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RESEARCH MEMORANDUM

INVESTIGATION OF TURBINE-OUTLET TEMPERATURE DISTRIBUTION OF XJ34-WE-32 TURBOJET ENGINE

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RESEARCH MEMORANDUM

INVESTIGATION OF TURBINE-OUTLET TEMPERATURE DISTRIBUTION OF XJ34-WE-32 TURBOJET ENGINE

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SUMMARY

Turbine-outlet radial temperature distributions of an XJ34-WE-32 turbojet engine were investigated in the altitude wind tunnel at the NACA Lewis laboratory over a range of pressure altitudes, engine-inlet air temperatures and flight Mach numbers at or near rated engine conditions.

From blade stress and consequently turbine-life considerations, the turbine-outlet temperature distribution was considered satisfactory at altitudes up to 25,000 feet at corrected engine speeds corresponding to rated speed (12,500 rpm); however, operation at either higher corrected engine speeds or higher altitudes resulted in an inversion of the turbine temperature distribution that was detrimental to turbine life.

The maldistribution of turbine temperature associated with the aforementioned changes in operating conditions was attributed to changes in compressor and combustor characteristics. An increase in the corrected engine speed beyond a value corresponding to rated speed resulted in an adverse radial velocity gradient at the compressor outlet; whereas changes in altitude did not appreciably change the compressor-outlet velocity gradient and it was presumed that the temperature inversion that occurred at high altitude originated in the engine combustor.

In order to improve the compressor-outlet velocity profiles, the engine manufacturer designed and fabricated a stage of stationary mixer vanes that was installed directly downstream of the last stage of straightening vanes at the compressor outlet. Installation of the mixer vanes produced a more favorable compressor-outlet velocity gradient which, coupled with increased turbulence, greatly improved the turbine radial temperature distribution and, unlike the engine without the mixer, the distribution was not appreciably affected by changes in flight condition, corrected engine speed, or temperature level. As a result of the turbine temperature distribution being unaffected by change in engine or flight conditions with the mixer installed, it was possible to operate the engine at rated turbine-outlet temperature without sacrificing turbine life.

INTRODUCTION

An investigation has been conducted in the altitude wind tunnel at the NACA Lewis laboratory to determine the performance and operational characteristics of an XJ34-WE-32 turbojet engine. During the initial phase of this program, it was found that an adverse radial temperature distribution, which indicated serious maldistribution of gas temperatures at the turbine inlet, existed at the turbine outlet. This adverse temperature distribution was similar to that reported in reference 1. From blade-stress and consequently turbine-life considerations, the temperature distributions were marginally tolerable at low altitudes but were aggravated by the increase in corrected engine speed associated with increased altitude so as to be detrimental to turbine life. Thus, in order to prolong turbine life, it was necessary to reduce the limiting exhaust gas temperature with a consequent reduction in thrust below the maximum potential thrust of the engine.

The maldistribution of turbine temperatures was primarily attributed to adverse radial-velocity gradients at the compressor outlet (combustor inlet). In order to improve the compressor-outlet velocity profiles, the engine manufacturer designed and fabricated a stage of stationary mixer vanes that was installed directly downstream of the last stage of straightening vanes at the compressor outlet. The effect of these mixer vanes on turbine-outlet temperature distribution was investigated over a range of pressure altitudes, engine-inlet air temperatures, and flight Mach numbers at or near rated engine conditions and the results of this investigation are presented herein. Pertinent data are presented in graphical form for comparing the turbine-outlet temperature distributions with and without mixer vanes.

APPARATUS AND INSTRUMENTATION

Engine

The XJ34-WE-32 axial-flow turbojet engine used in the altitude wind tunnel investigation has a sea-level static rating of 3370 pounds thrust (afterburner inoperative) at an engine speed of 12,500 rpm and a turbine-inlet temperature of 1525° F. For the engine used in this investigation, this temperature corresponds to a turbine-outlet temperature of approximately 1280° F. At this rating, the engine air flow is 58 pounds per second. The main components of the engine include an eleven-stage axial-flow compressor with a pressure ratio of about 4.0 at rated engine speed, a double-annulus basket-type combustor, a two-stage turbine, an afterburner, and a clamshell-type variable-area exhaust nozzle. The over-all length of the engine is approximately 185 inches, and the total dry weight is 1558 pounds. The engine is equipped with an electronic control that varies the engine fuel flow and exhaust-nozzle area to maintain a schedule of turbine-outlet temperature and engine speed. The temperature sensing device for the control consisted of nine parallel chromel-alumel thermocouples that were immersed in the gas stream 3/4 of the annular passage height, $17\frac{3}{8}$ inches downstream of the turbine flange.

Installation and Instrumentation

The engine was mounted on a wing section that spanned the 20-foot diameter test section of the altitude wind tunnel (fig. 1). Dry refrigerated air was supplied to the engine from the tunnel make-up air system through a duct connected to the engine inlet. Engine thrust and drag measurements by the tunnel balance scales were made possible by a frictionless slip joint located in the duct upstream of the engine. The air flow through the duct was throttled from approximately sea-level pressure to a total pressure at the engine inlet corresponding to the desired flight Mach number at a given altitude.

Temperature and pressure measurements throughout the engine were obtained at the stations shown in figure 2. The detailed location of the instrumentation at the compressor inlet, compressor outlet, and turbine outlet is shown in figure 3. The compressor outlet rakes for the engine without the mixer vanes were mounted $1\frac{3}{16}$ inches downstream of the the last stage of the compressor-outlet straightening vanes. With the mixer vanes installed, it was necessary to move the rakes downstream $2\frac{5}{8}$ inches beyond the last stage straightening vanes. The temperatures were measured and recorded by self-balancing potentiometers. The pressures were measured by alkazine and mercury manometers and were photographically recorded.

Mixer Vane

The mixer assembly (fig. 4) consisting of 60 stationary vanes was installed 5/16-inch downstream of the trailing edge of the second stage straightening vanes at the compressor outlet. Each vane had a chord of $1\frac{1}{2}$ inch and an approximate span of 3 inches and was constructed by fixing the midspan section parallel to the axis of the engine; the root and tip sections of adjacent vanes were twisted about 30° in opposite directions. The action of the mixer vanes on the compressor-outlet air flow was such that in alternate vanes the air at the tips was forced downward in the direction of increased area and the air at the roots followed an upward path also in the direction of increased area thus resulting in turbulent mixing of the air entering the combustor.

PROCEDURE

The engine was operated with and without mixer vanes at altitudes from 5000 to 40,000 feet and over a range of flight Mach numbers from 0.26 to 1.05. A range of corrected engine speeds from rated speed (12,500 rpm) to 13,474 rpm was obtained by varying the engine speed and inlet-air temperature. Corrected engine speed is defined as the ratio of actual engine speed to the square root of the ratio of engine-inlet absolute total temperature to the absolute static temperature of NACA standard atmosphêre at sea level. Variations in average turbine-outlet indicated temperature levels, ranging from 1130° to 1319° F, were obtained by controlling the fuel flow and exhaust-nozzle area.

The radial temperature distribution at the turbine-outlet annulus was obtained from an average of the individual thermocouple readings at each radial position from six circumferentially located rakes.

Fuel conforming to the specification MIL-F-5572, with a lower heating value of 19,000 Btu per pound and a hydrogen-carbon ratio of 0.185 was used throughout the investigation.

RESULTS AND DISCUSSION

Data are presented in graphical form to show the turbine-outlet temperature and compressor-outlet velocity distributions with and without mixer vanes for a range of corrected engine speeds and average turbine-outlet temperatures at several altitudes and flight Mach numbers. The temperature distributions are plotted radially as a function of passage height and the manufacturer's desired temperature limit curve is superimposed on each individual radial temperature distribution.

Desired Temperature Distribution

The manufacturer's desired radial turbine-outlet temperature distribution at the measuring station $4\frac{5}{8}$ inches downstream of the turbine flange is plotted in figure 5 as a function of passage height. The temperature varies spanwise from a value of 1130° F at the blade root to a peak value of 1415° F at a point on the blade $2\frac{3}{4}$ inches from the root ($3\frac{1}{4}$ in. from the inner wall at the measuring station) and then decreases to 1290° F at the blade tip. This temperature distribution was established by the manufacturer as the optimum curve from blade stress and maximum turbine-output conditions determined from investigation of both the turbine blades and stationary nozzles at simulated loads and temperatures corresponding to actual turbine operating conditions.

