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RESEARCH MEMORANDUM

PERFORMANCE OF A SHORT COMBUSTOR AT HIGH ALTITUDES USING HYDROGEN FUEL

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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RESEARCH MEMORANDUM

PERFORMANCE OF A SHORT COMBUSTOR AT HIGH ALTITUDES USING HYDROGEN FUEL*

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SUMMARY

An investigation was conducted in an altitude test chamber at the NACA Lewis laboratory to evaluate in a complete engine the performance of a 16-inch-long combustor designed at the NACA specifically for use with gaseous-hydrogen fuel. The investigation covered a range of combustor pressures from 1260 to 420 pounds per square foot absolute obtained by operating the engine over a range of simulated altitudes from 66,000 to 86,000 feet at a flight Mach number of 0.8.

Combustion efficiencies of approximately 86 percent were obtained at a combustor pressure of 420 pounds per square foot absolute. This was approximately the same as the efficiency obtained using hydrogen fuel in a conventional turbojet combustor having a 25-inch length. At a pressure level of 800 pounds per square foot absolute, the efficiency of the short combustor was 11 percent higher than that of the standard combustor operating with JP-4 fuel. The standard combustor using JP-4 fuel experiences blowout at approximately 65,000 feet. However, combustor blowout was not experienced with hydrogen in the short combustor at altitudes up to 86,000 feet. The minimum pressure at which ignition was obtained was 280 pounds per square foot absolute. The combustor pressure losses for both the standard and the short combustors were approximately the same.

INTRODUCTION

The desirability of extending the range and altitude capabilities of aircraft has created interest in high-energy fuels. One fuel which is currently receiving a great deal of attention is hydrogen because of its high gravimetric heating value, high flame speed, wide flammability limits, and large heat capacity, which makes it a promising coolant. Extension of engine operating limits to altitudes as high as 90,000 feet at a flight Mach number of 0.8 while retaining reasonably high combustion efficiency has been demonstrated in an engine using gaseous-hydrogen fuel in a conventional combustor (ref. 1).

*Title, Unclassified.

The high flame speed, stable combustion, and good efficiency at low pressures demonstrated by this fuel suggest the possibility of shortening the combustor while still maintaining good performance. Shortening the combustor offers the possibility of a significant saving in weight in future engines. The feasibility of short combustors is indicated in the combustor test rig investigations reported in reference 2.

An investigation was conducted in an altitude test chamber at the NACA Lewis laboratory to demonstrate the altitude performance characteristics of a short hydrogen-burning combustor (approx. 35 percent shorter than the standard engine combustor) installed in a current turbojet engine. The engine was operated over a range of altitudes from 66,000 to 86,000 feet at a flight Mach number of 0.8 and over a range of engine speeds and temperature ratios in order to simulate a wide range of combustor operating conditions. Data are presented to show the performance of this combustor at several altitudes, and its performance is compared with data obtained using hydrogen fuel and JP-4 fuel in a conventional-length combustor.

APPARATUS

Engine

An engine of current design equipped with an NACA-designed short combustor was used in this investigation. The engine has an approximate sea-level thrust rating of 8000 pounds.

Fuel

Gaseous-hydrogen fuel with a mole purity of 98 percent was used. Its lower heating value was 51,570 Btu per pound.

Combustor

A short annular combustor utilizing hydrogen fuel was designed and developed at the NACA Lewis laboratory. This combustor, which was used for the full-scale engine investigation reported herein, was designed on the basis of pilot experiments in combustor rig tests reported in reference 2.

The combustor was approximately 16 inches long, compared with the standard hydrocarbon-burning combustor length of 25 inches. To avoid extensive engine modification, the combustor was supported within the standard engine combustor housing. A comparison sketch of the short combustor liner and the standard liner mounted in the engine combustor housing is shown in figure 1. A sketch of the primary combustion zone, flameholder section, and fuel manifold system of the short combustor is shown in figure 2.

Two combustor configurations were run and will be designated herein as configurations A and B. The configurations differed only in the size of the inner air baffle attached to the flameholder (see fig. 2).

Installation and Instrumentation

The engine was installed in a 10-foot-diameter altitude test chamber. The instrumentation installed at various stations throughout the engine is shown in figure 3. Gas temperatures indicated by thermocouples have been corrected for thermocouple radiation and recovery errors. Fuel flow was measured with a calibrated ASME type orifice run.

PROCEDURE

Combustor performance data were obtained with configuration A over a range of combustor-inlet total pressures from 1260 to 420 pounds per square foot absolute, combustor-inlet total temperatures from 810° to 925° R, combustor air flows from 10.9 to 3.3 pounds per second, and combustor fuel-air ratios from 0.004 to 0.007. The range of combustor operating conditions was obtained by operating the engine over a range of simulated altitudes from 66,000 to 86,000 feet at a flight Mach number of 0.8. At each altitude the engine speed and temperature ratio were varied within the limits prescribed by the engine manufacturer. For purposes of comparison, performance data for configuration B were obtained at 76,000 feet at 100 percent rated corrected engine speed. Some data for configuration B were also obtained at the higher altitudes.

For starting, the engine was windmilled at approximately 60,000 feet and ignition was initiated with a spark plug, which discharged from the plug to the flameholder trailing edge.

RESULTS AND DISCUSSION

Operational Characteristics

Neither the minimum combustor blowout pressure nor the rich or lean combustor fuel-air ratio limits were obtained for this combustor during the investigation, because of limitations imposed by either the altitude facility or the operable range of the engine. Data were obtained for a range of combustor pressures from 1260 to 420 pounds per square foot absolute and of fuel-air ratios from 0.004 to 0.007. With the engine windmilling it was determined, however, that the minimum combustor total pressure at which ignition could be obtained was approximately 280 pounds per square foot absolute. This agreed closely with ignition data obtained in a combustor test rig on a similar combustor. Very stable combustor operation was obtained over the range of conditions investigated, and the occurrence of mild compressor surge at low pressures did not result in combustor blowout.

Combustor Performance

Because the performance of the combustor was evaluated when operating as part of the engine, it was not possible to isolate the effects of the combustor-inlet pressure, temperature, and velocity on combustor performance. Therefore, the combustor performance data obtained during this investigation are presented in their basic form in figure 4, which shows the variation of combustion efficiency with combustor total-temperature ratio at three altitudes and several values of corrected engine speed. The data cover a pressure range from 420 to 1260 pounds per square foot absolute and combustor-inlet temperatures between 810° and 925° R. Combustion efficiencies were found to be between 85 and 99 percent, with the higher values generally occurring at the higher combustor pressures. The increase in efficiency with increased engine speed at a given flight condition (fig. 4) is a result of increases in both combustor-inlet temperature and pressures that accompanied an increase in engine speed. An inability to maintain engine conditions constant at an altitude of 76,000 feet resulted in the data scatter at this operating condition.

The combustor performance data for configuration B are shown in figure 4(c). An improved fuel control system was used during the investigation of this configuration, which resulted in a reduction in the data scatter at the low combustor operating pressures.

To show more directly the effect of combustor-inlet pressure on combustor performance, all the data obtained during the investigation are summarized in figure 5, which shows the variation of combustion efficiency with combustor-inlet pressure for configurations A and B and for the standard combustor (ref. 1) operating with hydrogen fuel. Combustion efficiency was approximately 97 percent at 1260 pounds per square foot absolute and decreased to 86 percent at 420 pounds per square foot absolute. The efficiency of the short combustor was approximately the same as the standard combustor over the range of conditions investigated.

At a combustor pressure of 800 pounds per square foot absolute, the standard combustor operating with JP-4 fuel (see ref. 1) had an efficiency of 83 percent, as compared with 94 percent for the short combustor operating with hydrogen at this condition. The maximum operating altitude of the standard combustor using with JP-4 fuel is approximately 65,000 feet. The similarity in performance of configurations A and B in the engine is in contradiction with the results obtained in combustor rig tests, which indicated an improvement in performance with configuration B. The scaling necessary to adopt the test rig combustor to fit engine requirements, plus differences in combustor-inlet velocity profiles in the engine combustor, may have resulted in the absence of any difference between the two configurations in the full-scale engine tests.

