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TECHNICAL NOTE 2673

THEORETICAL PERFORMANCE OF AN AXIAL-FLOW COMPRESSOR IN A GAS-TURBINE ENGINE OPERATING WITH INLET WATER INJECTION

By Reece V. Hensley

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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THEORETICAL PERFORMANCE OF AN AXIAL-FLOW COMPRESSOR IN A GAS-TURBINE ENGINE OPERATING WITH INLET WATER INJECTION

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SUMMARY

The theoretical performance with inlet water injection of an axial-flow compressor operating as a component of a gas-turbine engine is evaluated for normal compressor pressure ratios of 4, 8, and 16. Continuous saturation throughout the compression process is assumed. The assumptions of choked turbine nozzles and a compression efficiency at any point in the compressor dependent on the evaporative cooling prior to that point are used to determine the changes in mass flow, compressor pressure ratio, compressor work, and over-all compressor efficiency.

The analysis indicates that the compressor work per pound of turbine gas flow is lower with inlet water injection than without even for conditions where large decreases in compressor efficiency occur; consequently, engine output per pound of turbine gas flow is greater with injection than without.

INTRODUCTION

Numerous investigations of the augmented performance of turbojet engines with liquid injected into the engine inlet have been made (references 1 and 2, for example). These investigations have generally been based on the assumption of equal turbine-work outputs during normal and augmented operation, and of a constant compressor slip factor with or without augmentation. These assumptions are more applicable to the centrifugal-compressor turbojet engine than to one having an axial-flow compressor and have afforded a satisfactory correlation between theoretical and experimental thrust augmentation values for a centrifugal-type engine.

In order to provide a better insight into the performance of an axial-flow compressor with inlet liquid injection, a method was developed at the NACA Lewis laboratory for predicting the compressor performance under these conditions. The details of the method and the calculated performance of axial-flow compressors with water injection are presented herein.

The method evaluates the compressor performance when saturation is maintained during the compression process. Variations in compressor mass flow with liquid injection and in compressor efficiency with evaporative cooling are included in the analysis. 2335

Calculated compressor performance data for several different compressor pressure ratios are presented for the ranges of flight Mach number and altitude of greatest interest for gas-turbine engine use under augmented conditions.

ANALYSIS

Conditions

The compressor performance was evaluated from the following component characteristics and general conditions (all symbols are defined in appendix A):

Compressor polytropic efficiency (normal)	0.88
Compressor pressure ratio (normal)	4,8,16
Subsonic diffuser dynamic pressure recovery	0.92
Supersonic diffuser total-pressure ratio, P_2/P_1:	
$M_0 = 1.1$	0.955
$M_0 = 1.5$	0.93
$M_0 = 2.0$	0.88
Turbine inlet temperature, $^{\circ}R$	2000
Injected water temperature, $^{\circ}R$	519
Ambient relative humidity	1.0

The compressor performance was evaluated for the combinations of flight Mach number and altitude that are of primary interest insofar as augmented gas-turbine engine performance is concerned. These conditions cover the Mach number ranges from 0 to 0.9 at sea level, 0.6 to 0.9 at an altitude of 15,000 feet, 0.6 to 2.0 at 35,000 feet, and 0.9 to 2.0 at 50,000 feet.

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Methods

Inlet gas flow. - The injection of a liquid such as water into the inlet of an engine produces an evaporative cooling effect upstream of the compressor inlet if there is a flight ram-temperature rise or if the ambient atmosphere is unsaturated. The cooling lowers the temperature at the compressor inlet with the result that the compressor operates at a higher than normal corrected speed $N/\sqrt{\gamma_2 g R_2 T_2}$ if the actual engine speed is held constant (corrected parameters used in the present report are derived in appendix B). The compressor-inlet gas flow therefore increases. This increase was determined, for the present analysis, from figure 1, the variation of the inlet corrected gas flow $\frac{W_2\sqrt{T_2}}{P_2}\sqrt{\frac{R_2}{\gamma_2 g}}$ with corrected engine speed. The temperature and vapor content at the compressor inlet were obtained from the psychrometric chart of reference 2, with saturation assumed at the compressor inlet. From these values and the thermodynamic data of references 3 and 4, weighted average values of γ_2 and R_2 were evaluated and used to determine the fraction of normal (or design, for the present analysis) corrected speed. The fraction of normal or design corrected gas flow was then read from figure 1, and the change in actual gas flow was obtained by elimination of the correction factors.

The gas flow at any point in the compressor was taken as the sum of the inlet gas flow and the additional vapor required to provide continuous saturation from the compressor inlet to the point in question.

Compressor efficiency. - The evaporation of water during compression provides a cooling effect which affects the work of compression and the compressor efficiency. Because the amount of water evaporated increases through the compressor and because the performance of a particular portion of the compressor is affected by all the evaporation occurring upstream of that portion, the compressor was considered as a series of sections or segments and the over-all performance was determined by an iterative process. Every segment of the compressor was assumed to operate normally with the same pressure ratio and component characteristics. The performance of these compressor segments was assumed to be adequately represented by the curve presented in figure 2, where the fraction of the segment maximum adiabatic efficiency $\eta_{S,ad}/\eta_{S,ad,max}$ is given as a function of the fraction of the segment inlet corrected speed for maximum efficiency $\frac{N/\sqrt{\gamma_S g R_S T_S}}{\left(N/\sqrt{\gamma_S g R_S T_S}\right)_{\eta_{max}}}$. The curve of figure 2 was constructed as an average curve for numerous single-stage compressors operating at conditions favorable for use in a gas-turbine engine, that is, relatively high stage pressure ratio with high efficiency. Under these conditions, the curve was only slightly affected by changes in

corrected gas flow of the magnitude resulting from water evaporation during compression. It was further assumed that with normal unaugmented operation all segments would be operating at the maximum efficiency point.

When water is injected at the compressor inlet, the performance of a particular segment is altered from its normal value by the evaporative cooling occurring in all the preceding segments. The correction factor $\sqrt{\gamma_S g R_S T_S}$, affected primarily by the change in T and to a lesser extent by changes in γ and R, decreases and the operating point shifts from the maximum point of figure 2 to a higher value of the corrected speed ratio, with a resultant decrease in efficiency for the segment. The decreased segment efficiencies, of course, result in a lowered over-all compressor efficiency. 2335

Compressor pressure ratio. - The total-pressure ratio across the compressor with evaporation during compression was determined by use of the assumptions of a constant turbine-inlet temperature and choked turbine nozzles. These are valid assumptions for maximum engine performance operation with compressor pressure ratios of the order investigated. The choked turbine nozzles result in equal turbine corrected gas flows for the normal and augmented cases, or

$$\left[\frac{W_4\sqrt{T_4}}{P_4}\sqrt{\frac{R_4}{\gamma_4 g}}\right]_n = \left[\frac{W_4\sqrt{T_4}}{P_4}\sqrt{\frac{R_4}{\gamma_4 g}}\right]_i \tag{1}$$

The ratio of the turbine-inlet pressures with and without water injection is then

$$\frac{P_{4,i}}{P_{4,n}} = \frac{W_{4,i}}{W_{4,n}}\sqrt{\frac{R_{4,i}\ \gamma_{4,n}}{R_{4,n}\ \gamma_{4,i}}}\sqrt{\frac{T_{4,i}}{T_{4,n}}} \tag{2}$$

With a constant turbine-inlet temperature and a constant pressure ratio across the combustion chamber, the compressor pressure ratios with and without injection are related as follows:

$$\frac{(P_3/P_2)_i}{(P_3/P_2)_n} = \frac{W_{4,i}}{W_{4,n}}\sqrt{\frac{R_{4,i}\ \gamma_{4,n}}{R_{4,n}\ \gamma_{4,i}}} \tag{3}$$

Calculations. - The calculation of the compressor performance with water injection was performed in the following manner: By use of the increased compressor-inlet gas flow accompanying injection (fig. 1), an estimated vapor content at the turbine inlet, and an estimated

increased value of the fuel flow required to maintain the turbine-inlet temperature constant, an approximate value of the compressor pressure ratio with injection $(P_3/P_2)_i'$ was obtained from equation (3). Weighted average values of R and γ, derived from the data of references 3 and 4, were used. A number of segments n was selected, giving an estimated segment pressure ratio $\left[(P_3/P_2)_i'\right]^{\frac{1}{n}}$.

