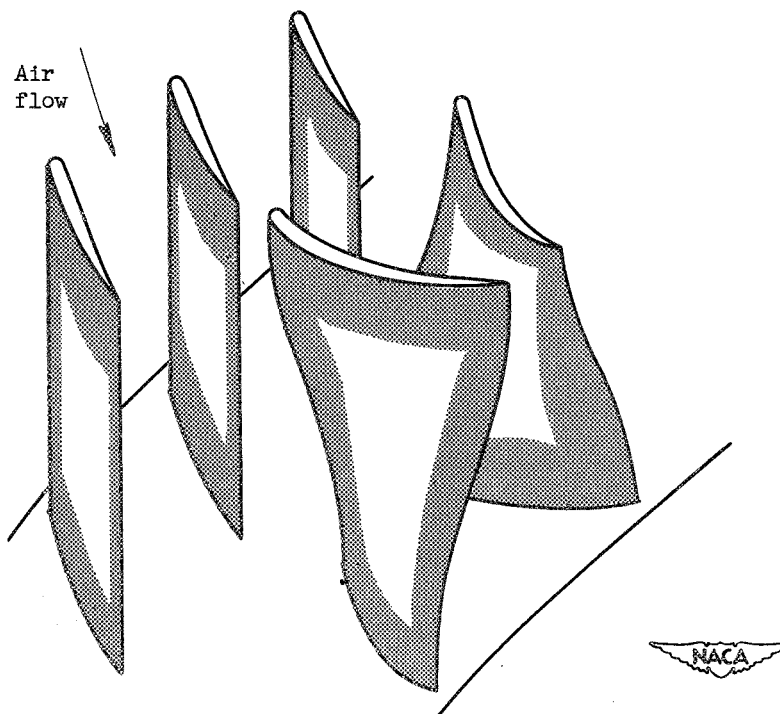


Figure 1. - Installation of J40-WE-6 engine in altitude wind tunnel.

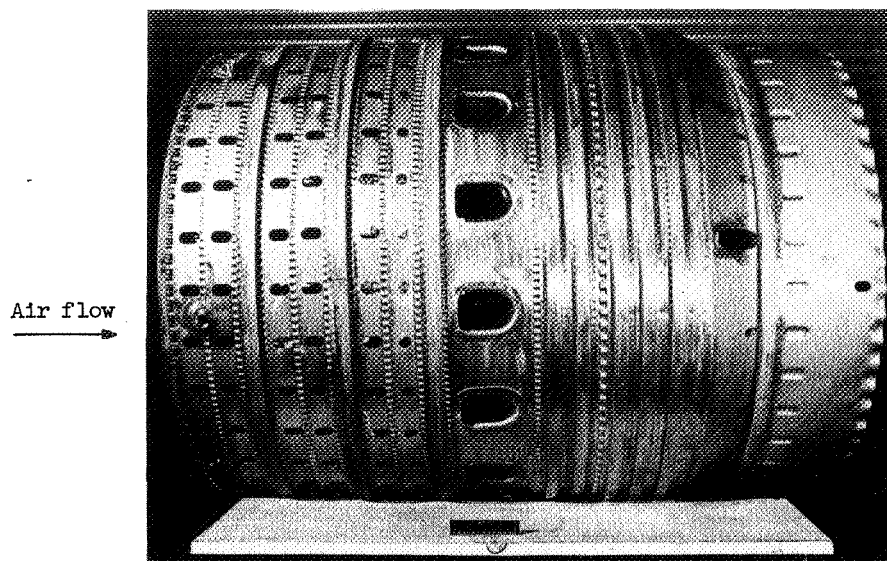


(a) Blade cross sections.

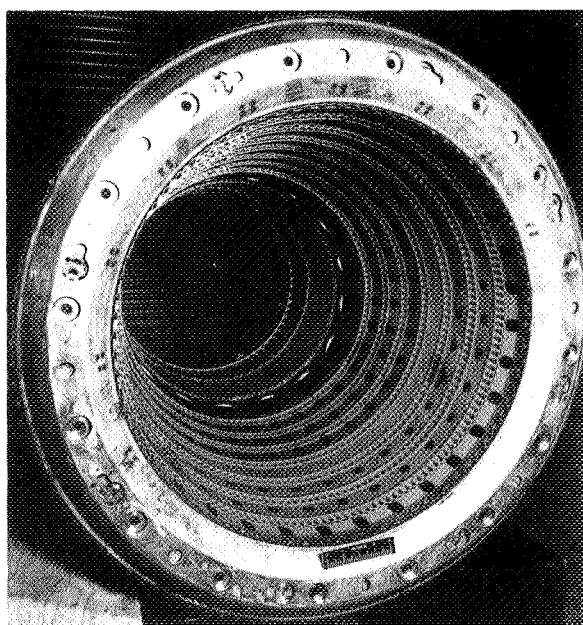


(b) Schematic view

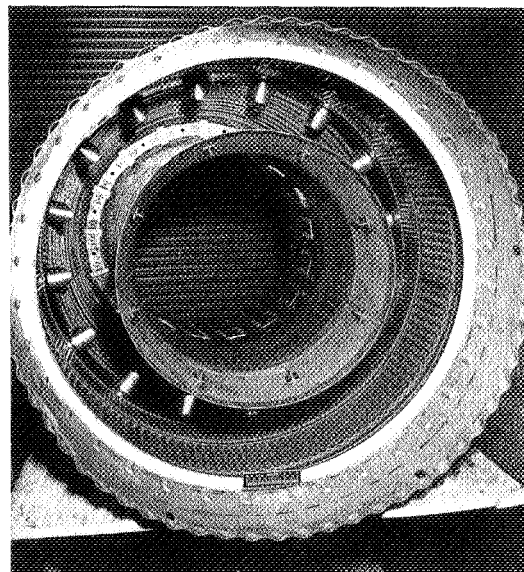
Figure 2. - Sketch of mixer-vane-assembly blading.



(a) Side view.



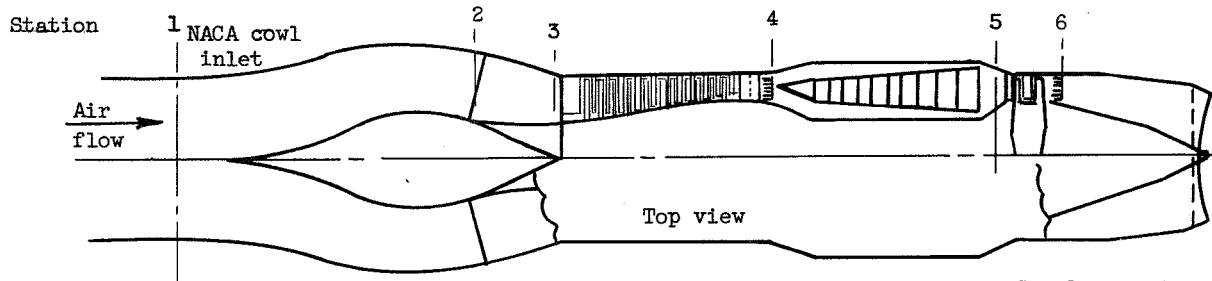
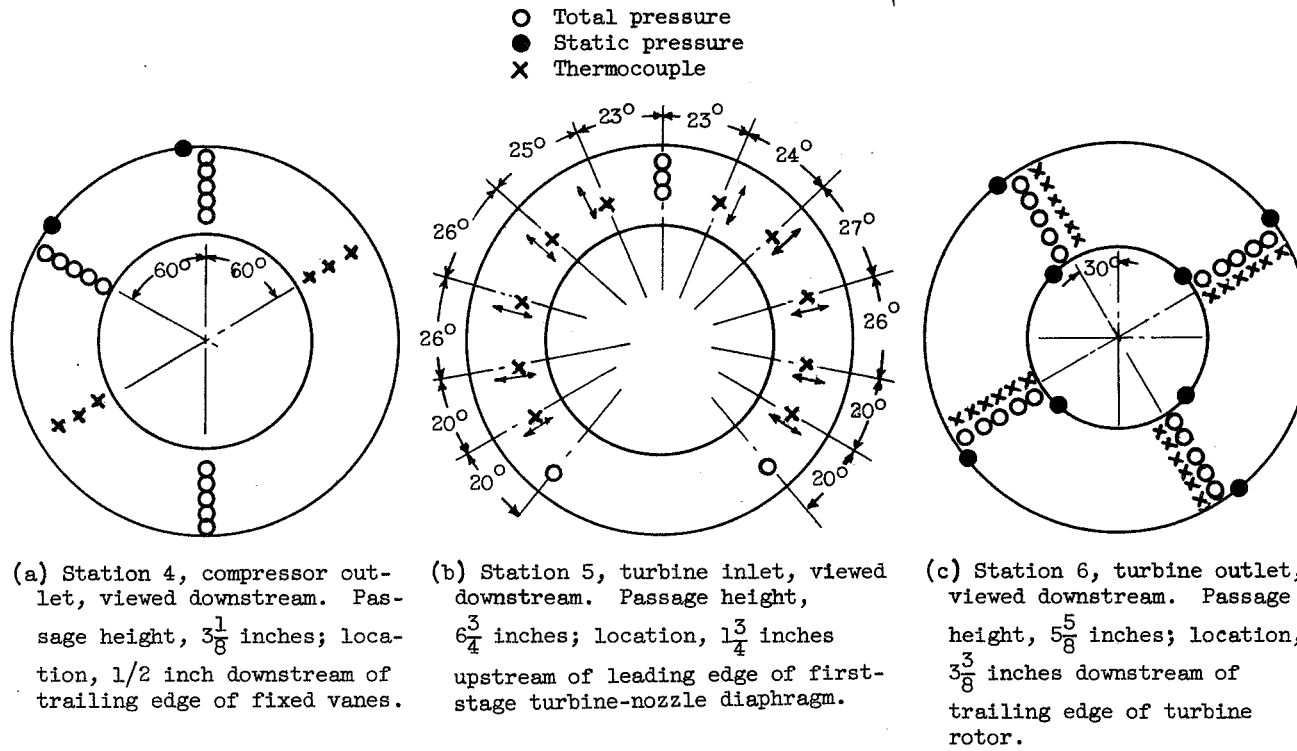
(b) Front view.