To facilitate comparison of the short-combustor performance with other combustors, the combustion efficiency data are also presented as a function of the conventional performance parameter PT/V_R in figure 6. (All symbols are defined in the appendix.) The reference velocity V_R was calculated using the total combustor area, mass flow, total temperature, and total pressure at the combustor inlet. The combustor reference velocity was approximately 78 feet per second for the range of combustor conditions investigated.

The combustor total-pressure loss shown in figure 7 was approximately 4 percent over the range of combustor operating conditions investigated. This compares with a 3.5-percent pressure loss with the standard engine combustor.

Temperature Profiles

A separate fuel control was used in each of the two manifolds to permit some control of the combustor-outlet (turbine-inlet) temperature profile (fig. 8). The difference in temperature across the passage depth could be changed 250° by operating on alternate manifolds. There was no noticeable change in efficiency for this range in temperature gradient.

The fuel flow through each manifold was proportioned to give the minimum combustor-outlet temperature gradient at a combustor pressure of approximately 800 pounds per square foot absolute. This proportion was maintained constant for the range of combustor conditions investigated. The resulting combustor-outlet temperature profiles over the range of combustor operating conditions are presented in figure 9. There was a circumferential temperature profile (fig. 9(a)) at the combustor outlet, which is due to incomplete mixing of the gas stream at the temperature survey station. There was little, if any, shift in radial profile (fig. 9(b)) when combustor mass flow was varied, that is, engine-speed variation at a constant combustor-outlet temperature. Likewise, the average radial profiles are unaffected by changes in combustor pressure level (fig. 9(c)) and by changes in combustor fuel-air ratios (fig. 9(d)). The temperature profiles at the turbine outlet for the same range of conditions are shown in figure 10.

SUMMARY OF RESULTS

The range of operation of the short combustor used in this investigation was limited because of facility and engine limitations. However, for the range of combustor conditions investigated, combustor blowout was not encountered even though the combustor was operated down to a combustor pressure of 420 pounds per square foot absolute and over a range of fuel-air ratios from 0.004 to 0.007. The minimum pressure at which ignition was obtained was approximately 280 pounds per square foot absolute.

At a pressure level of approximately 800 pounds per square foot absolute, the short combustor operating with hydrogen had an efficiency of 94 percent as compared with 83 percent obtained using JP-4 fuel in the standard engine combustor. This efficiency was also approximately the same as that of the standard combustor operating with hydrogen at this condition. Combustion efficiency decreased at the low pressures in the usual manner, dropping from 97 percent at 1260 pounds per square foot absolute to 86 percent at 420 pounds per square foot absolute. With the standard combustor using JP-4 fuel, the maximum practical operating altitude was 65,000 feet; however, with the short combustor using hydrogen fuel, combustor operation was obtained at 86,000 feet. Thus, with hydrogen fuel it is demonstrated that the combustor length can be shortened appreciably, which offers the possibility of a substantial saving in weight of future engines designed solely for this fuel.

Combustor-outlet temperature profiles were unaffected by pressure level, fuel-air ratio, or combustor mass flow. The combustor pressure losses for both the standard and the short combustors were approximately the same.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 1, 1956

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APPENDIX - SYMBOLS

P total pressure

T total temperature

V_R reference velocity

η_b combustion efficiency

Subscripts:

0 free stream

1 venturi throat

2 compressor inlet

3 compressor outlet

3a combustor inlet

4 turbine inlet

5 turbine outlet

9 exhaust-nozzle inlet

REFERENCES

1. Fleming, W. A., Kaufman, H. R., Harp, J. L., Jr., and Chelko, L. J.: Turbojet Performance and Operation at High Altitudes with Hydrogen and JP-4 Fuels. NACA RM E56E14, 1956.

2. Friedman, Robert, Norgren, Carl T., and Jones, Robert E.: Performance of a Short Turbojet Engine Combustor with Hydrogen Fuel in a Quarter-Annular Duct and Comparison with Performance in Full-Scale Engine. NACA RM E56D16, 1956.

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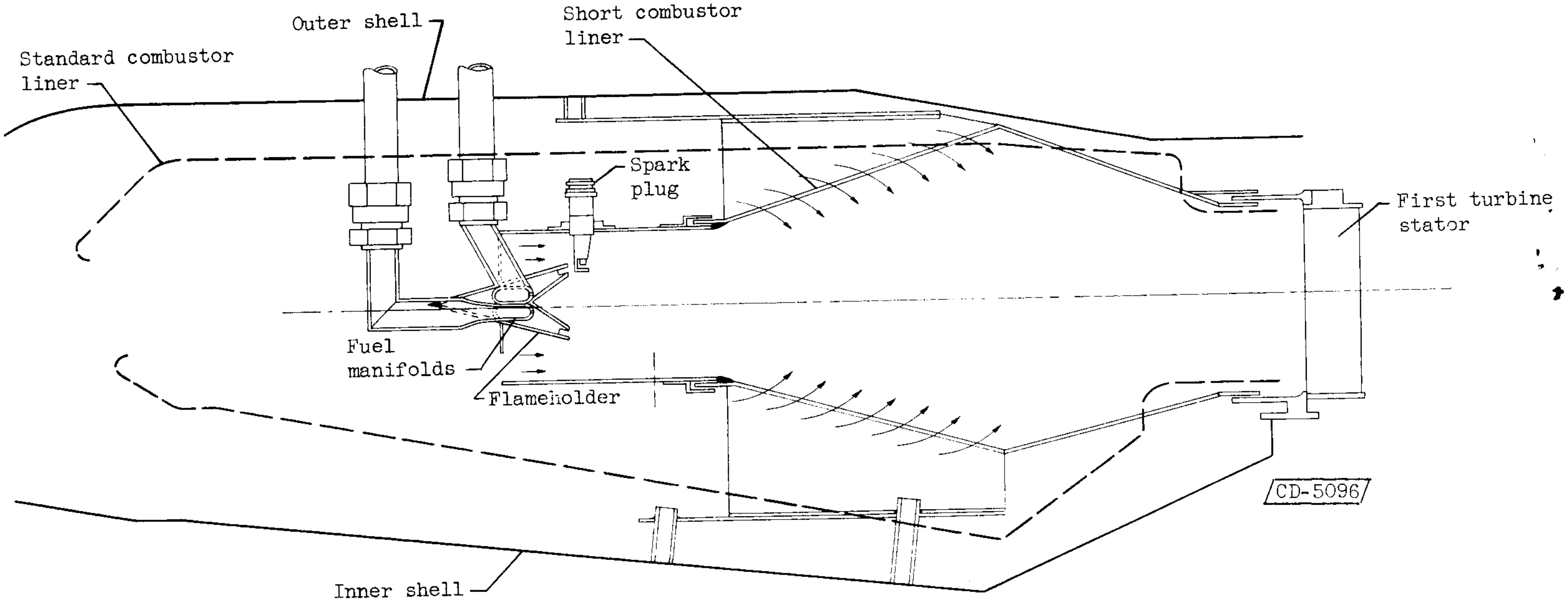

Figure 1. - Schematic drawing showing comparison between short and standard combustor outlines.