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Continuous saturation during compression was assumed and the Mollier diagrams of reference 2 were used in the evaluation of the segment performance. The methods used for an individual segment were basically the same as those applied to a complete compressor in reference 2. The enthalpy at the inlet of a particular segment was read from the Mollier diagram with the use of the segment-inlet temperature and pressure (obtained from the flight condition and the psychrometric chart of reference 2 for the first segment or from the outlet conditions of the preceding segment for any segment after the first one). The outlet pressure, which is the product of the inlet pressure and the estimated segment pressure ratio $\left[(P_3/P_2)_i'\right]^{\frac{1}{n}}$, was used to read the segment-outlet ideal enthalpy from the Mollier diagram at the segment-inlet entropy value. The actual enthalpy change was obtained by dividing the ideal change across the segment by the segment adiabatic efficiency. The segment adiabatic efficiency was obtained by multiplying the efficiency ratio value from figure 2 by the adiabatic efficiency corresponding to a polytropic efficiency of 0.88 for the estimated segment pressure ratio. The outlet enthalpy was then the sum of the inlet enthalpy and the actual enthalpy rise and, together with the outlet pressure, determined the segment-outlet temperature, vapor-air ratio, and entropy values on the Mollier diagram. The performance of all the segments was determined in sequence, and outlet conditions of the final segment represented the over-all compressor performance. The calculated compressor-outlet vapor-air ratio was compared with the initial estimated value, and a fuel-flow value was derived from the relation

$$W_{f,i} = W_{f,n} \frac{T_4 - T_{3,i}}{T_4 - T_{3,n}}$$

where a value of 2000° R was used for T_4. The fuel flow obtained from this equation was compared with the initial estimated fuel-flow value. The entire calculation procedure was repeated until the compressor-outlet characteristics from the step-wise calculations checked the estimated values.

For all the calculations, a sufficient number of segments n was used to insure essentially integrated values of the compressor performance factors.

Qualification

The analysis as presented herein is restricted to the case of a compressor operating as a component of a gas-turbine engine having choked turbine-inlet nozzles. This restriction is not necessary, however, for the general development of the analysis; by the selection of varying pressure ratios and mass flows, a general compressor performance map for operation with water injection could be derived from the normal compressor map.

Variations in mass flow through the engine and in compressor efficiency due to water injection upstream of the compressor inlet are accounted for in the analysis. These variations are evaluated relative to the design point. Any similar variations due to operation of a fixed-design compressor with varying inlet conditions are not considered. The analysis therefore implies families of compressors, each of which operates normally (that is, without injection) with a selected set of design characteristics. The method of analysis is general, however, and can be used to evaluate the performance of a fixed compressor design under varying operating conditions. 2335

RESULTS AND DISCUSSION

Compressor-Inlet Gas Flow

The increase in gas flow at the compressor inlet resulting from the injection of water upstream of the inlet is shown in figure 3 as a function of the flight Mach number for altitudes from sea level to 50,000 feet. All data presented were calculated for NACA standard altitude pressures and temperatures, but for an ambient relative humidity of 1.0. The ambient relative humidity will generally be less than 1.0, and the increase in inlet gas flow will therefore generally be greater than the value predicted for ambient saturation. For pressures and temperatures near the NACA standard altitude values, the possible error involved is slight. The maximum possible error results at sea-level static conditions for an ambient humidity of 0, where a gas flow ratio $\frac{W_{2,i}}{W_{2,n}}$ of 1.03 would result if zero humidity prevailed rather than the value of 1.0 shown. For conditions involving normal flight Mach numbers and altitudes, and probable prevailing humidities, the error is negligible.

The increase in inlet gas flow accompanying water injection varies directly with the normal inlet total temperature, increasing with flight Mach number and decreasing with increasing altitude up to the tropopause. At sea level the gas flow ratio increases from 1.0 at static conditions to 1.065 at a Mach number of 0.9. At an altitude of 35,000 feet the

ratio increases from a value of just over 1.0 at a Mach number of 0.6 to 1.16 at a Mach number of 2.0. In the stratosphere, the inlet flow ratio increases with altitude for a given flight Mach number even though the ambient temperature is constant. This reversal of the trend with altitude is the result of a constant vapor partial pressure but a decreasing air partial pressure with increasing altitude, which give a resultant increase in the vapor-air ratio for saturated conditions at the compressor inlet with increase in altitude at any particular flight Mach number. The increased vapor-air ratio results in a greater evaporative cooling effect and hence in an increase in the inlet flow ratio.

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Compressor Performance

The compressor performance with water injection is presented in figures 4 to 8 for the flight conditions investigated. The ambient conditions are the same as previously listed, and sufficient water to give a saturated mixture at the compressor outlet is injected into the induction passage. Continuous saturation during induction and compression was assumed for the calculations. Data are presented for normal compressor pressure ratios of 4, 8, and 16 in parts (a), (b), and (c), respectively, of each figure.

Compressor-outlet vapor content. - The compressor-outlet saturation vapor-air ratios are given in figure 4 for the flight conditions covered. The vapor contents vary directly with the flight Mach number and inversely with the altitude up to the tropopause. Above the tropopause there is an inversion in the trend, which can be explained in the same manner as that occurring in the inlet gas flow ratio. For the flight conditions considered, the greatest vapor-air ratio for the normal compressor pressure ratio of 4 is 0.087, and it occurs at a Mach number of 2.0 and an altitude of 50,000 feet. Corresponding values for the normal compressor pressure ratios of 8 and 16 are 0.132 and 0.202, respectively.

The accuracy of the saturation vapor-air ratios is dependent on the accuracy of the compressor efficiency values with evaporative cooling that were used in the analysis. The relative accuracy of the saturation vapor-air ratios is approximately equal to the relative accuracy of the over-all compressor adiabatic efficiency with water injection.

The effect of water injection with compressor-outlet saturation on the engine liquid consumption can be inferred from figure 4. Inasmuch as the normal engine fuel-air ratio with current turbine-inlet temperatures is about 0.015 to 0.02, it is apparent that the liquid consumption with the saturation liquid quantities at the compressor outlet for the normal compressor pressure ratio of 4 for the flight conditions investigated will be from approximately two to over five times the normal fuel consumption. The liquid consumption with the higher normal compressor pressure ratios will be even greater.

Compressor pressure ratio. - Compressor pressure ratios occurring with water injection are shown in figure 5. The general trends in the compressor pressure ratio are similar to those exhibited by the saturation water contents. The pressure ratio increases with Mach number and decreases with increasing altitude up to the tropopause, with an inversion of the altitude trend at altitudes above this point. The change in pressure ratio is due primarily to changes in the saturation vapor content and in the inlet gas flow ratio, since these are the major factors that influence changes in the right-hand side of equation (3). Over the range of conditions investigated, pressure ratios up to 5.15 occur with water injection for the normal compressor pressure ratio of 4; values as high as 10.8 and 23.3 occur for the normal compressor pressure ratios of 8 and 16, respectively. In each case these values occur at a Mach number of 2.0 and an altitude of 50,000 feet.