(c) Rear view.

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Figure 3. - Engine combustor, prototype J40-WE-8 engine.



(a) J40-WE-6 instrumentation station layout.

Figure 4. - Cross section of engine showing location of instrumentation.

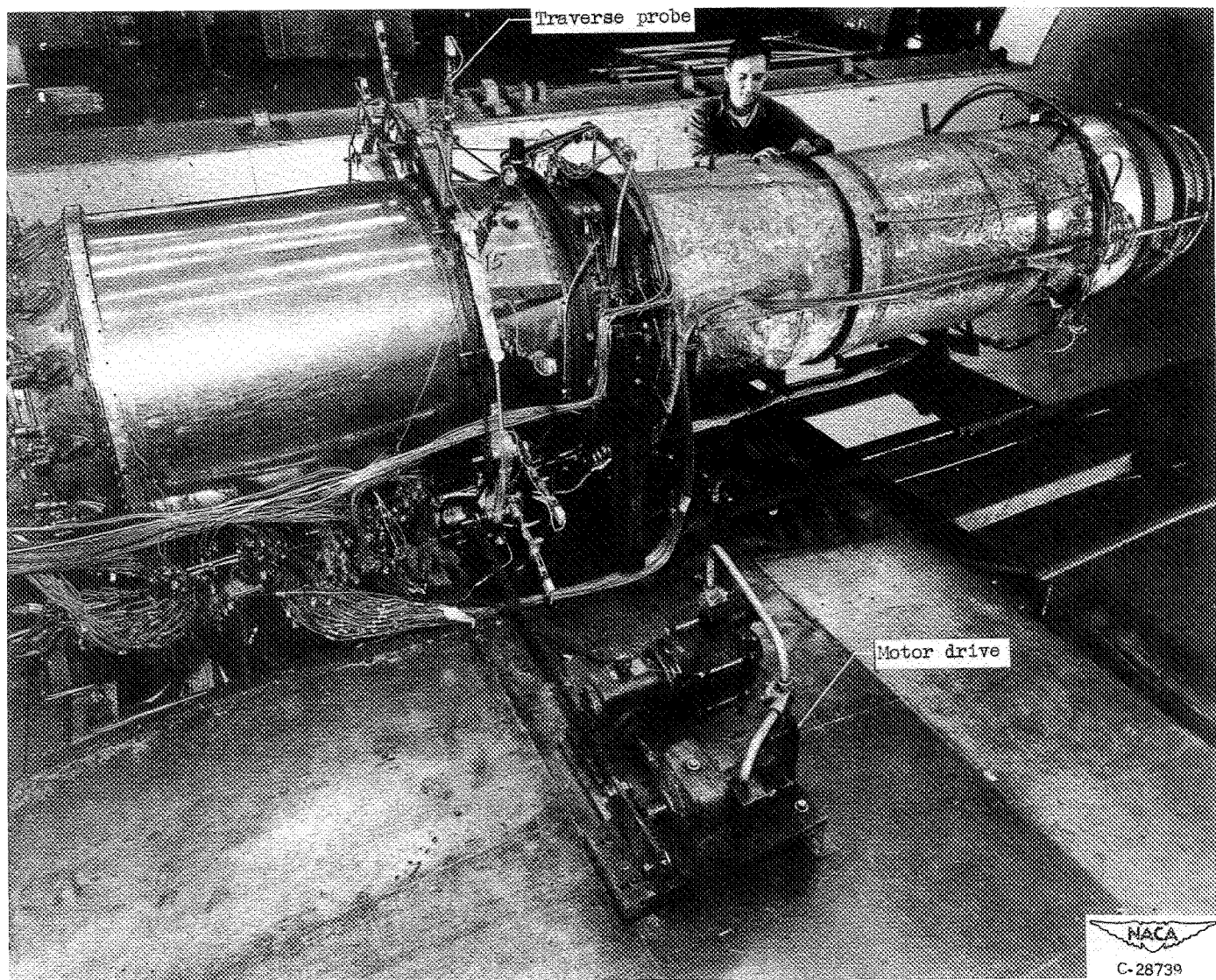


Figure 5. - Turbine-inlet temperature traverse mechanism.

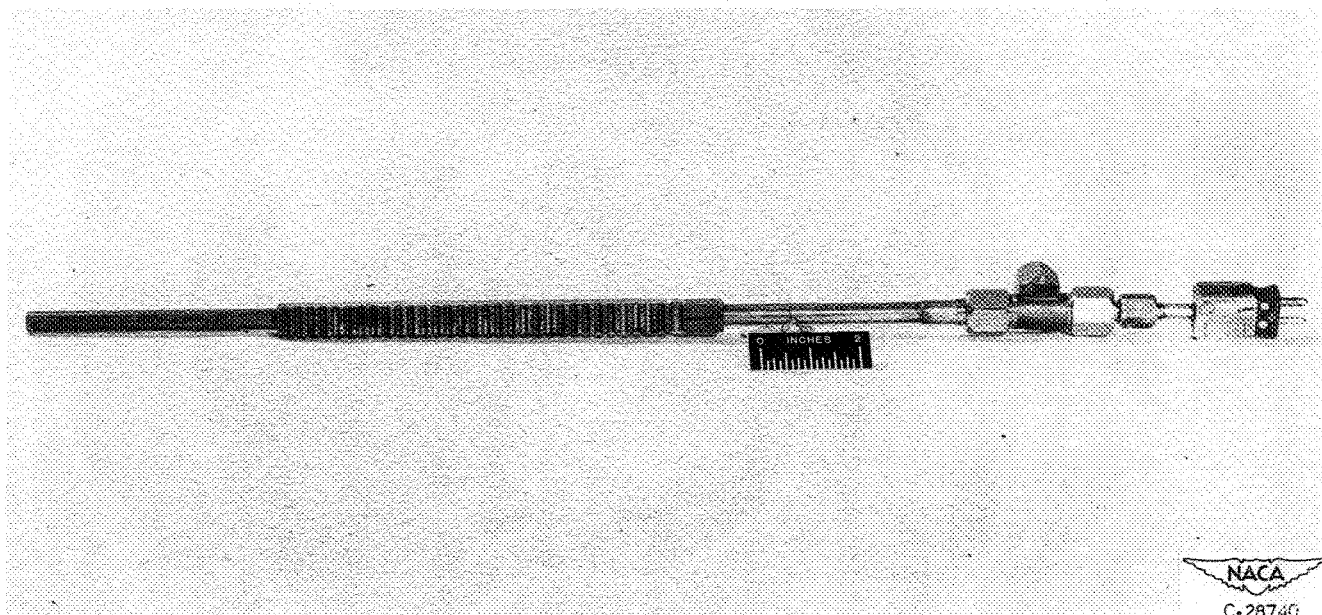


Figure 6. - Turbine-inlet sonic-flow temperature probe.