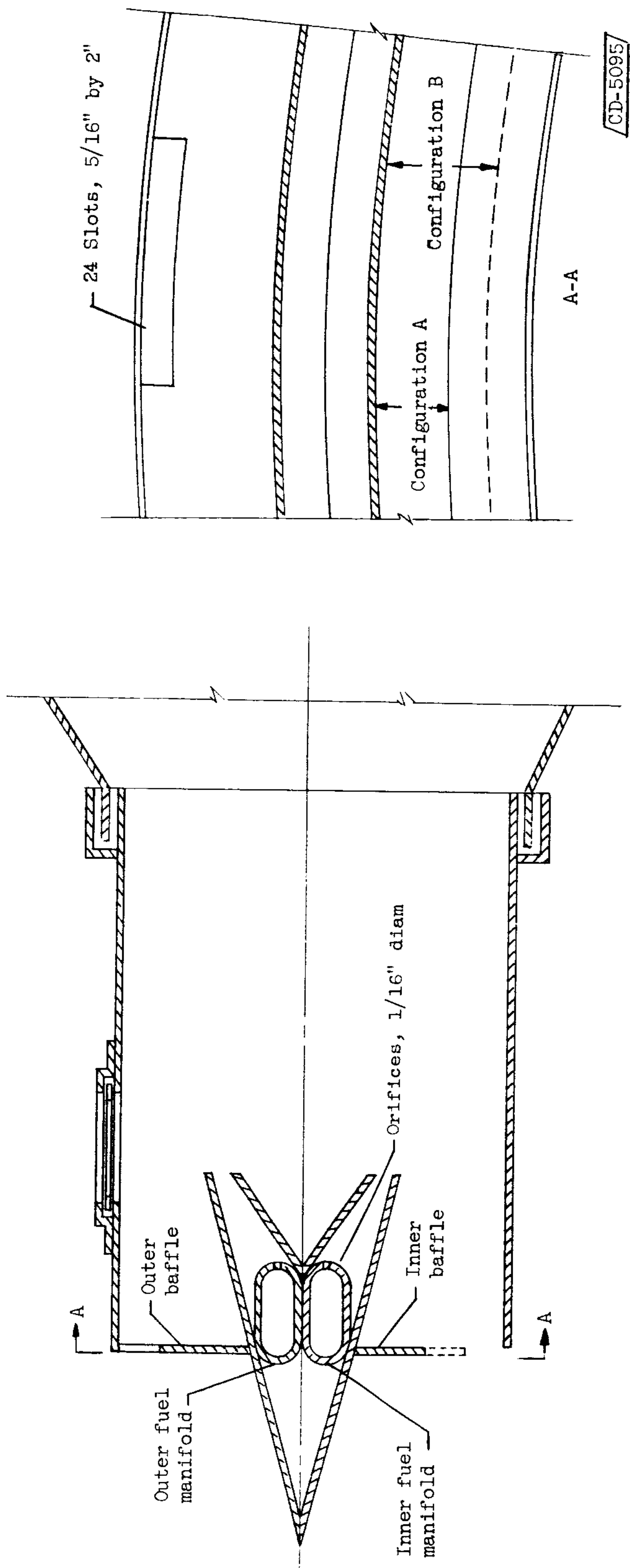

Figure 2. - Schematic drawing of flameholder section.

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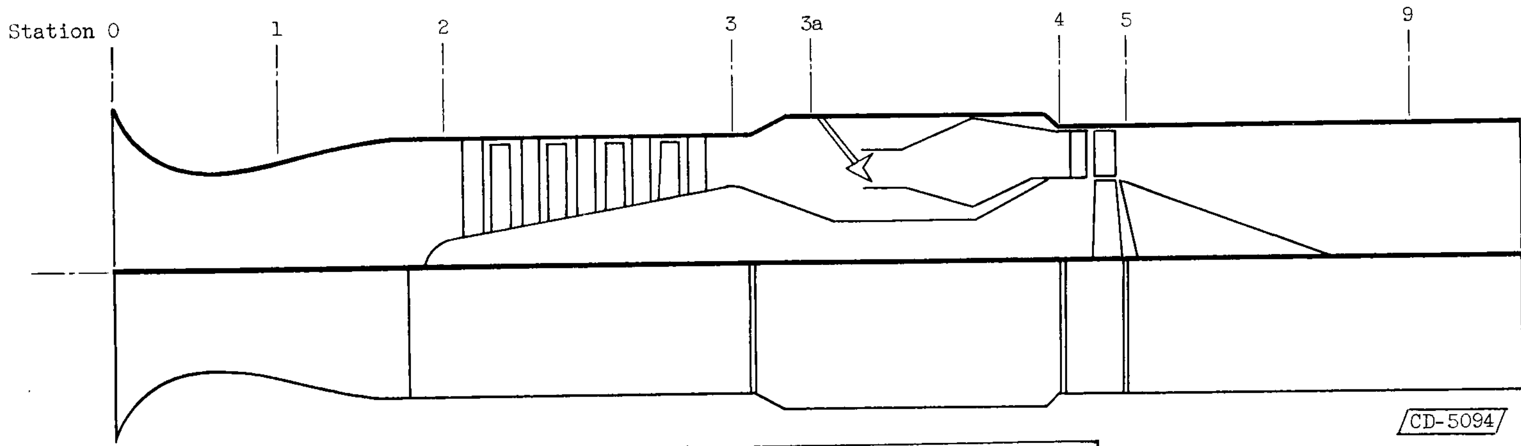

Station	Number of probes	
	Temperature	Pressure
1	————	8 Total 4 Wall static
2	8 Total	5 Total 4 Averaging rake
3	20 Total	20 Total
3a	————	31 Total 4 Wall static 1 Stream static
4	20 Total	20 Total
5	37 Total 4 Skin	24 Total 4 Wall static
9	24 Total 4 Skin	20 Total 4 Wall static

Figure 3. - Schematic drawing of engine showing instrumentation station locations.

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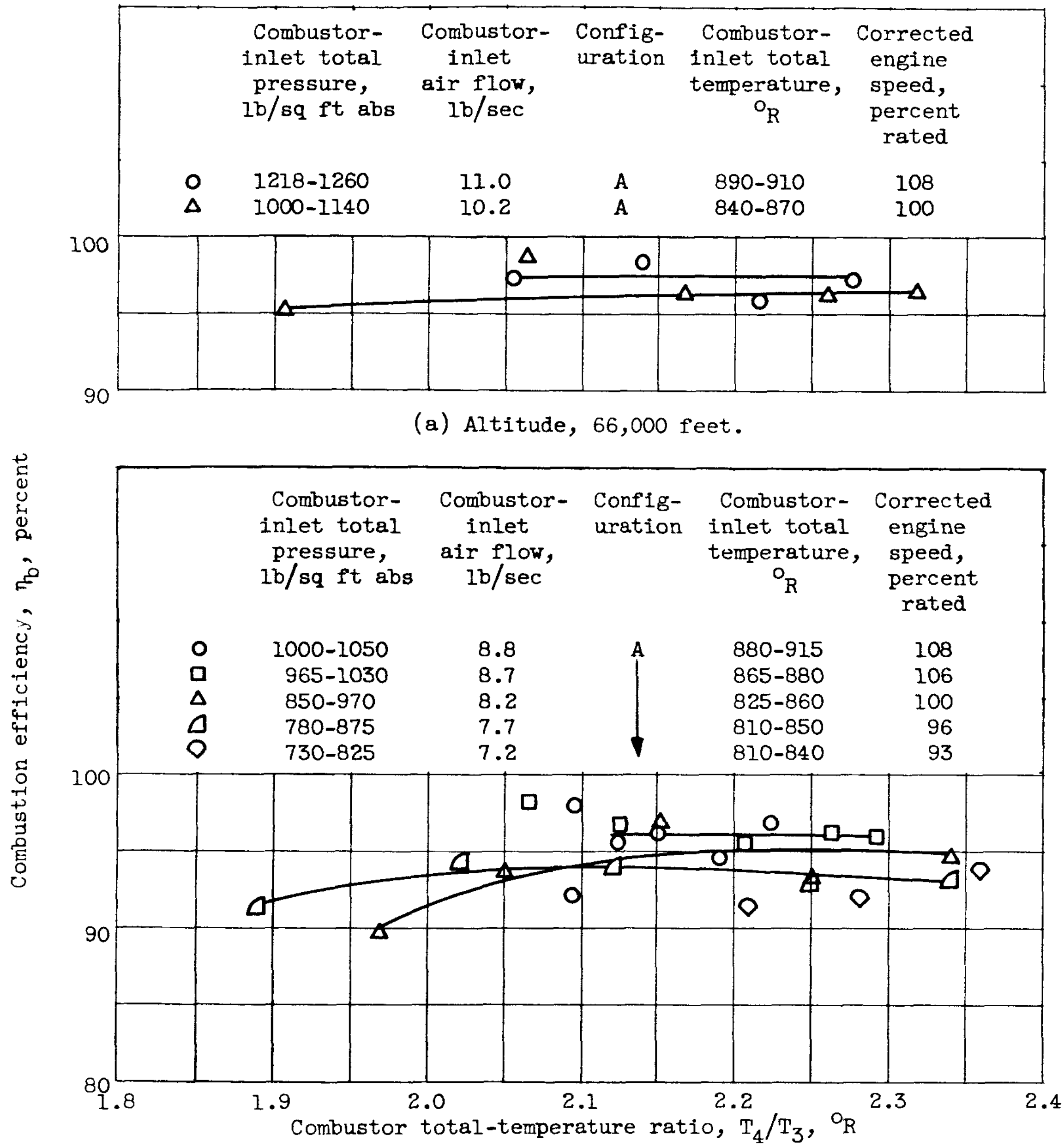

(a) Altitude, 66,000 feet.

