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RESEARCH MEMORANDUM

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THEORETICAL COMPARISON OF SEVERAL METHODS OF THRUST AUGMENTATION FOR TURBOJET ENGINES

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SUMMARY

A theoretical investigation has been made of various methods of thrust augmentation for turbojet engines. The methods investigated were tail-pipe burning, water injection at the compressor inlet, a combination of tail-pipe burning and water injection, bleedoff in conjunction with water injection at the compressor inlet, and rocket assist. The effects of ratio of augmented-to-normal total liquid consumption, flight conditions, and design compressor pressure ratio on the augmentation produced by each method were determined. A comparison was also made for a given time of operation of the weight of an augmented engine plus fuel and additional liquids to the weight of a standard engine plus fuel producing the same thrust.

Results indicated that the tail-pipe-burning plus water-injection method was best for large amounts of thrust augmentation and the tail-pipe-burning method was best for smaller amounts inasmuch as these methods have the lowest ratio of augmented-to-normal total liquid consumption for a given thrust increase of any of the methods considered.

Increasing the flight Mach number greatly increased the thrust augmentation produced for all of the methods considered, whereas increasing the altitude of operation decreased somewhat the amount of augmentation produced. The principal effect of increased engine-design compressor pressure ratio was to increase the range of application of the various methods.

For each method of augmentation, a certain time of operation existed for which the total weight of an augmented engine plus liquids is less than the weight of a standard engine plus fuel designed to produce the same thrust. These times ranged from approximately 2 minutes for rocket assist to 30 minutes for the tail-pipe-burning and the tail-pipe-burning plus water-injection methods for a flight Mach number of 0.85 and an altitude of 35,332 feet.

INTRODUCTION

Thrust augmentation of turbojet engines allows improved take-off performance (either shortened take-off or take-off with an increased load), increased climbing rate, and increased top speed of aircraft powered by turbojet engines. Several methods of thrust augmentation have been investigated by the NACA, including tail-pipe burning, water injection at the compressor inlet, a combination of tail-pipe burning and water injection, and bleedoff including water injection (references 1 to 7). A large amount of research has also been undertaken using rockets to assist the take-off of conventional aircraft. With the exception of rocket assist and tail-pipe burning, this research has been conducted primarily at sea-level static conditions on engine test stands.

By means of computations based on the results of existing experimental data, (a) the effect of flight speed and altitude on the thrust augmentation provided by the various systems and (b) the relative merits of the various augmentation methods for a given set of flight conditions and operating time with respect to their total propulsive weights have been determined at the NACA Cleveland laboratory.

In this analysis, tail-pipe burning, water injection at the compressor inlet, a combination of tail-pipe burning and water injection, bleedoff, and rocket assist are considered. Curves giving thrust augmentation as a function of the ratio of augmented-to-normal total liquid consumption for flight Mach numbers up to 1.50 and for altitudes of sea level and the tropopause (35,332 ft) are presented for each augmentation method. In order to illustrate the effect of a high airplane velocity, performance at an altitude of 35,332 feet and a flight Mach number of 2.50 is also shown. For those augmentation methods requiring exhaust-nozzle-area variation to maintain normal turbine-inlet temperature, the amount of area change required is presented. Engine performance was calculated using assumed component efficiencies readily attainable on current turbojet engines.

Curves are also presented from which the weight of additional equipment required for each of the various augmentation methods may be estimated. In order to determine the optimum turbojet power-plant installation, design curves are presented in which the total propulsive weight (engine plus fuel) of a standard engine is compared with the total propulsive weight (engine plus fuel, auxiliary equipment, and auxiliary liquids) of a smaller engine with thrust-augmentation devices (augmented engine) producing the same thrust. This comparison is made for various operating times.

METHODS OF THRUST AUGMENTATION

A schematic diagram of a turbojet engine equipped for thrust augmentation by means of the various systems investigated is presented in figure 1. A turbojet engine modified for thrust augmentation by means of tail-pipe burning, water injection at the compressor inlet, and bleedoff is shown in figures 1(a), 1(b), and 1(c), respectively. The use of rocket assist does not entail any change in the turbojet engine; therefore no sketch is presented. The operation of the various augmentation methods considered is subsequently described.

