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THEORETICAL AUGMENTATION OF TURBINE-PROPELLER ENGINE BY COMPRESSOR-INLET WATER INJECTION, TAIL-PIPE BURNING, AND THEIR COMBINATION

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Washington
March 1952

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SUMMARY

The theoretical performance of the turbine-propeller engine with augmentation by means of compressor-inlet water injection, tail-pipe burning, and a combination of the two methods was evaluated. The investigation covered altitudes and Mach numbers representing the most probable range of application for each of the augmentation methods. The effects on augmentation of variations in compressor and turbine efficiency, compressor pressure ratio, turbine-inlet temperature, and propeller-plus-gear efficiency were investigated. The effects of ambient humidity and temperature and of the degree of evaporation during compression were also investigated.

The augmentation from either compressor-inlet water injection or tail-pipe burning varied directly as the compressor pressure ratio and inversely as the turbine-inlet temperature, compressor efficiency, or turbine efficiency.

For an engine having an unaugmented pressure ratio of 8, a turbine-inlet temperature of 2000° R, and normal compressor and turbine polytropic efficiencies of 0.88, augmentations as great as 95 percent with water injection and 58 percent with tail-pipe burning were obtained. Greater augmentation was obtained from water injection than from tail-pipe burning under all conditions except for transonic speeds at an altitude of about 35,000 feet; at this altitude the augmentations were comparable but the liquid consumption with tail-pipe burning was considerably lower. In the transonic speed range at an altitude of 35,000 feet, augmentations from the individual methods were more than additive when the methods were used in combination. Liquid consumptions for the different augmentation methods were from 3.5 to 9.6 times the unaugmented consumption.

A large part of the maximum augmentation with water injection at the compressor inlet would result even if no evaporation occurred during compression.

Variations of ambient relative humidity had slight effect on the degree of augmentation with water injection.

Compressor-inlet water injection maintained standard take-off power with temperatures as high as 580° R at pressure altitudes up to 7500 feet. 2445

INTRODUCTION

Up to the present time little interest has been shown in the augmentation of turbine-propeller engines because this engine type has been considered less desirable than the turbojet engine for high-speed applications, and because the take-off performance of unaugmented turbine-propeller-powered aircraft is generally satisfactory. Consequently, the augmented performance of turbine-propeller engines has not been thoroughly investigated even though extensive studies of turbojet augmentation have been made (references 1 to 3).

Theoretical analyses (reference 4) indicate that at moderately high airspeeds, turbine-propeller-powered aircraft can operate over considerably longer ranges than can turbojet-powered aircraft, but that this superiority rapidly diminishes as the airspeed increases. With continued progress in the development of high-speed propellers, however, the highest airspeeds at which the turbine-propeller engine remains competitive with the turbojet engine will increase, and these two engine types may be competitive in the transonic speed range. In addition, augmentation of the turbine-propeller engine may be desirable for take-off or climb under adverse conditions (for example, with high ambient temperatures, pressure altitude considerably above sea level, or from short runways). Because of these considerations, a theoretical evaluation of turbine-propeller augmentation was made at the NACA Lewis laboratory and is presented herein. The augmentation methods investigated are (1) compressor-inlet water injection, (2) tail-pipe burning, and (3) combined water injection and tail-pipe burning. Each method of augmentation is evaluated at those altitudes and Mach numbers for which it is most applicable. The effects of changes in engine design characteristics on augmented performance are also shown.

ANALYSIS

Scope

Variations in compressor efficiency, mass flow through the engine, and compressor pressure ratio due to water injection at the compressor inlet are taken into account in the analysis. In other aspects of the investigation the analysis is restricted to design-point studies. Under this restriction, the points presented depict the performances of a

group of engines each of which has the components operating with identical characteristics, rather than the performance of one particular engine under varying operating conditions. The method therefore tends to evaluate the potentialities of the augmentation schemes for a fixed set of engine design and operating variables. Variations in mass flow, compressor pressure ratio, component efficiencies, and so forth with the engine operating conditions are not considered. The degree of augmentation possible has, however, been investigated for different values of the major component efficiencies and engine design variables; consequently, for a particular engine, if the change in any factor accompanying operation at an off-design point is known, the change in augmentation resulting from this off-design performance can be estimated from the data presented herein.

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At the present stage of development, the axial-flow compressor is considered most suitable for turbine-propeller engine application. As a result, compressor performance characteristics typical of this unit have been used in the analysis.

Engine characteristics. - The values of the major engine design variables and component characteristics used in the analysis are given in the following table:

Compressor pressure ratio	
Reference value	8
Additional values	4,16
Turbine-inlet temperature, °R	
Reference value	2000
Additional values	1500, 2500, 3000
Inlet-diffuser pressure loss, percent of inlet dynamic pressure	8
Compressor normal polytropic efficiency	
Reference value	0.88
Additional value	0.83
Turbine polytropic efficiency	
Reference value	0.88
Additional value	0.83
Combustion efficiency (basic engine)	0.97
Combustion pressure ratio, $\Phi(P_3/P_2)$	
Reference value,	
For $P_3/P_2 = 8$	0.985
For $P_3/P_2 = 4$	0.96
For $P_3/P_2 = 16$	0.99
Heating value of fuel, Btu/lb	18,600
Exhaust-nozzle thrust coefficient	0.96

Additional values used in calculating the augmented performance are as follows:

Tail-pipe-burner outlet temperature, °R	3500
Tail-pipe combustion efficiency	0.90
Tail-pipe-burner inlet Mach number	0.2
Tail-pipe friction pressure loss, proportion of dynamic pressure head	2
Temperature of injected water, °R	519

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Flight conditions investigated. - Each of the methods of augmentation was evaluated for the combinations of altitude and flight Mach number at which it was most effective or most likely to be applied. Compressor-inlet water injection was considered for altitudes from sea level to 35,000 feet and Mach numbers from 0 to 1.1. Tail-pipe burning was used for the same altitude range with Mach numbers from 0.6 to 1.1. The combination of water injection with tail-pipe burning was evaluated only at an altitude of 35,000 feet and Mach numbers of 0.9 to 1.1. Augmented performance at Mach numbers above 0.9 was evaluated only at an altitude of 35,000 feet.

Methods

Normal engine performance. - The basic unaugmented engine performance was obtained from direct calculations of the performance of the individual components using the thermodynamic data and methods of reference 5. This method depends on the determination of the state of the working fluid during its passage through the engine, using the enthalpy and entropy terms h and φ (all symbols are defined in appendix A). The shaft power was obtained from the difference between turbine and compressor enthalpy changes, and the jet thrust was calculated from the turbine outlet temperature and the available tail-pipe expansion pressure ratio. All equations used in the calculations are given in appendix B.

Engine performance was computed for several divisions of power between the pure turbine-propeller engine and the turbojet engine in order that the optimum division of power for each operating condition could be determined.

Performance with tail-pipe burning. - The performance of the engine with tail-pipe burning was determined from the basic unaugmented engine performance. Tail-pipe pressure losses accompanying the burning of the additional fuel required to attain a temperature of 3500° R were accounted for and the corresponding jet thrust then calculated.

Performance with compressor-inlet water injection. - In the analysis given herein, the compressor performance with water injection at the inlet was obtained directly from, or calculated using the method of reference 6. The method used therein to determine the compressor performance was briefly as follows:

Saturation at the compressor inlet was assumed for all operating conditions. Any evaporative cooling upstream of the inlet therefore increased the compressor-inlet gas flow in accordance with an assumed variation of the corrected gas flow with corrected engine speed. By assuming that the turbine nozzles were choked, the increase in gas flow through the compressor due to water injection (with complete evaporation upstream of the turbine) uniquely determined the accompanying increase in compressor pressure ratio. The evaporation of water prior to any point in the compressor lowered the temperature at that point below the normal value, with a resultant higher blade Mach number (ratio of blade velocity to velocity of sound in the air-vapor mixture at that point). The compressor efficiency was then determined by an iterative process, applied to successive portions of the compression process, which employed an assumed variation of compression efficiency with blade Mach number. The over-all compressor performance was then completely defined in terms of the increased gas flow and pressure ratio and the decreased efficiency.

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All water injected into the compressor was assumed to be at a temperature of 519° R, and sufficient evaporation upstream of the compressor was assumed to maintain saturation at the compressor inlet. Unless stated otherwise, an ambient relative humidity of 1.0 and continuous saturation during compression were implied for all water-injection performance data presented hereinafter.

All other portions of the gas-turbine cycle were calculated using the data and methods of reference 5. The only change in the procedure as compared with that used for the basic and tail-pipe burning cycles is the necessity of including enthalpy and entropy terms for the water vapor contents at all points in the cycle.

Performance with compressor-inlet water injection plus tail-pipe burning. - The performance with the combined method of augmentation was calculated by methods analogous to those applied to similar portions of the individual augmentation cycles, with the inclusion of enthalpy and entropy terms for the water vapor content for the tail-pipe burning portion of the cycle.

RESULTS AND DISCUSSION

The calculated performance factors for the turbine-propeller engine for normal and augmented operation are presented in figure 1 for a range of flight conditions and engine design variables. The factors given in figure 1 are the ratios of net thrust to normal air flow (where the net thrust is defined as the jet thrust minus the inlet momentum), shaft horsepower to normal air flow, and liquid flow to normal air flow. The data are given as functions of the tail-pipe pressure ratio P_5/p_0. From these data the engine performance can be ascertained as a function of the

power division between the propeller and the jet. Any desired propeller and gear efficiencies may be used to obtain the propulsion potentialities of the basic and augmented cycles.

The selected conditions for which data are shown are considered of major interest insofar as the possible applications of turbine-propeller augmentation are concerned, and have been included in order that performance factors for power divisions and propeller-plus-gear efficiencies differing from those used in the remaining discussion may be readily obtainable. 2445

The general manner in which each of the augmentation methods affects the performance of the turbine-propeller engine is shown in figure 1(b). Water injection increases the maximum tail-pipe pressure ratio attainable, or increases the shaft horsepower available at a given value of the tail-pipe pressure ratio. These effects result from the increase in turbine gas flow with water injection, which gives a higher compressor pressure ratio, and from the decreased compressor work required with water injection. Tail-pipe burning has no effect on the engine shaft power but increases the thrust considerably because of the higher tail-pipe-nozzle gas temperature. The combined methods affect the shaft power in exactly the same manner as water injection alone and increase the thrust somewhat more than does tail-pipe burning alone. This greater thrust increase results because the pressure losses accompanying tail-pipe burning are less important at the higher compressor pressure ratios accompanying water injection. The liquid flow is greatly increased by each method of augmentation. The smallest increase is caused by tail-pipe burning and the largest by the combined methods of augmentation.

In order to illustrate conveniently and to discuss some of the more important considerations accompanying the use of augmentation for turbine-propeller engines, the remainder of the discussion will be limited to points representing optimum or near optimum divisions of power between the propeller and the jet. The method of arriving at these optimum values is shown by figure 2. In figure 2, the thrust and shaft power factors of figure 1(b) are combined in a single total thrust term for several different propeller-plus-gear efficiencies and this total thrust term is plotted over the range of possible power divisions (or tail-pipe pressure ratios). Data are shown for normal operation as well as for each of the three augmentation schemes. Optimum thrust values occur for each of the methods; the magnitude of this optimum varies, of course, with the value of propeller-plus-gear efficiency as well as with the method of augmentation. The ratio of the optimum thrust with augmentation to the optimum thrust with normal operation, both for the same propeller-plus-gear efficiency, is defined as the augmented thrust ratio for the particular efficiency involved.

Reference Engine Augmented Performance

Effect of propeller-plus-gear efficiency. - The augmented thrust ratios for the reference engine at a typical flight condition (a Mach number of 0.9 at 35,000-ft altitude) are shown in figure 3 as a function of the propeller-plus-gear efficiency. The augmented thrust ratio with tail-pipe burning is larger than that with water injection for compressor-plus-gear efficiencies lower than 0.78 for this flight condition. The percentage thrust augmentation from the combined methods for this flight condition is approximately 15 percent greater than the sum of the augmentations available from the two methods applied separately, regardless of the conversion efficiency. The augmented thrust ratio with compressor-inlet water injection is independent of the propeller-plus-gear efficiency in the range covered, whereas the augmentation ratio with either tail-pipe burning or the combination of both methods varies inversely as the efficiency (the actual thrust values vary directly as the efficiency, however, as can be seen by reference to fig. 2). The constancy of the augmented thrust ratio with water injection for varying propeller-plus-gear efficiency can be explained as follows: If the propeller-plus-gear efficiency decreases, the optimum value of the tail-pipe pressure ratio increases (fig. 2). At the higher tail-pipe pressure ratio, the percentage augmentation of the shaft power increases as shown in figure 1, but concurrently, a smaller portion of the total engine output is derived from the shaft. These two changes are compensatory, with the result that the augmented thrust ratio is essentially independent of the propeller-plus-gear efficiency.

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Augmentation by tail-pipe burning alone and in combination with water injection may be more attractive as compared with water-injection augmentation if the probable changes in propeller efficiency accompanying augmentation by each of the methods are included. The probable trends in propeller efficiency can be predicted from figure 4, where the ratio of the shaft power with augmentation to the normal shaft power is plotted. The power transmitted to the propeller with augmented operation at optimum power division is approximately 33 percent above normal with water injection, approximately normal with combined operation, and about 30 percent below normal with tail-pipe burning. The increased propeller loading accompanying water-injection augmentation may therefore decrease the propeller efficiency.

Effect of flight condition on augmented performance. - The augmented thrust ratio for the reference engine characteristics is presented in figure 5 as a function of altitude and flight Mach number. With compressor-inlet water injection, the augmentation varies directly with the Mach number and inversely as the altitude. At sea level, the augmentation increases from just greater than 50 percent at low Mach numbers to 95 percent at a Mach number of 0.9. At 35,000 feet, the augmentation is 22 percent at a Mach number of 0.6 and 43 percent at a Mach number of 1.1. Although not

shown on figure 5, the augmentation at altitudes above 35,000 feet is approximately equal to that at 35,000 feet. There is, however, a slight increase with altitude above the tropopause because the constant temperature with a decreasing pressure in this range results in a proportionately higher vapor partial pressure with a resultant slight increase in the vapor-air ratios attainable in the compressor and hence a slight increase in augmentation. 2445

The augmented thrust ratio for tail-pipe burning is greatly affected by variations in Mach number, but is less sensitive to altitude changes than is the ratio for water injection. Tail-pipe burning is most effective at low altitudes but is much less effective under these conditions than is water injection. The maximum augmentation obtained with tail-pipe burning is 58 percent, and occurs at a Mach number of 0.9 at sea level; under these conditions water injection gives an augmentation of 95 percent. Only in the transonic speed range at altitudes near the tropopause does the augmentation from tail-pipe burning compete with that from compressor-inlet water injection. For all lower speeds and altitudes, water injection is much superior for maximum thrust augmentation.

In the transonic speed range at an altitude of 35,000 feet, the augmentation from the combined methods is about 15 to 20 percent greater than the sum of the augmentations from the two individual methods, the augmentation ratio varying from 1.75 at a Mach number of 0.9 to 2.06 at a Mach number of 1.1.