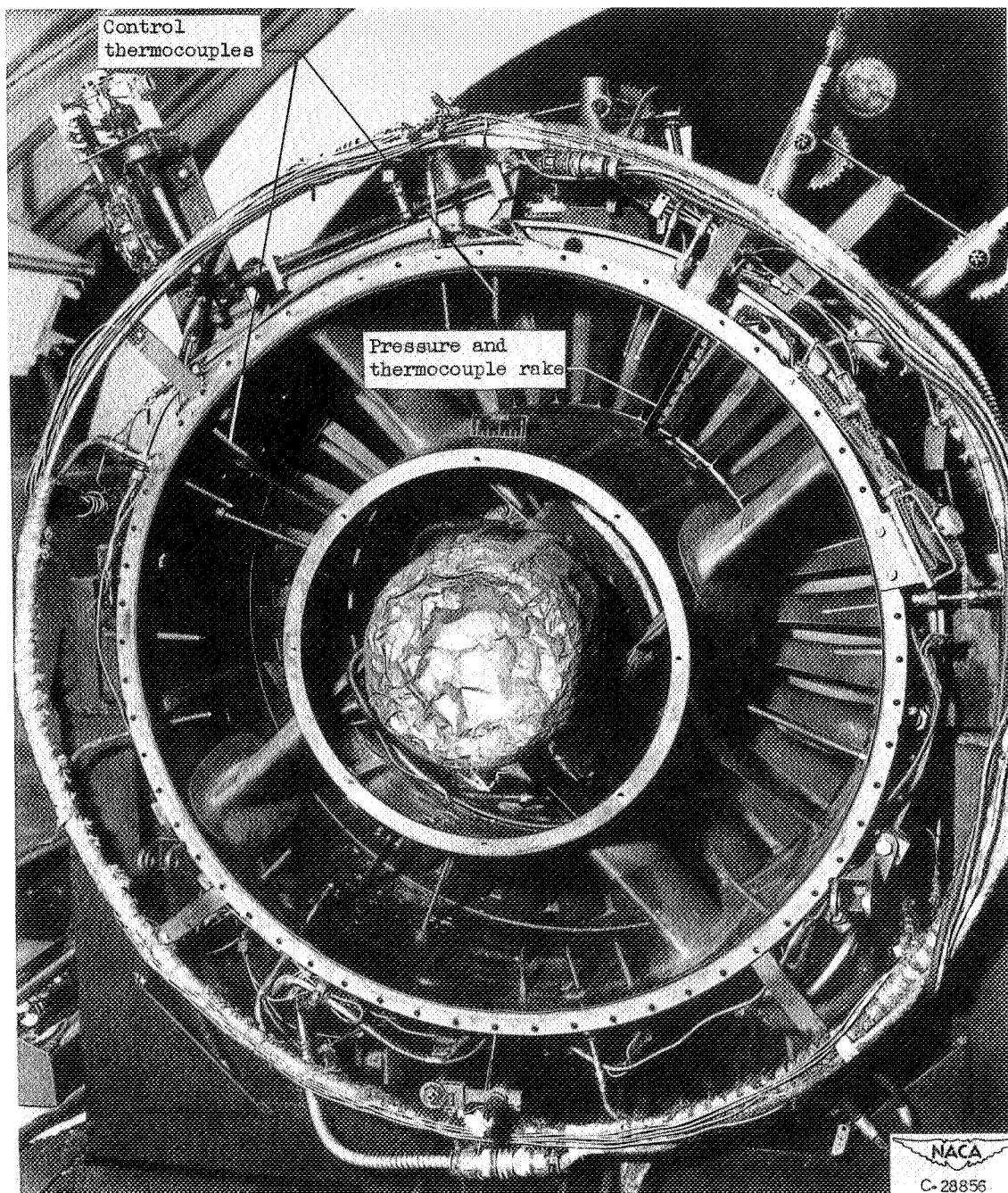


Figure 7. - Instrumentation installed at turbine outlet

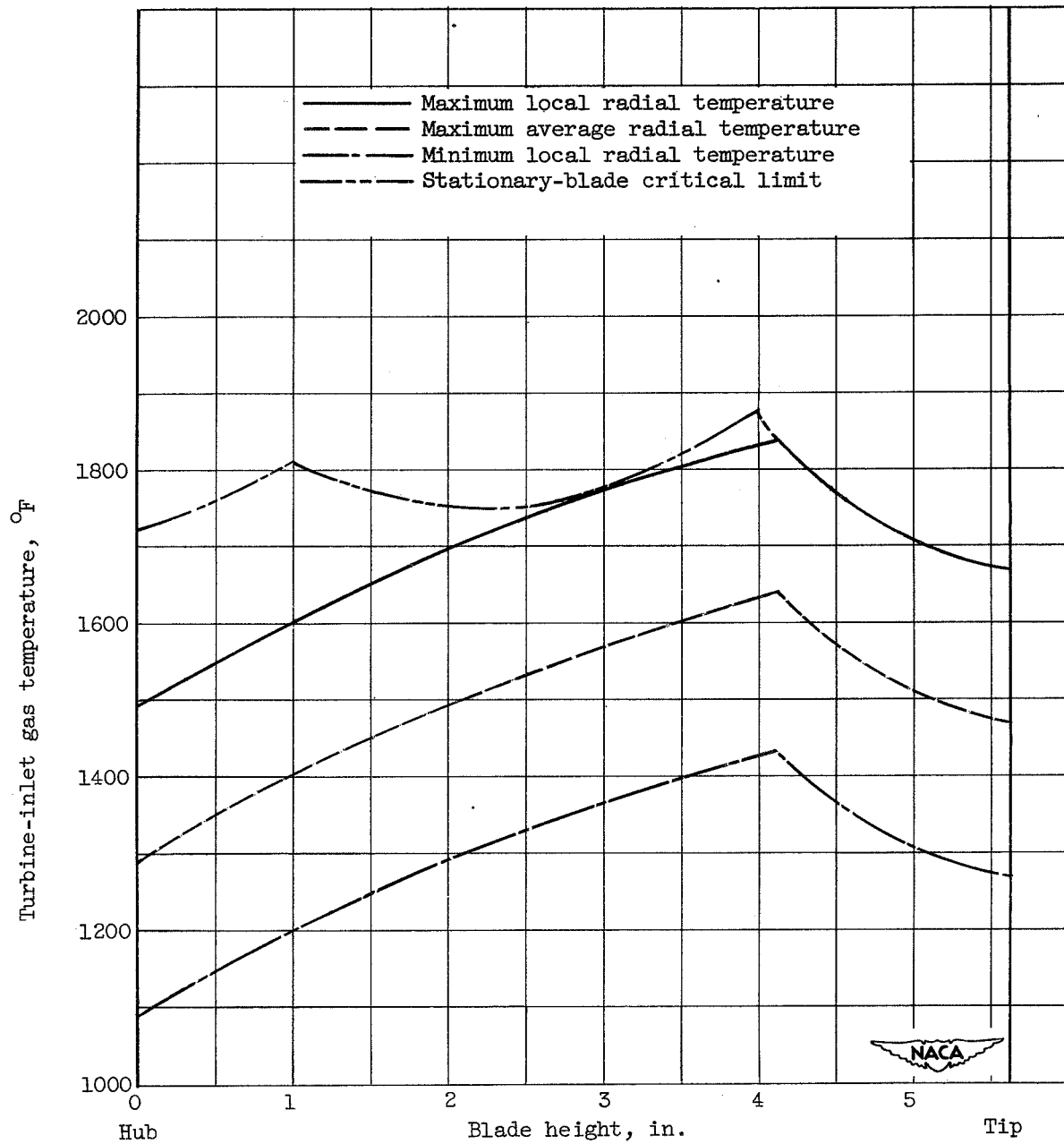


Figure 8. - Limitations on turbine-inlet temperature.