Tail-pipe burning. - Additional fuel is burned in the tail pipe downstream of the turbine (fig. 1(a)). The temperature of the gases at the exhaust-nozzle inlet and hence the jet velocity and thrust are therefore increased. Because the temperature of the gases in the tail pipe is not subject to the limitations imposed by the turbine materials, burning to much higher temperatures in the tail-pipe burner than in the engine combustion chamber is possible. Experimental investigations of thrust augmentation by tail-pipe burning are discussed in references 1 and 2.

Water injection at compressor inlet. - By injecting water ahead of the inlet of a compressor (fig. 1(b)), evaporative cooling down to the saturation temperature can be obtained prior to mechanical compression. When water in addition to that required for saturation at the compressor inlet is injected at the inlet, further cooling is obtained by evaporation during the compression process. Because the temperature of the fluid throughout the compression process is reduced, a higher pressure ratio is obtained for a given compressor work input per pound of air-water mixture. This higher pressure ratio results in an increased mass flow through the engine and an increased jet velocity, both of which tend to increase the thrust.

Adding just sufficient water to saturate the air at the compressor inlet is an effective means of augmentation only at high flight speeds when temperatures are high at this point and an appreciable amount of cooling is possible. This method of augmentation is applicable to engines equipped with any type of compressor.

By the addition of sufficient water at the compressor inlet to saturate the air at some point during the compression process, appreciable thrust augmentation may be obtained under static and low-speed flight conditions as well as at high flight speeds. Experimental data indicate that this method of augmentation is satisfactory for engines equipped with centrifugal-type compressors, but that less augmentation is to be gained for axial-compressor-type engines than for the centrifugal-compressor-type engines because of centrifugal separation of the water from the air. Several experimental investigations of thrust augmentation by water injection are reported in references 3 to 6. 1012

In order to prevent freezing at high-altitude operation, a mixture of water and alcohol must be used rather than water alone. Experimental results indicate that by using water-alcohol mixtures, the thrust augmentation produced and the attendant liquid consumptions are about the same as those using water alone; results are therefore presented only for water injection.

<u>Water injection plus tail-pipe burning.</u> - The method using water injection plus tail-pipe burning is simply a combination of the two afore-mentioned augmentation methods. An experimental investigation of this method is presented in reference 7. The use of water injection at the compressor inlet is limited by the type of compressor, as previously mentioned.

<u>Bleedoff.</u> - In the bleedoff method of thrust augmentation (fig. 1(c)), air is removed at the compressor outlet, ducted to an auxiliary burner where fuel is burned at fuel-air ratios approaching stoichiometric, and the gases discharged through an auxiliary nozzle. Water is injected in the engine combustion chamber to replace the air that is bled off; a mixture of exhaust gases and a large amount of water vapor are thus provided for the turbine working fluid. The fuel flow to the engine combustion chamber is adjusted in order to maintain normal turbine-inlet temperatures and water is injected at the compressor inlet to provide additional augmentation. A shut-off valve must be provided ahead of the bleedoff burner to stop the bleedoff flow and allow normal engine operation.

Most of the thrust augmentation of the bleedoff system is attributable to the thrust of the auxiliary jet, with the maximum thrust being produced for stoichiometric fuel-air ratio in the bleedoff burner. The remainder of the thrust augmentation is provided by the injection of water at the compressor inlet, which augments the thrust of both the primary and auxiliary jets. The bleedoff method of thrust augmentation can be utilized by engines having either centrifugal- or axial-type compressors, but the benefits to be derived from the injection of water at the inlet of an axial-flow compressor are subject to the limitations discussed in the preceding section.