The liquid-consumption characteristics of the turbine-propeller engine cycle both with and without augmentation are shown in figures 6 and 7 as functions of the flight condition. The liquid consumptions used are those corresponding to the optimum division of power for each of the conditions shown when a propeller-plus-gear efficiency of 0.80 is used. The augmented liquid ratio (total fuel flow plus injected coolant flow divided by the normal fuel flow) is given in figure 6. The augmented liquid ratio exhibits characteristics similar to those of the augmented thrust ratio, increasing with Mach number and decreasing as the altitude is increased. For water injection, the augmented liquid ratio varies from about 3.8 to 9.6 for the range investigated. With tail-pipe burning, the augmented fuel (or liquid) consumption is always lower than that for water injection at the same flight condition and varies from 3.5 to 4.5 times the normal fuel consumption for all the conditions investigated. The increase in liquid consumption with combined augmentation is approximately equal to the sum of the increases for the individual methods applied separately. At an altitude of 35,000 feet in the transonic speed range, the ratio for the combined augmentation is about 7.3 to 8.2.

The specific liquid consumption for normal and augmented operation is presented in figure 7. This parameter is based on the total propulsive thrust computed for a propeller-plus-gear efficiency of 0.80; this

propulsive thrust is defined as the sum of the jet thrust and the propeller thrust at a shaft-to-thrust conversion efficiency of 0.80 less the momentum drag of the inlet air. For normal operation, the thrust specific fuel consumption for the range investigated lies between 0.5 and 1.0 pound per hour per pound thrust. With tail-pipe burning, the specific fuel consumption varies from about 1.6 to 2.6 pounds per hour per pound thrust and, with water injection, the specific liquid consumption varies from about 1.6 to over 4.5 pounds per hour per pound thrust over the range shown. In the transonic speed range at an altitude of 35,000 feet, where the augmented thrust gains are approximately equal, the tail-pipe-burning specific fuel consumption is considerably lower than the specific liquid consumption with water injection. The specific liquid consumption with combined augmentation is about 3.0 to 3.6 pounds per hour per pound thrust in the transonic speed range at an altitude of 35,000 feet.

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The water-injection data of figures 5 to 7 were calculated for the injection of water alone. As the inlet temperature for part of the flight range shown is below the freezing point, a nonfreezing mixture must be substituted for the water. The effect of such a change in the injected fluid is not investigated in this analysis, but it may be assumed that the same general results would arise from the substitution in the turbine-propeller engine as in the turbojet engine. According to references 1 and 3, the substitution of water-alcohol mixtures has slight effect on the performance of a turbojet engine with liquid injection except to decrease the fuel flow required as compared with that necessary when water alone is injected. If a nonfreezing mixture of alcohol and water in the correct proportion were used for injection, no increase in fuel flow above the normal value would be necessary, as the heat of combustion of the alcohol would compensate for the greater enthalpy rise across the combustor required with the lower compressor-outlet temperatures and changed gas properties in the combustor that accompany this method of augmentation.

As stated previously, the data of figures 5 to 7 are based on a propeller-plus-gear efficiency of 0.80. For a different value of this efficiency, or for a scheduled variation with Mach number, the relative merits of tail-pipe burning and compressor-inlet injection as discussed in the preceding paragraphs would be essentially unaltered, as figure 3 shows. For a moderate range of efficiencies about the value of 0.80, the augmentation with water injection would remain essentially constant and that with tail-pipe burning would vary only a few percent. (This result would also be true for Mach numbers and altitudes other than those of fig. 3.) Therefore, the major conclusions drawn from figures 5 to 7, which are based on rather large percentage augmentations, would still be applicable.

Effect of Design Changes

Component efficiencies. - The effect of changes in compressor and turbine polytropic efficiencies on the augmented thrust ratio for a Mach number of 0.9 at an altitude of 35,000 feet is shown in figure 8. Efficiencies of 0.88 and 0.83 are considered. (The compressor polytropic efficiency is the normal value. With water injection, the actual efficiency is decreased because of the evaporative cooling.) With water injection, the augmented thrust ratio for an engine having a normal compressor efficiency of 0.83 is about 0.06 greater than for an engine with an efficiency of 0.88, whereas with tail-pipe burning, the ratio is only slightly greater for the lower efficiency. The variation of augmentation with turbine efficiency is greater; with water injection, the augmented thrust ratio is from 0.20 to 0.25 greater for the efficiency of 0.83 than for 0.88, and with tail-pipe burning the ratio is about 0.07 higher for the lower efficiency value. The changes resulting from compressor and turbine efficiency variations are relatively independent of the value of propeller-plus-gear efficiency.

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Although the augmented thrust ratio increases with a decrease in either compressor or turbine efficiency, the thrust in either case decreases, as can be seen by comparing figures 1(b), 1(i), and 1(j). The increase in augmentation ratio merely indicates that the decreased component efficiency decreases the unaugmented thrust proportionately more than the augmented thrust.

Normal compressor pressure ratio. - The effect on augmented thrust ratio of variations in the normal compressor pressure ratio is shown in figure 9 for a Mach number of 0.9 at an altitude of 35,000 feet. For both augmentation by water injection and by tail-pipe burning, the augmentation ratio varies approximately linearly with the normal compressor pressure ratio. With water injection, the augmentation at a pressure ratio of 16 is about 3.7 times the augmentation at a pressure ratio of 4. With tail-pipe burning, the augmentation at a pressure ratio of 16 is 1.5 to 1.7 times that at a pressure ratio of 4. Because the augmentation with water injection is independent of propeller-plus-gear efficiency, whereas that with tail-pipe burning varies inversely with the efficiency, the relative augmented thrusts attainable by the two methods at different normal pressure ratios are dependent on the conversion efficiency. At a pressure ratio of 5, equal augmentations result if the propeller-plus-gear efficiency is 0.9 and at lower efficiencies tail-pipe burning offers greater augmentation. At a pressure ratio of 16, equal augmentations result when the efficiency is 0.6 and water injection is the more effective method for any higher efficiency.

Turbine-inlet temperature. - Augmentation available with turbine-inlet temperatures from 1500° to 3000° R is shown in figure 10. A Mach number of 0.9 and an altitude of 35,000 feet were used in obtaining the

data presented. Augmentation available by the use of tail-pipe burning decreases rapidly as the turbine-inlet temperature is increased. This trend results from the decreased tail-pipe fuel addition required for the assumed constant jet-exit total temperature as the turbine-inlet temperature (and concurrently the turbine-exit temperature) is increased. The augmentation with water injection likewise decreases with increasing turbine-inlet temperature, but much less rapidly. As a result, water injection augmentation becomes superior relative to tail-pipe burning as the turbine-inlet temperature is increased.

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Although the augmentation ratios decrease with increasing turbine-inlet temperature, the normal thrust and the augmented thrusts all increase with turbine-inlet temperature as figures 1(b) and 1(h) show.

Evaporation Effectiveness

For all the data presented previously, complete evaporation of all the water injected into the engine inlet, continuous saturation up to the compressor outlet, and no excess water above the compressor-outlet saturation quantity were assumed. Supplemental calculations were made to evaluate the effects of deviations from these assumptions, and the results are presented in figure 11. Because the principal effect of water injection appears in the shaft power rather than in the jet thrust (see fig. 1), and the shaft power contribution to the total engine output when operating with optimum division of power is proportionately greatest at static conditions, sea-level static engine-inlet conditions were chosen for the calculations.

In figure 11, the augmented shaft power ratio for complete expansion in the turbine, which approximates the optimum division of power under zero ram conditions, is plotted against the total water-air ratio for two assumed evaporation conditions. The solid curve represents continuous saturation during compression with the entire water addition occurring at the compressor inlet. The circled point at $m = 0.075$ represents compressor-outlet saturation (that is, the condition assumed for all previously presented water-injection data). The dashed curve represents the addition of all water at the compressor inlet but with no evaporation during compression. In both cases continuous temperature equilibrium between any liquid water present during compression and the air-vapor mixture was assumed. These two conditions represent the possible extremes of evaporation effectiveness.

From the solid curve it is apparent that the relative effectiveness of water injection (assuming complete evaporation during compression of the water injected) decreases slightly as the amount of water injected increases to the quantity required for compressor-outlet saturation.

The augmentation with no evaporation is from 40 to 50 percent of that for continuous saturation for water-air ratios up to the saturation value. For higher water-air ratios, the difference decreases until at a ratio of 0.15 the minimum augmentation is 81 percent of the maximum augmentation. Because the augmentation with no evaporation is a large portion of the augmentation with complete evaporation and any degree of evaporation would give an augmentation intermediate between these two extremes, experimental values might be expected to approach fairly closely the theoretical values for continuous saturation.

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The trends in the augmentation curves of figure 11 can be explained in the following manner. The injection of a given amount of water results in the same increase in mass flow and compressor pressure ratio (because the turbine-inlet temperature is constant, the turbine nozzles are choked and the engine-inlet gas flow is independent of evaporation during compression) whether the water evaporates during compression or not. Both these increases tend to increase the engine output; the augmentation resulting from increases in these two factors is represented by the dashed curve. If evaporation occurs during compression, less work is required to produce a given pressure ratio. Consequently, more of the turbine power appears as shaft power, with a further augmentation of the engine power. This factor gives rise to the difference between the two curves of figure 11. As the amount of water injected is increased, the evaporative cooling becomes less effective in augmenting the engine as compared with the increase in mass flow and pressure ratio and the possible spread in augmentation with degree of evaporation during compression therefore decreases.

Variation of Inlet Conditions

For the data presented up to this point, NACA standard altitude conditions of pressure and temperature and a relative humidity of 1.0 have been assumed. The effects of variations in these quantities on the compressor-inlet water-injection augmentation were evaluated and the results are presented in figure 12. The augmented shaft power ratio at static inlet conditions with complete expansion in the turbine is given as a function of pressure altitude for relative humidities of 0 and 1.0 with ambient temperatures of 550° and 580° R and with the NACA standard altitude temperature variation. With the standard temperature variation, the effect of humidity is slight; the augmented shaft power ratio is about 1.48 with a humidity of 1.0, and 1.52 with a humidity of 0 at sea level. Both the augmented power ratio and the humidity effect decrease with increasing altitude. At the higher constant temperatures and humidity of 1.0, the augmented power ratio is unaffected by changes in pressure altitude, the augmentation ratio being about 1.62 at 550° R and 1.70 at 580° R. With zero relative humidity and constant temperature, the augmentation increases with pressure altitude as the constant vapor

partial pressure gives rise to a higher inlet vapor-air ratio, greater cooling at the compressor inlet, and a larger increase in inlet gas flow at the higher pressure altitudes. For the temperature of 550° R, augmentation at zero humidity is 0.05 to 0.08 greater than with ambient saturation. The corresponding difference with a temperature of 580° R is from 0.13 to 0.17.

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Inasmuch as NACA standard atmosphere conditions have been assumed in previously presented data and the effect of humidity is greatest with static inlet conditions, it is apparent that the effect of humidity on the conclusions stated heretofore is negligible.

Take-Off Performance with Water Injection

One probable application of water injection augmentation for the turbine-propeller engine is to maintain take-off performance under conditions of adverse ambient temperature or from airports located at altitudes considerably above sea level. The effectiveness of water injection in maintaining sea-level standard take-off performance can be estimated using the data of figure 12. The data for a relative humidity of 1.0 for the three different temperature relations are replotted in figure 13. Instead of the augmented shaft power ratio the ratio of the augmented shaft power at the conditions specified to the normal shaft power at NACA sea level standard conditions is given. This factor therefore includes the effects of change in density (and therefore engine mass flow) due to temperature and pressure variation, as well as the changes in augmentation ratio depicted by figure 12. At a given pressure altitude, the power available decreases as the ambient temperature increases, indicating that the greater augmentation at high temperatures (fig. 12) is insufficient to compensate for the decrease in mass flow accompanying increasing inlet temperatures. By using compressor-inlet water injection with compressor-outlet saturation, normal sea-level engine power can be maintained for pressure altitudes up to 7500 feet with an ambient temperature of 580° R or up to 10,000 feet with NACA standard altitude conditions. These figures are for ambient saturation; for lower relative humidity, water-injection augmentation would be even more effective in maintaining normal take-off performance, as is apparent from figure 12.

SUMMARY OF RESULTS

The theoretical analysis of the augmented performance of a multistage axial-flow compressor turbine-propeller engine indicated that large augmentations result from either compressor-inlet water injection or tail-pipe burning and that their combination is more effective than either applied separately. The augmentation from either compressor-inlet water injection or tail-pipe burning varied directly with the compressor pressure ratio and inversely as the turbine-inlet temperature, compressor efficiency, or turbine efficiency.

The following augmentation characteristics were determined with an assumed propeller-plus-gear efficiency of 0.8 for a reference engine having an unaugmented pressure ratio of 8, compressor and turbine polytropic efficiencies (without augmentation) of 0.88, and a turbine-inlet temperature of 2000° R.

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1. With compressor-inlet water injection providing compressor-outlet saturation, thrust augmentation at sea level varied from about 50 percent at low airspeeds to 95 percent at a Mach number of 0.9. The augmentation varied from 22 to 43 percent for Mach numbers of 0.6 to 1.1 at an altitude of 35,000 feet. Liquid flows varied from 3.8 to 9.6 times the normal fuel flow over the flight range investigated.

2. With tail-pipe burning to a temperature of 3500° R, thrust augmentation as great as 58 percent was obtained. This maximum value occurred at a Mach number of 0.9 at sea level, where water injection gave an augmentation of 95 percent. Thrust augmentation comparable with that from water injection was obtained only in the transonic speed range at an altitude of about 35,000 feet. Under all other conditions water injection was superior. Augmented fuel flows varied from 3.5 to 4.5 and were always lower than the augmented liquid flow with water injection at the same flight condition.

3. When the two methods were used in combination, the augmentations were greater than additive, giving augmentations of 75 to 106 percent in the transonic speed range at an altitude of 35,000 feet. The liquid flow increases of the two methods were additive and the resultant liquid flows for their combination were from 7.3 to 8.2 times the normal fuel flow.

4. A large part of the maximum augmentation with water injection would result even if no evaporation occurred during compression.

5. Variations in ambient relative humidity had slight effect on the degree of augmentation with water injection, particularly at temperatures near NACA standard values.

6. Water injection with compressor-outlet saturation maintained takeoff power corresponding to NACA standard sea-level conditions to pressure altitudes as high as 7500 feet with ambient temperatures up to 580° R.

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

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APPENDIX A

SYMBOLS

The following symbols are used in the calculations and the figures:

C_F	exhaust-nozzle thrust coefficient
c_p	specific heat at constant pressure, Btu/(lb)(°R)
D	drag, lb
F	thrust, lb
f	fuel-air ratio
g	acceleration due to gravity, 32.2 ft/sec^2
$\overline{H}$	lower heating value of fuel, Btu/lb
h	enthalpy, Btu/lb
hp	shaft horsepower
J	mechanical equivalent of heat, 778 ft-lb/Btu
M	Mach number
m	vapor-air ratio
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft absolute
R	gas constant, ft-lb/(lb)(°R)
T	total temperature, °R
t	static temperature, °R
W	mass flow, lb/sec
γ	ratio of specific heats
Δ	incremental value
η	efficiency

Φ function of

φ $\int \frac{c_p}{T} dT$, Btu/(lb)(°R)

ψ_h $\frac{(h_g-h_a)(1+f)}{f}$, Btu/lb

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Subscripts:

a air

B tail-pipe burner

b combustion

c compressor

e engine

f fuel

g combustion gas

i inlet

j jet

p polytropic

t turbine

v water vapor

0 ambient air

1 engine diffuser inlet

2 compressor inlet

3 compressor outlet

4 turbine inlet

5 turbine outlet

6 tail-pipe nozzle inlet

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APPENDIX B

DETAILS OF PERFORMANCE CALCULATIONS

Unaugmented Engine

The compressor-inlet total pressure was obtained from the relation

$$P_2 = p_0 + 0.92(P_1 - p_0) \tag{B1}$$

where

$$P_1 = p_0 \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \tag{B2}$$

The corresponding compressor-inlet temperature was obtained from the equation

$$T_2 = t_0 \left(1 + \frac{\gamma-1}{2} M^2\right) \tag{B3}$$

The momentum drag of the inlet air flow was given by the relation

$$\frac{D_i}{W_a} = \frac{M\sqrt{\gamma_a g R_a t_0}}{g} \tag{B4}$$

A value of 53.35 foot-pounds per pound per °R was used for R_a.