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Compressor efficiency. - The compressor adiabatic efficiency values for the conditions discussed previously are given in figure 6. This efficiency is defined as the ratio of the isentropic or ideal enthalpy change during compression with evaporation to the actual enthalpy change during compression. The compressor efficiency, in general, varies inversely as the compressor-outlet vapor-air ratio, increasing with altitude up to 35,000 feet and decreasing with increasing Mach number. With the normal compressor pressure ratio of 4 the compressor efficiency with water injection is only slightly lower than normal for all subsonic speeds, lying within 0.015 of the normal value of 0.855. At supersonic speeds the efficiency decreases rapidly, reaching values of 0.78 and 0.76 at a Mach number of 2.0 and altitudes of 35,000 and 50,000 feet, respectively. The decreases in efficiency with water injection are much larger for the normal compressor pressure ratios of 8 and 16. For the normal pressure ratio of 8 the efficiency in the subsonic speed range is as much as 0.035 lower than the normal value of 0.842 and decreases to 0.675 for a Mach number of 2.0 at 50,000 feet. For the normal pressure ratio of 16 the efficiency in the subsonic speed range is as much as 0.083 below the normal value of 0.830 and decreases to 0.575 at a Mach number of 2.0 and an altitude of 50,000 feet.

Compression work. - The ratio of the actual compressor work with water injection to the normal compressor work is given in figure 7. This factor is the ratio of the total compressor work in the two cases rather than the work per pound of air or gas and consequently indicates the change in work required from the turbine. The ratio varies from a minimum value of about 0.89 to a maximum value of 1.23 for the range of flight conditions investigated. For all subsonic flight conditions the ratio is less than 1.0, indicating that under these conditions the increases in compressor pressure ratio and total gas flow have been obtained with a smaller compressor work, notwithstanding the decrease in compressor efficiency. Even for the supersonic conditions, where

the ratio may be greater than 1.0, the relative work required per pound of turbine gas flow (obtained by dividing the ratio of figure 7 by the ratio of turbine gas flows with and without injection) is always less with water injection than without. As a consequence, water injection under the conditions assumed in this investigation will give a greater engine output per pound of turbine gas flow than is attainable with normal operation even though the decrease in compressor efficiency accompanying the injection is very large.

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Compressor-outlet temperature. - Figure 8 presents the compressor-outlet total temperatures for outlet saturation as a function of the flight condition. In general, the temperature varies with the normal compressor-inlet total temperature. For the normal compressor pressure ratio of 4, the temperatures for the flight conditions investigated vary from about 550° to 670° R; for normal pressure ratios of 8 and 16 the temperatures are approximately 50° and 100° R, respectively, higher than for the pressure ratio of 4 at a particular flight condition. The values with evaporative cooling for the pressure ratio of 4 are from 100° to 450° R below normal values (not shown), the smallest differences occurring for the lowest Mach numbers at the high altitudes and the largest occurring for the highest Mach numbers investigated. The temperature depression is even greater for the pressure ratios of 8 and 16. The large decreases in compressor-outlet temperature with liquid injection may affect the engine combustion characteristics and may preclude operation with the saturation quantity of injected liquid under some conditions.

Applicability of Analysis

Several factors not previously discussed should be considered in the application of this method of compressor performance evaluation. The data of figure 2 were selected as average values representative of a number of individual compressor stages and, although not representing exactly the performance of any particular stage, reflect the general characteristics of all the data examined. Further, the assumption that all segments of the compressor normally operate at the peak efficiency value should yield a close approximation to the actual compressor performance if the over-all normal compressor efficiency is high, because high over-all efficiencies can be obtained only when all portions of the compressor operate at high efficiency. Where the over-all normal efficiency is low, the assumption may be less applicable because the lower efficiency might result from the individual segments operating at lower than peak values as well as from a possible lowering of the maximum efficiency value for an individual segment. For a fixed-design compressor operating at less than its maximum efficiency, the lower efficiency is obviously due to the individual segments operating away from the peak efficiency values. The present method of determining the compressor performance with evaporative cooling would be less applicable under these conditions.

The degree to which the actual evaporation phenomena in an axial-flow compressor are approximated by the idealized assumption of continuous saturation throughout the process will, of course, affect the applicability of the results presented. Because accurate determinations of the degree of saturation existing throughout an axial-flow compressor operating with inlet injection are unavailable, no general statements relative to the validity of the analysis in this respect can be made.

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The values of compressor pressure ratio with water injection that are presented herein are theoretically determined. For a particular compressor some of the values shown may be unobtainable because of the incidence of compressor surge with increased back pressure within the range of liquid injections covered.

As the inlet temperature for some of the flight conditions considered is below the freezing point, a nonfreezing liquid would necessarily have to be substituted for the injected water. Such a substitution has not been considered in this analysis. Reference 1 states, however, that the substitution of an alcohol-water mixture in place of water in experimental tests has been found to have slight effect on the augmented thrust of a turbojet engine. It may therefore be assumed that the major effects on compressor performance are similar with water injection and with water-alcohol injection.

SUMMARY OF RESULTS

A theoretical analysis based on the assumptions of choked turbine nozzles and a compression efficiency dependent on the amount of evaporative cooling was used to evaluate the performance of an axial-flow compressor operating in a gas-turbine engine with inlet water injection and compressor-outlet saturation.

The analysis indicated that the compressor work per pound of turbine gas flow was always lower with inlet water injection than without even at low altitudes, high Mach numbers, or high compressor pressure ratios where large decreases in compressor efficiency occurred. Consequently, engine output per pound of turbine gas flow will be greater with injection than without.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 26, 1951

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APPENDIX A

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
a	velocity of sound, ft/sec
d	diameter, ft
g	acceleration due to gravity, 32.2 ft/sec^2
k	constant
M	Mach number
m	vapor-air ratio
N	compressor rotational speed, rpm
n	number of compressor segments used in calculation
P	total pressure, lb/sq in. absolute
p	static pressure, lb/sq in. absolute
R	gas constant, ft-lb/(lb)($^{\circ}$R)
T	total temperature, $^{\circ}$R
t	static temperature, $^{\circ}$R
U	rotor tip velocity, ft/sec
V	flow velocity, ft/sec
W	gas flow, lb/sec
W_f	fuel flow, lb/sec
γ	ratio of specific heats
η	efficiency
ρ	density, lb/cu ft

Subscripts:

a air

ad adiabatic

d design

i with water injection

max maximum

n normal

S segment

v vapor

0 ambient or flight

1 engine diffuser inlet

2 compressor inlet

3 compressor outlet

4 turbine inlet

Superscript:

' trial or approximate value

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APPENDIX B

CORRECTION PARAMETERS

In developing the corrected parameters appearing in figures 1 and 2, it was assumed that the performance of a continuous-flow rotating machine is a function only of the rotor-tip Mach number (that is, the ratio of the rotor-tip velocity to the velocity of sound in the gas at the rotor plane).

Developing from the expression for the rotor-tip Mach number, then

$$\frac{U}{a} = \frac{\pi N d}{60\sqrt{\gamma g R t}} \tag{B1}$$

or, converting to total temperatures,

$$\frac{U}{a} = k\,\frac{N}{\sqrt{\gamma g R T}}\sqrt{1 + \frac{\gamma-1}{2}M^2} \tag{B2}$$

Transposing terms gives

$$\frac{U/a}{k\sqrt{1 + \frac{\gamma-1}{2}M^2}} = \frac{N}{\sqrt{\gamma g R T}} \tag{B3}$$

As M is a function of U/a, the right-hand side of equation (B3) is also a function of U/a except for the possible change in the term $\frac{\gamma-1}{2}$. For the range of γ encountered in the present investigation, the variation in the value of the left side of the equation due to variation in γ was slight for the pertinent range of M. The expression $N/\sqrt{\gamma g R T}$ was therefore chosen for the corrected speed.

The expression for corrected gas flow was developed from the definition of Mach number in the following manner:

$$M = \frac{V}{a} = \frac{W}{\rho A a} \tag{B4}$$

$$= \frac{W R t}{p A \sqrt{\gamma g R t}} \tag{B5}$$

Using total values of pressure and temperature

$$M = \frac{W}{A}\frac{\sqrt{T}}{P}\sqrt{\frac{R}{\gamma g}}\left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{B6}$$

or

$$\frac{MA}{\left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} = \frac{W\sqrt{T}}{P}\sqrt{\frac{R}{\gamma g}} \tag{B7}$$

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Since A is a constant, the left side of equation (B7) is dependent on M (or U/a) except for possible variations in γ. In the present analysis the error arising from neglect of this variation was small. The expression $\frac{W\sqrt{T}}{P}\sqrt{\frac{R}{\gamma g}}$ was therefore chosen for the corrected flow.