<u>Rocket assist.</u> - Rocket assist cannot be considered a thrust-augmentation method in the same sense as the other methods

considered herein, inasmuch as the turbojet engine remains unchanged and another power plant is simply added to the aircraft. However, because of the wide use of rocket assist for take-off and its competitive nature with the various augmentation methods considered, 1012 rocket assist is presented for comparison.

The ram jet was not considered because in the high-speed range in which the ram jet is useful, it is the principal power plant and a comparison of the turbojet engine and the ram jet is more properly treated in other investigations, which compare various engine types (reference 8).

ANALYSIS

In order to evaluate the various thrust-augmentation methods, a comparison is made both on the basis of thrust produced for a given set of operating conditions and on the basis of additional weight involved by the use of each method.

Calculation of Thrust Augmentation

The normal and augmented performances of the turbojet engines were determined from step-by-step calculations of the state changes undergone by the working fluid in passing through the various engine components. The results are presented in the form of thrust augmentation (ratio of increase in thrust to normal thrust) as a function of the augmented liquid ratio (ratio of augmented total liquid consumption to normal total liquid consumption) at the same operating conditions.

Engine performance was determined by assuming reasonable values for component efficiencies and engine-design parameters and calculating the normal and the augmented engine performance for a series of altitudes and flight Mach numbers. The analysis was made for two fixed engines differing only in design compressor pressure ratio. The low-pressure-ratio-compressor engine had a pressure ratio corresponding to current turbojet engines, whereas the high-pressure-ratio-compressor engine had a compressor work input equal to twice that of the low-pressure-ratio-compressor engine. For all conditions, the engines were assumed to operate at maximum rotational speed. The assumptions and the methods used in calculating the changes of state undergone by the working fluid in passing through the various engine components, which allow calculation of the engine performance, are described in the following paragraphs.

Inlet diffuser. - The inlet-diffuser performance was assumed to be unaffected by the use of any of the augmentation methods, and calculations were therefore the same for all configurations. Gas conditions at the diffuser outlet were determined from the diffuser-inlet conditions by use of thermodynamic data (reference 9) and the assumed values of diffuser polytropic efficiency. The diffuser efficiency was assumed to be 1.00, 0.85, 0.80, and 0.70 for flight Mach numbers of 0, 0.85, 1.50, and 2.50, respectively, and was assumed constant for all altitudes.

Compressor. - For all engine configurations and flight conditions not involving water injection at the compressor inlet, the pressure and the temperature of the gas at the compressor outlet were calculated using the inlet-diffuser discharge conditions, the compressor work input, an assumed value of compressor polytropic efficiency of 0.80, and the data of reference 9.

Because the rotational speed was held constant and because compressor work is a function only of rotational speed (slip coefficient remaining constant), the values of compressor work for all flight conditions were maintained constant. Values of 85.32 Btu per pound for the low-pressure-ratio compressor and 170.64 Btu per pound for the high-pressure-ratio compressor were used; these values correspond to one- and two-stage centrifugal compressors, respectively, operating at tip speeds of 1500 feet per second and slip coefficients of 0.95. All results, except where otherwise noted, are also applicable to axial-flow-type compressors operating at the same compressor polytropic efficiency and work input. The pressure ratios produced vary with change in flight conditions due to variation in compressor-inlet temperature. For sea-level static conditions, the pressure ratios produced are approximately 4 and 11 for the one- and two-stage compressors, respectively. Hereinafter, these compressors will be called the low- and high-pressure compressors, respectively.

For the cases in which water was injected at the compressor inlet, the compressor polytropic efficiency was decreased 1 percent below the assumed value of 0.80 for each percentage of water injected in excess of that required to saturate the air at the compressor inlet. This decrease in compressor efficiency was determined from examination of experimental data.

Three processes were involved in finding the gas conditions at the compressor outlet for the case where water was injected at the compressor inlet. These processes are as follows:

1. The cooling that resulted from saturation at constant pressure of the air prior to compression was determined from an unpublished psychrometric chart developed by the NACA, which is applicable to a wide range of initial pressures. This step gives the temperature and the pressure of the saturated air at the compressor inlet.