Temperature Inversion Problem

Effect of corrected engine speed and altitude. - The effect of corrected engine speed and altitude on the average radial turbine-outlet temperature distribution for the engine without the mixer assembly is shown in figure 6. The radial temperature distribution (fig. 6(a)) at an altitude of 25,000 feet and rated engine speed (corrected engine speed of 12,512 rpm) is considered satisfactory from the standpoint of the manufacturer's desired limit. For the same flight conditions, increasing the corrected engine speed to 13,238 rpm resulted in an inversion of the temperature pattern; that is, the temperature near the turbine root was considerably higher than the temperature at the tip. The increase in temperature at the root section exceeded the manufacturer's average limit and further increase in the average gas temperature at the turbine outlet would result in severe local overtemperaturing. As a result of this temperature inversion at high corrected engine speeds, it was necessary to operate the engine at lower average turbine-outlet temperatures to conserve turbine life. The reduction in average temperature was accompanied by reduced thrust output of the engine. A similar inversion of turbine-outlet temperature also occurred (fig. 6(b)) with increase in altitude to 40,000 feet at a constant corrected engine speed of 12,427 rpm.

Another consequence of the temperature inversion problem was the location of the control thermocouple probes which sensed turbine-outlet temperature. The probes were immersed into the gas stream 3/4 of the annular passage height at the turbine outlet and provided the temperature signal for the electronic control. Inasmuch as the electronic control varied engine fuel flow and exhaust-nozzle area to maintain a schedule of turbine outlet temperature and engine speed, safe turbine temperatures were maintained only when the temperature distribution remained constant and corresponded to that for which the control was calibrated. When engine conditions were changed and a temperature inversion existed, the control thermocouples (located in the region of the turbine-root section) sensed a temperature higher than the true average turbine-outlet temperature and consequently limited the thrust output.

Effect of temperature level. - The effect of variations in turbine-outlet temperature level for the engine without the mixer assembly on the radial turbine-outlet temperature distribution at altitudes of 5000 and 40,000 feet and an average corrected engine speed of 13,283 rpm is shown in figure 7. At low altitude (fig. 7(a)), the temperature distribution was satisfactory for the low temperature levels; however, at high turbine-outlet temperature (1274° F), the distribution was undesirable. For an altitude of 40,000 feet (fig. 7(b)), undesirable temperature distributions existed at all temperature levels with a trend toward a less desirable distribution with decrease in temperature level.

Effect of flight Mach number. - The effect of flight Mach number on radial turbine-outlet temperature distributions (without mixer) at an altitude of 25,000 feet and corrected engine speed of 12,415 rpm is shown in figure 8. Variations in flight Mach number did not appreciably affect the temperature distribution, however, an increase in flight Mach number slightly improved the temperature distribution with respect to the desired limit.

Explanation of Inversion Problem

The adverse radial temperature distribution shown to exist for the engine without the mixer at the turbine outlet during conditions of either high corrected engine speed or high altitude is partially explained by the effect of the two aforementioned conditions on the average radial compressor-outlet velocity distribution (fig. 9). At a condition for which the temperature distribution at the turbine outlet was satisfactory (corrected engine speed, 12,512 rpm; altitude, 25,000 ft) the radial compressor-outlet velocity distribution (fig. 9(a)) was fairly uniform across the flow passage with velocities of approximately 300 feet per second at the root and tip sections and a peak velocity occurring at the midspan of about 350 feet per second. An increase in corrected engine speed at the same flight conditions, which resulted in an adverse turbine-outlet temperature distribution, was associated with an increase in the peak velocity to 450 feet per second at the tip section and a decrease in velocity at the root section to approximately 100 feet per second. The lower velocity at the root section and consequently the lower air flow in the inner portion of the compressor-outlet annulus resulted in a fuel rich region in the inner annulus of the combustion basket and an increase in turbine root temperature. The change in velocity profile at the compressor outlet is attributed to a change in compressor characteristics with change in compressor-inlet Mach number (corrected engine speed). Another possible factor contributing to the adverse temperature distribution is insufficient turbulence in the combustion chamber to thoroughly mix the gas before it enters the turbine. The temperature shift due to an increase in altitude is, however, not accompanied by any definite shift in the compressor-outlet velocity distribution (fig. 9(b)); therefore, the temperature inversion that occurs at high altitude is presumed to primarily originate in the engine combustor.

Solution of Inversion Problem

In order to improve the compressor-outlet radial velocity profiles, the engine manufacturer designed and fabricated a stage of stationary mixer vanes that was installed directly downstream of the last stage of straightening vanes at the compressor outlet. The effect of these mixer vanes on radial turbine-outlet temperature distribution for a range of corrected engine speeds, altitudes, temperature levels, and flight Mach numbers is presented in figures 10 to 12, respectively. In general, it is shown that the turbine-outlet temperature profile shift associated with both increase in corrected engine speed and altitude was no longer evident with the compressor-outlet mixer vanes installed. As a result of the turbine temperature distribution being unaffected by changes in engine or flight conditions with the mixer installed, the engine can be operated at rated turbine-outlet temperature without sacrificing turbine life.

The satisfactory turbine-outlet temperature distributions for the engine with the mixer installed are attributed to the action of the mixer on the compressor-outlet velocity distribution coupled with introduction of turbulence into the air stream entering the engine combustor. The average radial compressor-outlet velocity distributions with mixer (fig. 13) were approximately symmetrical about the center of the annulus and were not appreciably affected by changes in corrected engine speed or altitude.

CONCLUDING REMARKS

Turbine-outlet radial temperature distributions of an XJ34-WE-32 turbojet engine were investigated in the altitude wind tunnel at the NACA Lewis laboratory over a range of pressure altitudes, engine-inlet air temperatures and flight Mach numbers at or near rated engine con conditions.

From blade stress and consequently turbine-life considerations, the turbine-outlet temperature distribution was considered satisfactory at altitudes up to 25,000 feet at corrected engine speeds corresponding to rated speeds (12,500 rpm); however, operation at either higher corrected engine speeds or higher altitudes resulted in an inversion of the turbine temperature distribution which was detrimental to turbine life.

The maldistribution of turbine temperature associated with the aforementioned changes in operating conditions was attributed to changes in compressor and combustor characteristics. An increase in the corrected engine speed beyond a value corresponding to rated speed resulted in an adverse radial velocity gradient at the compressor outlet; whereas changes in altitude did not appreciably change the compressor-outlet velocity gradient and it was presumed that the temperature inversion that occurred at high altitude originated in the engine combustor.

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Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 1, 1951

REFERENCE

1. Saari, Martin J., and Prince, William R.: Altitude-Wind-Tunnel Investigation of a 3000-Pound-Thrust Axial-Flow Turbojet Engine. VII - Pressure and Temperature Distributions. NACA RM E8C17, 1948.