The compressor performance was evaluated by the methods of reference 5, using the equation

$$\varphi_{a,3} = \varphi_{a,2} + \Delta\varphi_{a,c} \tag{B5}$$

where

$$\Delta\varphi_{a,c} = \frac{1}{\eta_{c,p}} \frac{R_a}{J} \ln \frac{P_3}{P_2} \tag{B6}$$

and the charts of reference 5 to determine the compressor-outlet temperature. The enthalpy rise across the compressor was then computed from

$$\Delta h_{a,c} = h_{a,3} - h_{a,2} \tag{B7}$$

The fuel-air ratio for a particular turbine-inlet temperature was determined from the relation

$$f_e = \frac{h_{a,4} - h_{a,3}}{\eta_{b,e}\,\overline{H} - h_{a,4} - \psi h_{,4} + h_f} \tag{B8}$$

given in reference 5.

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The turbine performance was evaluated using the relations

$$\varphi_{g,5} = \varphi_{g,4} + \Delta\varphi_{g,t} \tag{B9}$$

and

$$\Delta\varphi_{g,t} = \eta_{t,p}\,\frac{R_t}{J}\,\ln\frac{P_5}{P_4} \tag{B10}$$

with an assumed value of 53.4 for R_t to determine the turbine-outlet condition for values of P_5/P_4. The enthalpy change across the turbine was then obtained as

$$\Delta h_{g,t} = h_{g,5} - h_{g,4} \tag{B11}$$

The engine shaft power was evaluated from

$$\frac{(hp)}{W_a} = \frac{J}{550}\left[\Delta h_{g,t}\,(1+f_e) - \Delta h_{a,c}\right] \tag{B12}$$

The jet thrust was calculated from the equation

$$\frac{F_j}{W_a} = C_F\,(1+f_e)\sqrt{\frac{2\gamma R_j}{g(\gamma-1)}}\sqrt{T_5}\left[1 - \left(\frac{p_0}{P_5}\right)^{\frac{\gamma-1}{\gamma}}\right]^{\frac{1}{2}} \tag{B13}$$

for cases where the pressure ratio across the jet nozzle was subcritical and from the equation for a convergent nozzle

$$\frac{F_j}{W_a} = C_F\,(1+f_e)\sqrt{\frac{R_j}{\gamma g}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}}\sqrt{T_5}\left[\frac{2}{\left(\frac{\gamma+1}{2}\right)^{\frac{1}{\gamma-1}}} - \frac{p_0}{P_5}\right] \tag{B14}$$

for supercritical pressure ratios. A value of 53.4 was used for R_j in equations (B13) and (B14), average values of γ were employed, and p_0/P_5 was obtained from the pressure ratios across the preceding components.

Tail-Pipe Burning

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All quantities calculated up to the turbine outlet were the same as for the unaugmented engine.

The tail-pipe fuel-air ratio was calculated from

$$f_B = \frac{(1+f_e)(h_{a,6}-h_{a,5}) + f_e(\psi_{h,6}-\psi_{h,5})}{\eta_{b,B}\,\overline{H} - h_{a,6} - \psi_{h,6} + h_f} \tag{B15}$$

The jet thrust was calculated from equation (B13) with the substitution of 3500 for T_5, $(f_e + f_B)$ for f_e, p_0/P_6 for p_0/P_5, and with the adjustment of the values of γ for the higher tail-pipe temperatures. By including the tail-pipe friction and momentum pressure drops, p_0/P_6 was obtained from p_0/P_5.

Water Injection

The compressor performance values were either obtained from reference 6, or were calculated by the method of that reference.

The fuel-air ratio was given by the equation

$$f_e = \frac{h_{a,4} - h_{a,3}}{\eta_{b,e}\,\overline{H} - h_{a,4} - \psi_{h,4} + h_f} + \frac{m_3(h_{v,4} - h_{v,3})}{\eta_{b,e}\,\overline{H}} \tag{B16}$$

The remaining portion of the cycle was calculated in the same manner as for the unaugmented engine except that terms were added to account for the water vapor where required. The following changes were necessary:

(1) Equation (B9) was changed to

$$\varphi_{g,5} = \varphi_{g,4} + \frac{m_3\,\varphi_{v,4}}{1 + f_e} + \frac{1 + m_3 + f_e}{1 + f_e}\,\Delta\varphi_{(g+v),t} \tag{B17}$$

(2) The value of R_t (for equation (B10)) was

$$R_t = \frac{(1+f_e)53.4 + m_3 \times 85.8}{1 + f_e + m_3} \tag{B18}$$

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(3) Equation (B11) became

$$\Delta h_{g,t} = h_{g,5} - h_{g,4} + \frac{m_3(h_{v,5}-h_{v,4})}{1 + f_e} \tag{B19}$$

(4) In equation (B13), $(1 + f_e + m_3)$ was substituted for $(1 + f_e)$ and the average value of γ was based on the properties of the combustion gas-water vapor mixture.

Water Injection Plus Tail-Pipe Burning

The performance with combined methods of augmentation was derived from the performance with water injection.

The tail-pipe fuel-air ratio was obtained from

$$f_B = \frac{(1+f_e)(h_{a,6}-h_{a,5}) + f_e(\psi_{h,6}-\psi_{h,5})}{\eta_{b,B}\,\overline{H} - h_{a,6} - \psi_{h,6} + h_f} + \frac{m_3(h_{v,6}-h_{v,5})}{\eta_{b,B}\,\overline{H}} \tag{B20}$$

The jet thrust was determined in the manner explained for tail-pipe-burning augmentation; $(f_e+f_B+m_3)$ was substituted for (f_e+f_B) and the water-vapor content was considered in determining γ.

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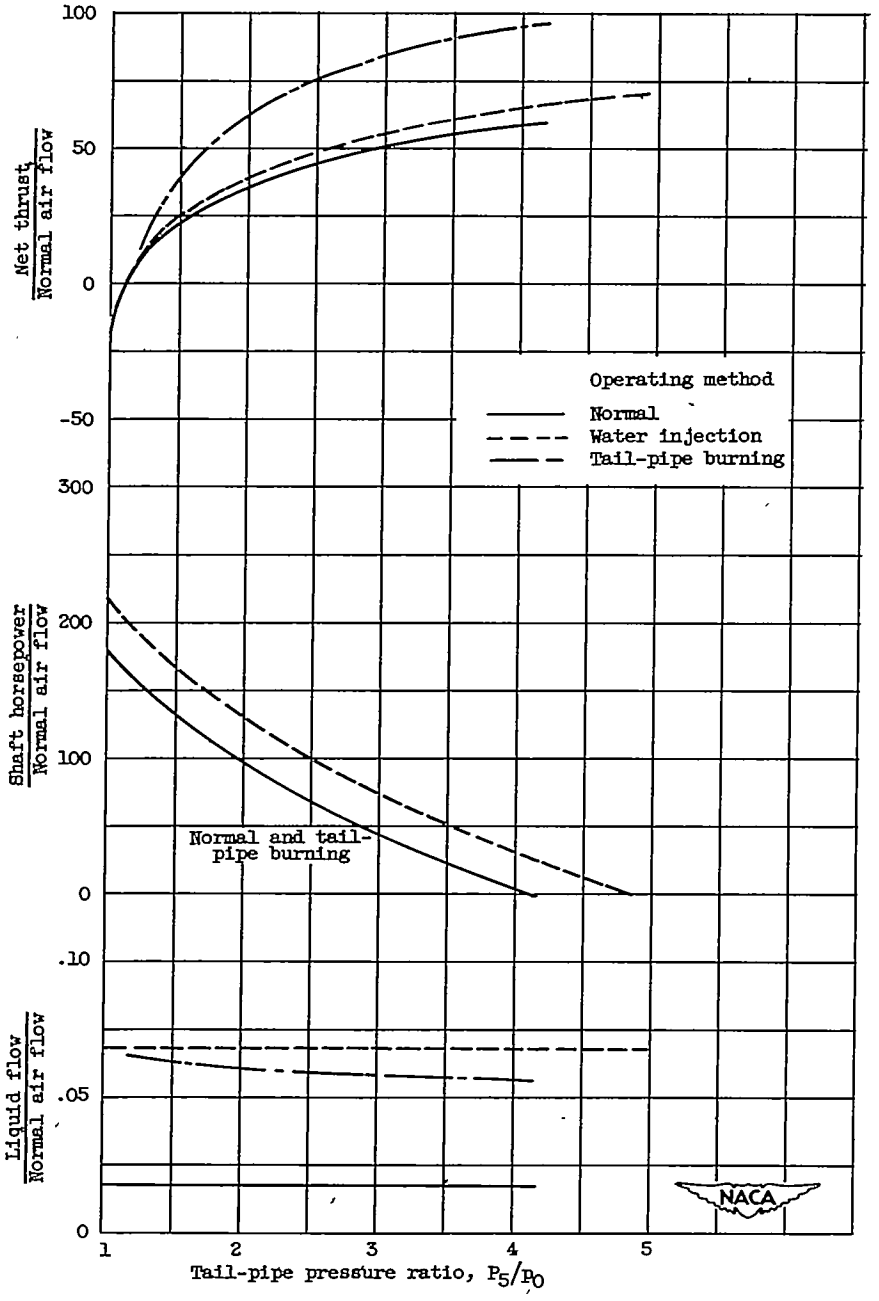

(a) Reference-engine characteristics; flight Mach number, 0.6; altitude, 35,000 feet.

Figure 1. - Augmented performance of turbine-propeller engine.

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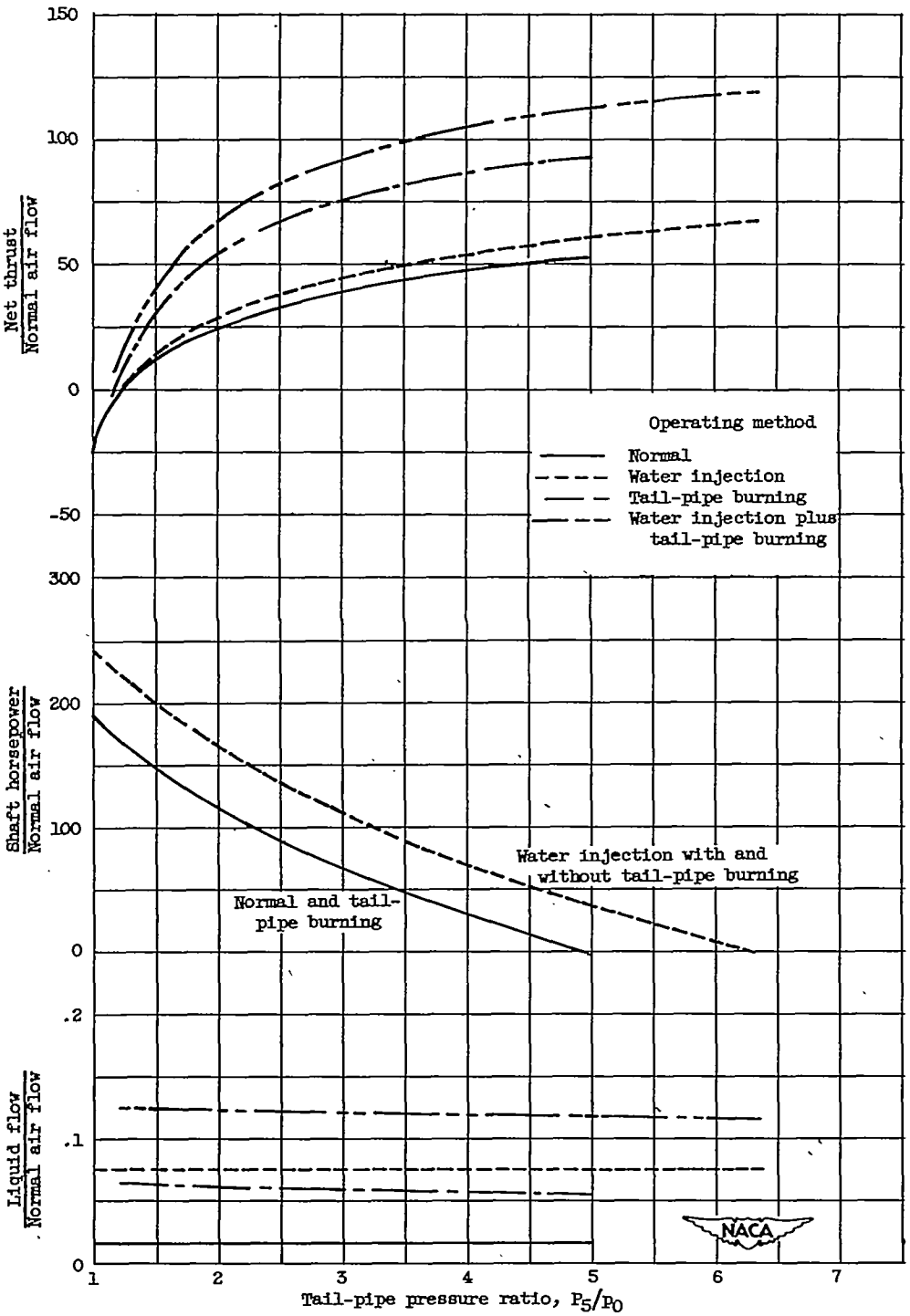

(b) Reference engine characteristics; flight Mach number, 0.9; altitude, 35,000 feet.

Figure 1. - Continued. Augmented performance of turbine-propeller engine.