(b) Altitude, 70,000 feet.

Figure 4. - Effect of combustor-inlet conditions on combustion efficiency variation with combustor total-temperature ratio. Combustor reference velocity of 78 feet per second; Mach number, 0.8.

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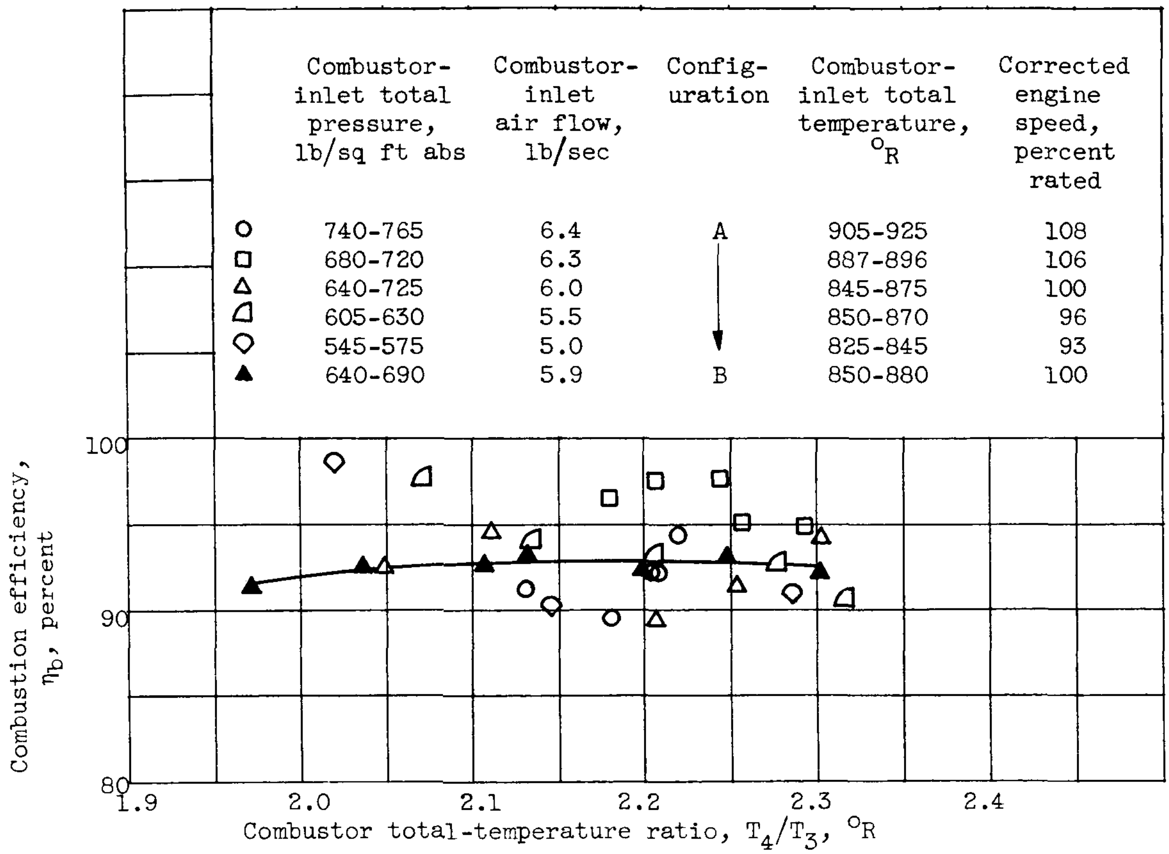

(c) Altitude, 76,000 feet.

Figure 4. - Concluded. Effect of combustor-inlet conditions on combustion efficiency variation with combustor total-temperature ratio. Combustor reference velocity of 78 feet per second; Mach number, 0.8.

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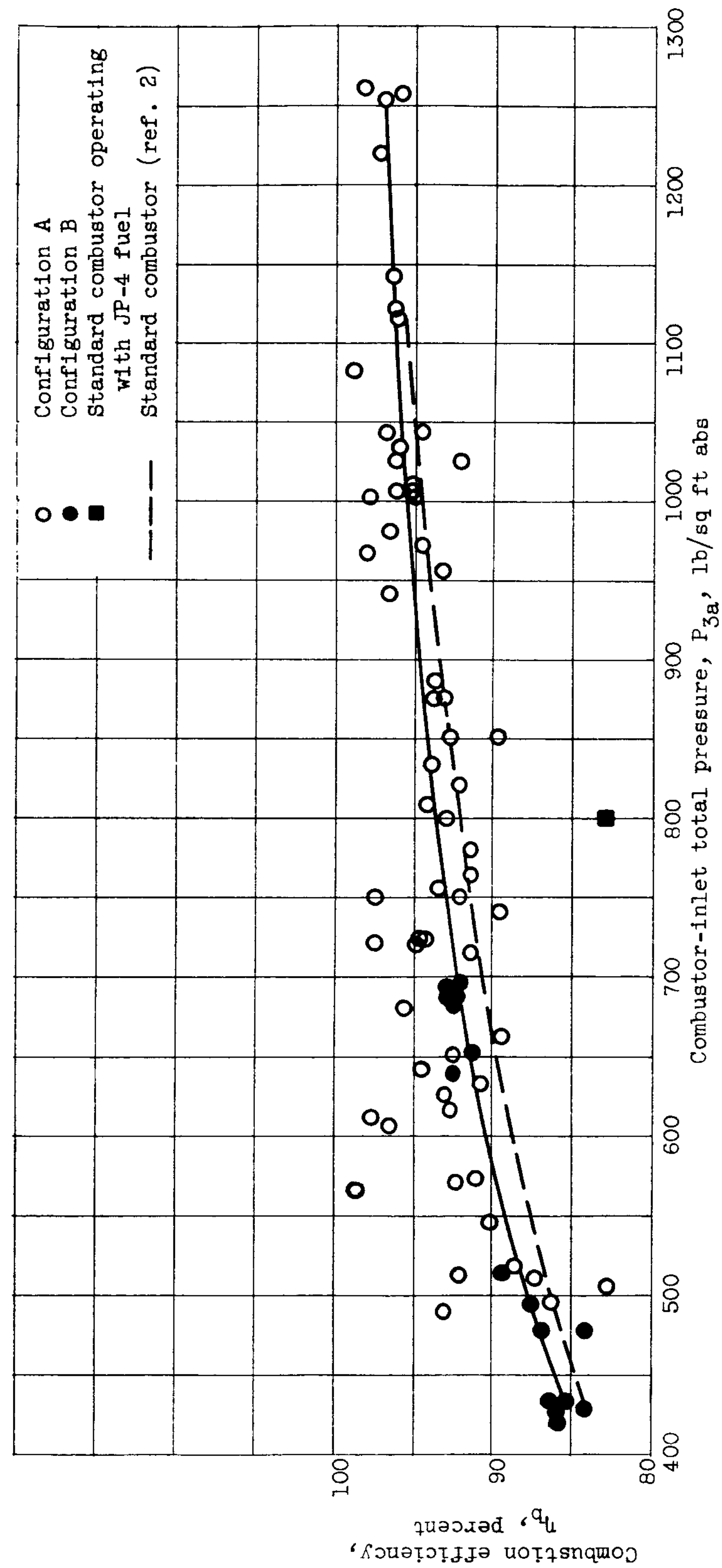

Figure 5. - Variation of combustion efficiency with combustor-inlet total pressure.