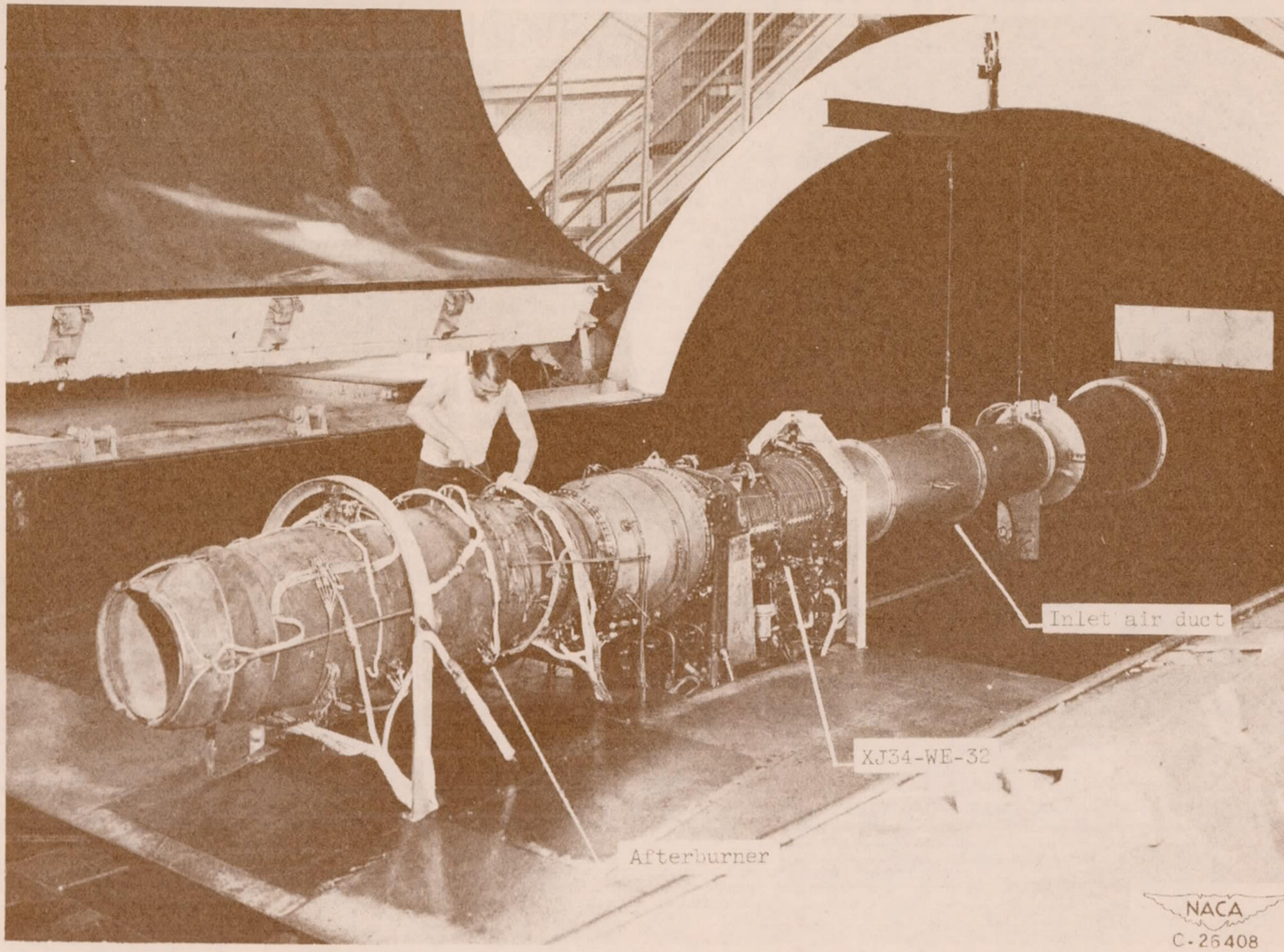

Figure 1. - Installation of XJ34-WE-32 in altitude wind tunnel.

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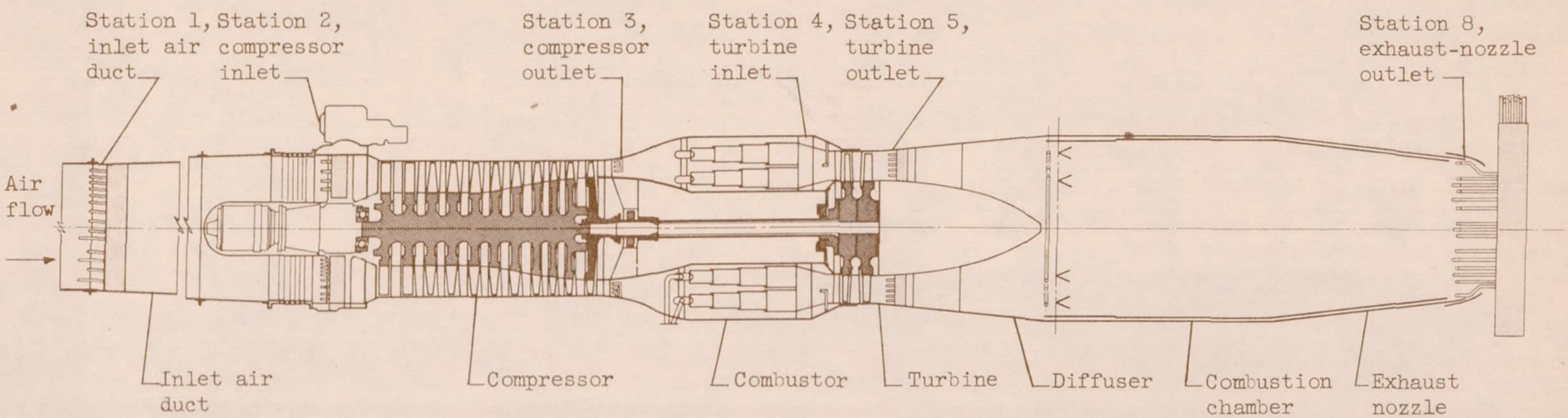

Figure 2. - Cross section of engine showing location of instrumentation.

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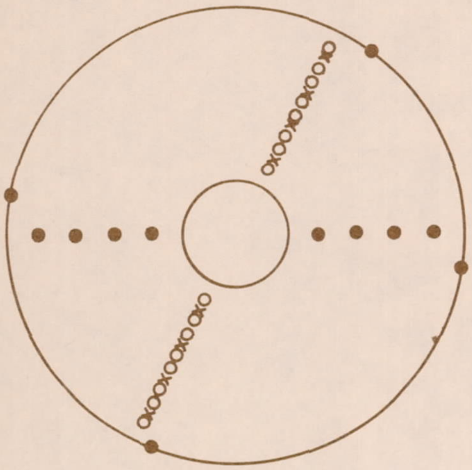
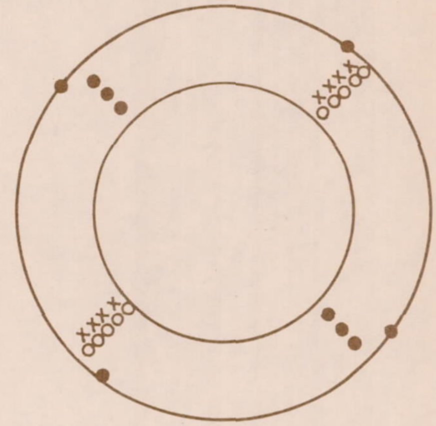
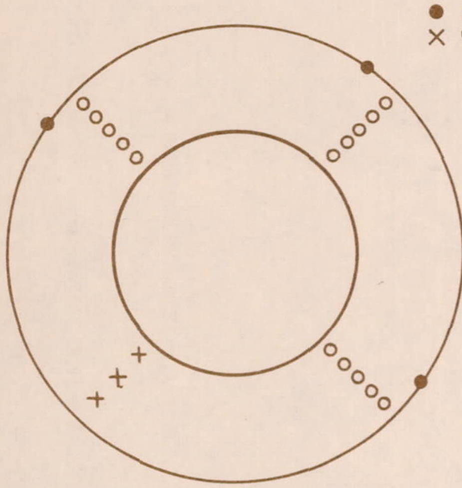


(a) Station 2, compressor inlet, 3/4 inch downstream of compressor-inlet flange.

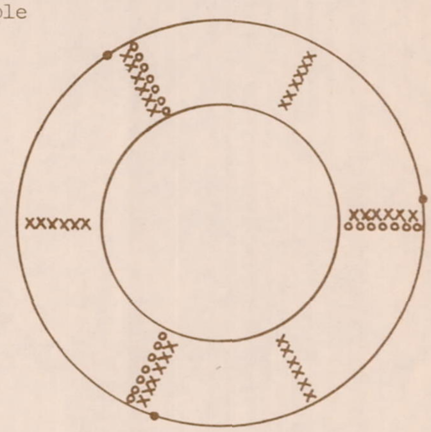


(b) Station 3, compressor outlet without mixer vanes, $1\frac{3}{16}$ inches downstream of last stator.

O Total pressure
● Static pressure
X Thermocouple



(c) Station 3, compressor outlet with mixer vanes, $2\frac{3}{4}$ inches downstream of last stator.



(d) Station 5, turbine outlet, $4\frac{5}{8}$ inches downstream of turbine flange.

Figure 3. - Pressure and temperature survey instruments as installed at measuring stations in engine, viewed looking downstream.