2. Any water injected at the compressor inlet in excess of that required to saturate the air at this point evaporates during the compression process. The conditions of pressure and temperature immediately after all of the water is evaporated were determined by use of an unpublished Mollier chart (enthalpy-entropy diagram for air saturated with water vapor), the work input to the compressor for that part of the process during which water is evaporating, and the compressor polytropic efficiency.

3. If all the water was evaporated at some point prior to completion of the compression process, the remaining portion of the process was assumed to be adiabatic. The compressor-outlet conditions were determined using the conditions after all the water was evaporated, the compressor polytropic efficiency (the same as that during the evaporation process), the remaining compressor work input, and values of the specific-heat ratio and gas constant, which are consistent with the prevailing water-air ratios.

The methods used in calculating the change in air-mass flow resulting from water injection at the compressor inlet are subsequently described.

Turbine. - Temperature and pressure ratios across the turbine were calculated from the turbine work (equal to compressor work) using an assumed value of turbine polytropic efficiency of 0.85 for all conditions and values of specific-heat ratio and gas constant, which are consistent with the average exhaust-gas temperature and the prevailing fuel-air and water-air ratios. For all engine configurations having low-pressure compressors, the turbine-outlet temperature was held constant at 1650° R and for all engine configurations having high-pressure compressors, the turbine-outlet temperature was held constant at 1500° R. These assumptions resulted in a turbine-inlet temperature of approximately 1950° R, which is characteristic of current turbojet engines, for the low-pressure-ratio engines and 2100° R for the high-pressure-ratio engines.

The mass flow through the engine was claculated assuming sonic velocity at the turbine-nozzle throat. The effective turbine-nozzle-throat area was held constant for all configurations, and the ratio of turbine-outlet-annulus area to turbine-nozzle-throat area was assumed to be 2.5 and 5.0 for engines equipped with low- and high-pressure compressors, respectively. This choice of area ratios resulted in turbine-outlet velocities of approximately 1000 feet per second. The turbine-outlet velocity was calculated using the outlet total pressure and temperature, the mass flow per unit area, and the gas properties. For all configurations except those using tail-pipe burning, the ratio of tail-pipe area to turbine-outlet-annulus area was assumed to be 1.2, which is representative of current turbojet engines. For engines using tail-pipe burning, this ratio was increased to 2.5 in order to reduce the tail-pipe burner-inlet velocities to about 400 feet per second. The polytropic efficiency of the diffusion process from turbine-annulus area to either tail-pipe area or burner-inlet area was assumed to be 0.85.

Burners. - The fuel required in the engine combustion chamber in order to obtain the desired turbine-inlet temperatures was determined by use of the constant-pressure combustion charts contained in reference 10. The effective heating value of the fuel (lower heating value multiplied by combustion efficiency) was assumed to be 18,000 Btu per pound for the engine, tail-pipe, and bleedoff combustion chambers. For a heating value of 18,700 Btu per pound, this effective heating value corresponds to a combustion efficiency of approximately 0.96.

For the tail-pipe burner, with no water injected at the compressor inlet, the temperatures resulting from combustion in the tail-pipe burner were determined from the charts of reference 10 for over-all fuel-air ratios up to 0.05 and the temperatures for richer mixtures were determined from the charts of reference 11. The data contained in reference 11 take account of the effects of dissociation.

The temperatures resulting from combustion in the auxiliary or bleedoff burner were determined from the data contained in reference 11.

For the cases where water was injected either at the compressor inlet or into the engine combustion chamber, when calculating the required fuel-air ratio, account was taken of the heat required to change the liquid water or water vapor to steam at the desired combustion-chamber-outlet temperature.

The ratio of total-pressure loss to inlet total pressure for both the engine combustion chamber and the bleedoff burner was assumed to be 0.03. For the tail-pipe burner, a drag coefficient (ratio of total-pressure loss to inlet-velocity head) of 0.5 was assumed and the friction and momentum pressure losses were determined using the charts contained in reference 12.