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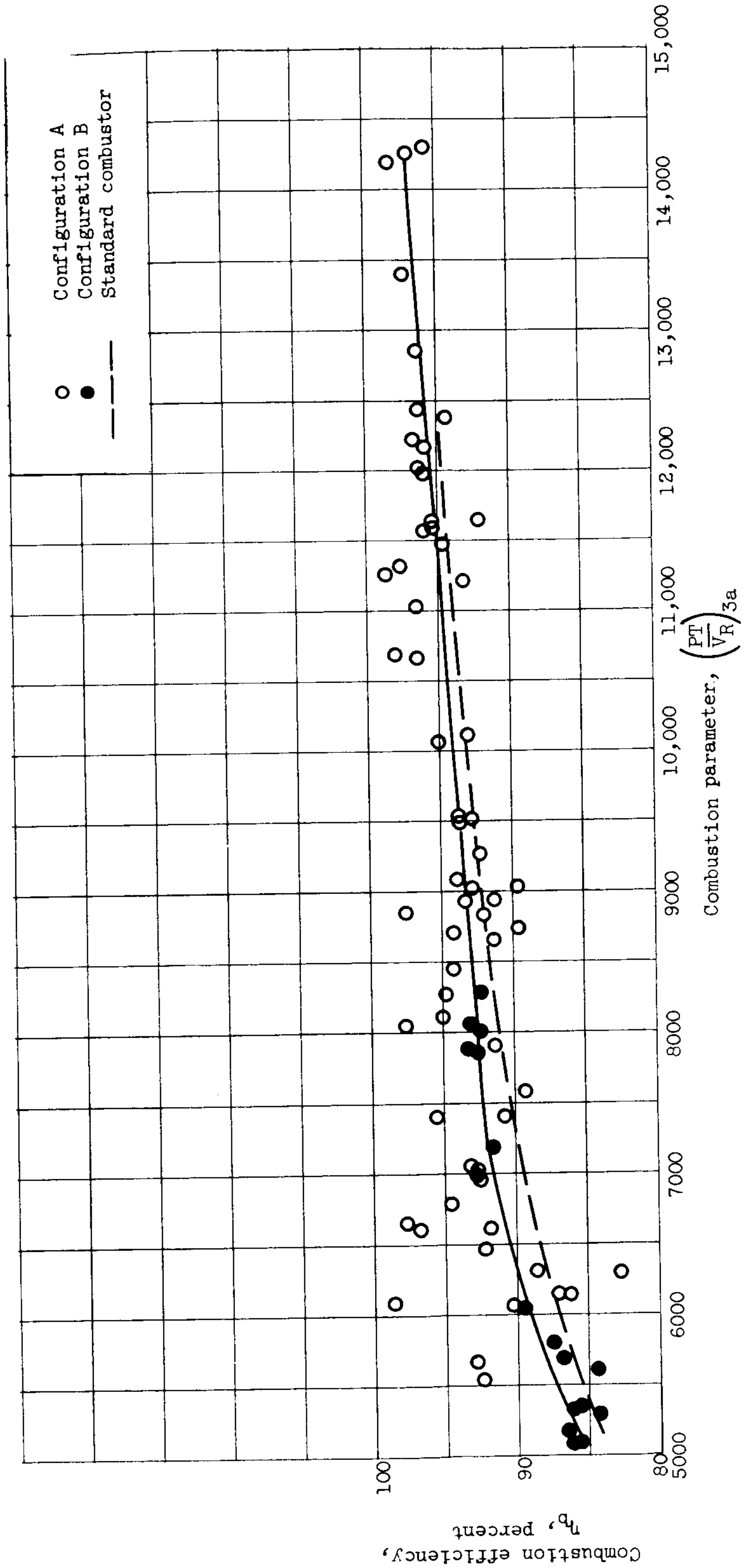

Figure 6. - Variation of combustion efficiency with combustion parameter $\left(\frac{PT}{V_R}\right)_{3a}$.

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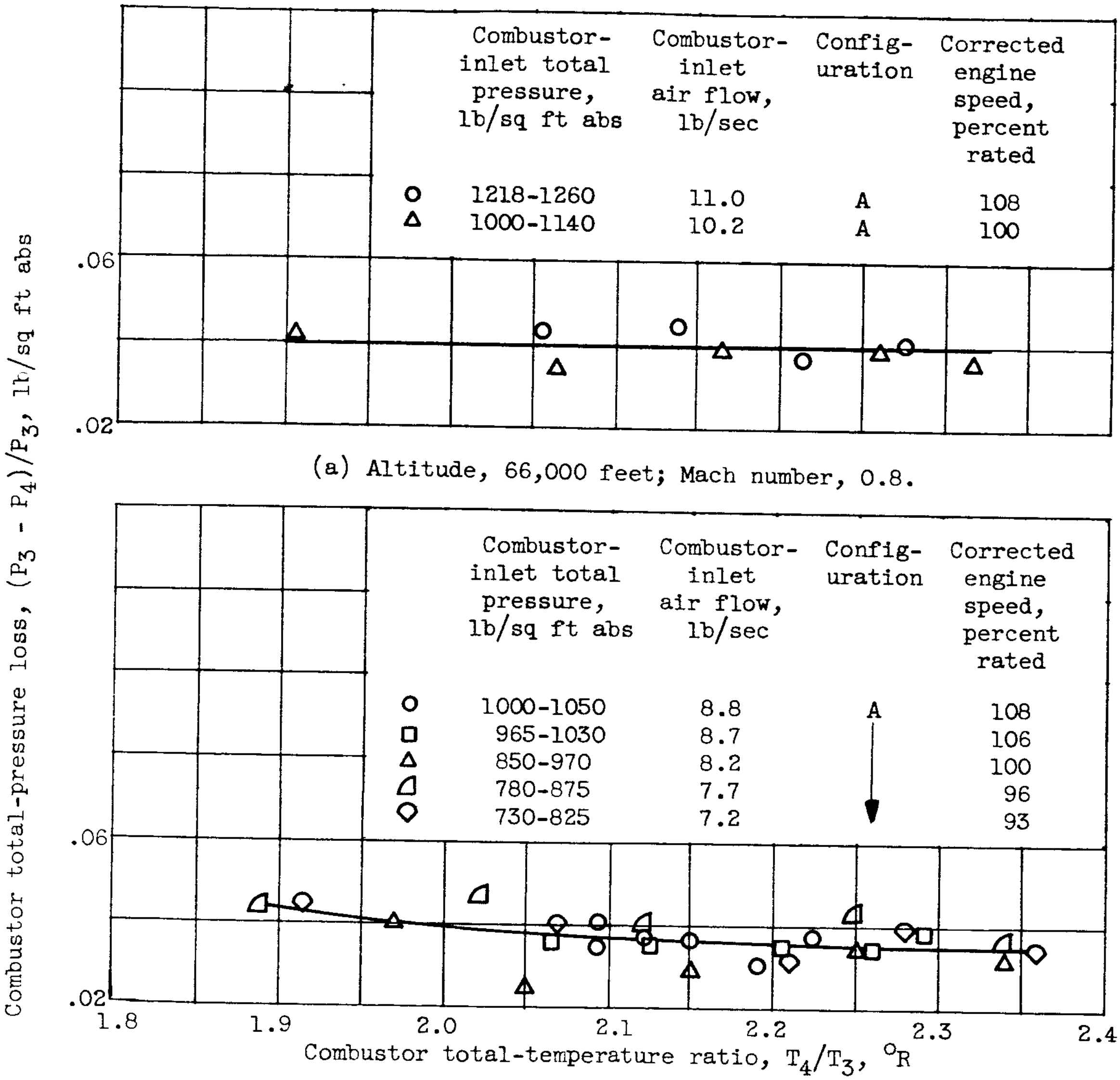
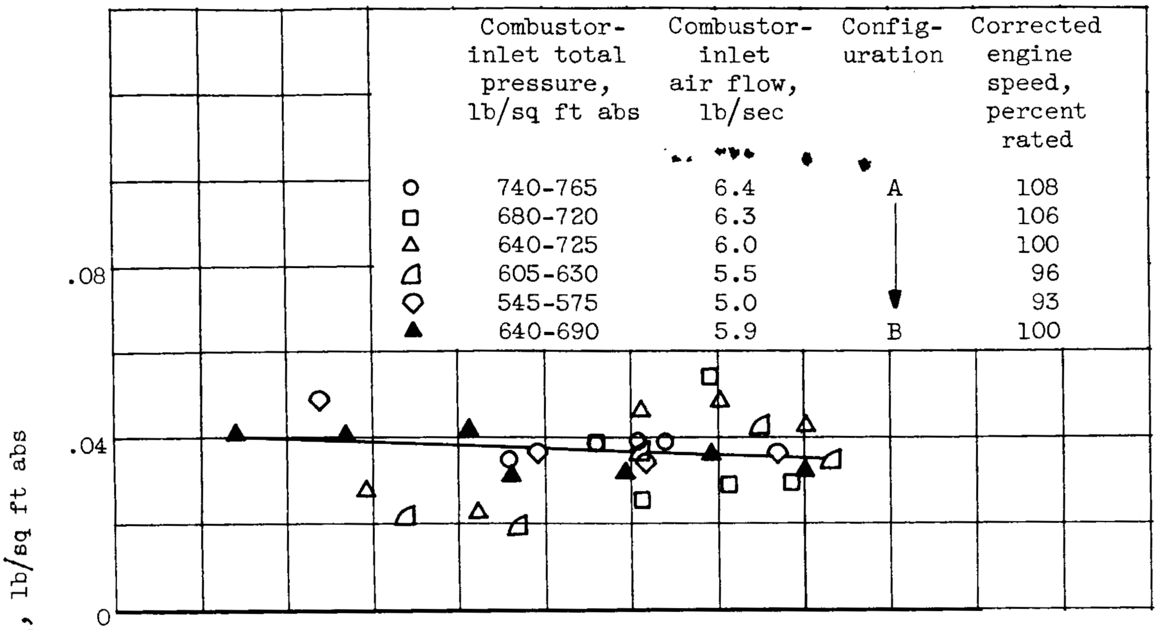