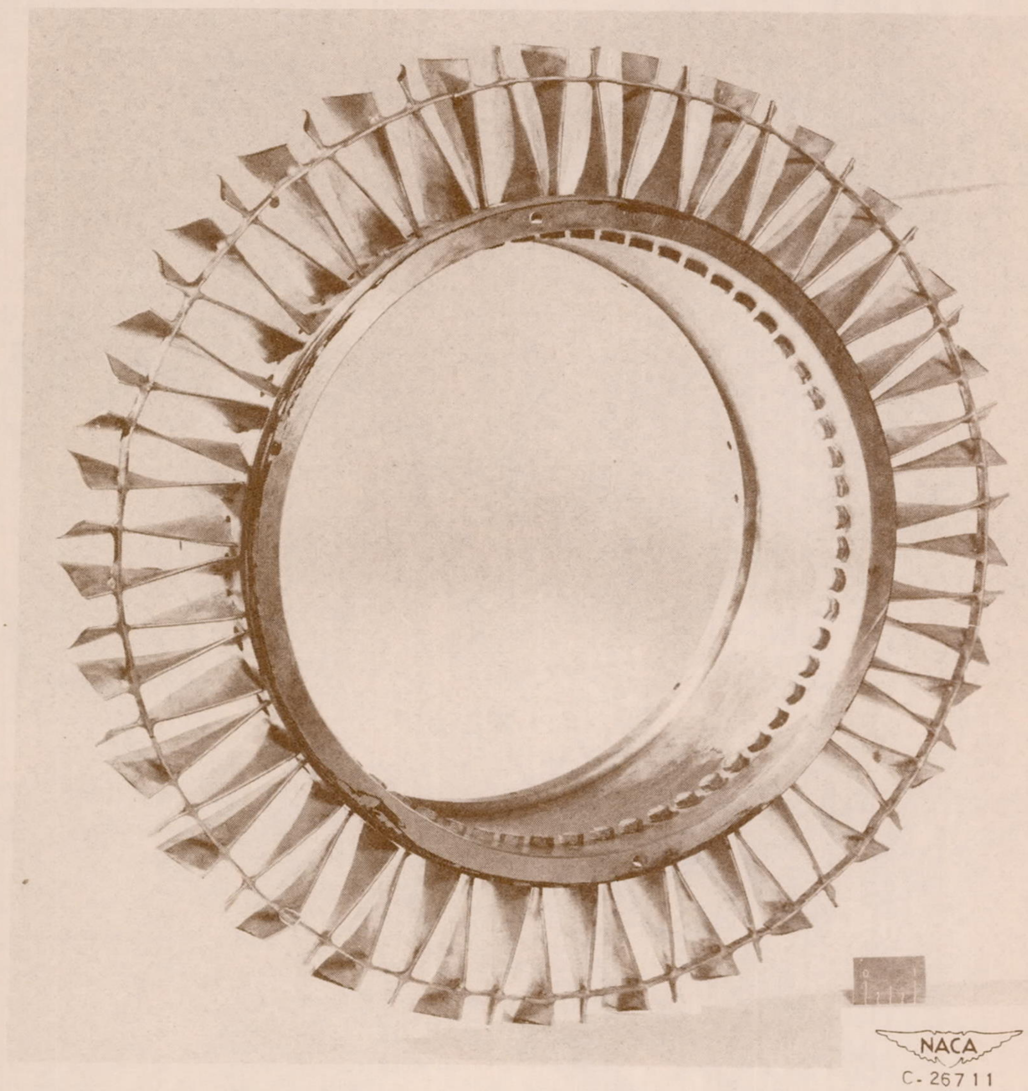


Figure 4. - Compressor-outlet mixer vane assembly.

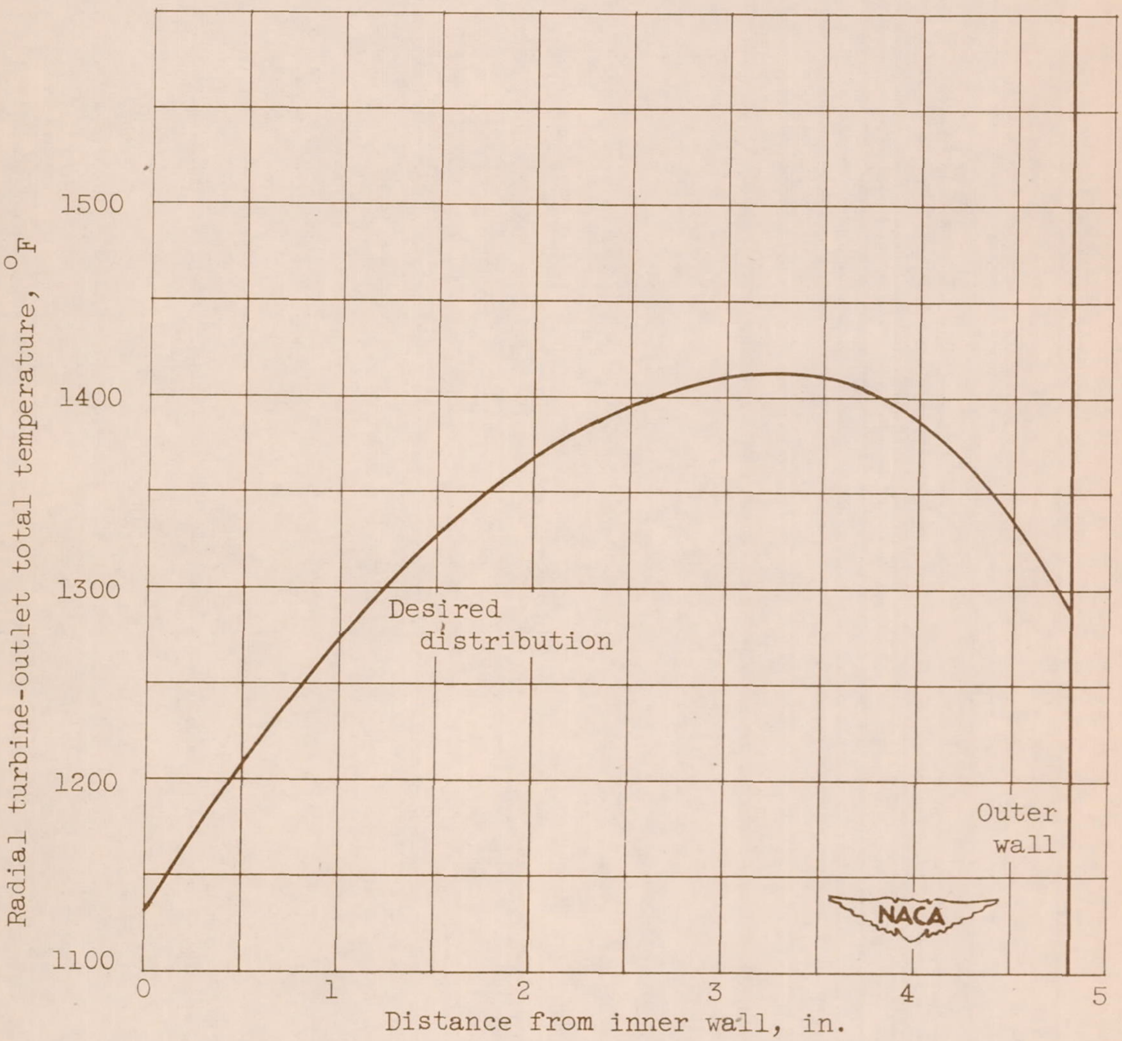
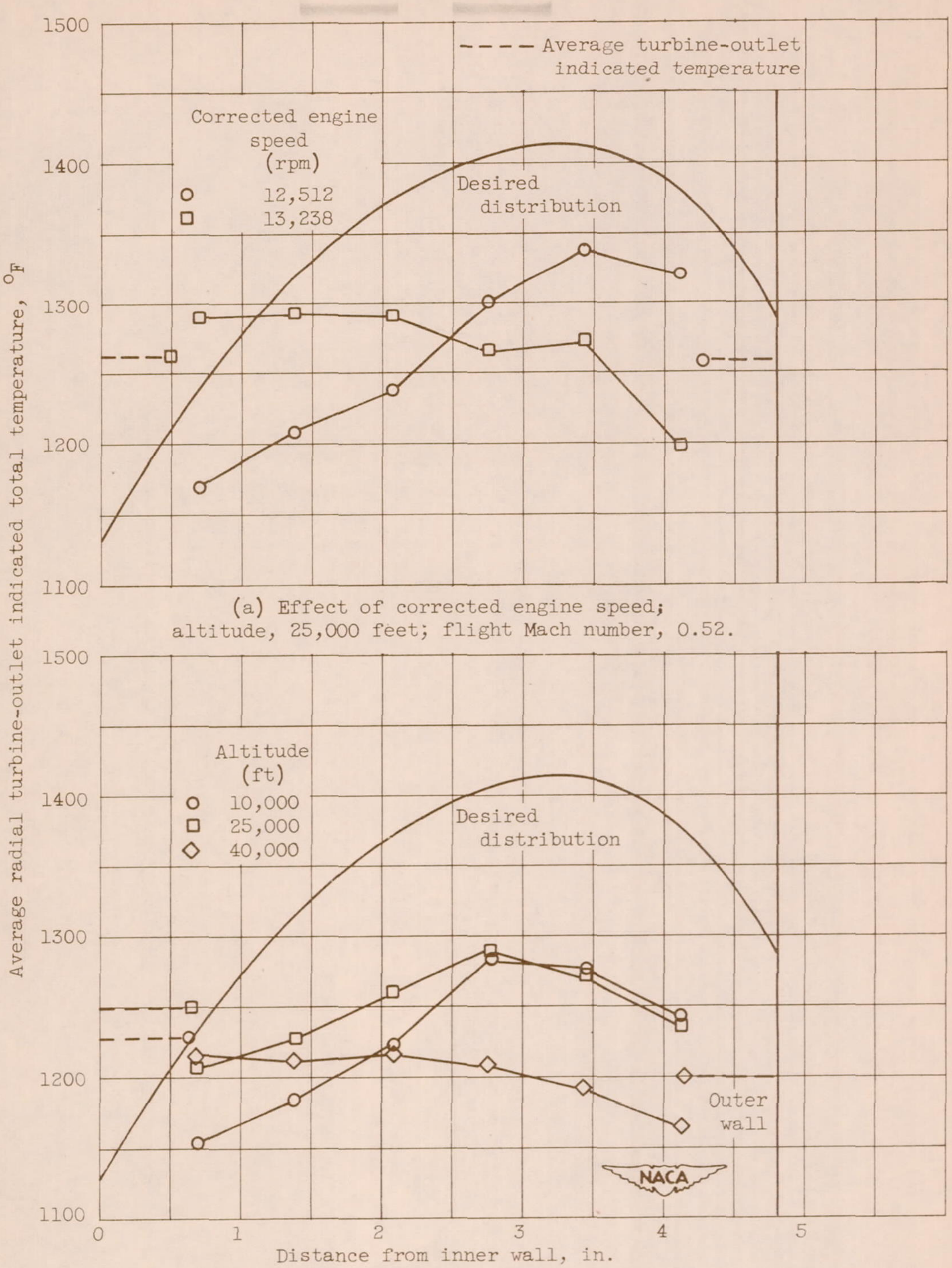