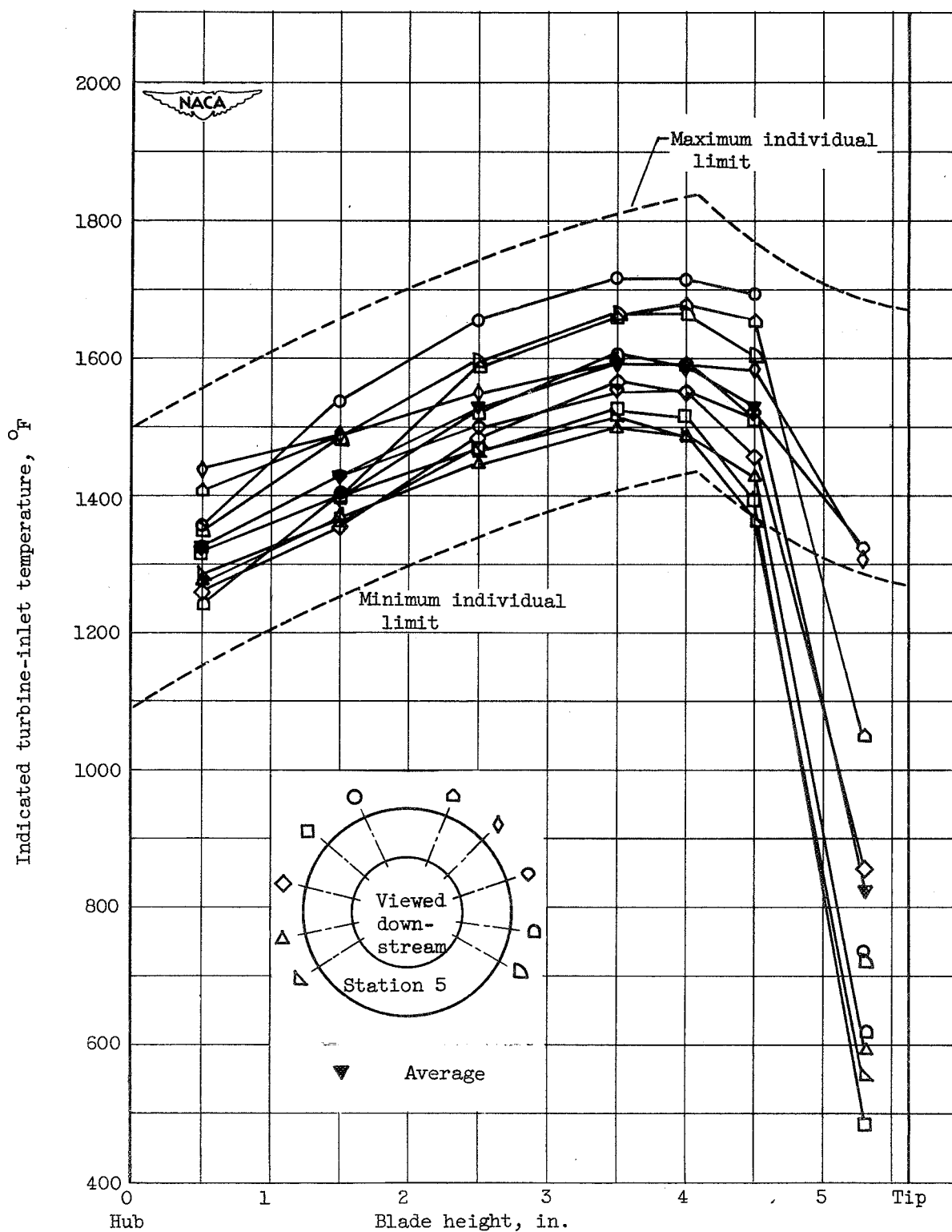


Figure 9. - Individual radial turbine-inlet temperature distributions. Altitude, 20,000 feet; flight Mach number, 0.64; corrected engine speed, 7200 rpm.

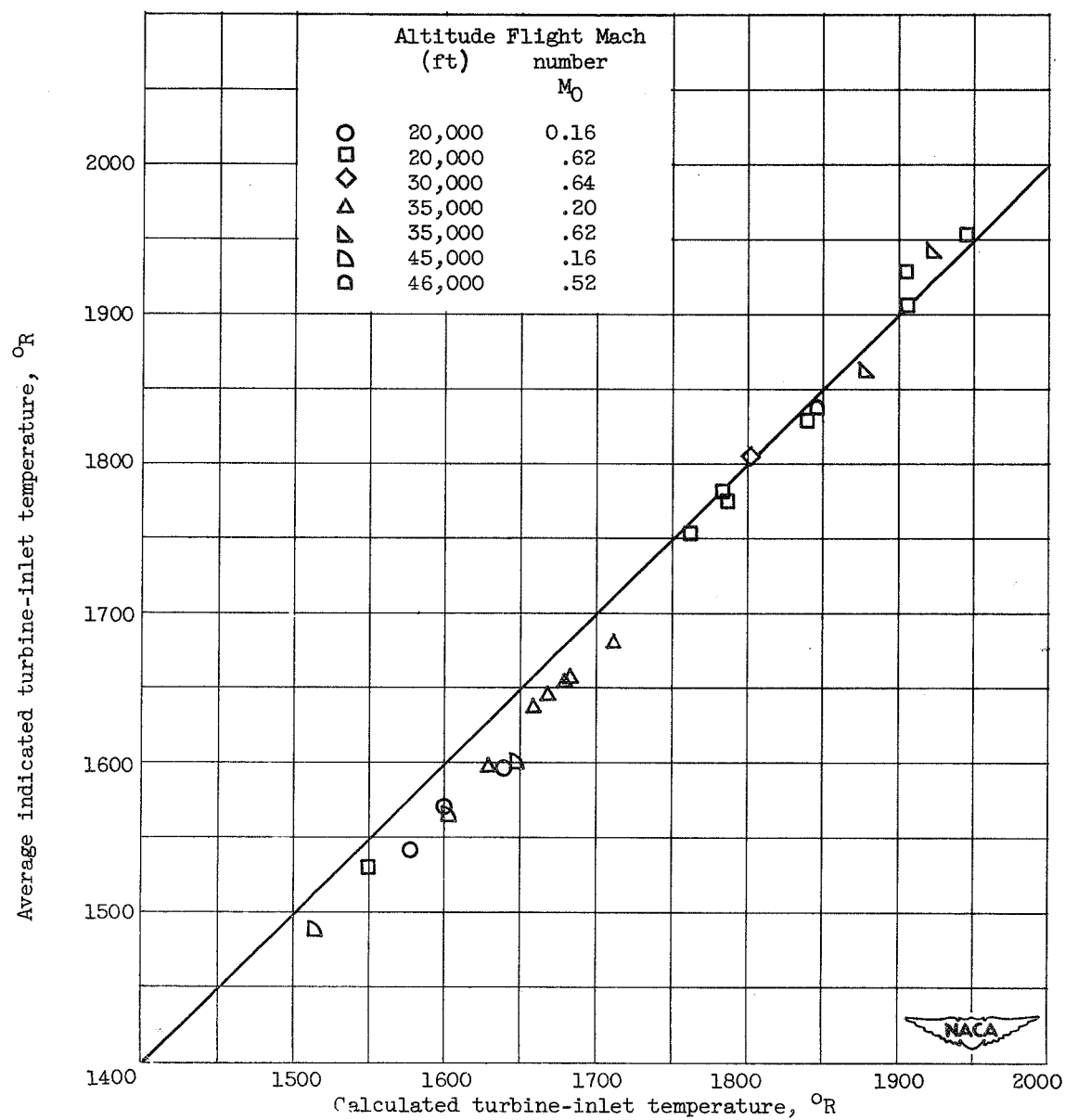
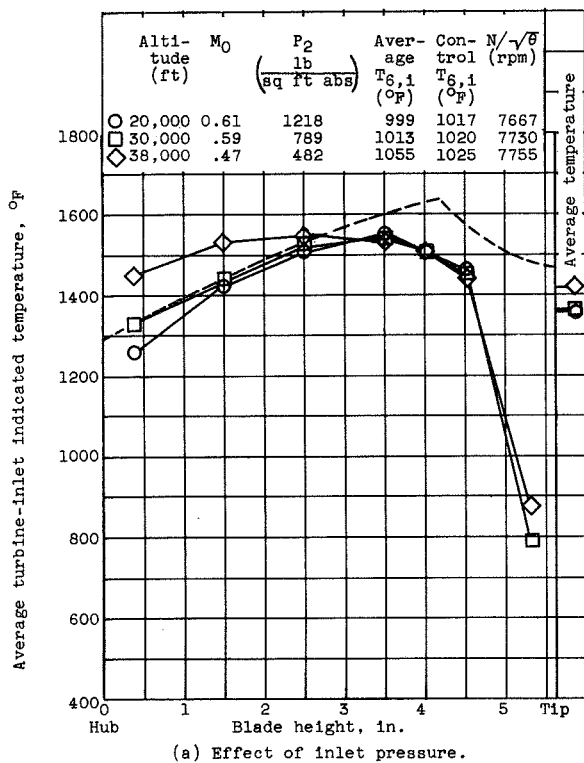
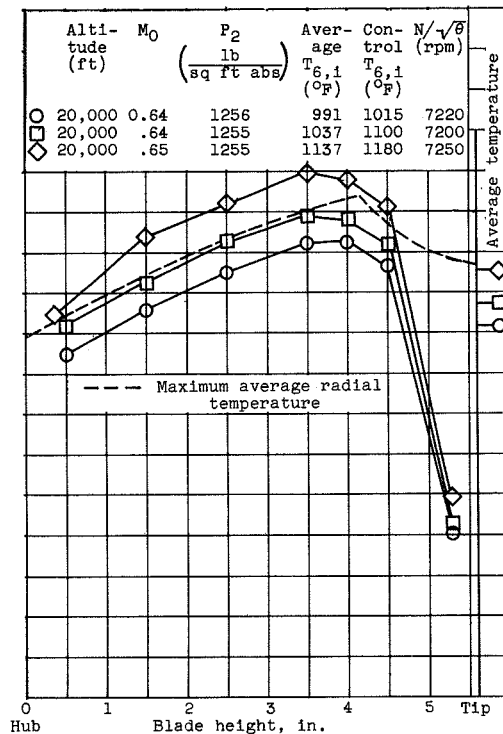