The assumption that the inlet-flow Mach number is a function of the rotor-tip Mach number then gives a single curve in figure 2. Similarly, the assumption that the efficiency of a compressor segment is a function of the rotor-tip Mach number gives a single curve in figure 1.

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REFERENCES

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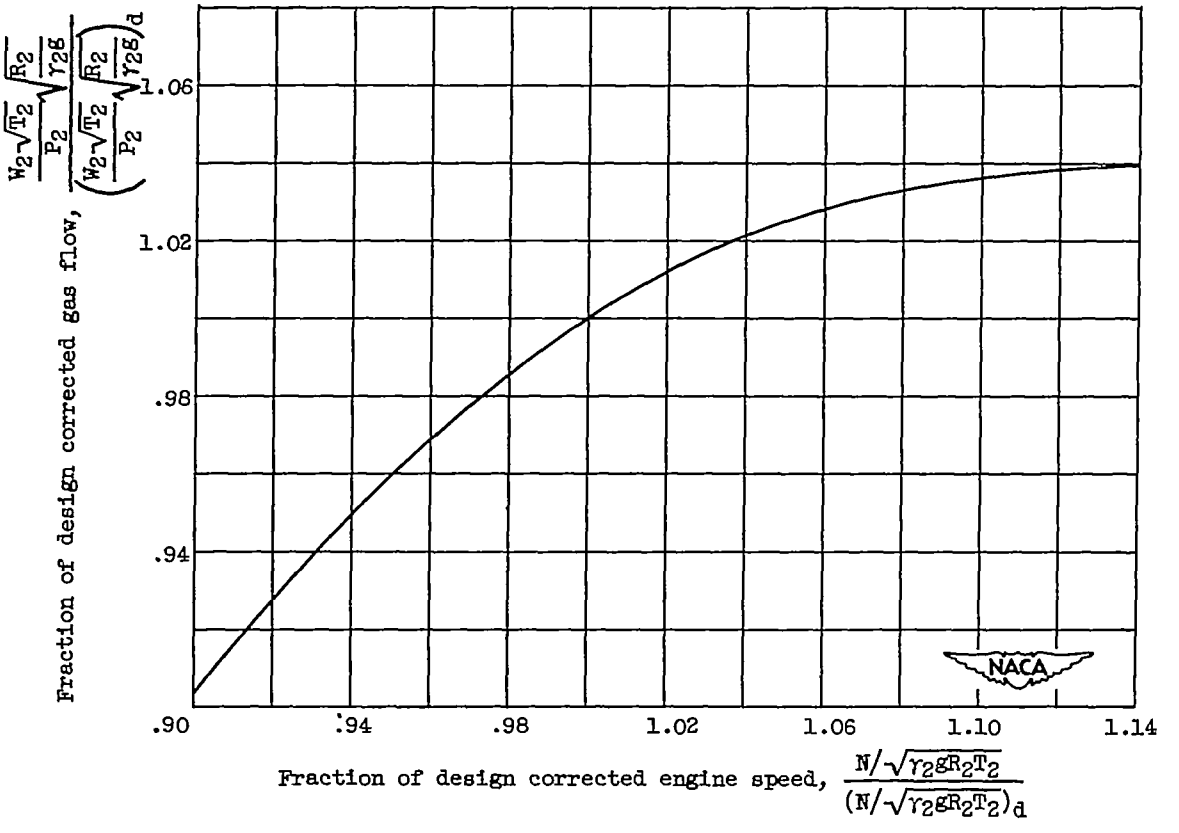

Figure 1. - Variation of compressor-inlet corrected gas flow with corrected engine speed.

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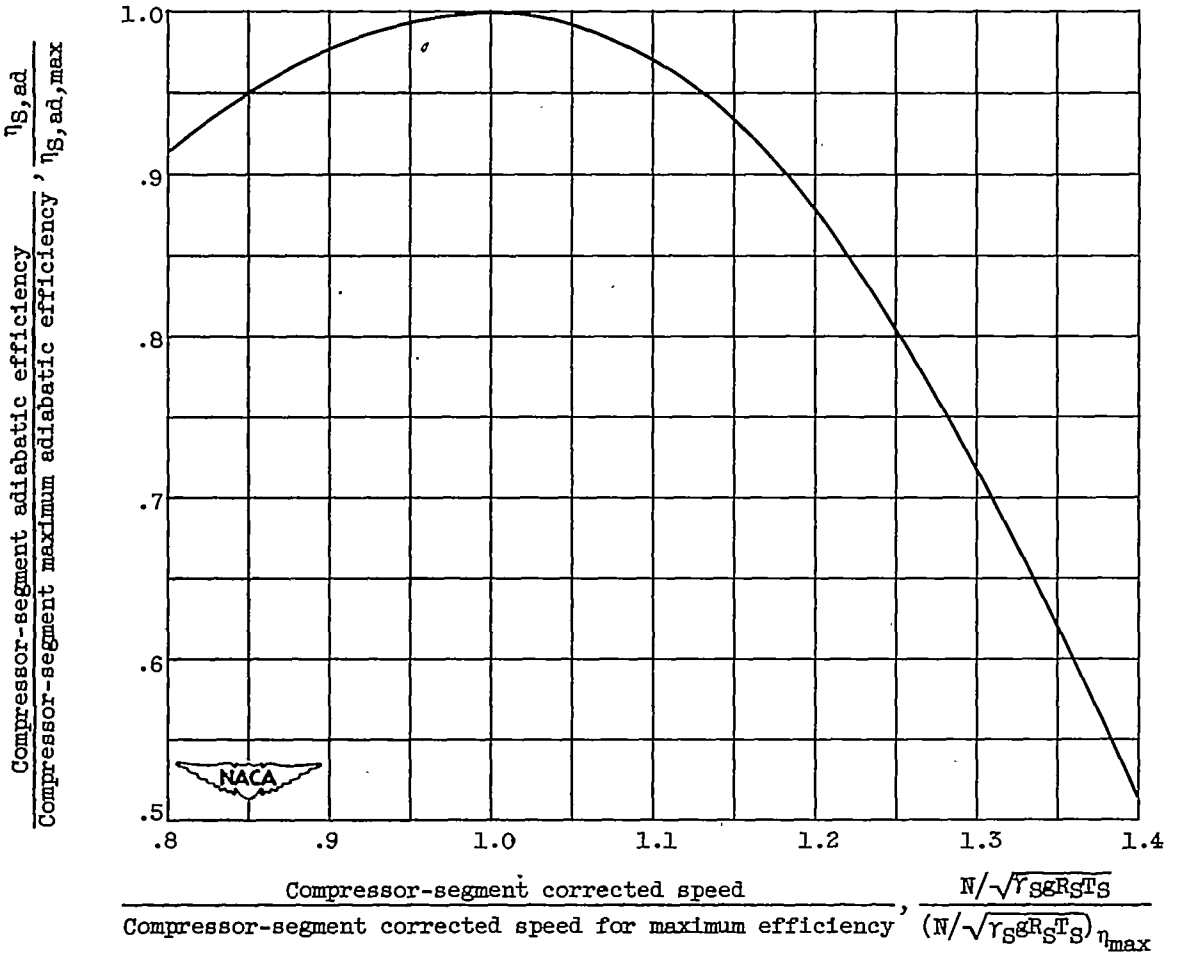

Figure 2. - Variation of compressor-segment adiabatic efficiency with compressor-segment corrected speed.