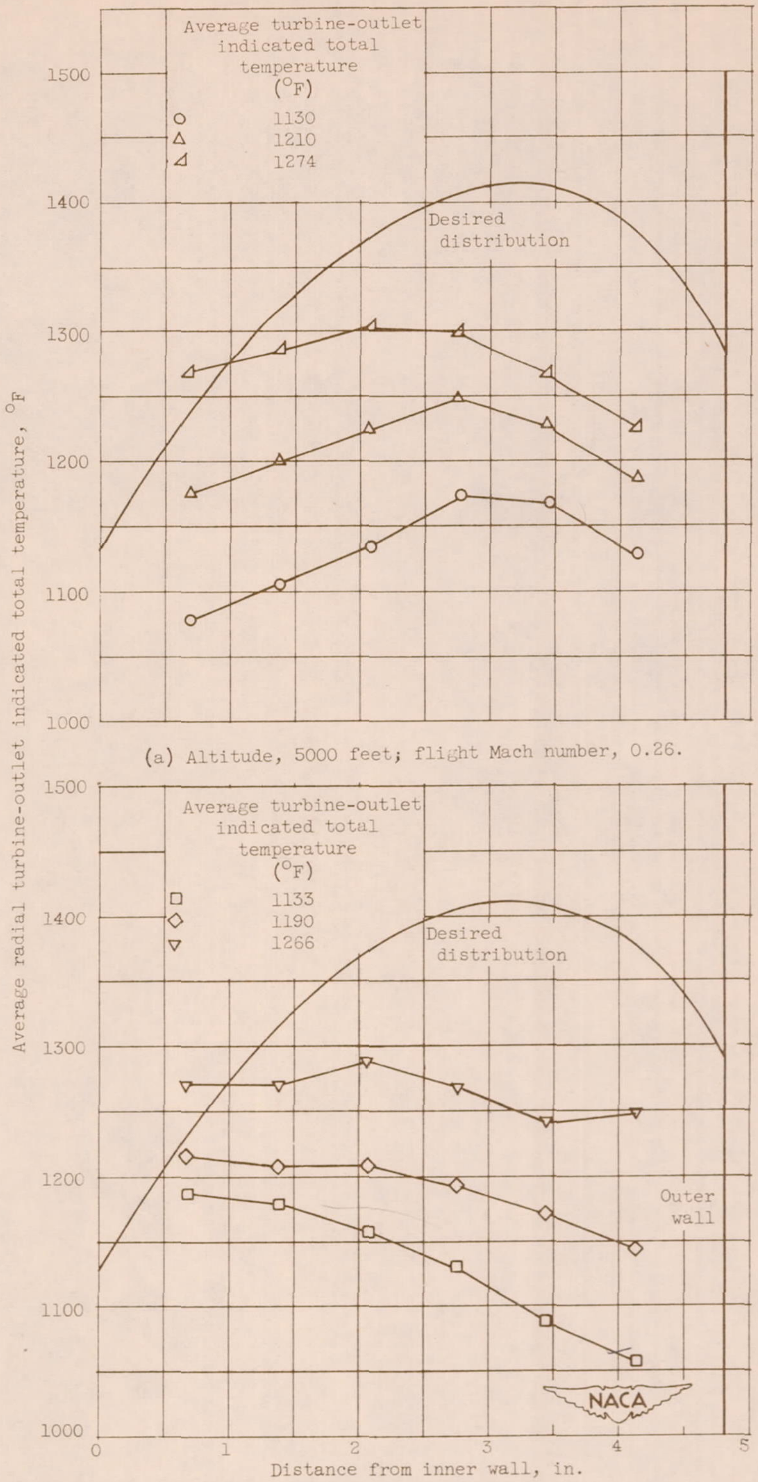
Figure 5. - Limitation of radial turbine-outlet total temperature $4\frac{5}{8}$ inches downstream of turbine flange in XJ34-WE-32 engine.



(a) Effect of corrected engine speed; altitude, 25,000 feet; flight Mach number, 0.52.

(b) Effect of altitude; average corrected engine speed, 12,427 rpm; flight Mach number, 0.52.

Figure 6. - Effect of corrected engine speed and altitude on radial turbine-outlet temperature distribution in XJ34-WE-32 engine without mixer vanes.



(b) Altitude, 40,000 feet; flight Mach number, 0.52.

Figure 7. - Effect of temperature level on radial turbine-outlet temperature distribution in XJ34-WE-32 engine without mixer vanes. Average corrected engine speed, 13,283 rpm.