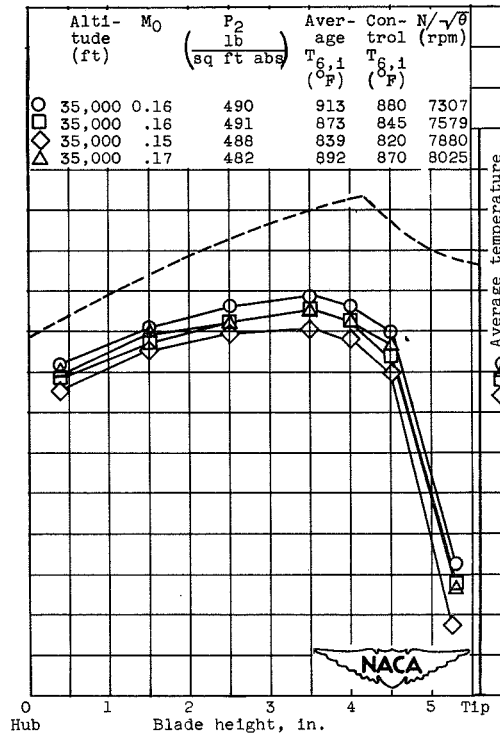
Figure 10. - Comparison of average indicated turbine-inlet temperature with calculated turbine-inlet temperature in J40-WE-6 engine.



(a) Effect of inlet pressure.

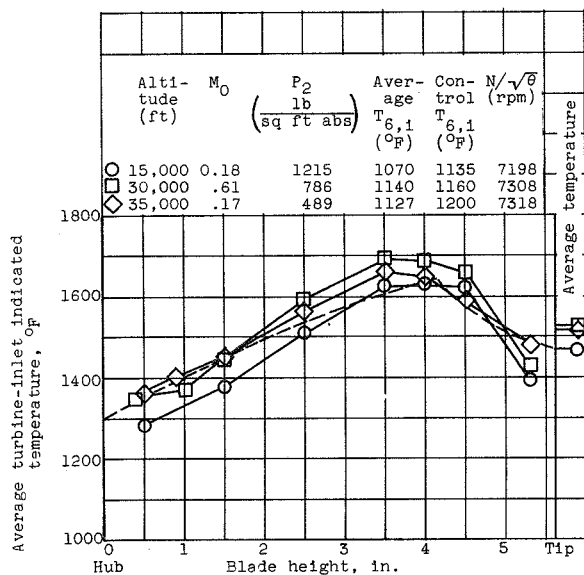


(b) Effect of temperature level.

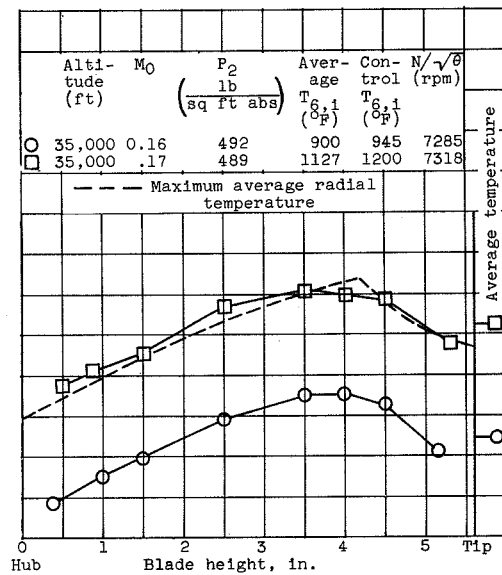


(c) Effect of corrected engine speed.

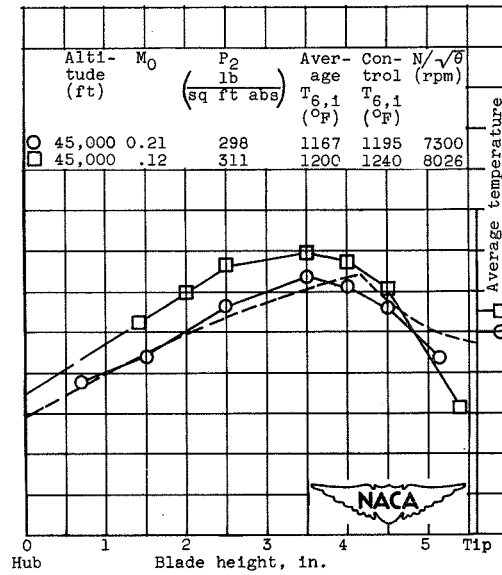
Figure 11. - Effect of inlet pressure, temperature level, and corrected engine speed on average radial turbine-inlet indicated temperature distribution in J40-WE-6 engine. Engine speed, 7260 rpm.



(a) Effect of inlet pressure.

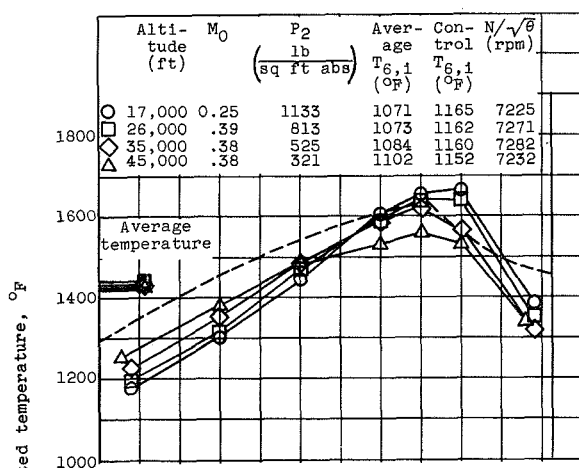


(b) Effect of temperature level.

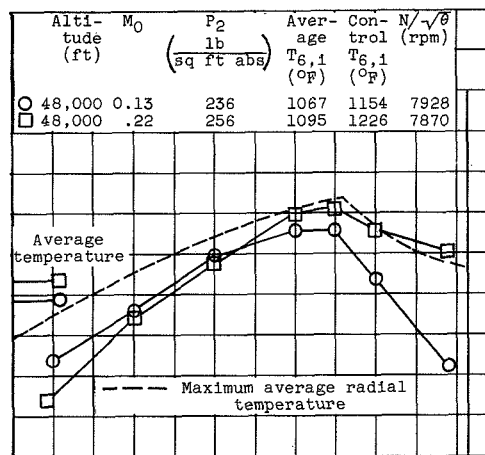


(c) Effect of corrected engine speed.

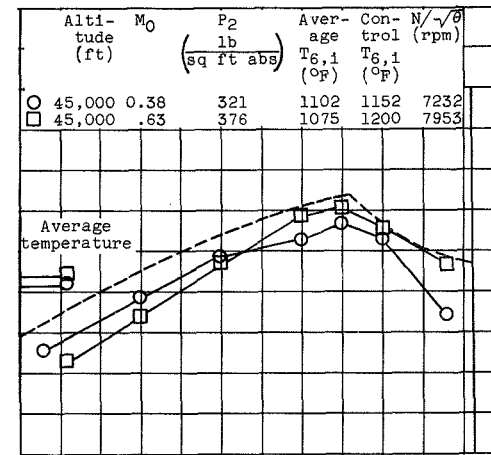
Figure 12. - Effect of inlet pressure, temperature level, and corrected engine speed on average radial turbine-inlet indicated temperature distribution in interim J40-WE-6 engine. Engine speed, 7260 rpm.



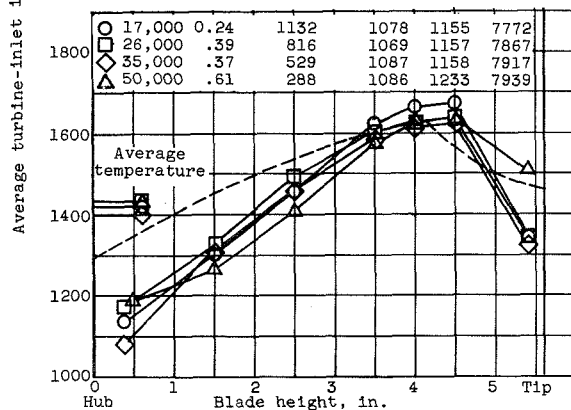
(a) Effect of inlet pressure. Average corrected engine speed, 7252 rpm.