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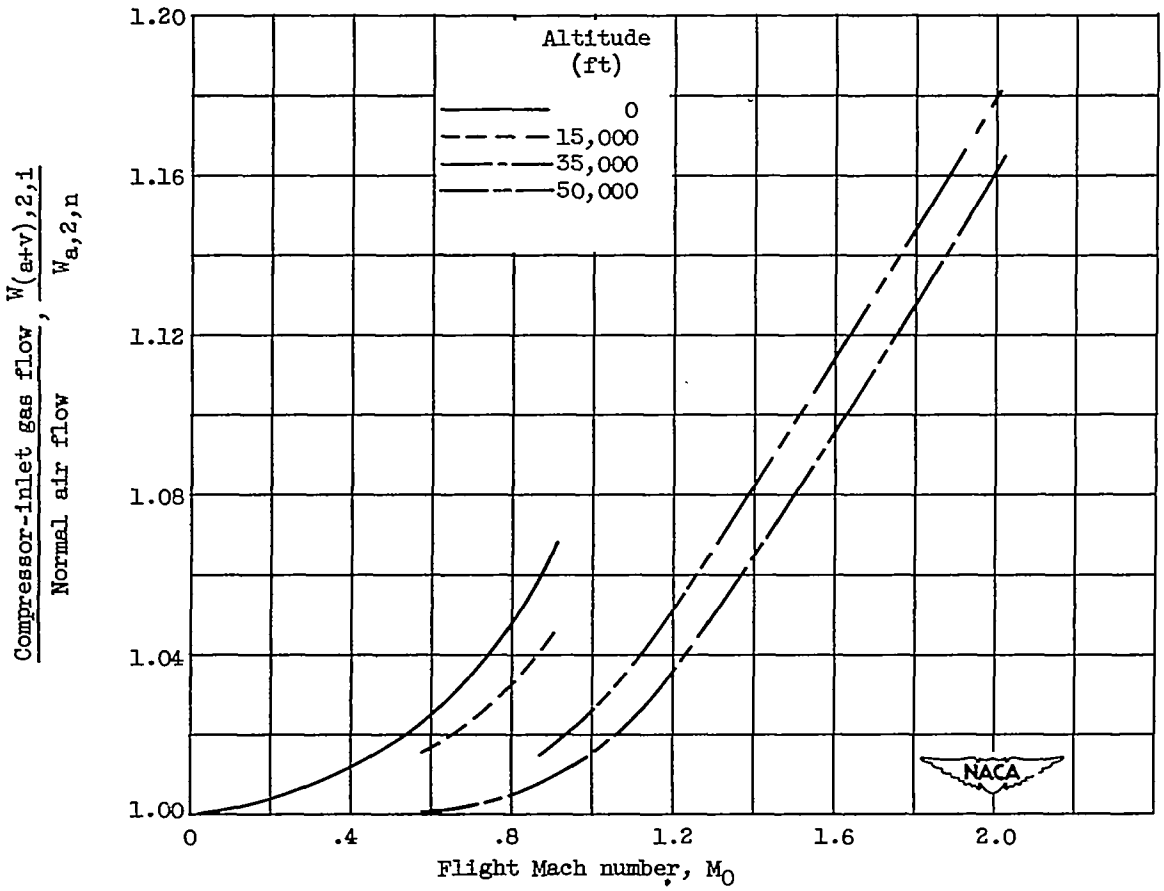

Figure 3. - Effect of flight condition on compressor-inlet gas flow with water injection providing saturation at the inlet.

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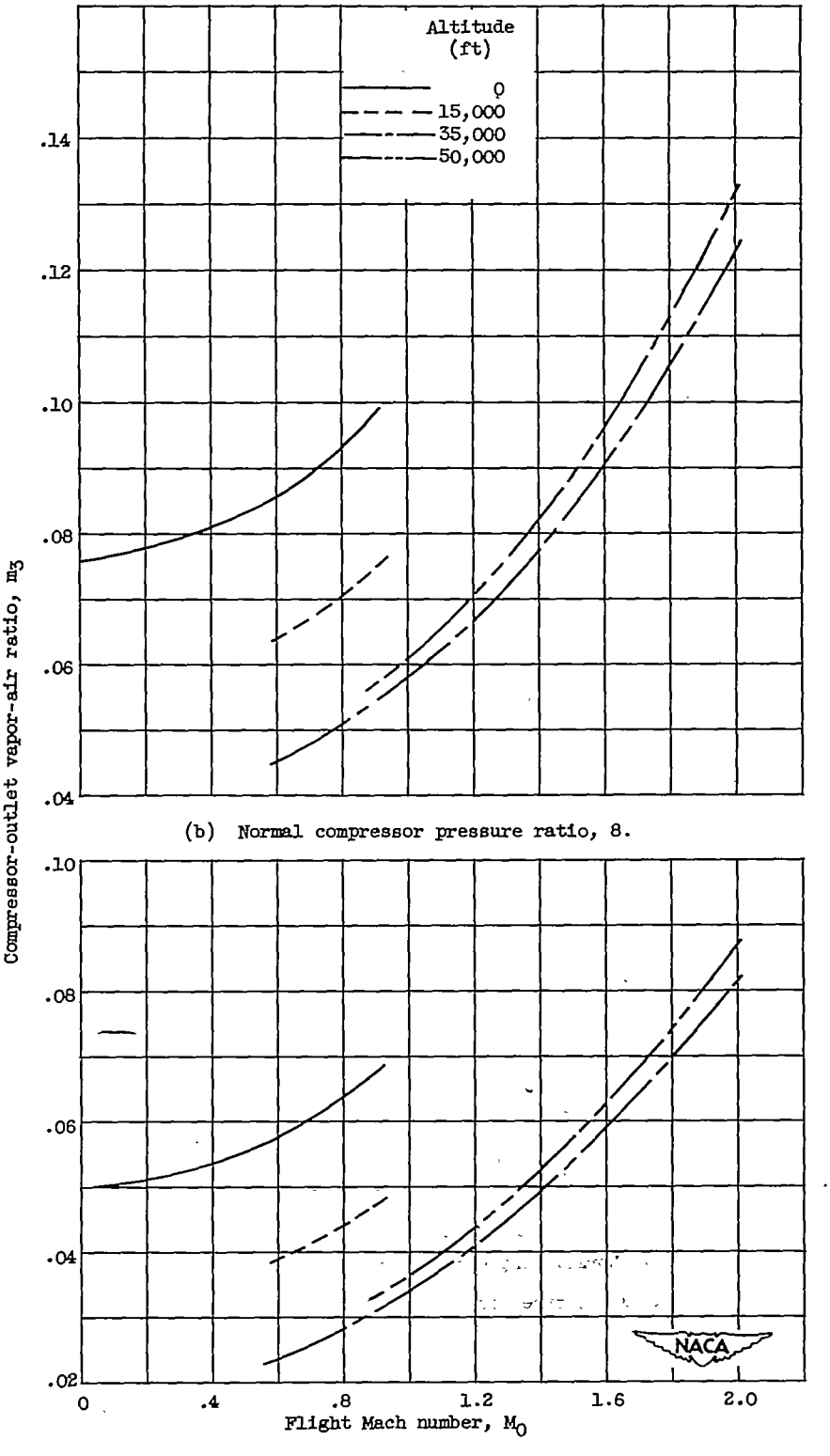

(b) Normal compressor pressure ratio, 8.

(a) Normal compressor pressure ratio, 4.

Figure 4. - Compressor-outlet-saturation vapor-air ratios.