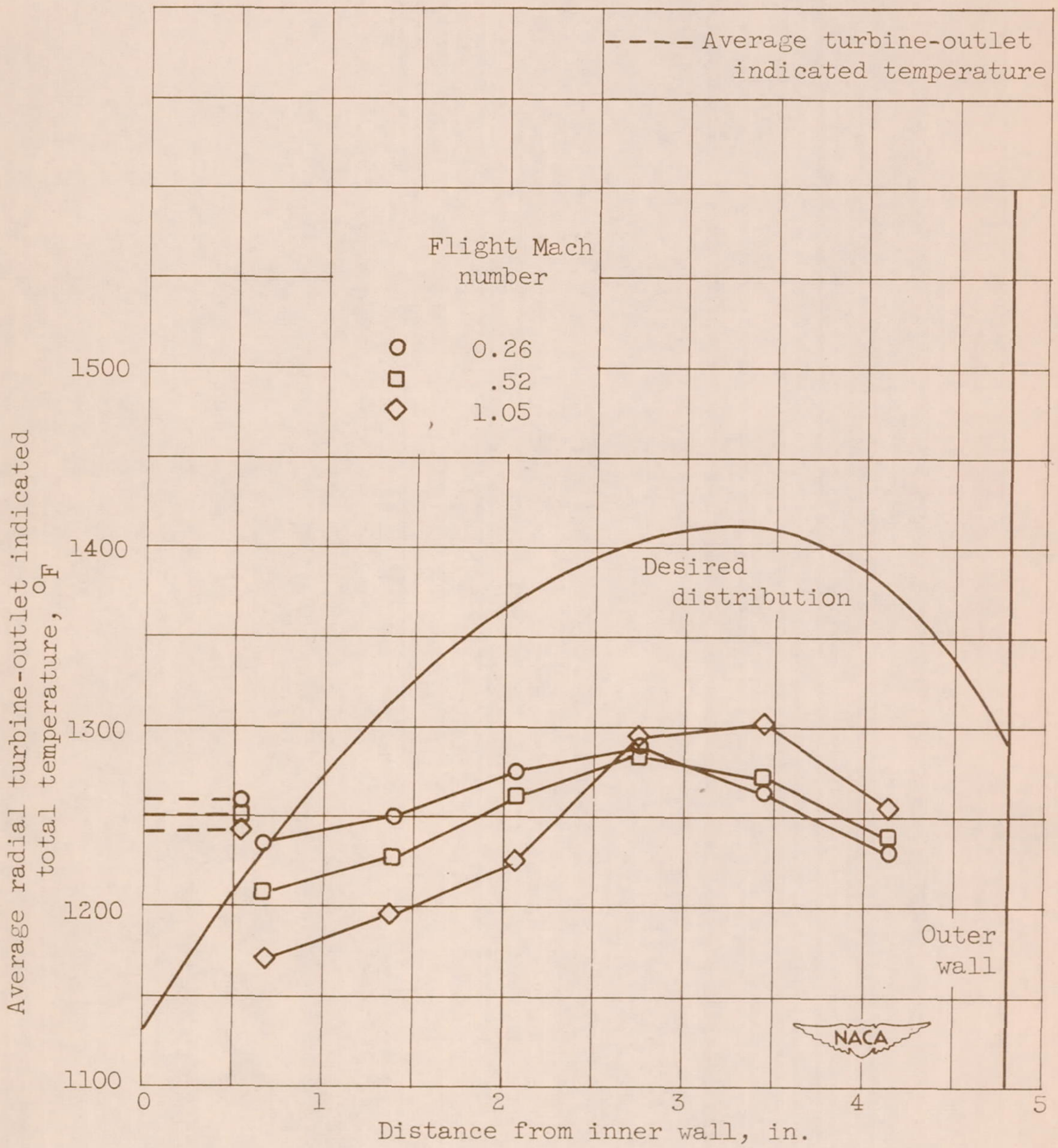
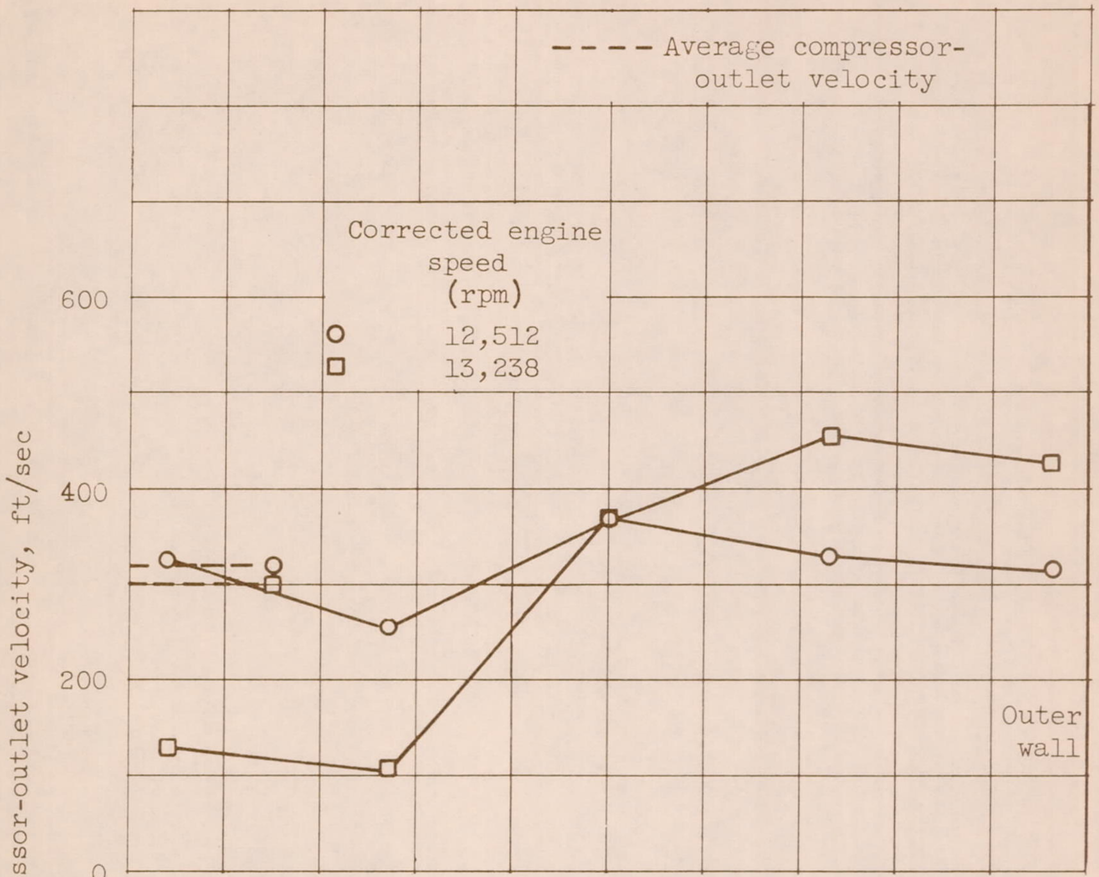
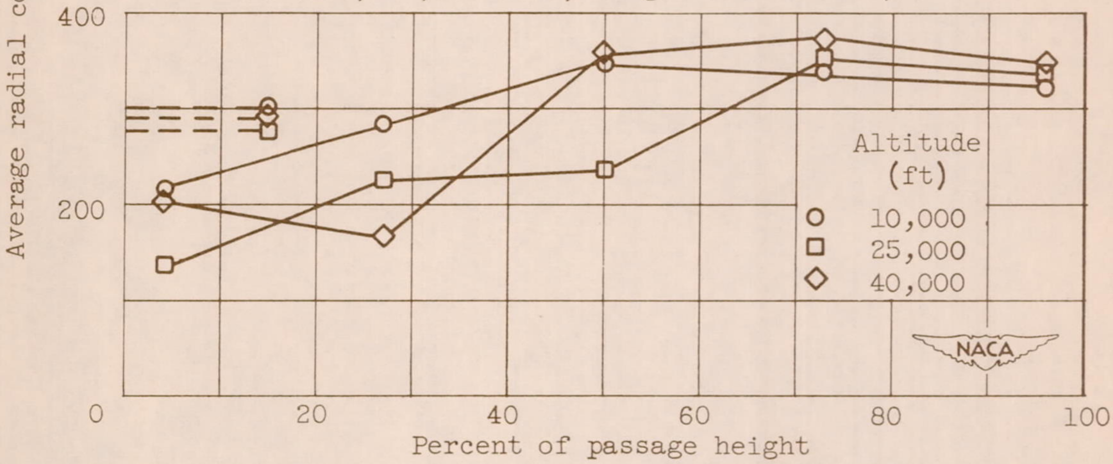


Figure 8. - Effect of flight Mach number on radial turbine-outlet temperature distribution in XJ34-WE-32 engine without mixer vanes. Altitude, 25,000 feet; corrected engine speed, 12,415 rpm.