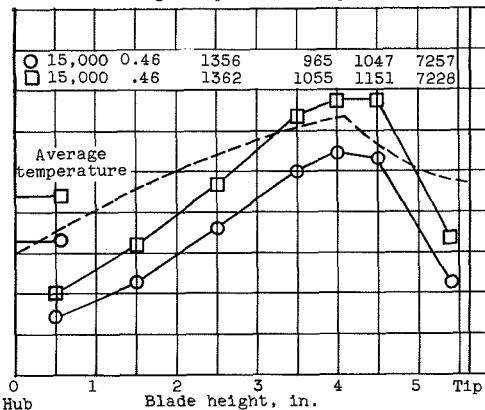
(c) Effect of temperature level. Average inlet pressure, 246 pounds per square foot absolute; corrected engine speed, 7900 rpm.



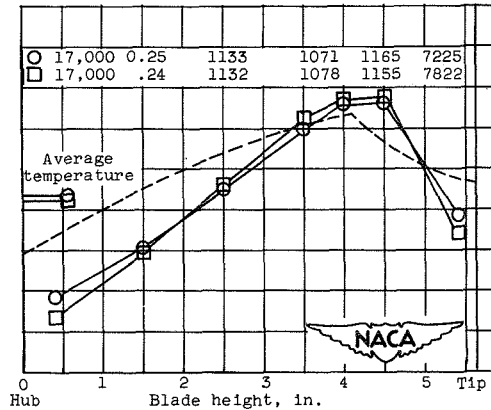
(e) Effect of corrected engine speed. Average inlet pressure, 348 pounds per square foot absolute.



(b) Effect of inlet pressure. Average corrected engine speed, 7874 rpm.

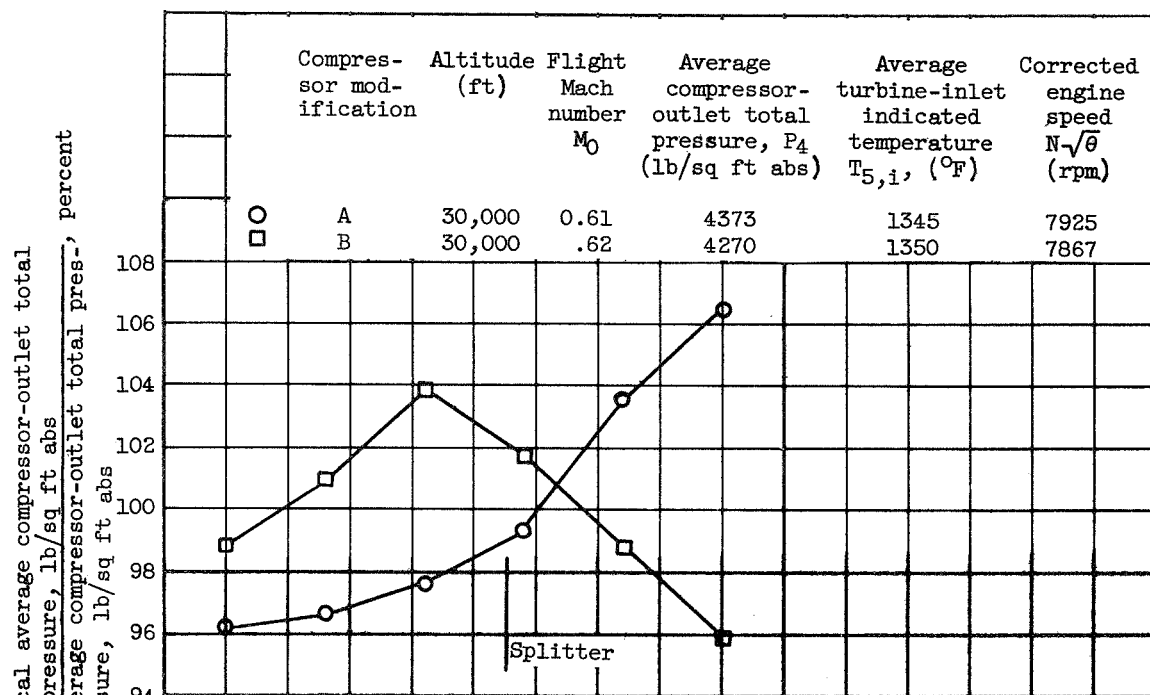


(d) Effect of temperature level. Average inlet pressure, 1359 pounds per square foot absolute; corrected engine speed, 7242 rpm.

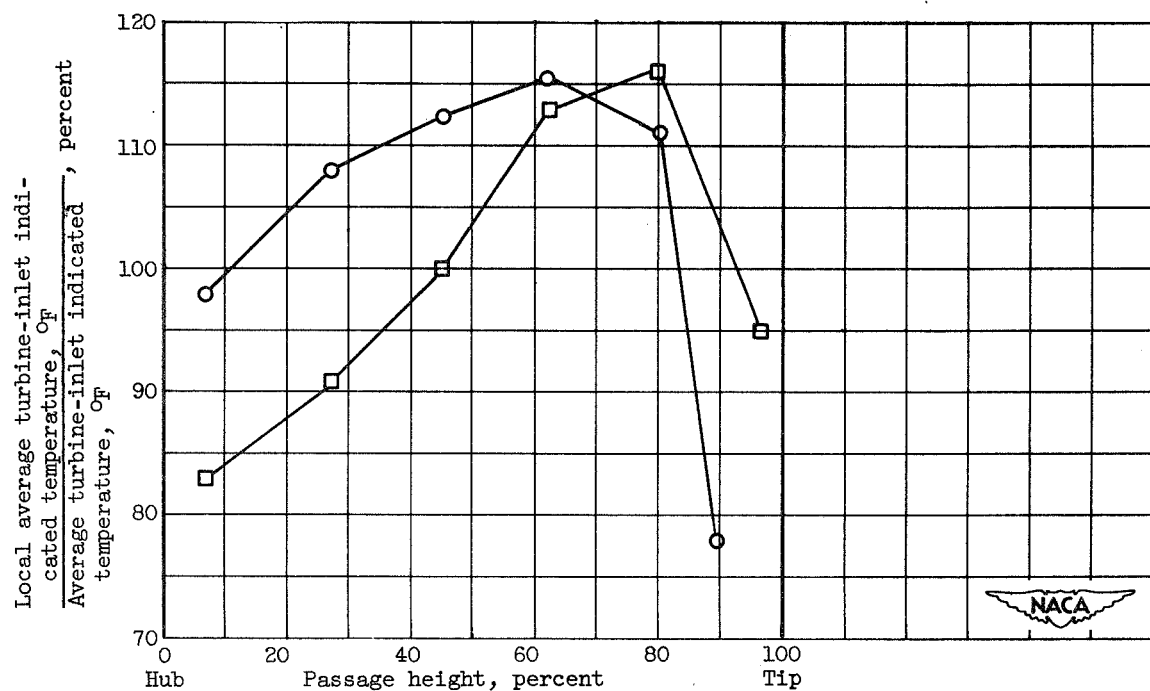


(f) Effect of corrected engine speed. Average inlet pressure, 1133 pounds per square foot absolute.

Figure 13. - Effect of inlet pressure, temperature level, and corrected engine speed on average radial turbine-inlet indicated temperature distribution in prototype J40-WE-8 engine. Engine speed, 7260 rpm.



(a) Compressor-outlet total pressure.



(b) Turbine-inlet indicated temperature.

Figure 14. - Correlation of average radial turbine-inlet indicated temperature distribution with average compressor-outlet total-pressure distribution for two compressor configurations in modified interim J40-WE-6 engine. Engine speed, 7260 rpm.