Exhaust nozzles. - The exhaust nozzles, both engine and bleedoff, were assumed to be of the convergent type. For all exhaust nozzles, the velocity coefficient was assumed to be 0.975 and the jet velocities were calculated using the exhaust-nozzle-inlet temperature and pressure, the ambient pressure, and the values of specific-heat ratio and gas constant, which are consistent with prevailing gas temperatures and water-air and fuel-air ratios. For cases where greater-than-critical pressure ratios existed across the exhaust nozzle, the jet thrust was calculated as the momentum of the gases issuing from the nozzle at sonic velocity plus the thrust increment produced by the pressure differential (difference between exhaust-nozzle-throat pressure and ambient-air pressure) acting on the exhaust-nozzle area. For all of the conditions except those employing the bleedoff method of thrust augmentation, the engine exhaust nozzle was assumed to be of the adjustable-area type and the area was calculated to give the required gas flow at the existing conditions of temperature and pressure. For the bleedoff method, the engine was assumed to be equipped with a fixed-area nozzle, as subsequently described.

Rocket assist. - The performance using rocket assist was calculated using an assumed specific impulse of 190 pounds per pound per second. This value was assumed constant with change in flight speed and altitude. For rockets currently in use for jet-assisted take-off, this value of specific impulse is believed to be somewhat optimistic for solid-type rockets and conservative for liquid-type rockets.

Ranges for Thrust-Augmentation Calculation

The performance of the standard and augmented engines was calculated for the low- and high-pressure compressor, flight Mach numbers of 0, 0.85, and 1.50, and for altitudes of sea level and the tropopause (35,332 ft). For the engine having the low-pressure compressor, performance is also presented for a flight Mach number of 2.50 and an altitude of 35,332 feet. For the engine having a high-pressure compressor operating at sea level and a Mach number of 1.50, no data are presented for the methods involving the evaporation of water during compression because: (a) The charts that were used in calculating compressor performance with water injection were limited to pressures less than the resulting compressor-outlet pressure; and (b) the values of compressor efficiency in this range are uncertain due to the very high water-air ratios necessary for saturation at the compressor outlet.

The calculated values of thrust, fuel consumption, and exhaust-nozzle area of the standard engines considered are presented in the following table for various flight conditions. The values given are for 1 square inch of turbine-nozzle area, and hence may be scaled up to any desired size, providing the assumed values of component efficiencies can be maintained. The values of the normal thrust and fuel consumption given in the table can be used in conjunction with the figures to determine the augmented thrust and liquid consumption for various flight conditions.

Engine compressor	Altitude (ft)	Flight Mach number	Thrust per unit turbine-nozzle area (lb/sq in.)	Fuel consumption per unit turbine-nozzle area (lb/sec)/(sq in.)	Ratio of exhaust-nozzle area to turbine-nozzle area (sq in./sq in.)
Low-pressure ratio	0	0.00	39.6	0.0119	2.14
	0	.85	33.1	.0144	2.14
	0	1.50	34.6	.0188	2.15
	35,332	.85	14.4	.0051	2.14
	35,332	1.50	15.6	.0067	2.15
	35,332	2.50	9.8	.0083	2.15
High-pressure ratio	0	0.00	105.3	0.0255	4.44
	0	.85	76.9	.0290	4.44
	0	1.50	60.3	.0330	4.45
	35,332	.85	39.6	.0119	4.46
	35,332	1.50	35.3	.0139	4.46

Despite the change in altitude and flight speed, the exhaust-nozzle area of the two engines considered remains essentially constant for a constant tail-pipe temperature.

The range of calculations for the various augmentation methods considered are described in the following paragraphs:

Tail-pipe burning. - The performance of the engine equipped for tail-pipe burning was calculated for various tail-pipe burner fuel-air ratios up to an over-all fuel-air ratio (engine and tail-pipe combustion chambers) of stoichiometric. The fuel-air ratio of the engine combustion chamber changes somewhat with change in flight conditions in order to maintain constant turbine-outlet temperature.