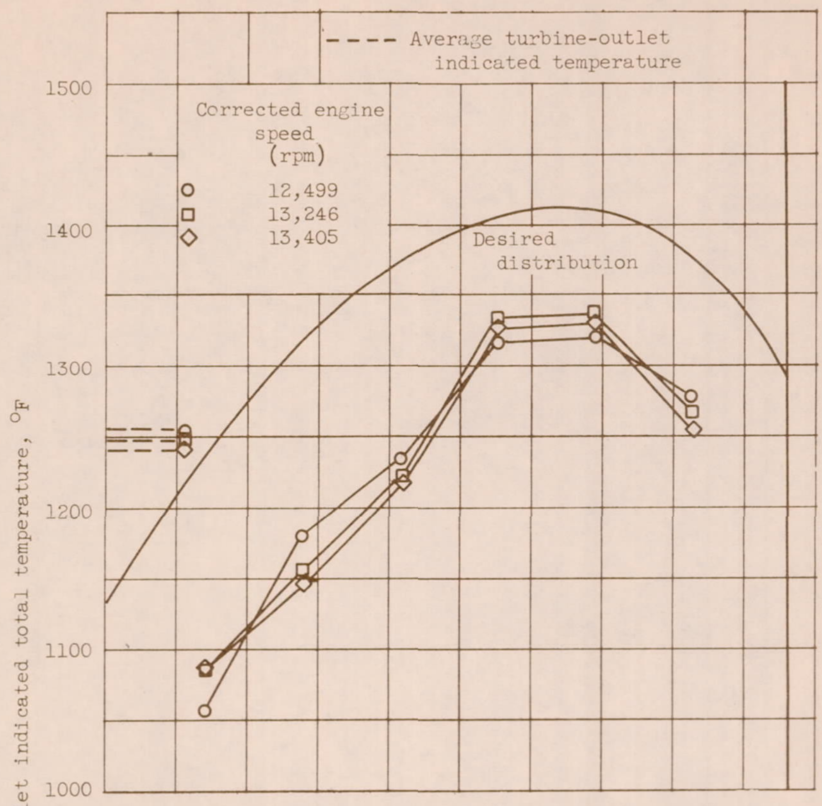


(a) Effect of corrected engine speed; altitude, 25,000 feet; flight Mach number, 0.52.

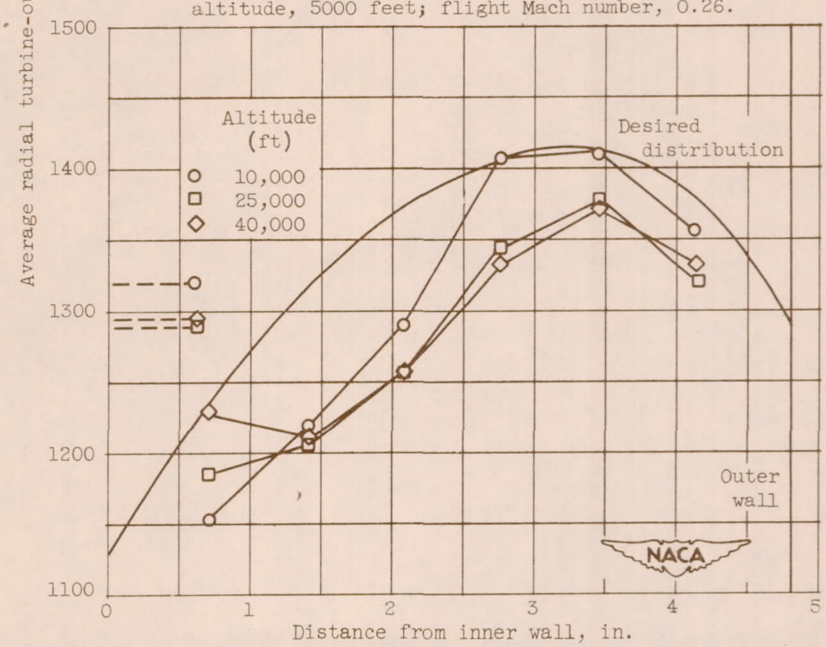


(b) Effect of altitude; average corrected engine speed, 12,427 rpm; flight Mach number, 0.52.

Figure 9. - Effect of corrected engine speed and altitude on radial compressor-outlet velocity distribution in XJ34-WE-32 engine without mixer vanes.



(a) Effect of corrected engine speed; altitude, 5000 feet; flight Mach number, 0.26.



(b) Effect of altitude; average corrected engine speed, 13,208 rpm; flight Mach number, 0.52.

Figure 10. - Effect of corrected engine speed and altitude on radial turbine-outlet temperature distribution in XJ34-WE-32 engine with mixer vanes.

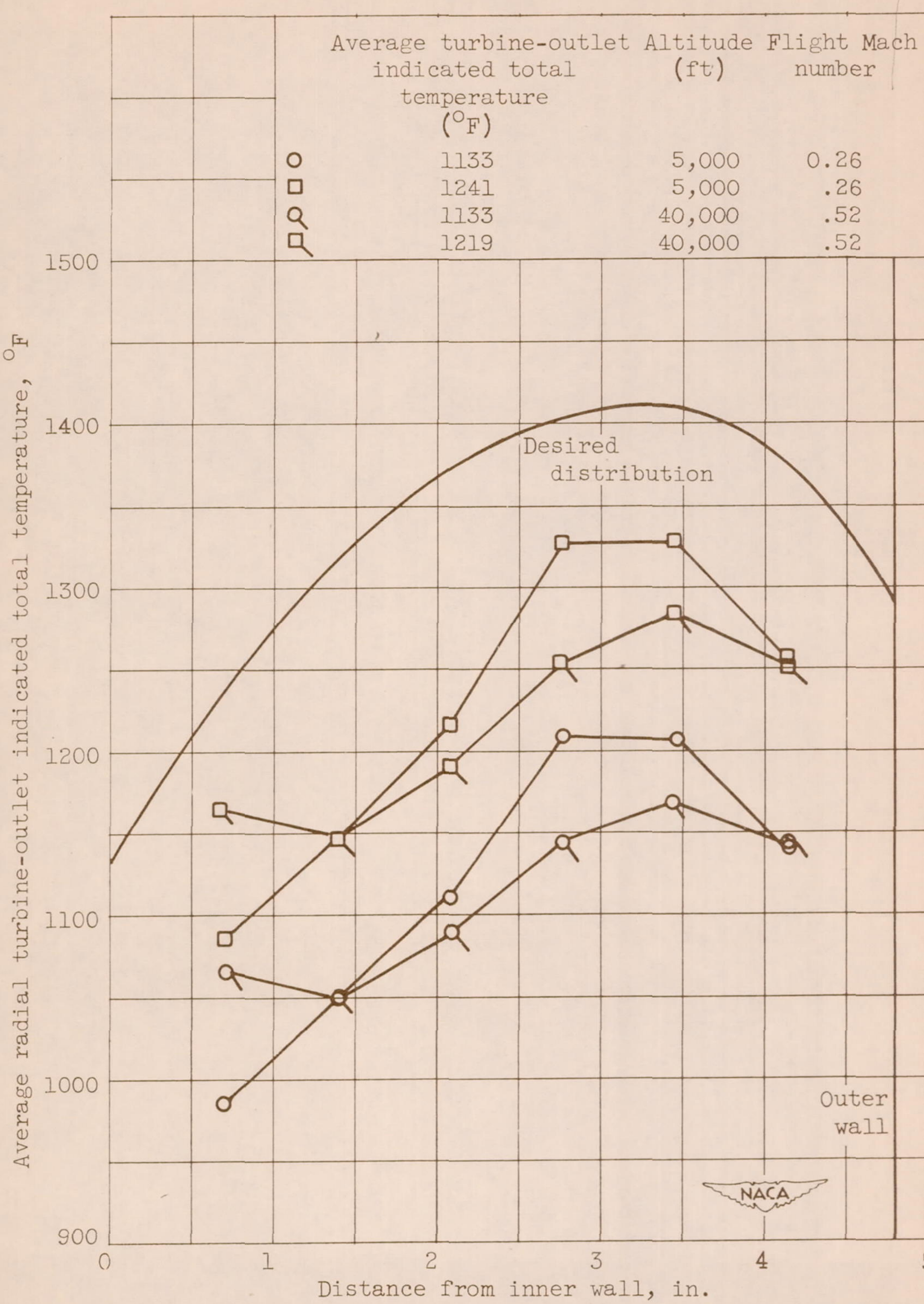


Figure 11. - Effect of temperature level on radial turbine-outlet temperature distribution in XJ34-WE-32 engine with mixer vanes. Average corrected engine speed, 13,474 rpm.