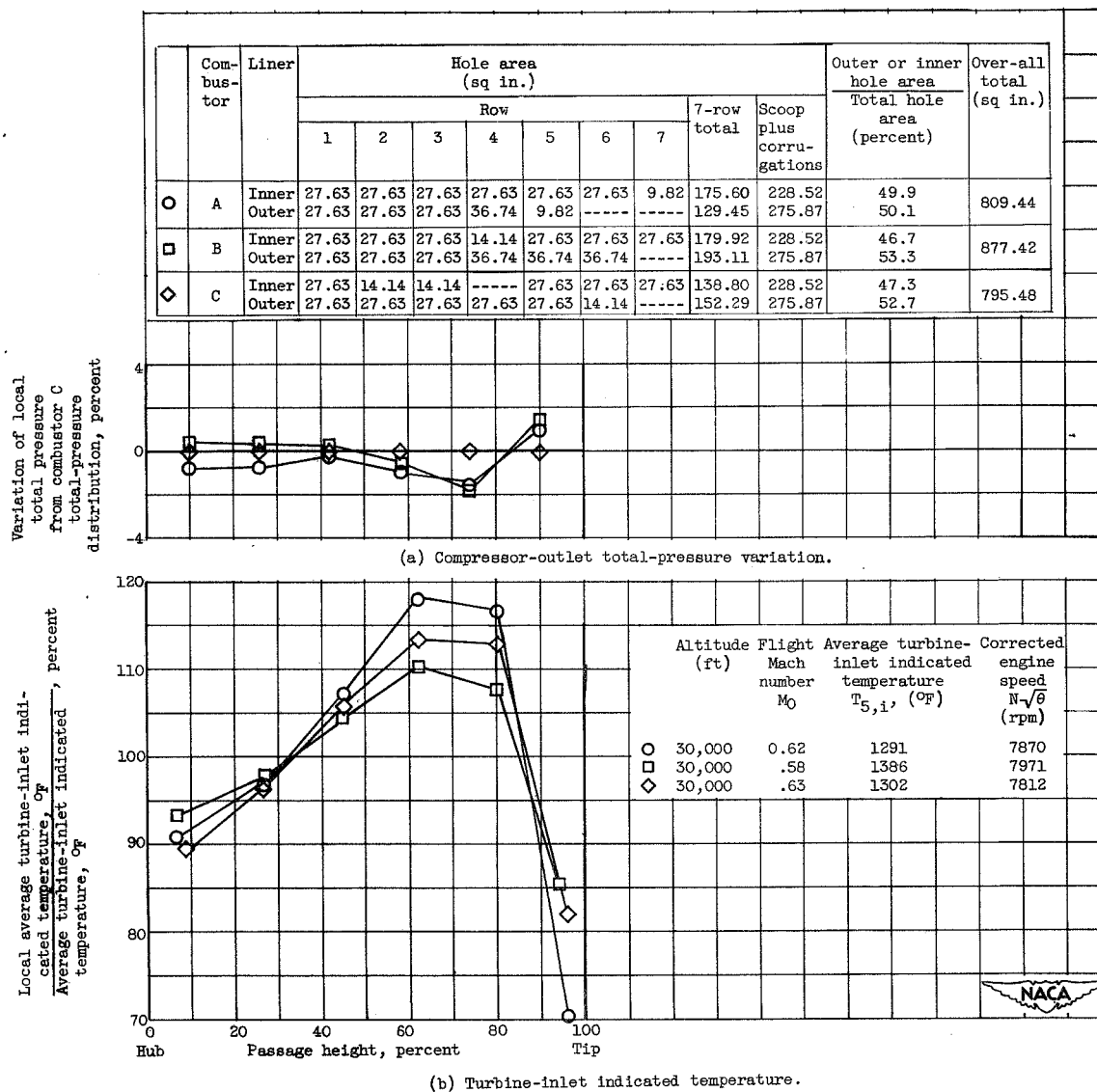
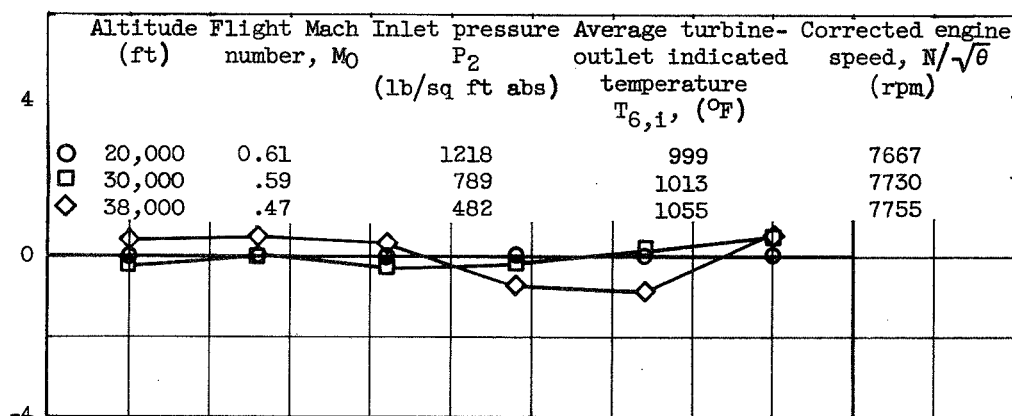
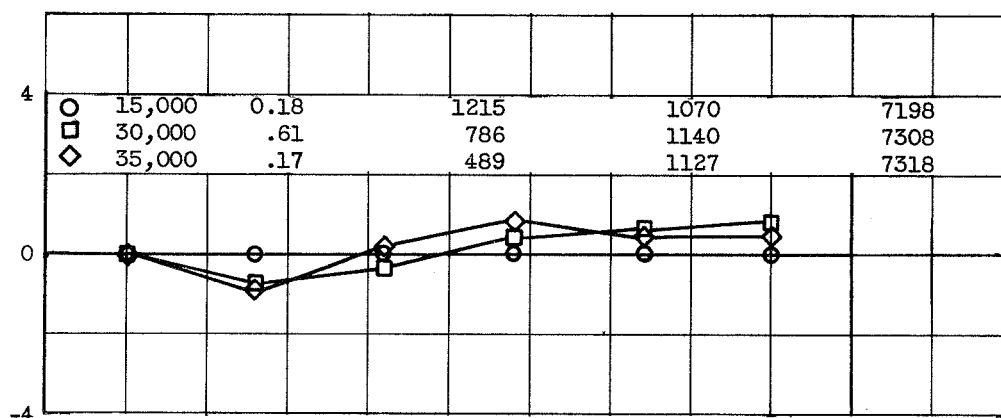


Figure 15. - Effect of engine combustor modifications on average radial turbine-inlet indicated temperature distribution in prototype J40-WE-8 engine.

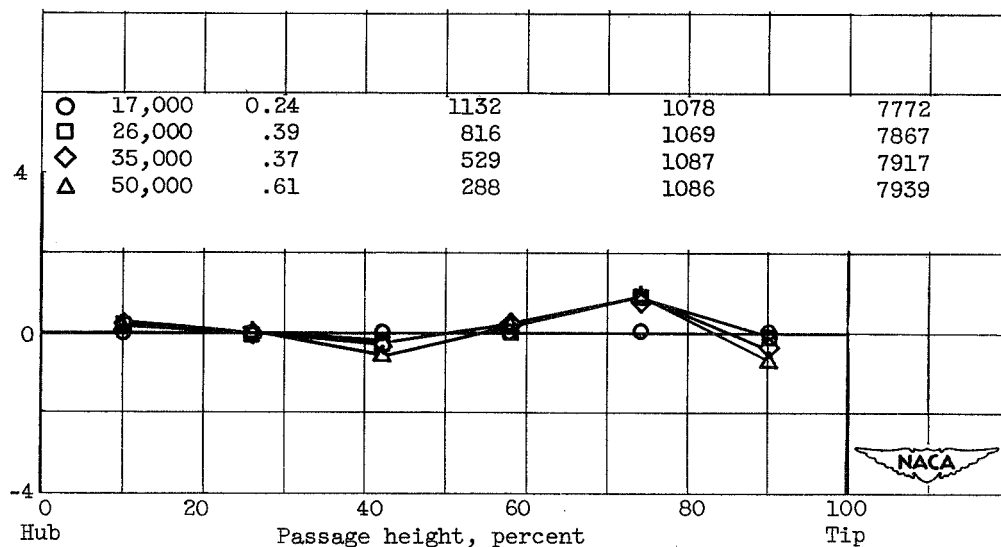
Variation of local total pressure from total-pressure distribution obtained at high inlet pressure, percent



(a) J40-WE-6 engine.



(b) Interim J40-WE-6 engine.



(c) Prototype J40-WE-8 engine.

Figure 16. - Effect of inlet pressure on variation of average compressor-outlet total-pressure distribution in J40-WE-6, interim J40-WE-6, and prototype J-40-WE-8 engines.