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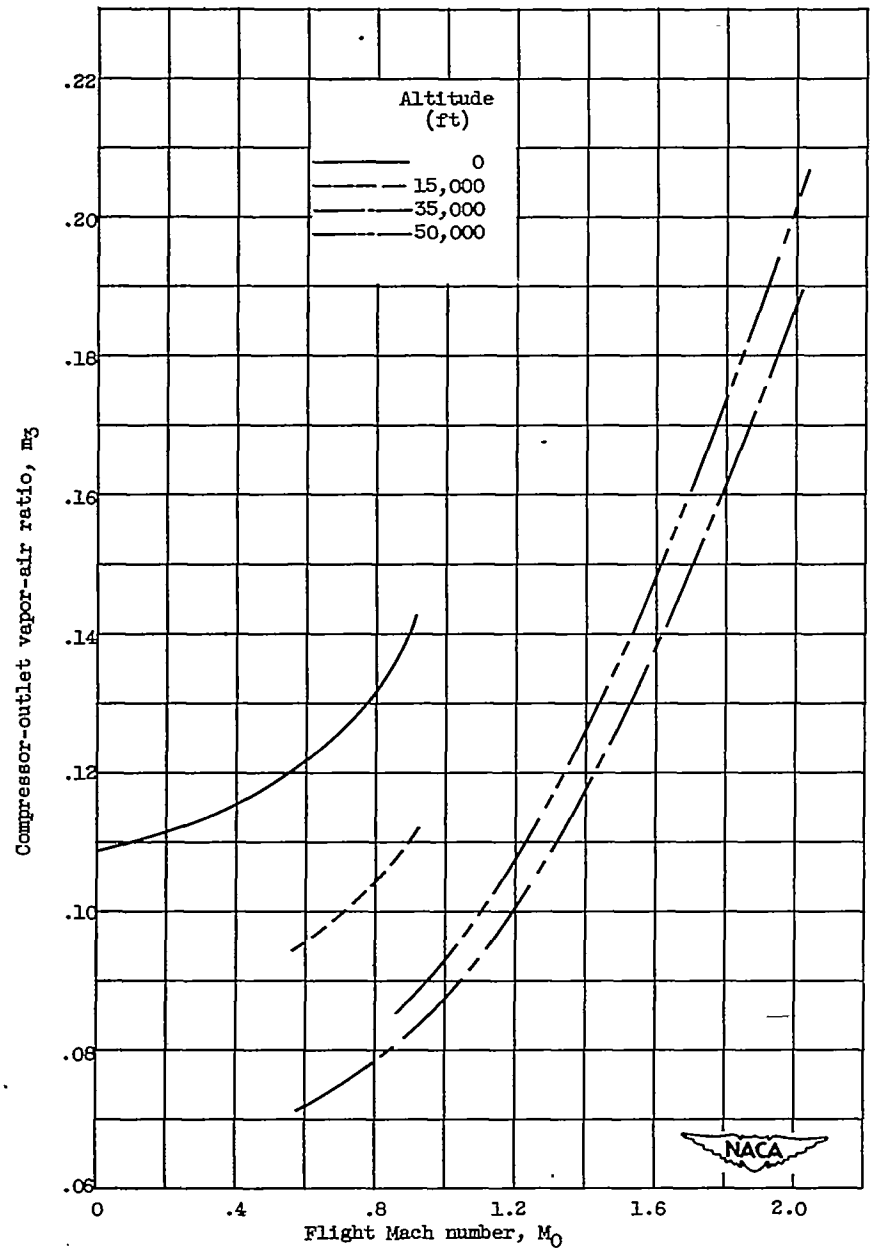

(c) Normal compressor pressure ratio, 16.

Figure 4. - Concluded. Compressor-outlet-saturation vapor-air ratios.

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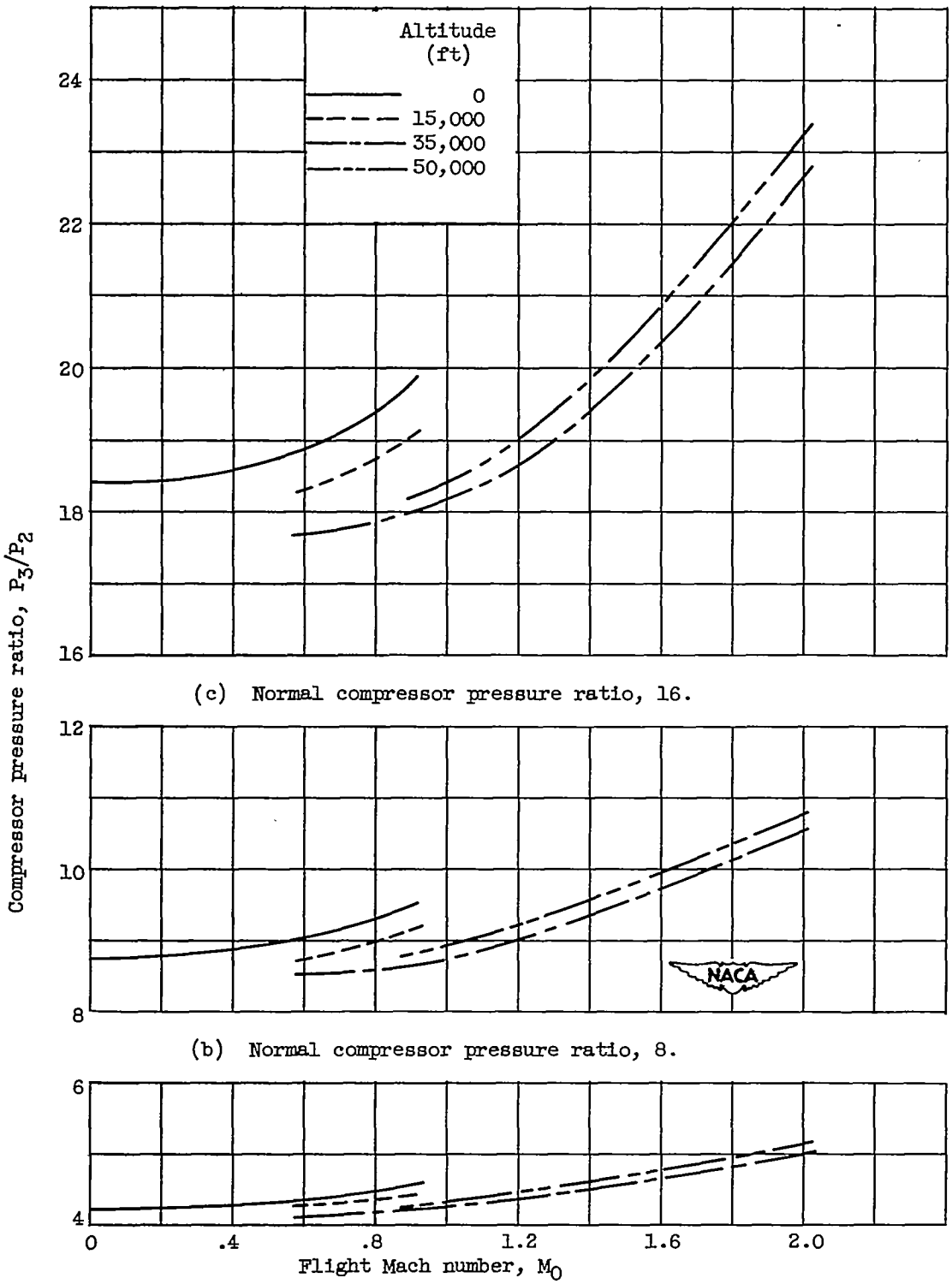

(c) Normal compressor pressure ratio, 16.

(b) Normal compressor pressure ratio, 8.

(a) Normal compressor pressure ratio, 4.

Figure 5. - Effect of flight condition on compressor pressure ratio with water injection providing compressor-outlet saturation.