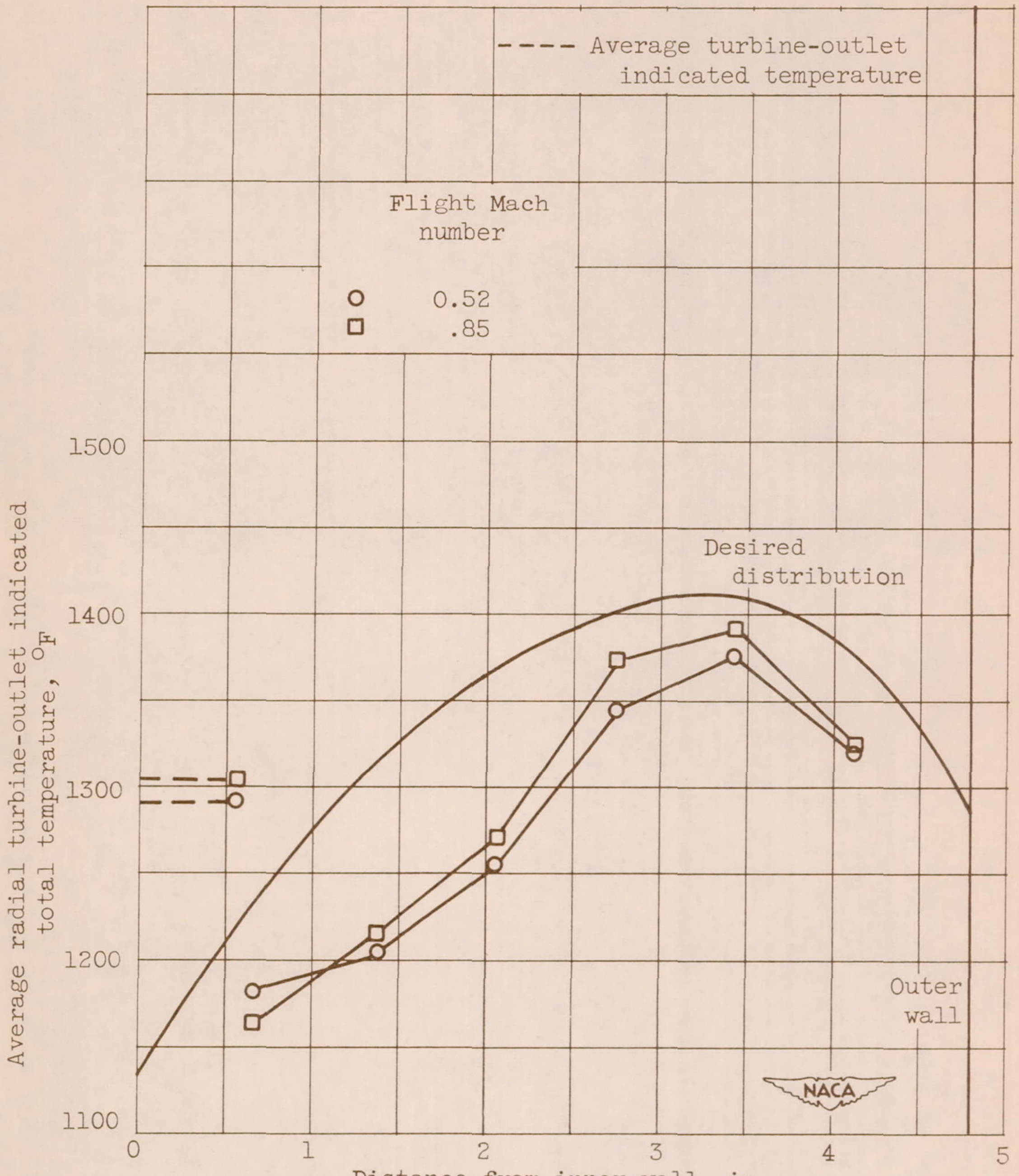
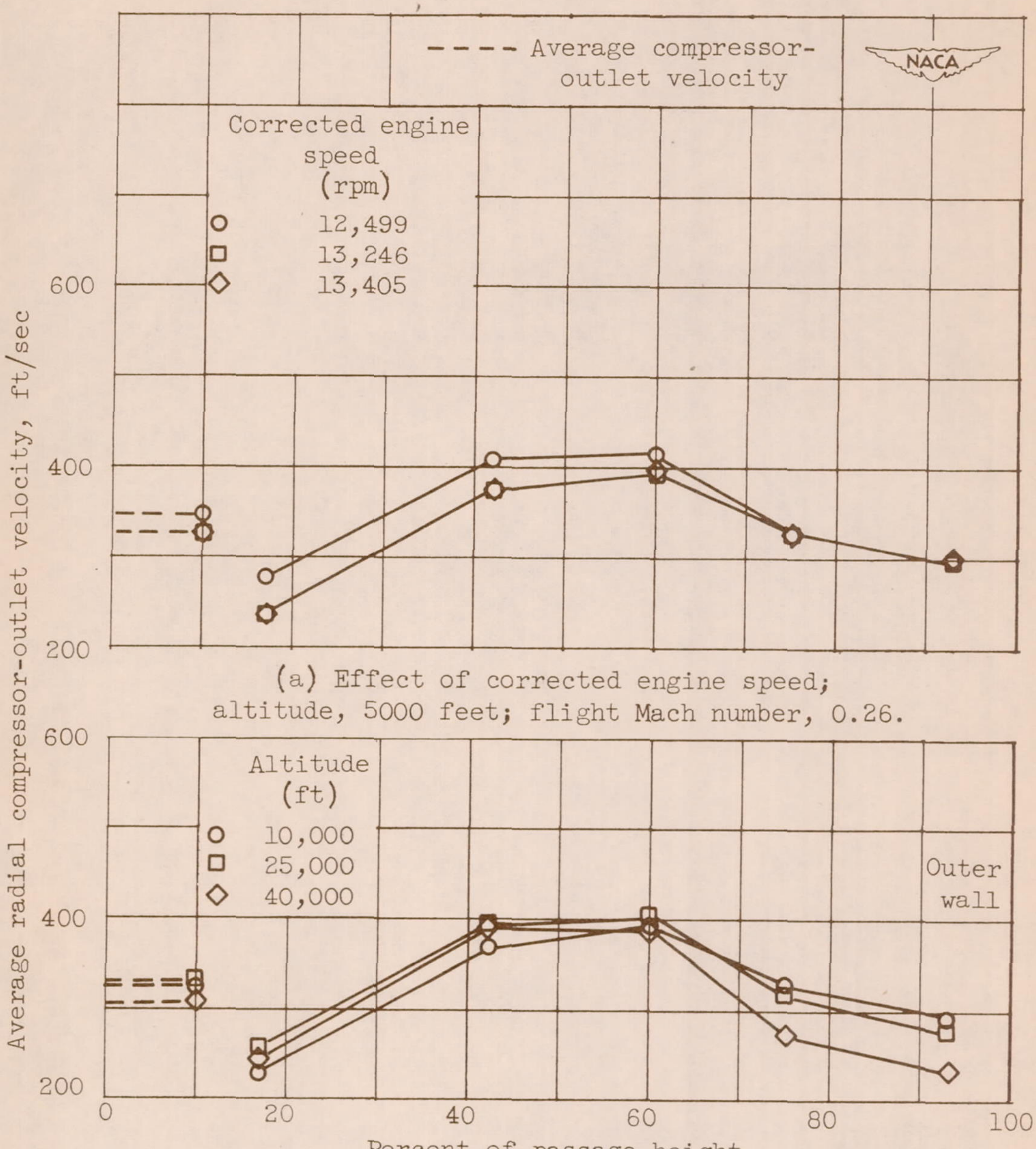


Figure 12. - Effect of flight Mach number on radial turbine-outlet temperature distribution in XJ34-WE-32 engine with mixer vanes. Altitude, 25,000 feet; corrected engine speed, 13,184 rpm.



(a) Effect of corrected engine speed; altitude, 5000 feet; flight Mach number, 0.26.

(b) Effect of altitude; average corrected engine speed, 13,208 rpm; flight Mach number, 0.52.

Figure 13. - Effect of corrected engine speed and altitude on radial compressor-outlet velocity distribution in XJ34-WE-32 engine with mixer vanes.

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RESEARCH MEMORANDUM

INVESTIGATION OF TURBINE-OUTLET TEMPERATURE

DISTRIBUTION OF XJ34-WE-32 TURBOJET ENGINE

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maa/11-7-51

Engines, Turbojet 3.1.3

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Abstract

Turbine-outlet radial temperature distributions of an XJ34-WE-32 turbojet engine were investigated in the altitude wind tunnel at the NACA Lewis laboratory over a range of pressure altitudes, engine-inlet air temperatures and flight Mach numbers at or near rated engine conditions. From blade stress considerations, the turbine-outlet temperature distribution was considered satisfactory at altitudes up to 25,000 feet at corrected engine speeds corresponding to rated speed (12,500 rpm); however, operation at either higher corrected engine speeds or higher altitudes resulted in an inversion of the turbine temperature distribution that was detrimental to turbine life. Installation of a compressor-outlet mixer greatly improved the turbine radial temperature distribution.