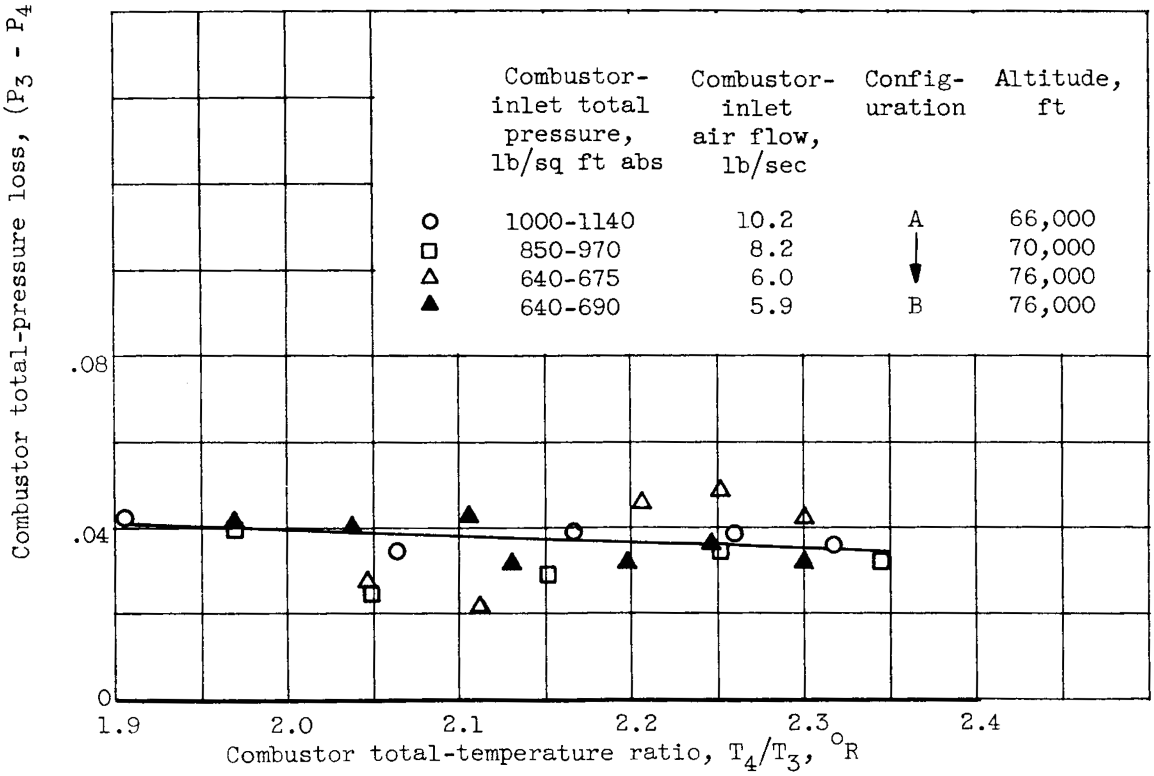
(a) Altitude, 66,000 feet; Mach number, 0.8.

(b) Altitude, 70,000 feet; Mach number, 0.8.

Figure 7. - Variation of combustor total-pressure loss with combustor total-temperature ratio.



(c) Altitude, 76,000 feet; Mach number, 0.8.



(d) Corrected engine speed, 100 percent rated.

Figure 7. - Concluded. Variation of combustor total-pressure loss with combustor total-temperature ratio.