Water injection. - For thrust augmentation by water injection at the compressor inlet, the performance was calculated for various amounts of water injected at the compressor inlet, varying from no water to just sufficient water to saturate the air at the compressor outlet.

Water injection plus tail-pipe burning. - For the combination of water injection plus tail-pipe burning, the over-all fuel-air ratio (engine and tail-pipe combustion chambers) was assumed to be maintained constant at stoichiometric and the performance was calculated for various amounts of water injected at the compressor inlet up to the amount required to saturate the air at the compressor outlet.

Bleedoff. - Performance calculations for the bleedoff method of augmentation were made assuming a constant-area engine exhaust nozzle. If this area is increased, bleedoff of much larger quantities of air is possible for a given amount of water injection into the engine combustion chamber, which results in larger values of thrust augmentation; the resulting increase in compressor air flow and turbine pressure ratio, however, might adversely affect the efficiencies of these components. Calculations indicated that by maintaining the engine exhaust-nozzle area constant the change in operating conditions for the compressor and the turbine was negligible. In contrast to the other methods of thrust augmentation for which the engines were assumed to be equipped with variable-area exhaust nozzles, for the bleedoff method of augmentation the engine exhaust-nozzle area was assumed to be maintained constant at the correct value for normal sea-level static engine operation.

The performance of the engines utilizing the bleedoff method of thrust augmentation was calculated for two amounts of water injected at the compressor inlet: (1) that amount required to saturate the air at the compressor inlet, and (2) that amount required to saturate the air at the compressor outlet.

For each of the two conditions of water injection, the bleedoff flows were varied from a minimum to a maximum, as subsequently described. The minimum bleedoff flow is that amount necessary to maintain normal turbine-inlet temperature with water injected at the compressor inlet but with no water injected into the engine combustion chambers. The maximum bleedoff flow is obtained when stoichiometric fuel-air ratio is required in the engine combustion chamber because of injection of the necessary amount of water at this point. For all cases, the fuel-air ratio of the bleedoff burner was assumed to be stoichiometric. 1012

The bleedoff nozzle was assumed to have the correct area for operation at each value of thrust augmentation. The required bleedoff-nozzle areas are different for various augmented liquid ratios at the same flight condition and vary slightly for different flight conditions at the same augmented liquid ratio; therefore, in order to obtain efficient variation in thrust augmentation for the same flight condition an adjustable-area exhaust nozzle is required. For any designated amount of thrust augmentation, however, operation is possible with a fixed-area nozzle, and some variation in augmented liquid ratio and accompanying thrust augmentation would result at different flight conditions.

Rocket assist. - For the rocket-assist method, there is, theoretically, no limit to the amount of thrust augmentation possible. For the purpose of comparison, calculations were therefore made only over a range of thrust-augmentation values similar to that obtained for the other methods considered.

Frontal-Area and Weight Considerations

The various methods of thrust augmentation were considered qualitatively on the basis of frontal area and quantitatively on the basis of weight. The weight of additional equipment involved by the use of the various methods was determined and the ratios of weight of a standard turbojet engine plus fuel to the weight of a smaller augmented engine plus fuel and liquids producing the same thrust and for the same operating time were compared.

Frontal area. - The use of water injection and tail-pipe burning does not entail any change in frontal area although tail-pipe burning may change the aerodynamic characteristics of the engine nacelle because of a change in length or shape. The use of bleedoff and rocket assist may, depending upon the installation, necessitate a slight increase in frontal area. In order to evaluate this change, however, detailed design studies of various installations would be required and these studies would be beyond the scope of this report. No attempt was made, therefore, to deduct nacelle drag from the calculated net thrust.

Weight of additional equipment. - The weight of additional equipment required for the various augmentation methods at sea-level static conditions was estimated from the weight of existing experimental equipment by taking into account any modifications required for airplane installation. Estimating the weight of equipment required for design operation at any other flight condition was somewhat difficult because of the lack of actual design data; the problem is, however, similar to the usual problem of calculating the required standard engine weight for design operation at various flight conditions.