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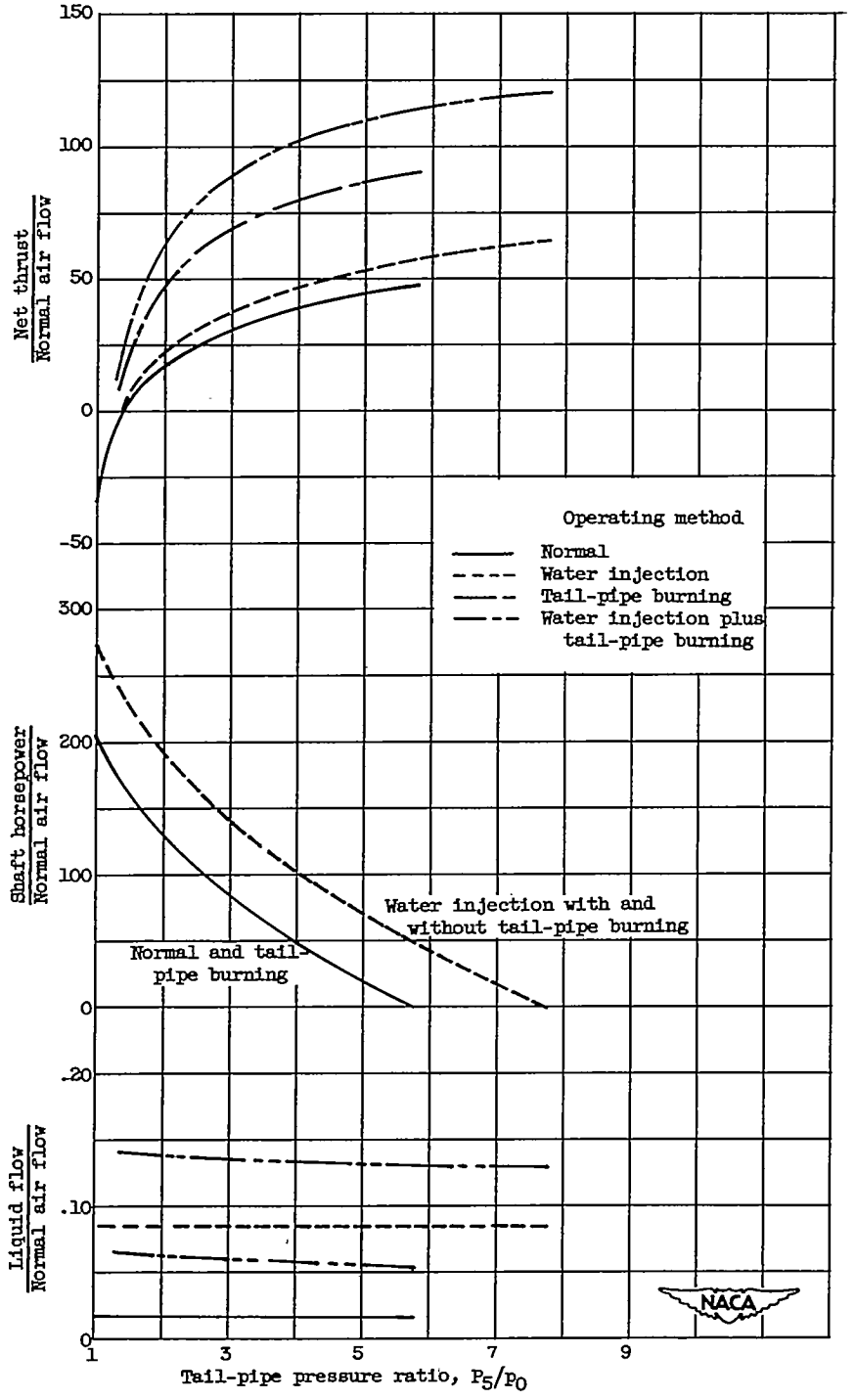

(c) Reference engine characteristics; flight Mach number, 1.1; altitude, 35,000 feet.

Figure 1. - Continued. Augmented performance of turbine-propeller engine.

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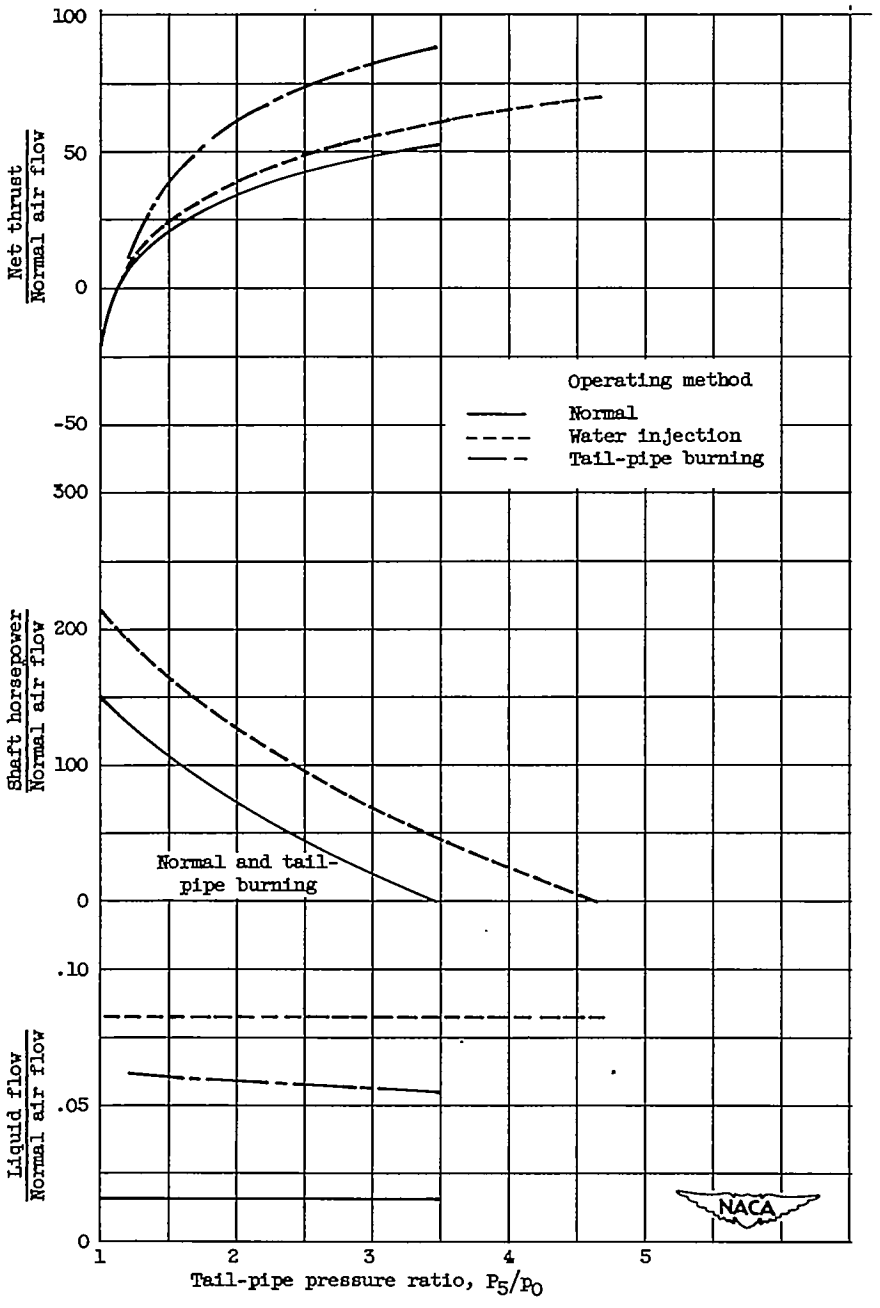

(d) Reference engine characteristics; flight Mach number, 0.6; altitude, 15,000 feet.

Figure 1. - Continued. Augmented performance of turbine-propeller engine.

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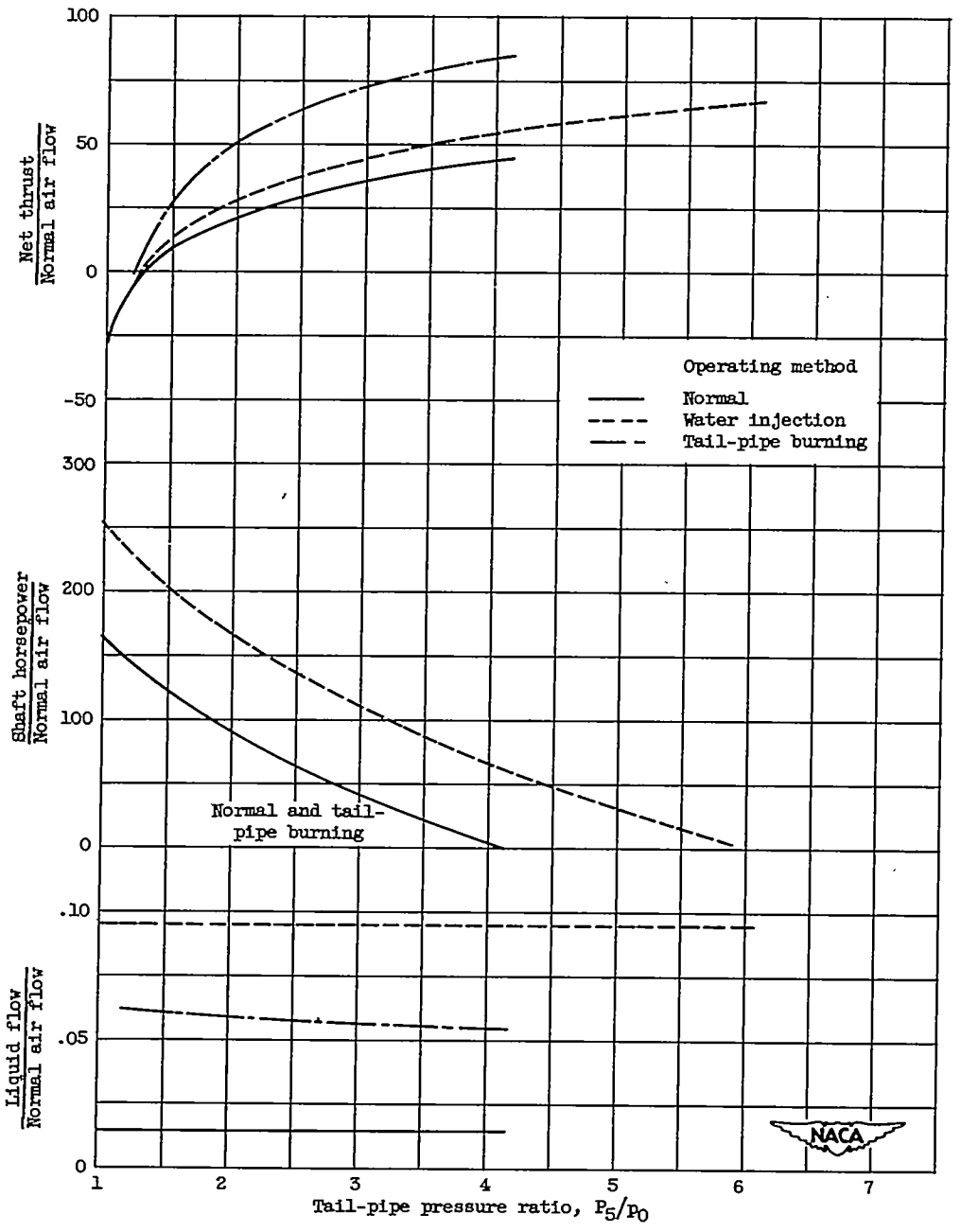

(e) Reference engine characteristics; flight Mach number, 0.9; altitude, 15,000 feet.

Figure 1. - Continued. Augmented performance of turbine-propeller engine.

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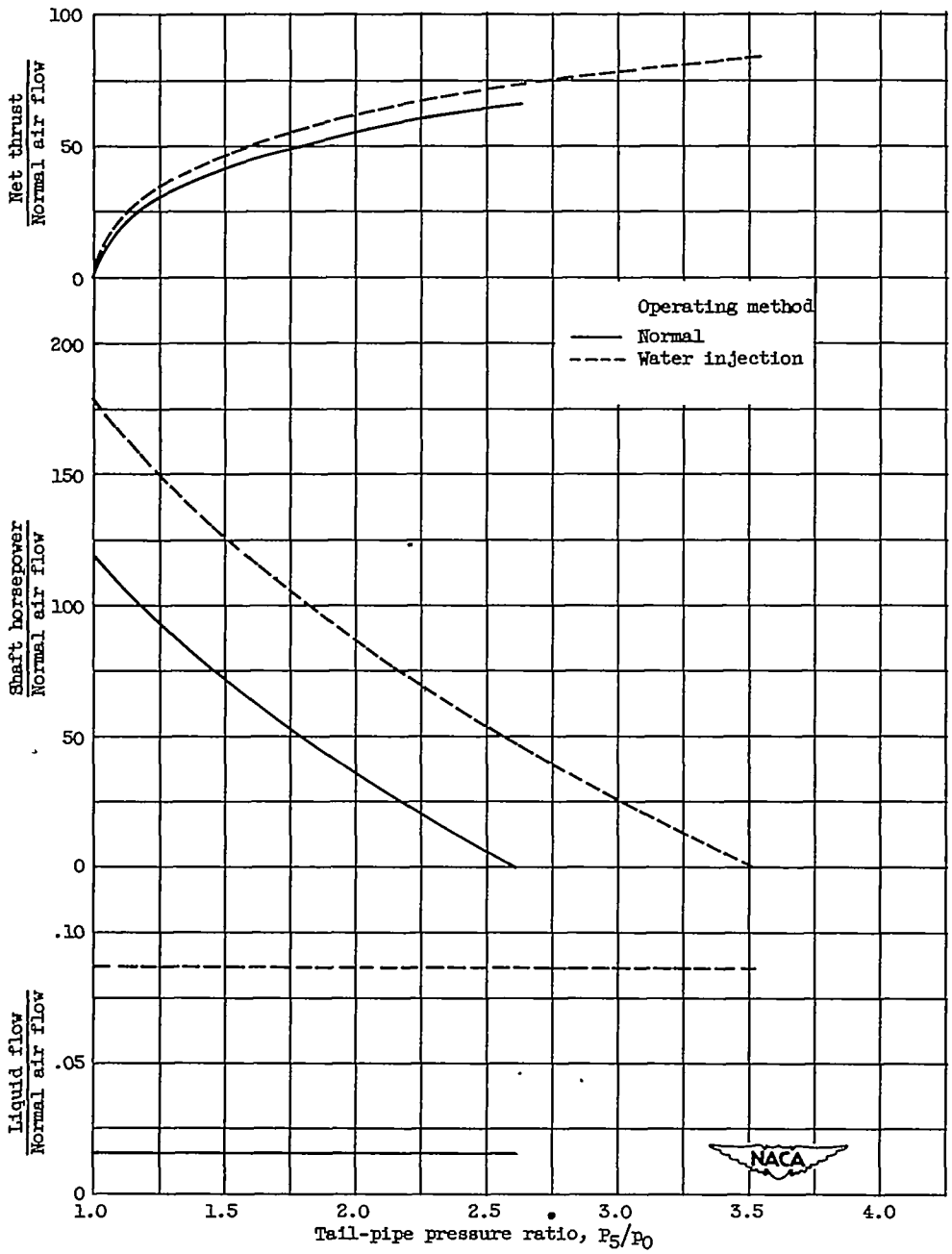

(f) Reference engine characteristics; sea-level static inlet conditions.

Figure 1. - Continued. Augmented performance of turbine-propeller engine.