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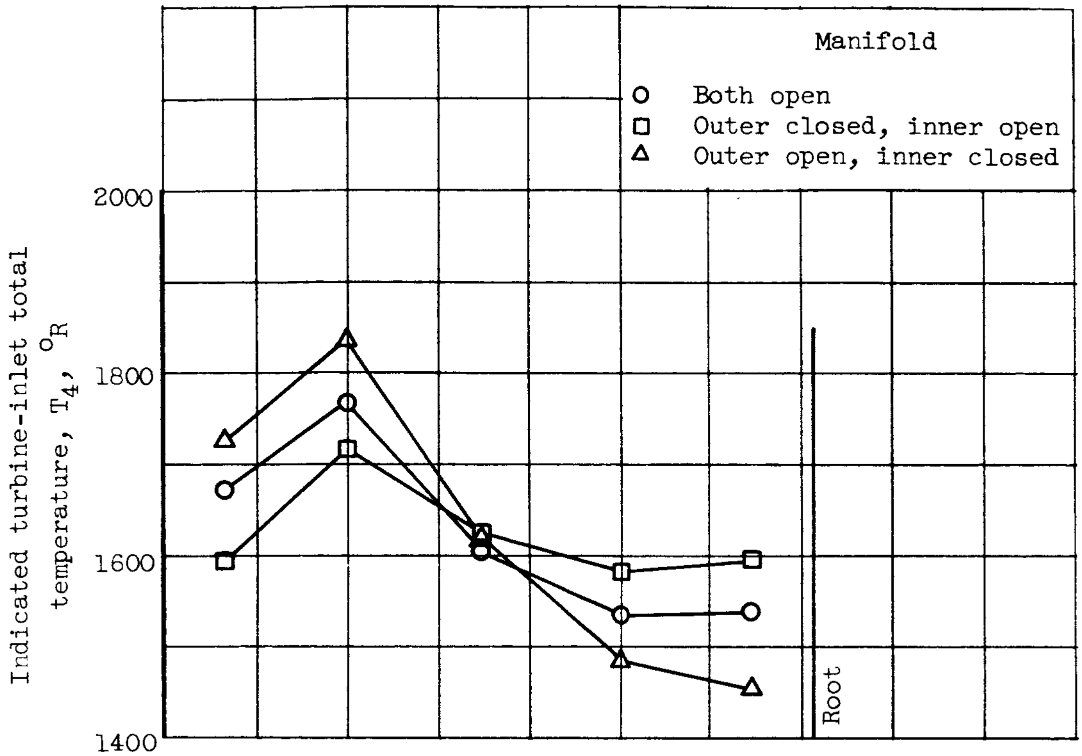
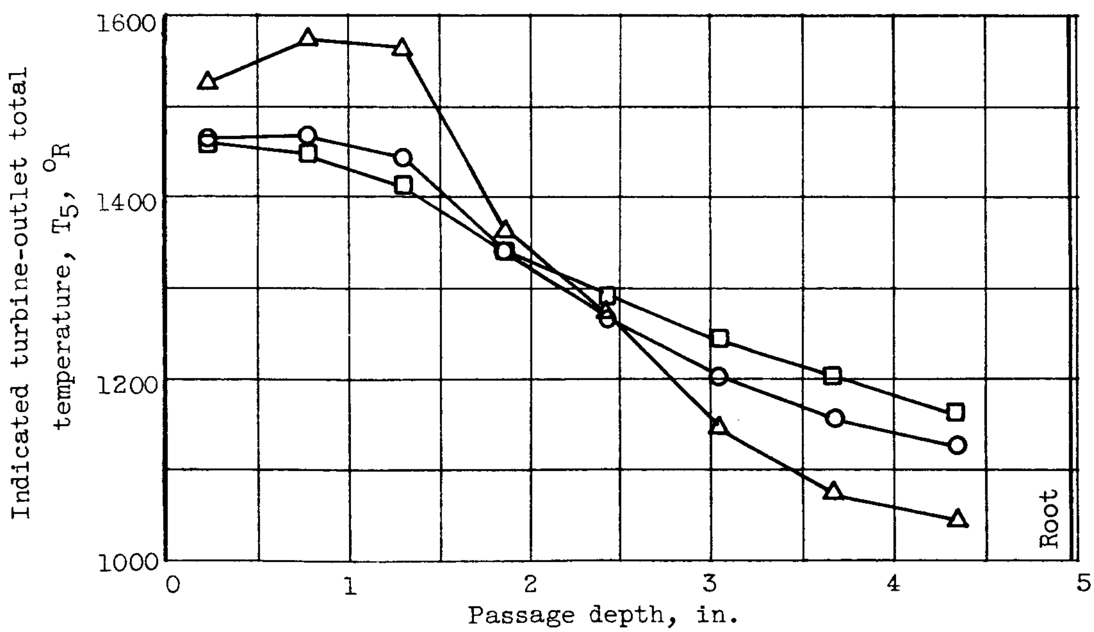


(a) Turbine inlet.



(b) Turbine outlet.

Figure 8. - Variation of turbine-inlet and -outlet total-temperature profiles at three settings of inner and outer manifolds.

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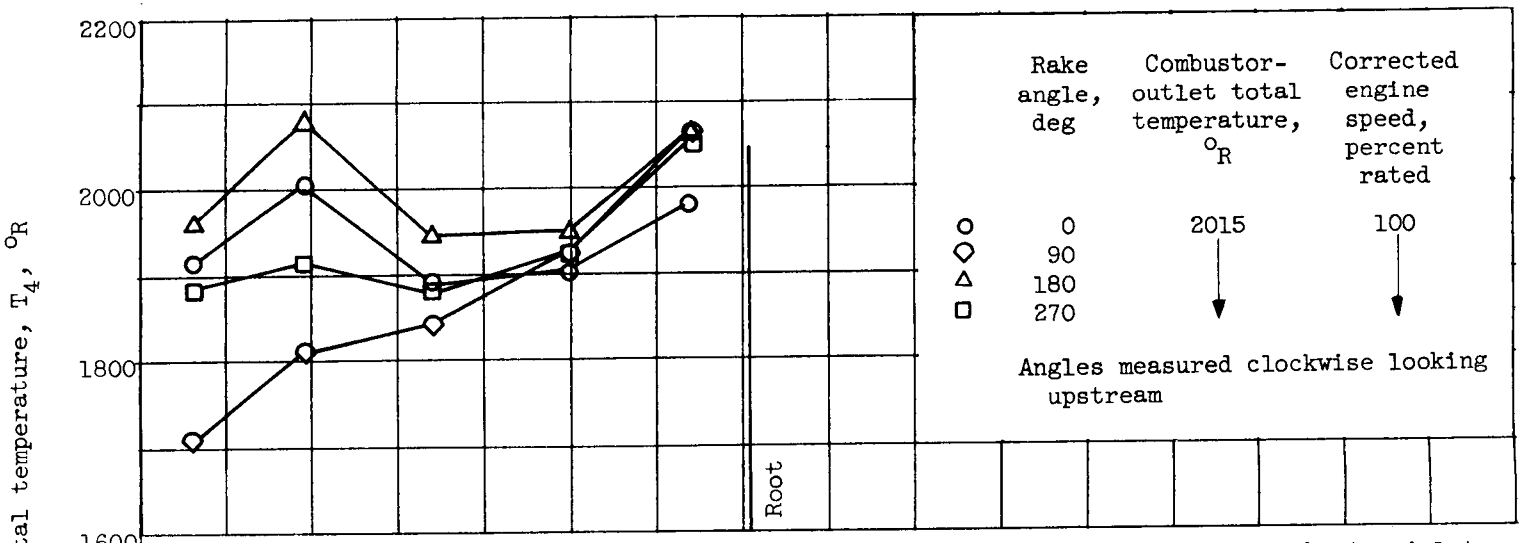
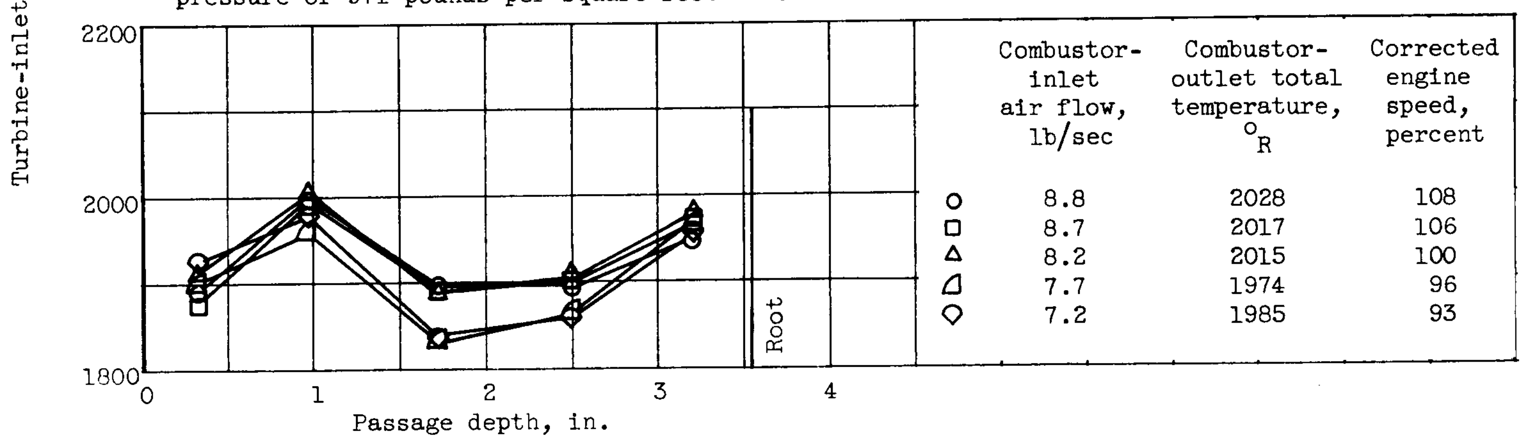


(a) Effect of circumferential location on radial total-temperature profile at combustor-inlet pressure of 971 pounds per square foot absolute.



(b) Effect of combustor air flow on radial total-temperature profile. Rake angle, 0°.

Figure 9. - Turbine-inlet indicated radial total-temperature profiles.