For any particular method with the exception of rocket assist, operating at a given flight speed and altitude, the weight of additional equipment required was calculated as the weight of equipment required for sea-level static conditions at the same augmented liquid ratio as at the assumed flight conditions. The weight of additional equipment at conditions other than sea-level static conditions was assumed to be a function of the augmented liquid ratio rather than of the amount of augmentation produced, because the volume increase in the various flows and therefore size of equipment is proportional to the percentage increase in liquid flow or augmented liquid ratio and not to the thrust augmentation. For the rocket-assist method of thrust augmentation, the additional weight of equipment was assumed to be a function of the additional thrust and the time of operation.

The following empirical equation was devised to define the additional weight of equipment:

$$\frac{\Delta W}{\Delta F_s} = \frac{A}{\left(\frac{\Delta F}{F}\right)_s} + B$$

where

ΔW additional weight, (lb)

ΔF_s thrust increase at sea-level static conditions resulting from operation at same augmented liquid ratio as at assumed flight conditions, (lb)

A, B constants determined by particular methods under consideration

$\left(\frac{\Delta F}{F}\right)_s$ sea-level static-thrust augmentation resulting from operation at same augmented liquid ratio as at assumed flight conditions

The additional weight ΔW, for all methods except the rocket-assist method, does not include weight of additional fuel, injected liquids, or tanks. For the rocket, the additional weight does not include rocket propellants but does include the weight of tanks.

The following table lists the values of A and B determined from examination of weights of existing experimental equipment:

	A	B
Tail-pipe burning	0.025	0.025
Water injection	0.020	0
Tail-pipe burning plus water injection	0.045	0.010
Bleedoff		
Water at inlet to saturate at compressor outlet	0.025	0.040
Water at inlet to saturate at compressor inlet	.035	.040
Rocket assist	0	[a]0.070 (3t +1)

[a]Factor t (time in min) accounts for fact that weight (not including fuel) of rockets producing given thrust is function of time of operation.

The value of B for the rocket-assist method was empirically calculated from the weights of existing solid- and liquid-type rockets operating for periods of time from 5 to 60 seconds. Solid-propellant rockets are not generally considered applicable for periods of more than 30 seconds.

<u>Total propulsive weight.</u> - In order to calculate the ratio of total propulsive weight of an augmented engine to total propulsive weight of a larger standard engine producing the same thrust for a given time, the following equation was derived:

$$\frac{W_{T,a}}{W_T} = \frac{0.45 + A + \left(\frac{\Delta F}{F}\right)_s B + 0.01833\ t\ f\ \frac{(W_{l,a}/W_l)}{(F_s/F)}}{\left(1 + \frac{\Delta F}{F}\right)\left[0.45 + 0.01833\ t\ f\ \frac{1}{(F_s/F)}\right]}$$

where

$W_{T,a}$ total propulsive weight of augmented engine (engine, fuel, auxiliary equipment, and auxiliary liquids), (lb)

W_T total propulsive weight of standard engine (engine and fuel), (lb)

f thrust specific fuel consumption of standard engine at assumed flight conditions, (lb/hr)/(lb thrust)

$\frac{W_{l,a}}{W_l}$ augmented liquid ratio (ratio of augmented-to-normal total liquid consumption)

$\frac{F_s}{F}$ ratio of sea-level static thrust of standard engine to thrust of standard engine at assumed flight conditions

$\frac{\Delta F}{F}$ thrust augmentation at assumed flight conditions

The specific weight of the standard engine was assumed to be 0.45 pound of engine weight per pound of sea-level static thrust produced. This value of specific weight is readily attainable in current turbojet engines and was assumed independent of the amount of thrust produced. The factor 0.01833 accounts for the weight of the tanks, which is assumed to be 10 percent of the weight of fuel or liquid, and converts the units of time from minutes to hours in order to be consistent with the units of thrust specific fuel consumption. Considerable departure from the values of A and B chosen would have very little effect on the results obtained because the weight of additional equipment involved by the use of each method is a small percentage of the total weight. The method and data presented herein would allow a comparison of total propulsive weight to be made for any of the operating conditions considered; however, for illustration, the comparison was made for an engine having a low-pressure compressor and operating at a flight Mach number of 0.85 and an altitude of 35,332 feet.