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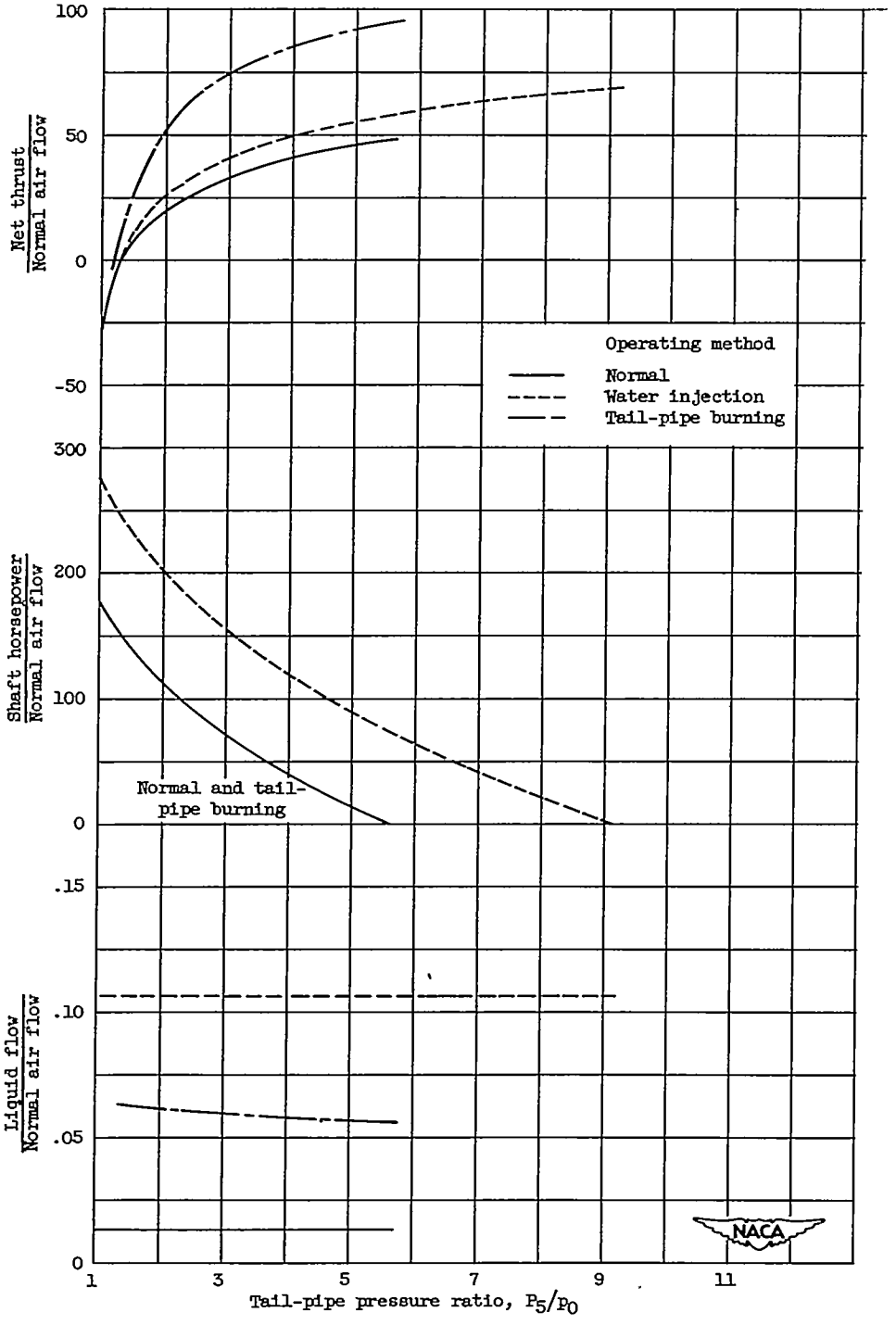

(g) Normal compressor pressure ratio, 16; flight Mach number, 0.9; altitude, 35,000 feet.

Figure 1. - Continued. Augmented performance of turbine-propeller engine.

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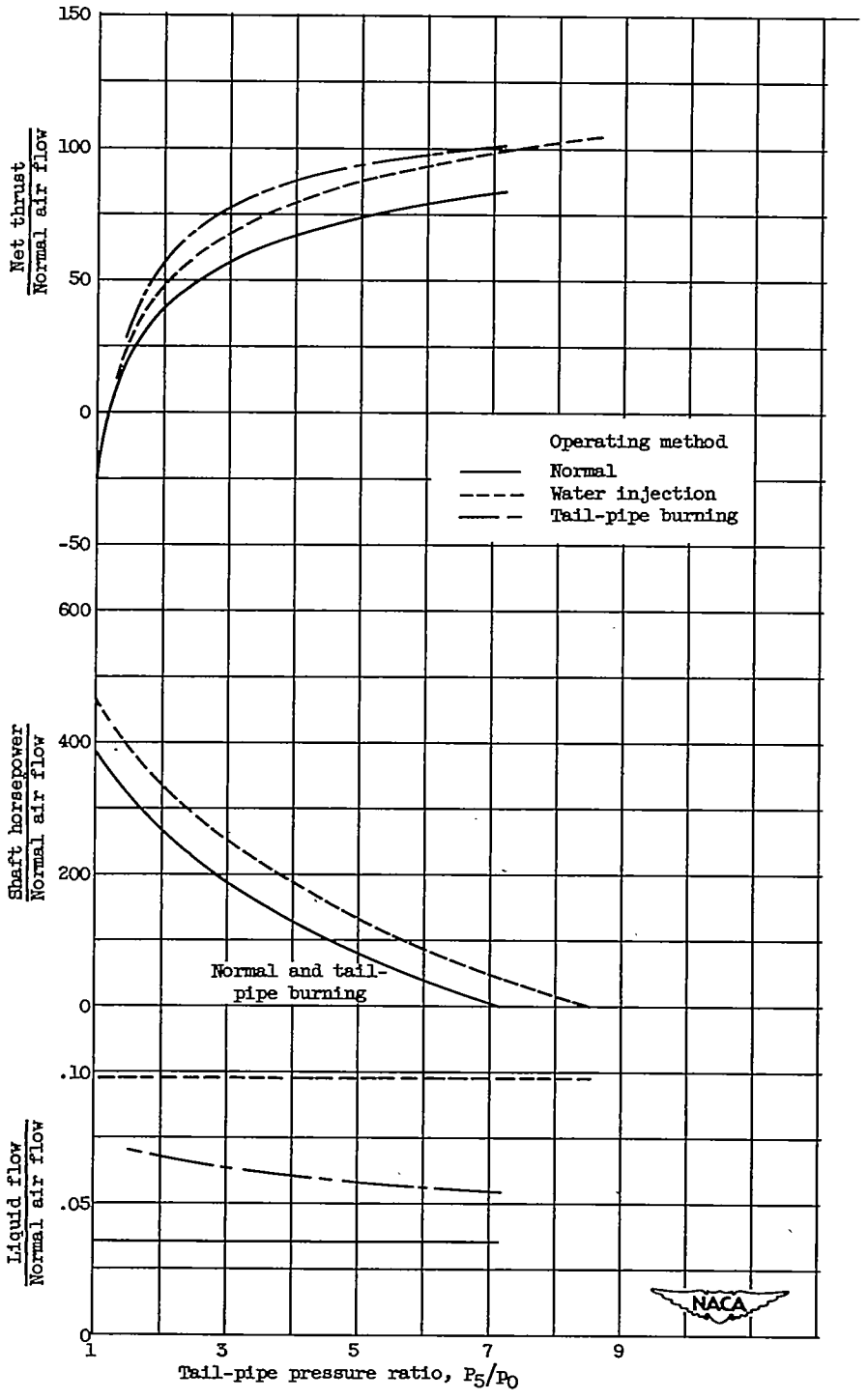

(h) Turbine-inlet temperature, 3000° R; flight Mach number, 0.9; altitude, 35,000 feet.

Figure 1. - Continued. Augmented performance of turbine-propeller engine.

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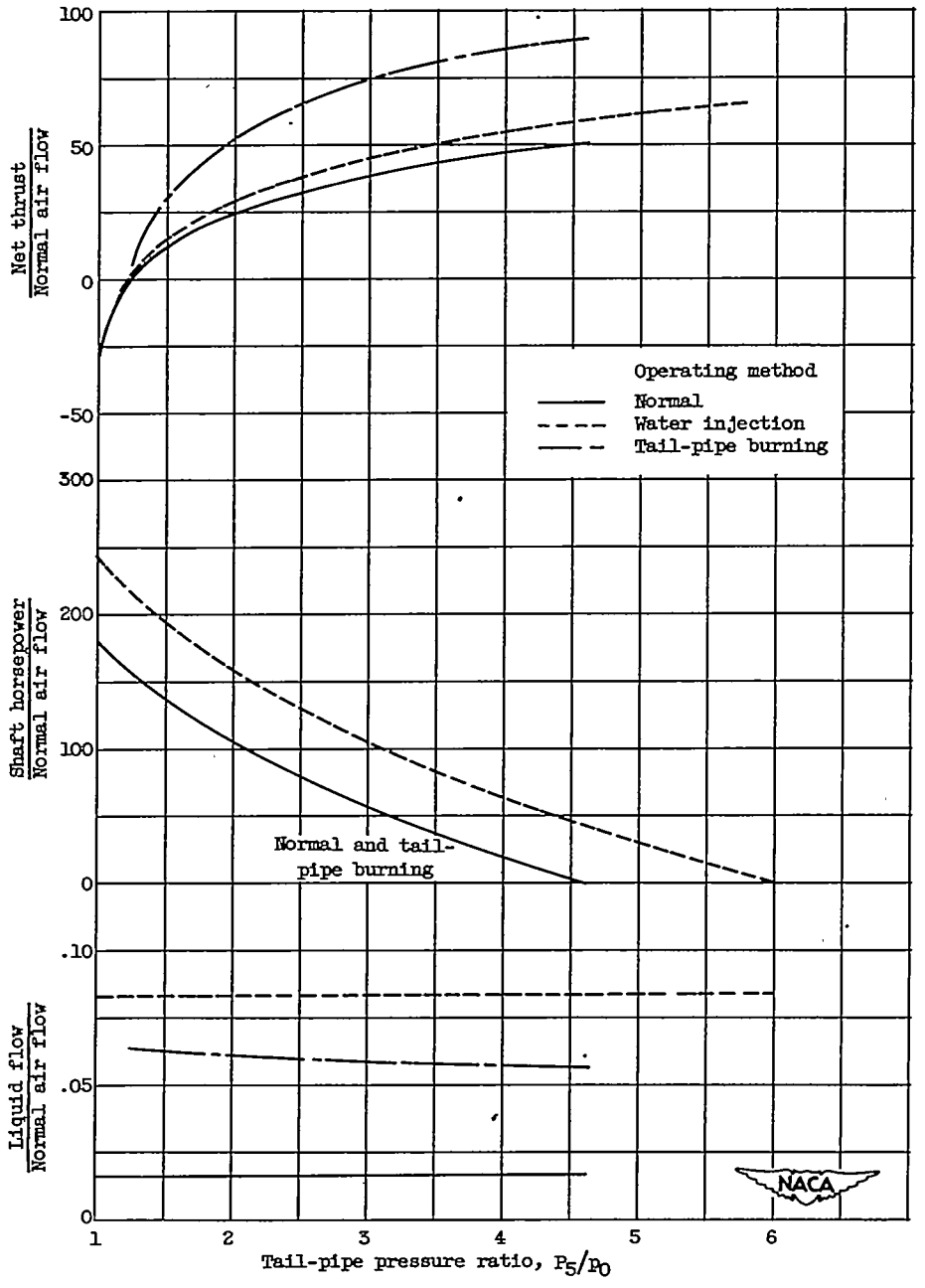

(i) Normal compressor polytropic efficiency, 0.83; flight Mach number, 0.9; altitude, 35,000 feet.

Figure 1. - Continued. Augmented performance of turbine-propeller engine.

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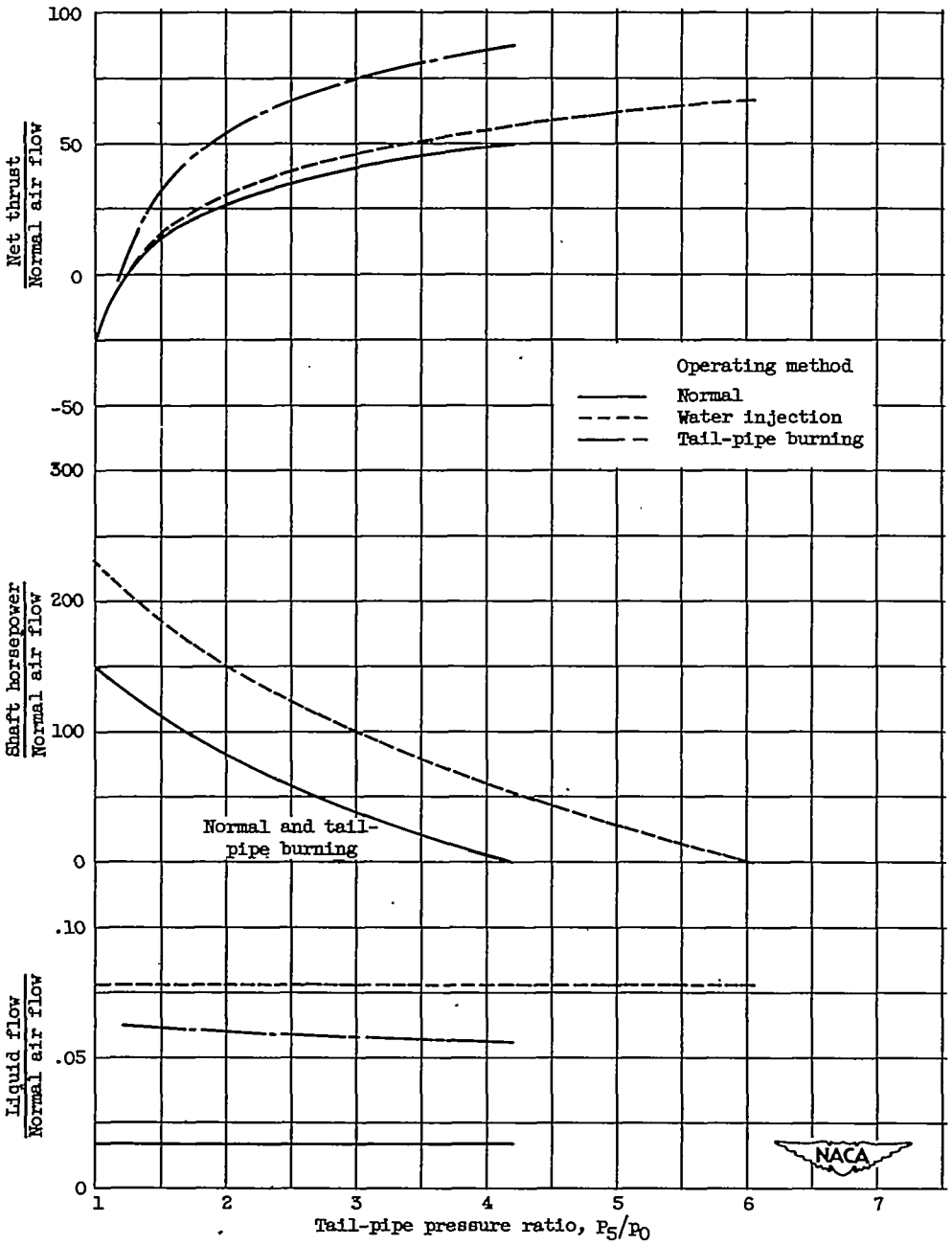

(j) Turbine polytropic efficiency, 0.83; flight Mach number, 0.9; altitude, 35,000 feet.

Figure 1. - Concluded. Augmented performance of turbine-propeller engine.