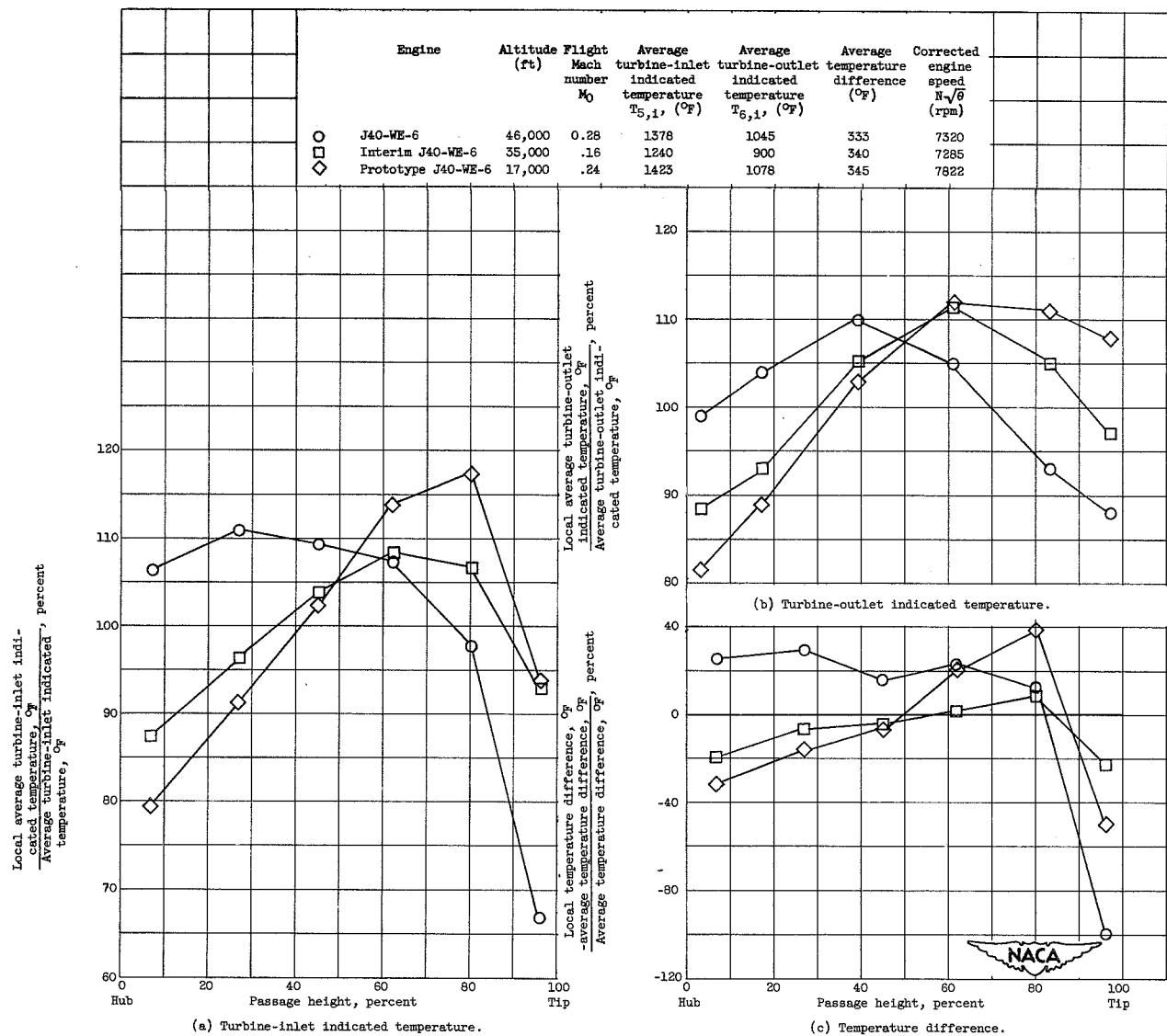


Figure 17.- Comparison of turbine-inlet and turbine-outlet indicated radial temperature distributions in J40-WE-6, interim J40-WE-6, and prototype J40-WE-8 engines.

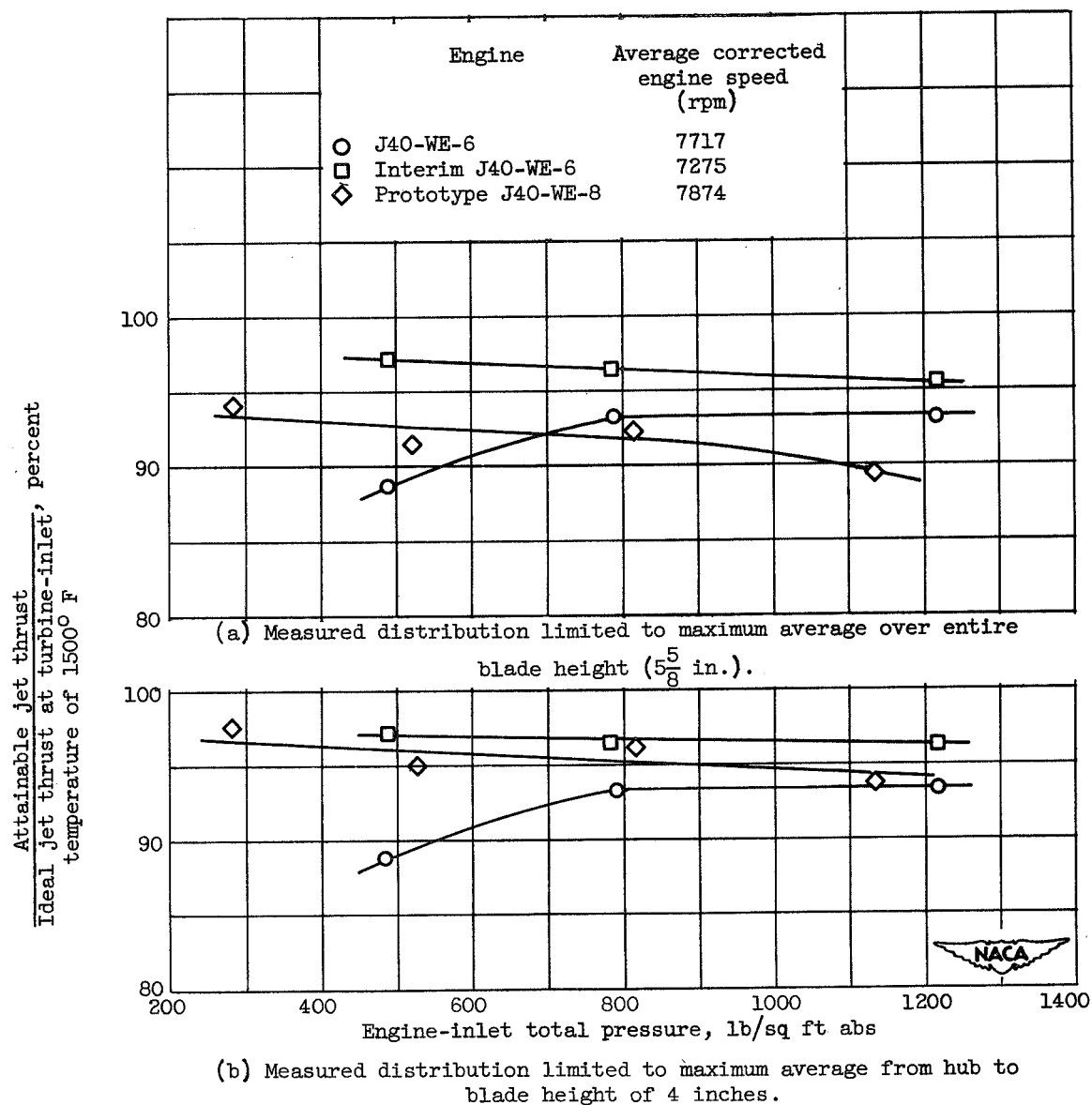


Figure 18. - Effect of turbine-inlet temperature distribution on ideal performance of three engines investigated. Engine speed, 7260 rpm.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,

RESEARCH MEMORANDUM

ALTITUDE INVESTIGATION OF GAS TEMPERATURE DISTRIBUTION AT TURBINE
OF THREE SIMILAR AXIAL-FLOW TURBOJET ENGINES

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Abstract

An investigation of the effect of inlet pressure, corrected engine speed, and turbine temperature level on turbine-inlet gas temperature distributions was conducted on a J40-WE-6, interim J40-WE-6, and prototype J40-WE-8 turbojet engine in the altitude wind tunnel at the NACA Lewis laboratory. The engines were investigated over a range of simulated pressure altitudes from 15,000 to 55,000 feet, flight Mach numbers from 0.12 to 0.64, and corrected engine speeds from 7198 to 8026 rpm. The gas temperature distribution at the turbine of the three engines over the range of operating conditions investigated was considered satisfactory from the standpoint of desired temperature distribution with one exception - the distribution for the J40-WE-6 engine indicated a trend with decreasing engine-inlet pressure for the temperature to exceed the desired in the region of the blade hub. Installation of a compressor-outlet mixer vane assembly remedied this undesirable temperature distribution. Experimental data have shown that turbine-inlet temperature distributions are influenced in the expected manner by changes in compressor-outlet pressure or mass-flow distribution and by changes in combustor hole-area distribution. Similarity between turbine-inlet and turbine-outlet temperature distribution indicated only a small shift in temperature distribution imposed by the turbine rotors. Attainable jet thrusts of the three engines were influenced in different degrees and directions by changes in temperature distributions with change in engine-inlet pressure. Inability to match the desired temperature distribution resulted, for the J40-WE-6 engine, in an 11-percent thrust loss based on an average turbine-inlet temperature of 1500° F at an engine-inlet pressure of 500 pounds per square foot absolute.