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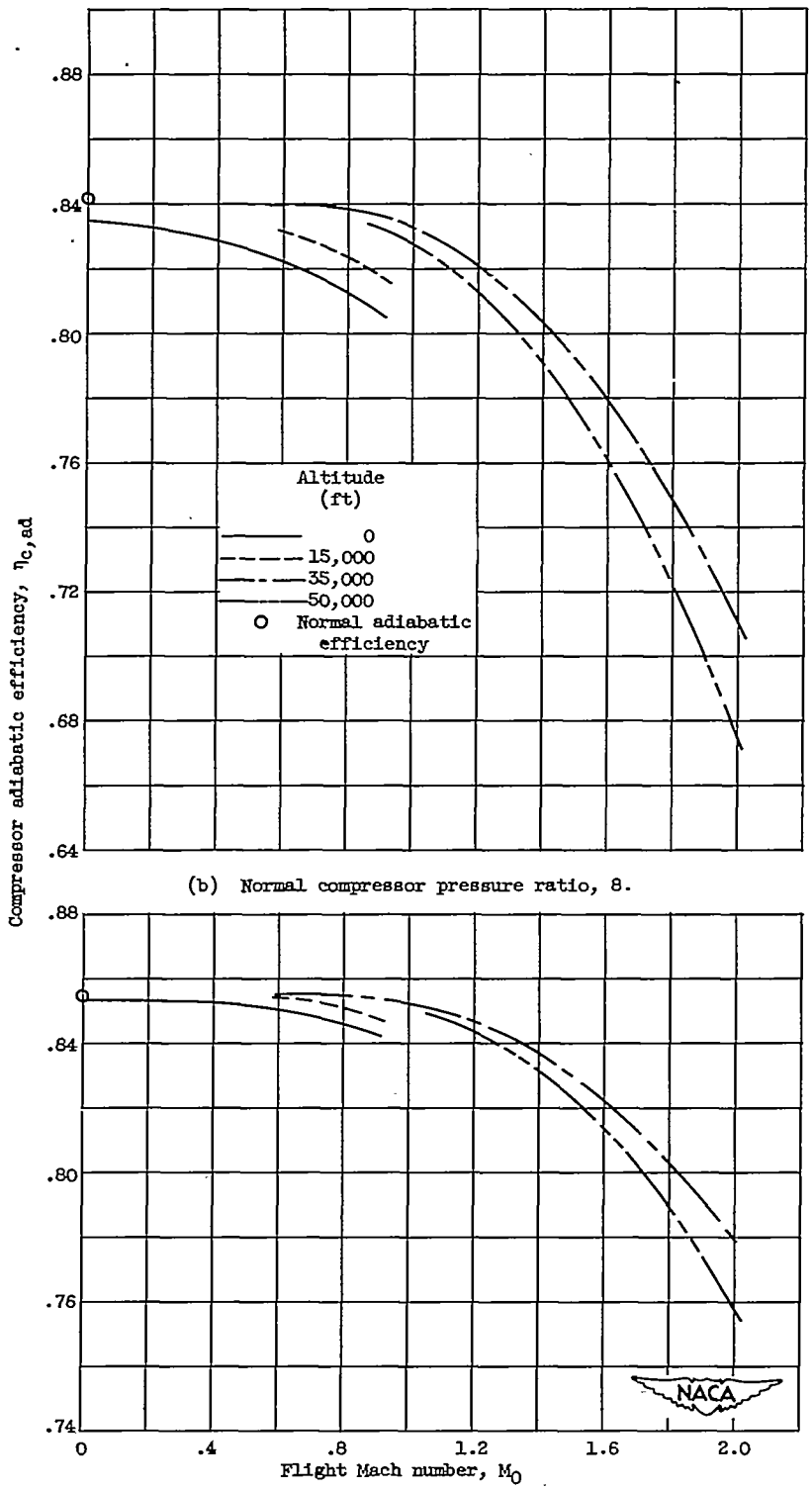

(b) Normal compressor pressure ratio, 8.

(a) Normal compressor pressure ratio, 4.

Figure 6. - Effect of flight condition on compressor adiabatic efficiency with water injection providing compressor-outlet saturation.

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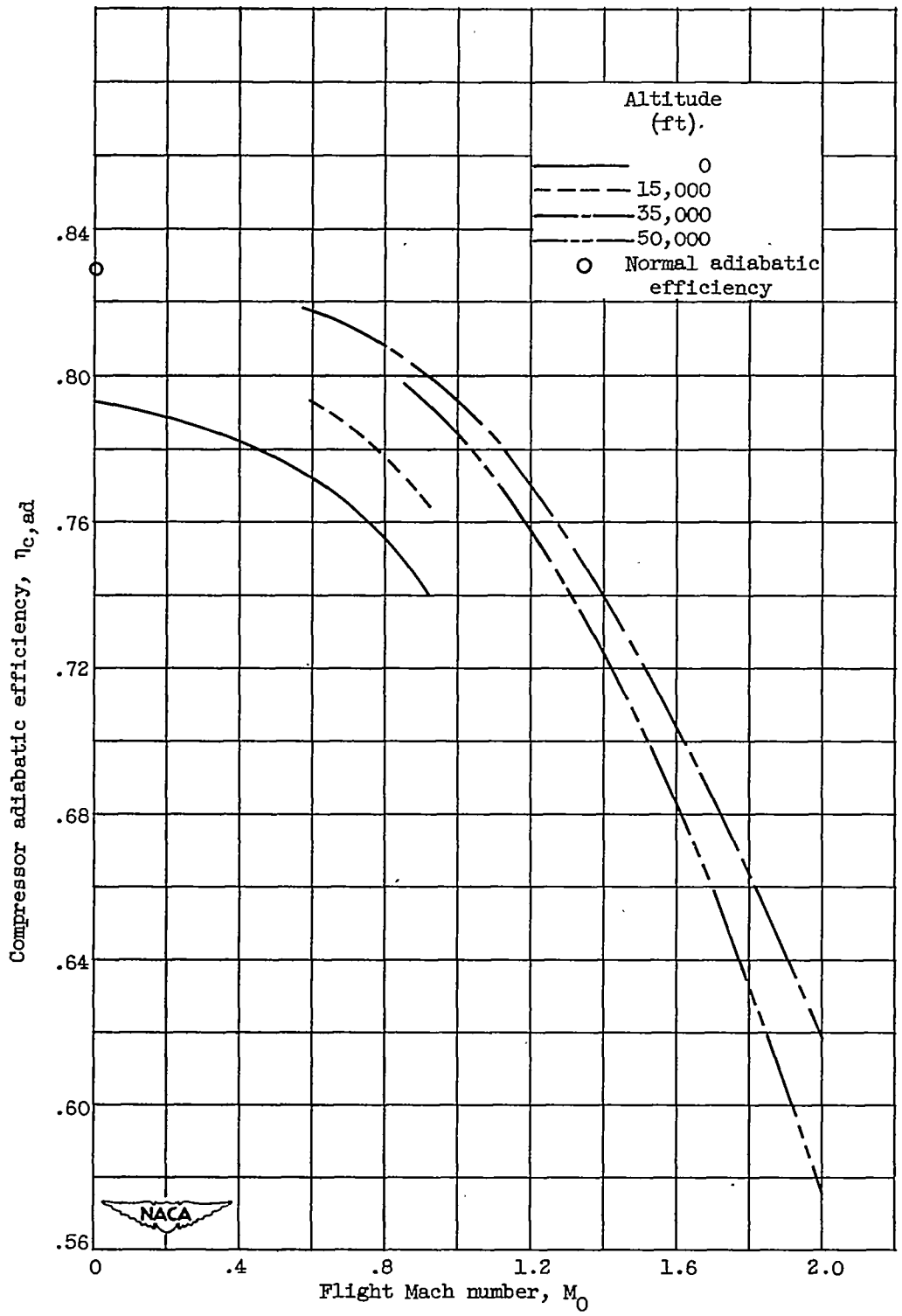
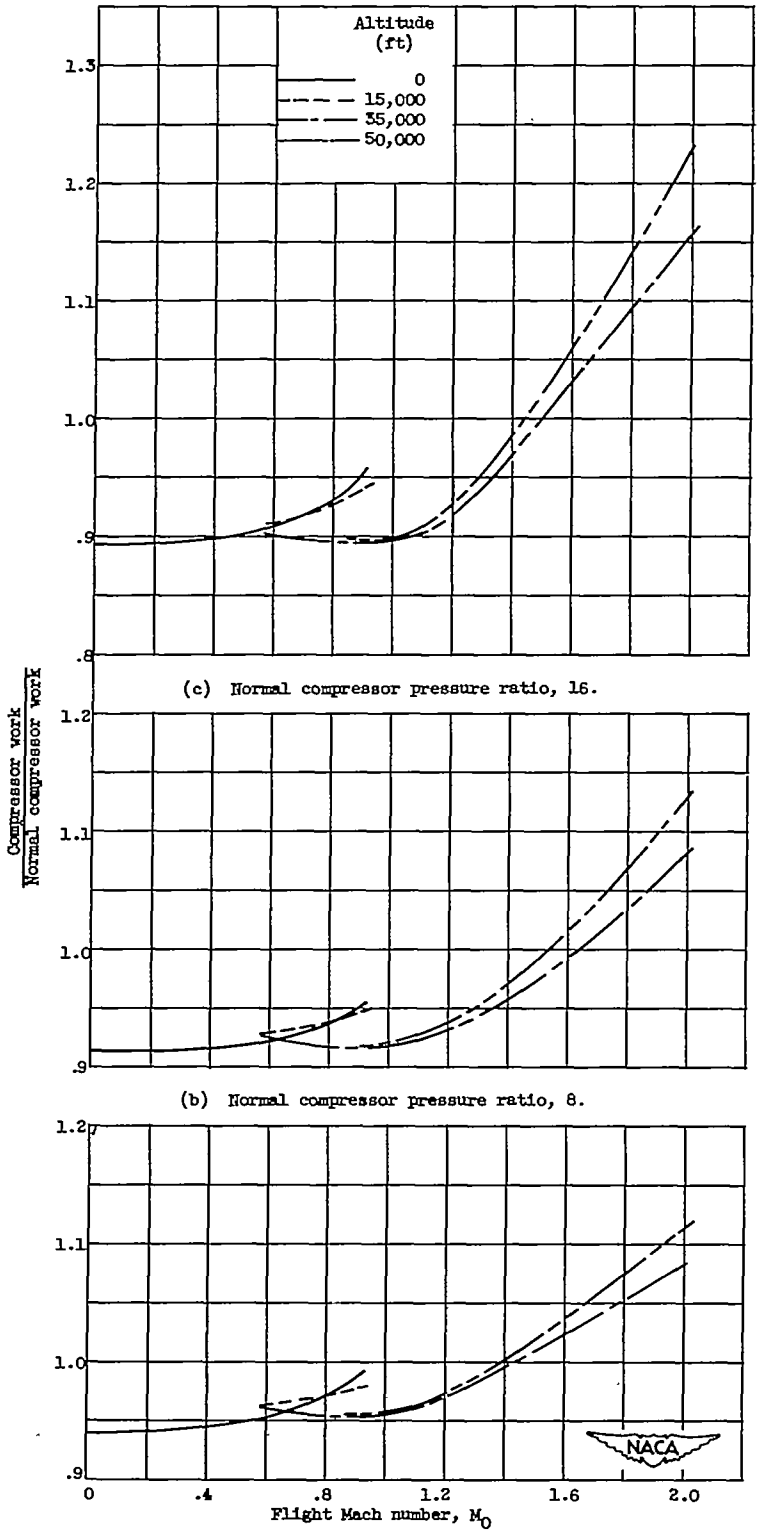