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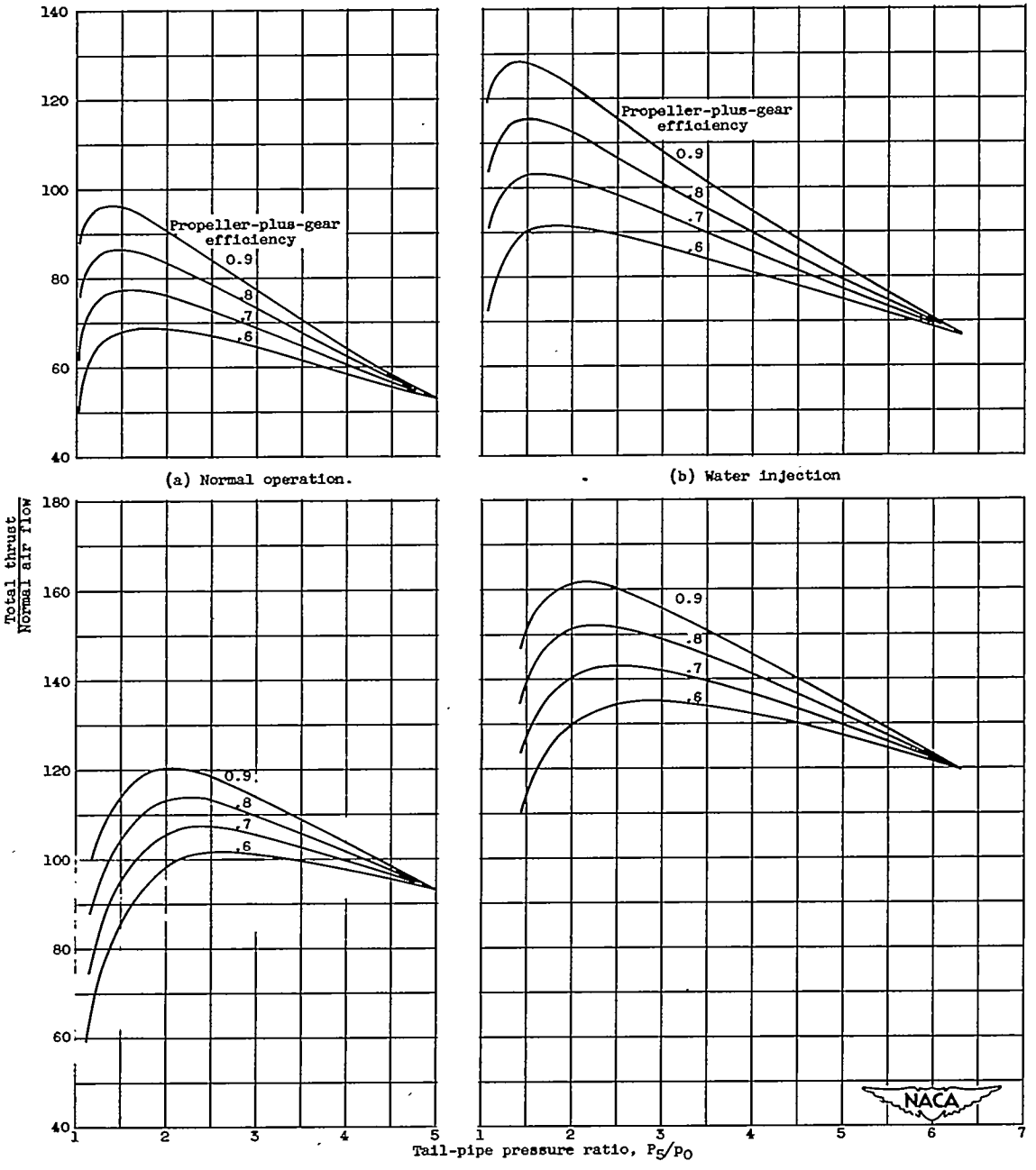

Figure 2. - Effect of propeller-plus-gear efficiency and power division on total thrust. Reference engine characteristics; flight Mach number, 0.9; altitude, 35,000 feet.

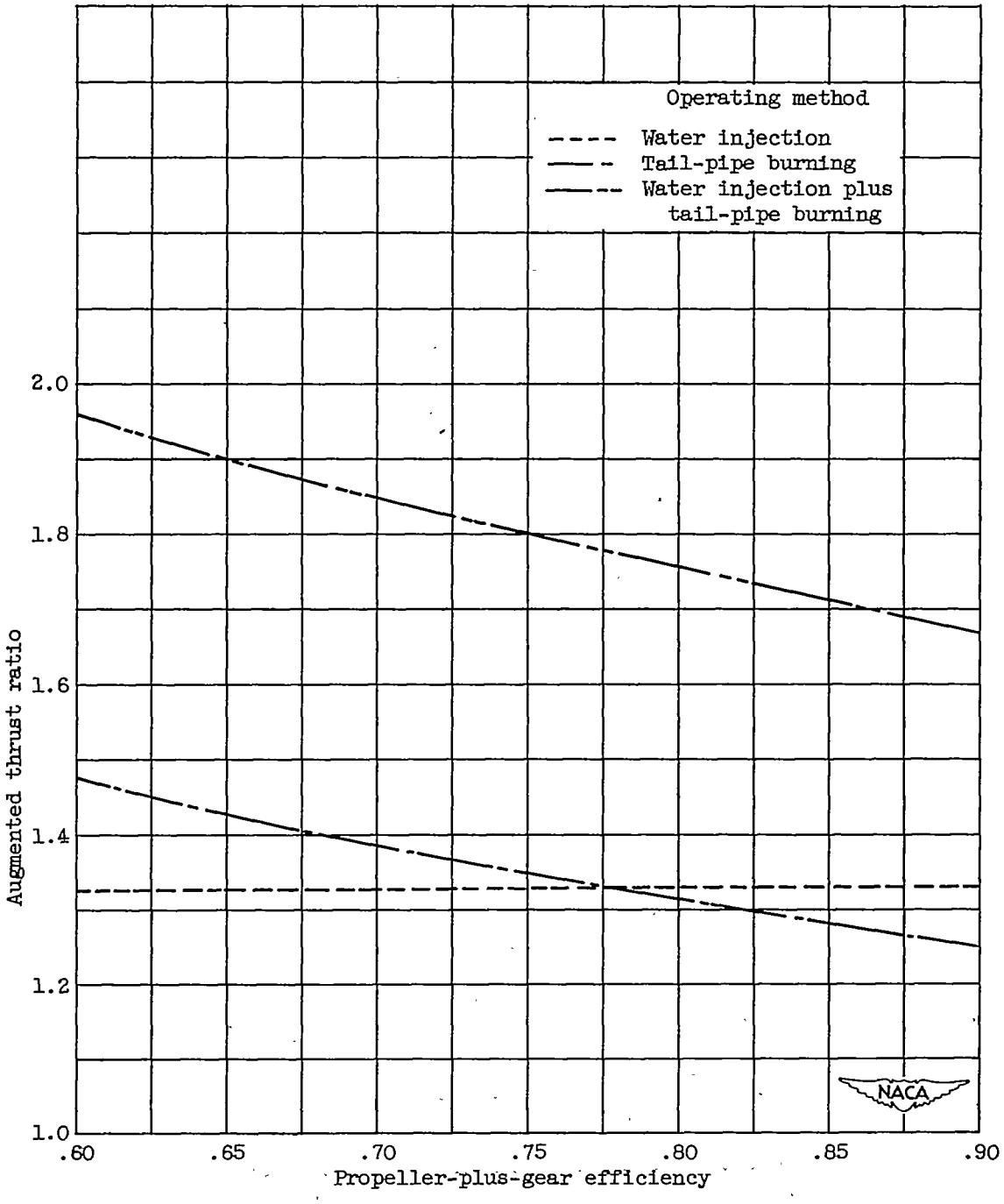

Figure 3. - Variation of augmented thrust ratio with propeller-plus-gear efficiency. Reference engine characteristics; flight Mach number, 0.9; altitude, 35,000 feet.

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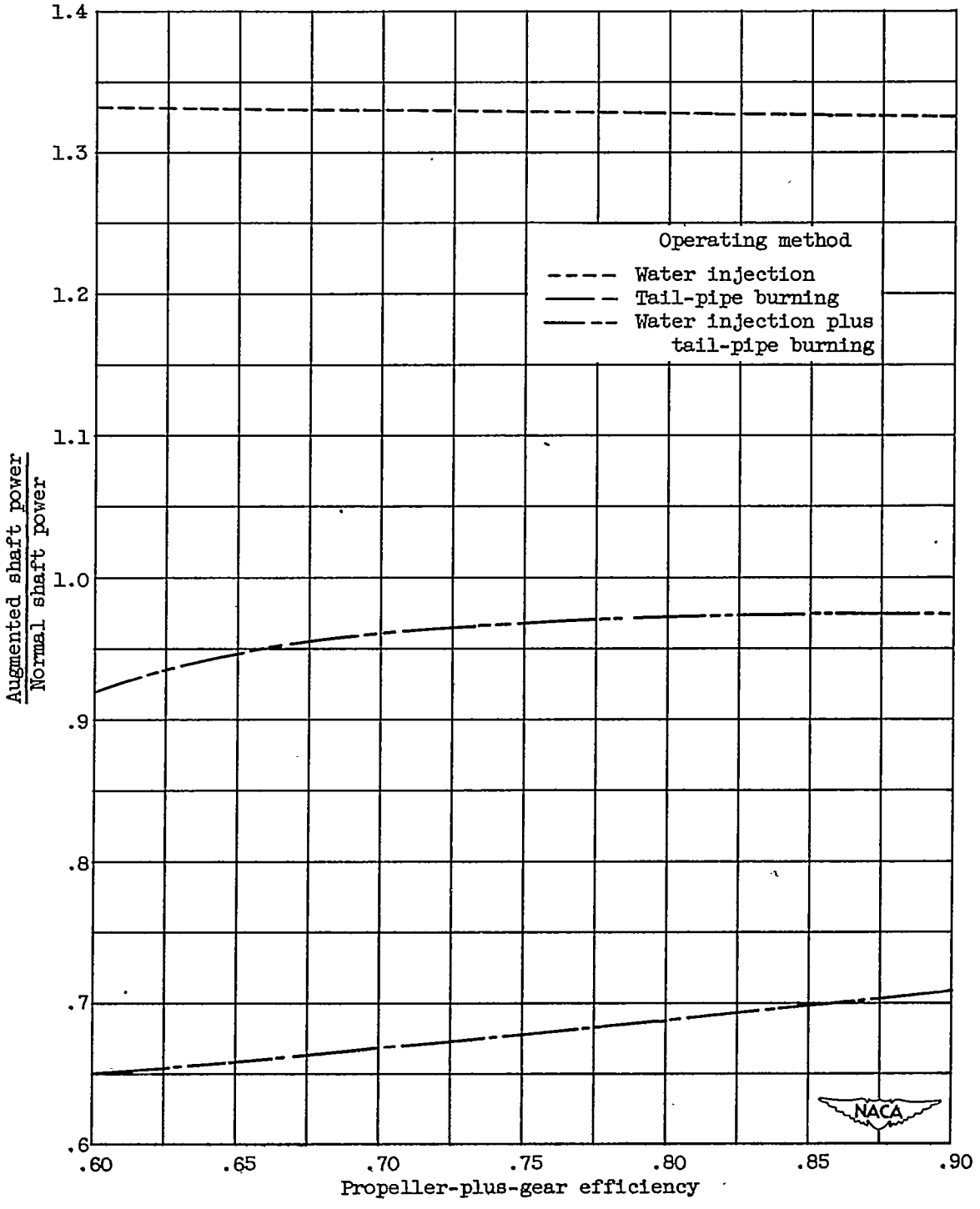

Figure 4. - Effect of augmentation method on engine shaft power. Reference engine characteristics; flight Mach number, 0.9; altitude, 35,000 feet.

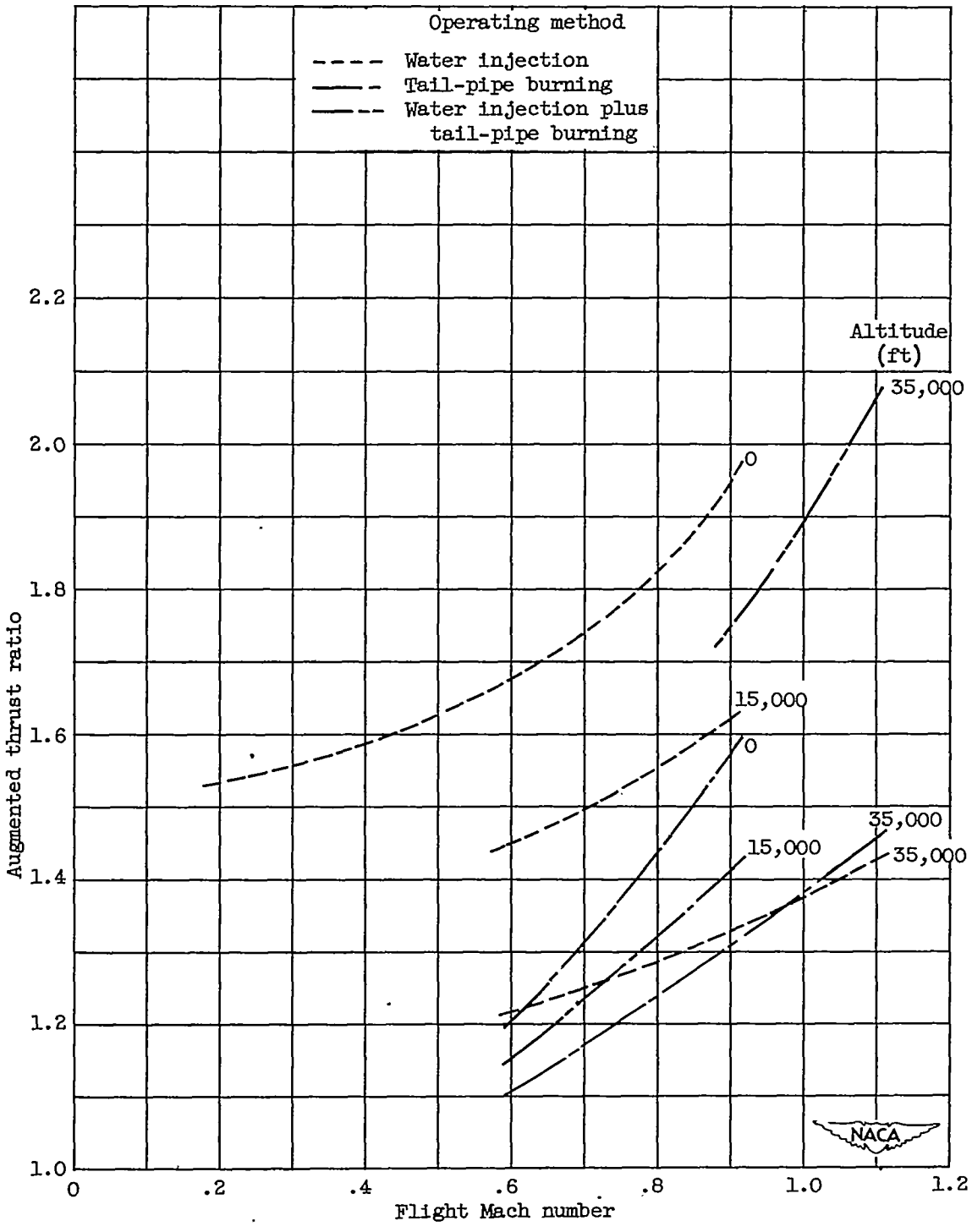

Figure 5. - Variation of augmented thrust ratio with flight condition and method of augmentation. Reference engine characteristics; propeller-plus-gear efficiency, 0.80.