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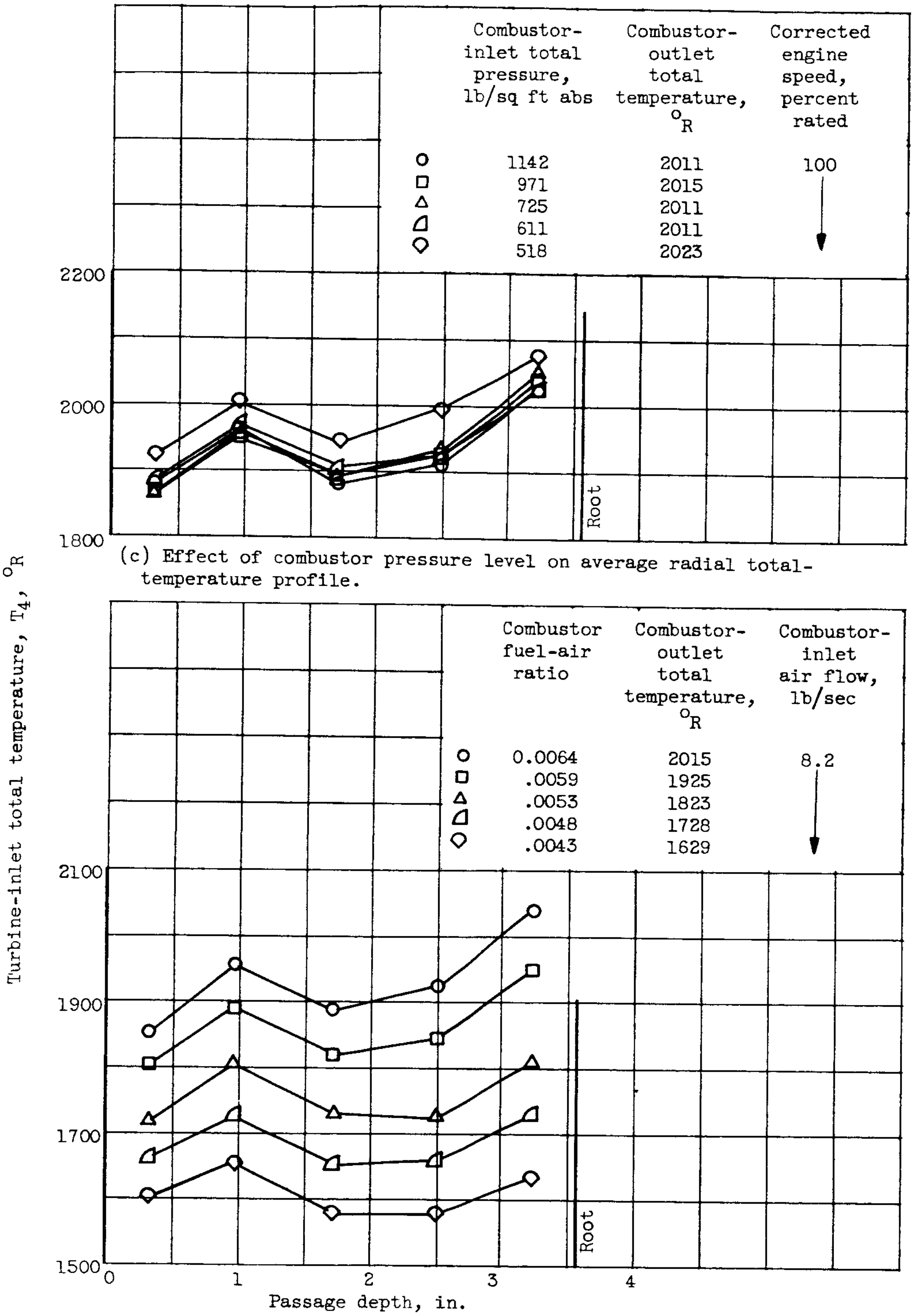

(c) Effect of combustor pressure level on average radial total-temperature profile.

(d) Effect of combustor fuel-air ratio on average radial total-temperature profile.

Figure 9. - Concluded. Turbine-inlet indicated radial total-temperature profiles.

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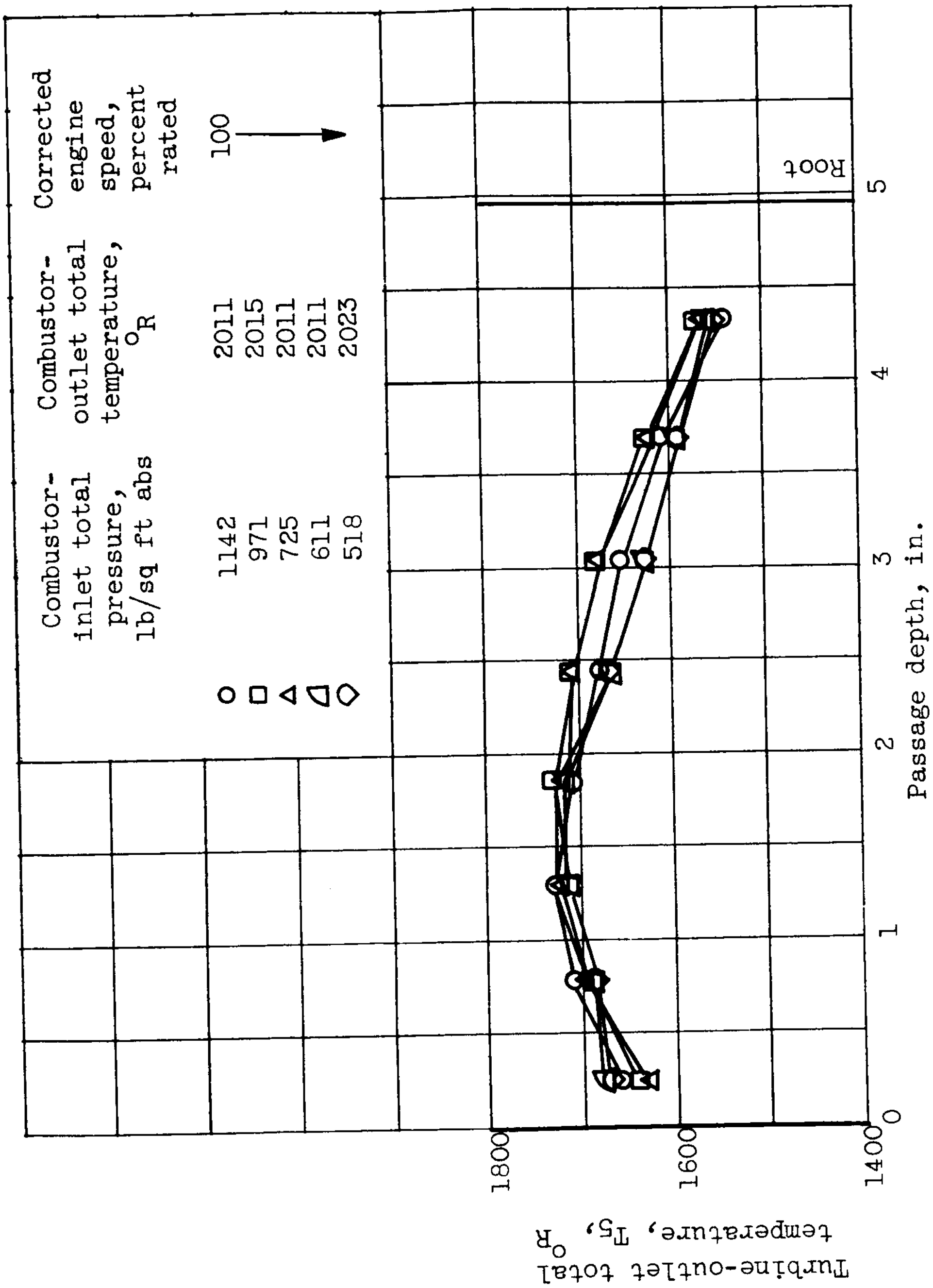

Figure 10. - Turbine-outlet indicated radial total-temperature profile.

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