(c) Normal compressor pressure ratio, 16.

Figure 6. - Concluded. Effect of flight condition on compressor adiabatic efficiency with water injection providing compressor-outlet saturation.



(c) Normal compressor pressure ratio, 16.

(b) Normal compressor pressure ratio, 8.

(a) Normal compressor pressure ratio, 4.

Figure 7. - Effect of water injection providing compressor-outlet saturation on compressor work.

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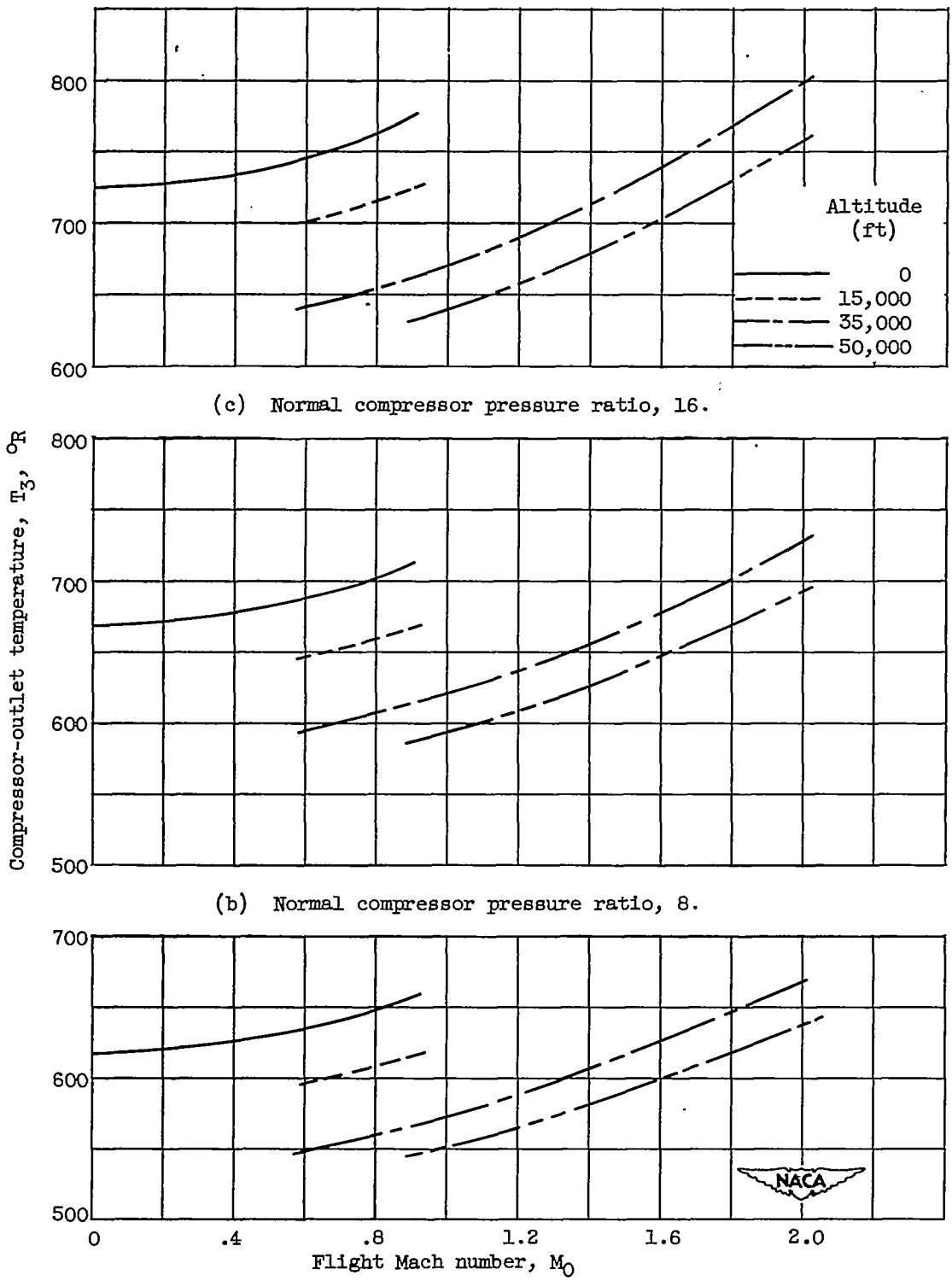

(c) Normal compressor pressure ratio, 16.

(b) Normal compressor pressure ratio, 8.

(a) Normal compressor pressure ratio, 4.

Figure 8. - Effect of flight condition on compressor-outlet temperature with water injection providing outlet saturation.

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