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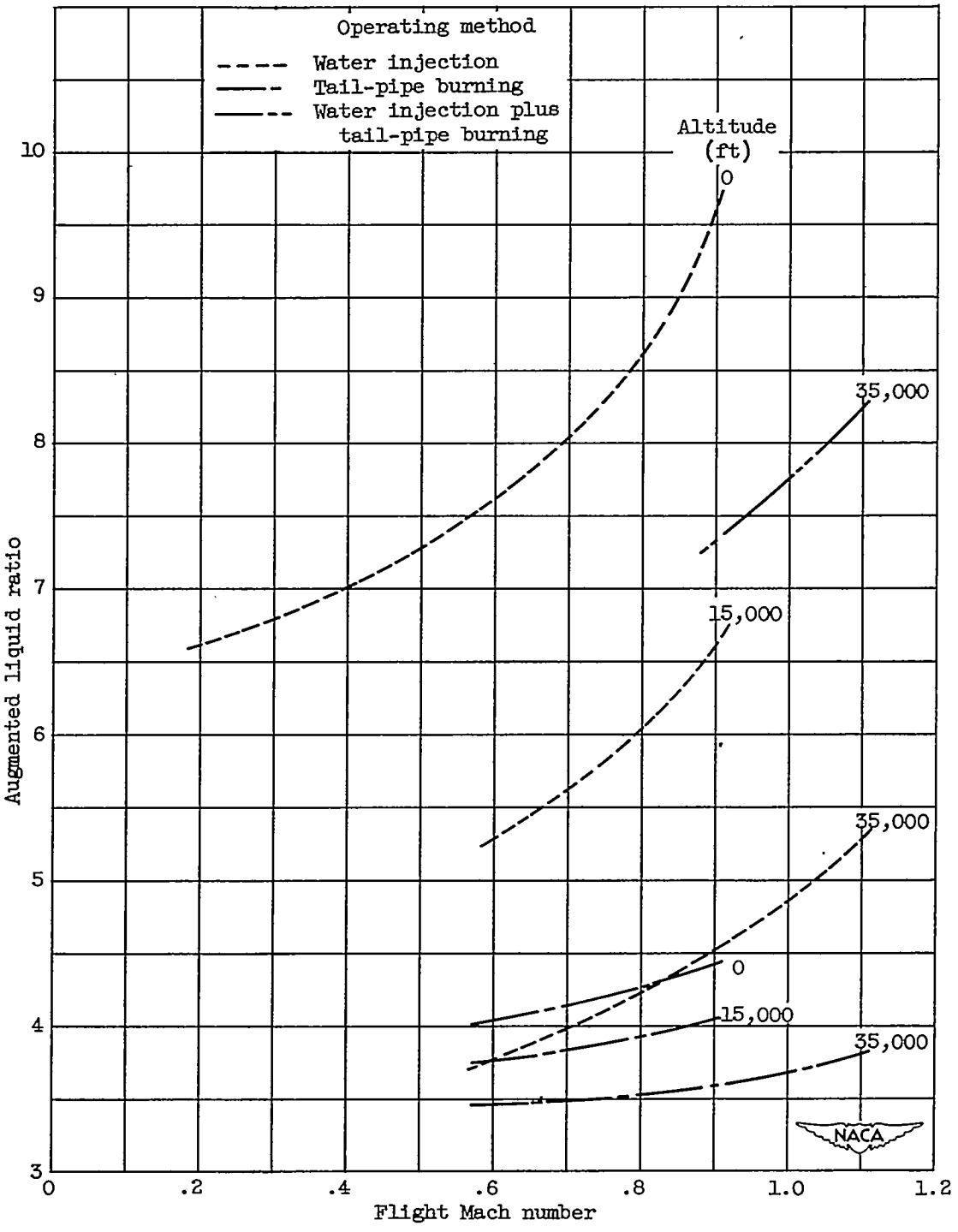

Figure 6. - Variation of augmented liquid ratio with flight condition and method of augmentation. Reference engine characteristics; propeller-plus-gear efficiency, 0.80.

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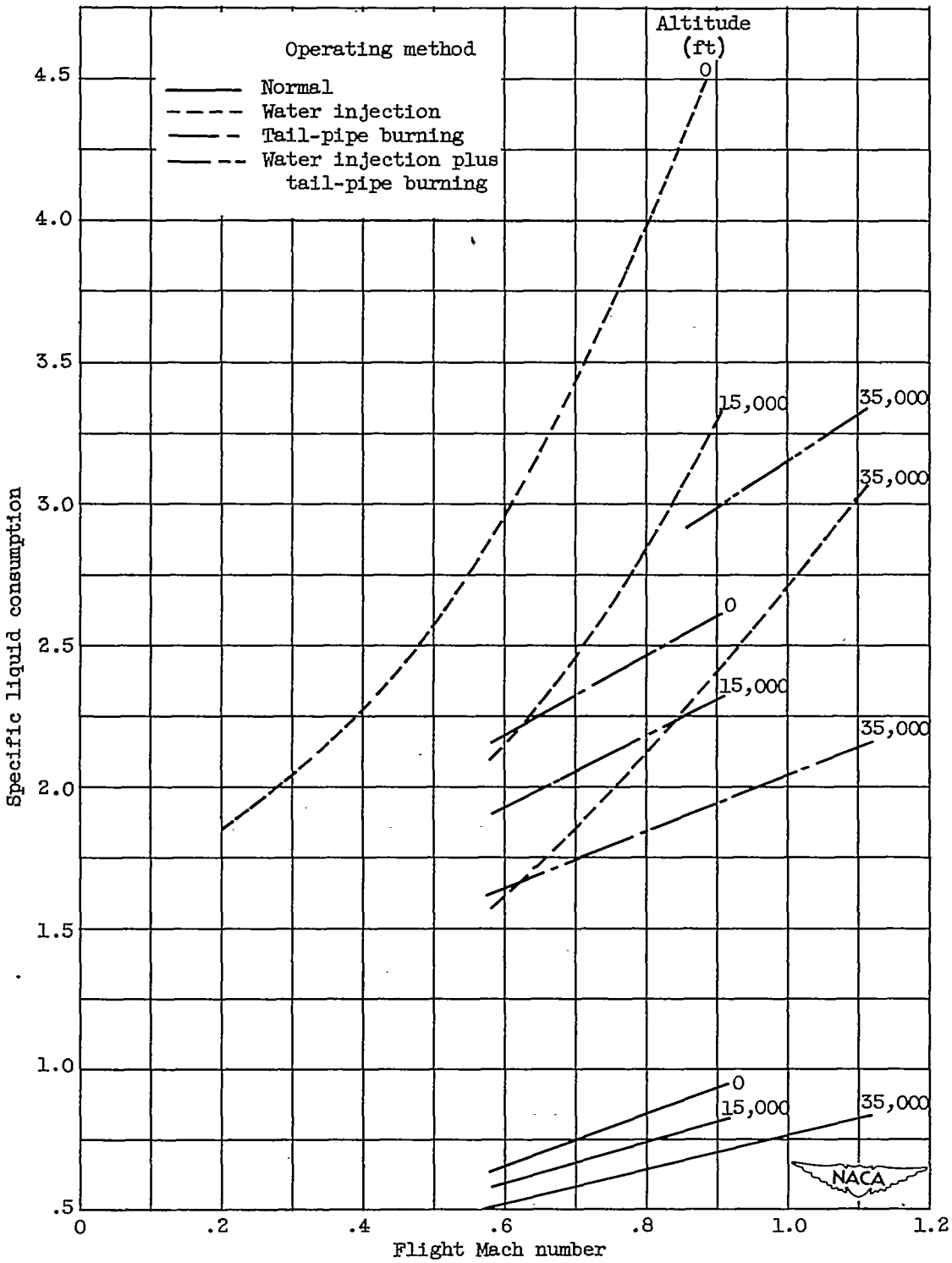

Figure 7. - Variation of specific liquid consumption with flight condition and method of augmentation. Reference engine characteristics; propeller-plus-gear efficiency, 0.80.

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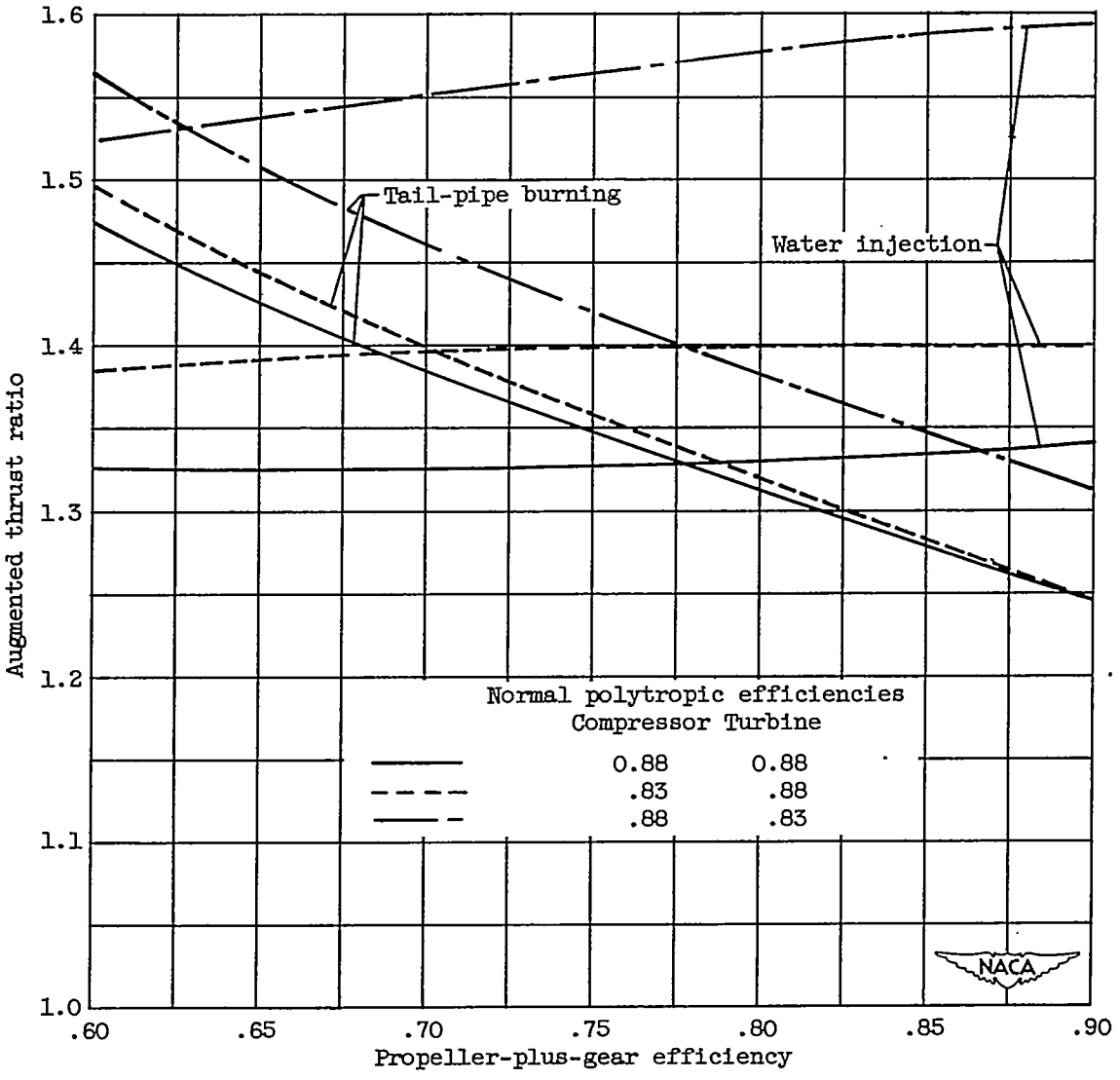

Figure 8. - Effect of lowered component efficiencies on augmented thrust ratio. Flight Mach number, 0.9; altitude, 35,000 feet.

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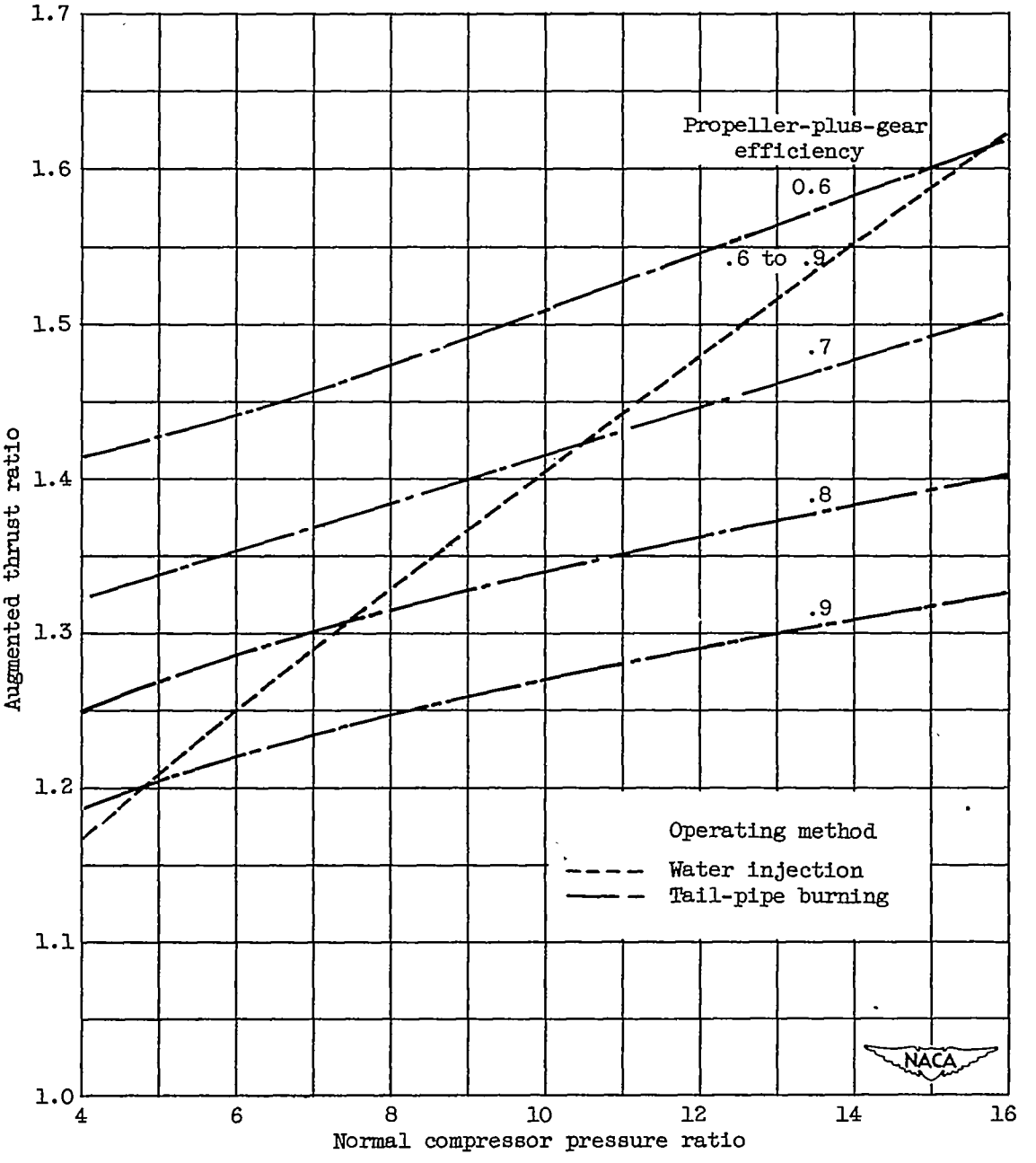

Figure 9. - Variation of augmented thrust ratio with normal compressor pressure ratio. Flight Mach number, 0.9; altitude, 35,000 feet.

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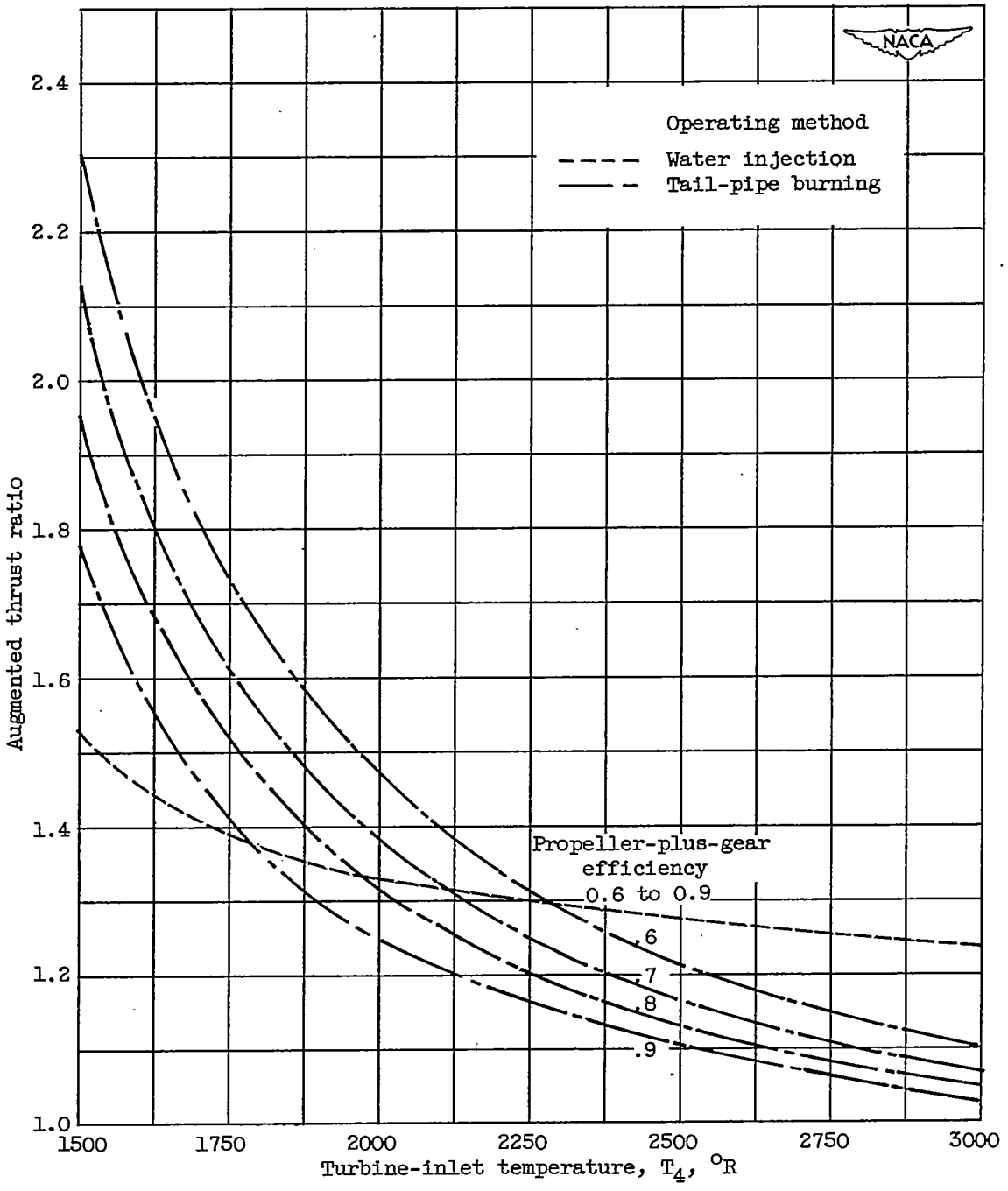

Figure 10. - Variation of augmented thrust ratio with turbine-inlet temperature. Flight Mach number, 0.9; altitude, 35,000 feet.

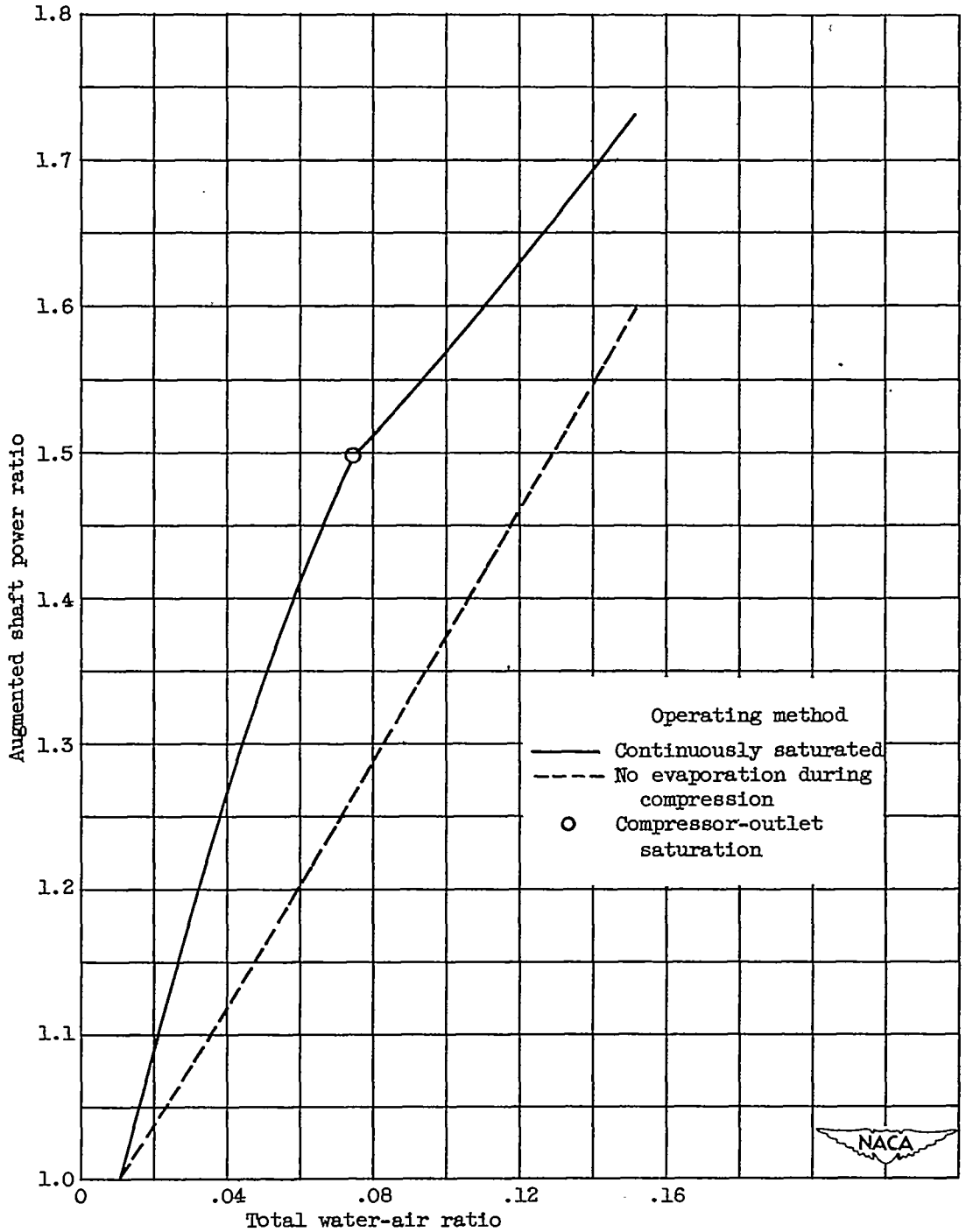

Figure 11. - Effect of percentage evaporation on augmented shaft power ratio. Reference engine characteristics; flight Mach number, 0; altitude, 0.

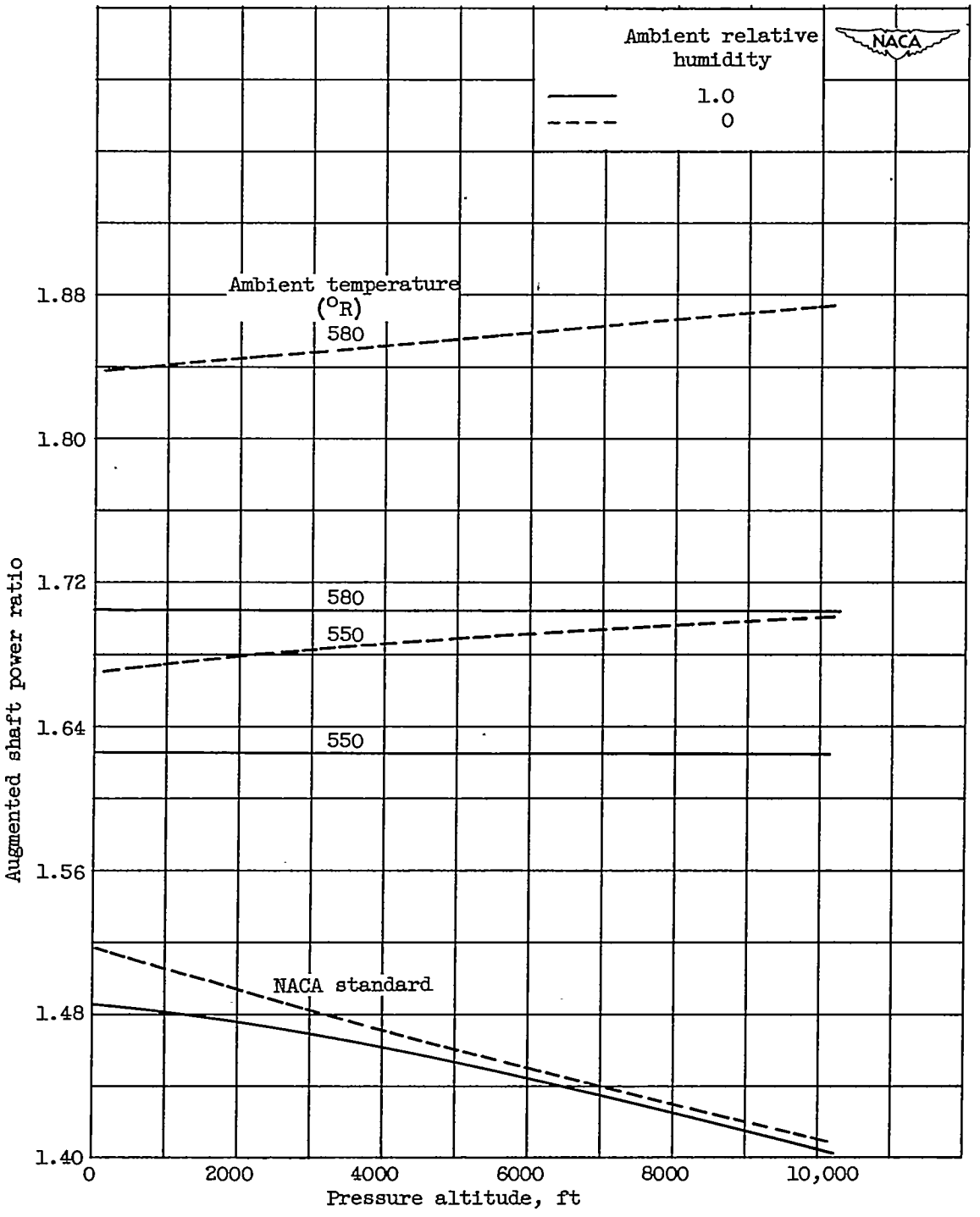

Figure 12. - Effect of ambient conditions on augmented shaft power ratio. Reference engine characteristics; flight Mach number, 0.

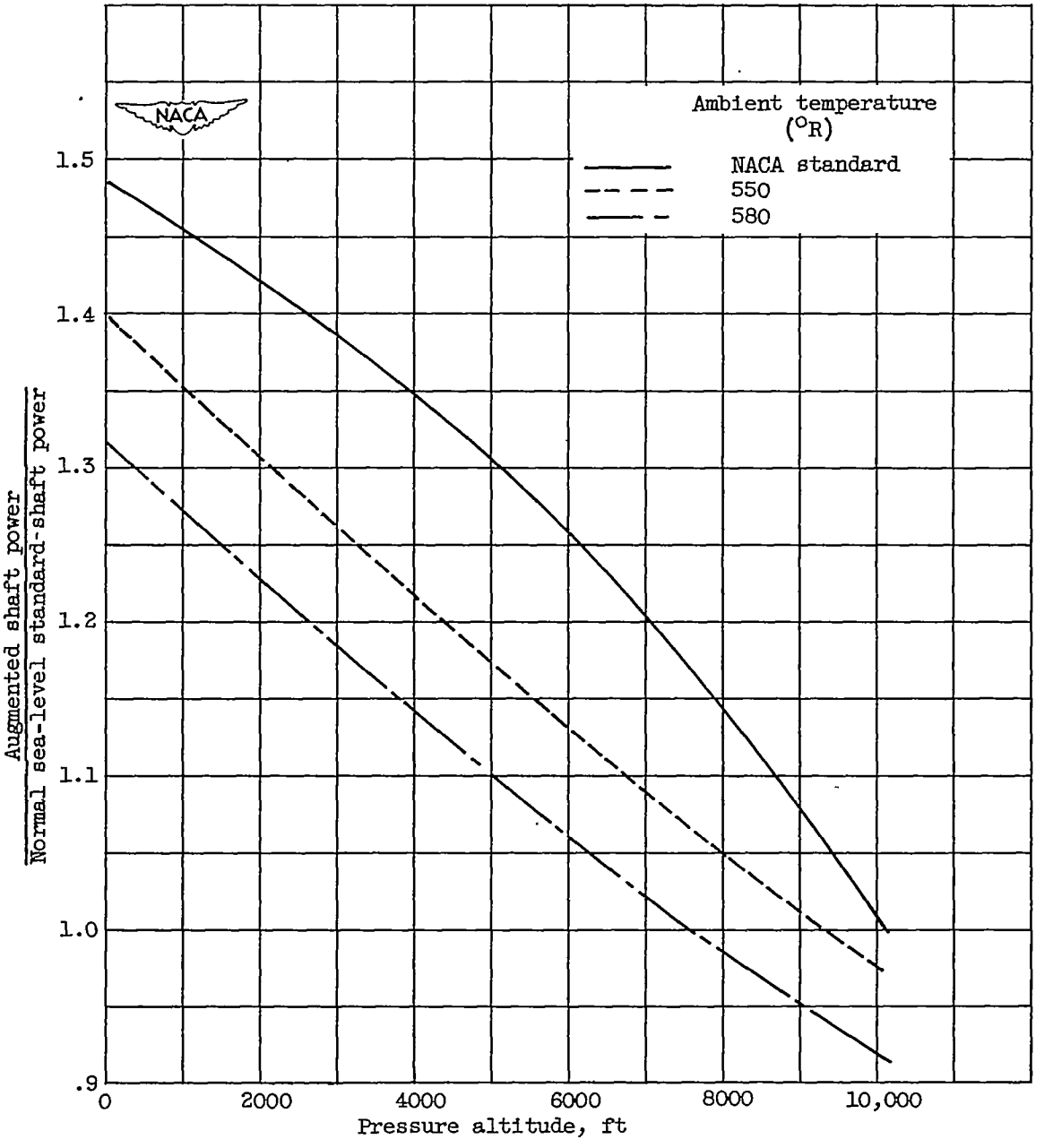

Figure 13. - Effect of ambient conditions on ratio of augmented shaft power to normal sea-level standard shaft power. Reference engine characteristics; flight Mach number, 0.

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