RESULTS AND DISCUSSION

Thrust Augmentation

The thrust augmentation (ratio of increase in thrust to normal thrust) for the engine having the low-pressure-ratio compressor is shown in figure 2 as a function of the augmented liquid ratio (ratio of augmented total liquid consumption to normal total liquid consumption) for the various augmentation methods. Figures 2(a), 2(b), and 2(c) are for sea-level altitude and flight Mach numbers of 0, 0.85, and 1.50, respectively; figures 2(d), 2(e), and 2(f) are for an altitude of 35,332 feet and flight Mach numbers of 0.85, 1.50, and 2.50, respectively. Thrust augmentation as a function of the augmented liquid ratio is shown in figure 3 for the engine with the high-pressure-ratio compressor.

For all curves involving water injection at the compressor inlet, the solid lines are applicable to axial- and centrifugal-type engines, and the dashed lines are applicable to centrifugal-type engines and questionable for axial-type engines. The solid curves represent amounts of water injected at the compressor inlet up to that amount required for saturation at the compressor inlet and the dashed lines represent amounts of water injected varying from the amount required to saturate the air at the compressor inlet to the amount required to saturate the air at the compressor outlet. The thrust augmentation predicted for amounts of water injected greater than that required to saturate the air at the compressor inlet (shown as dashed lines) is considered questionable for axial-compressor-type engines inasmuch as these amounts have not as yet been experimentally attained because of centrifugal separation of the water in passing through the compressor.

In order to give an indication of the amount of exhaust-nozzle-area change necessitated by the use of the various methods, the ratio of required augmented exhaust-nozzle area to sea-level static normal exhaust-nozzle area for several significant operating conditions is indicated on the curves of figures 2 and 3. The tail-pipe-burning method requires a large increase in exhaust-nozzle-area ratio, whereas water injection at the compressor inlet somewhat decreases the required area ratio. The combination of tail-pipe burning and water injection results in a smaller increase in required exhaust-nozzle area than tail-pipe burning alone. The use of rocket assist does not alter the turbojet engine and for bleedoff the exhaust-nozzle area has been assumed constant at the value required for normal sea-level static operation. All values given are for the ratios of effective areas.

Examination of figures 2 and 3 indicates that the thrust augmentation produced by the bleedoff and rocket-assist methods increases approximately linearly with increase in augmented liquid ratio. For water injection and tail-pipe burning, the thrust augmentation increases rapidly at first and then at a decreasing rate as the augmented liquid ratio increases. Because in this analysis the combination of tail-pipe burning and water injection was considered only for an over-all fuel-air ratio across the engine and tail-pipe combustion chambers of stoichiometric, the curves for tail-pipe burning in conjunction with water injection appear as extensions to the curves for tail-pipe burning alone and have the same general shape as the curves for water injection alone.

The superiority at all flight speeds and altitudes of the combined tail-pipe-burning and water-injection method for large amounts of thrust augmentation and of the tail-pipe-burning method alone for smaller amounts of augmentation is shown in figures 2 and 3. Although the water-injection method is inferior to tail-pipe burning and is limited to small amounts of augmentation, it has the advantage of extreme simplicity. For a given thrust increase, the rocket-assist method of thrust augmentation requires the greatest augmented liquid ratio with the bleedoff method being only slightly better. For the engine having a low-pressure-ratio compressor, the thrust augmentation available for the tail-pipe burning method is 55 percent at sea-level static conditions and an augmented liquid ratio of 4, as indicated in figure 2(a). For the same augmented liquid ratio and the same operating conditions, the thrust augmentation produced by the other methods are 32 percent for water injection, 17 percent for the rocket-assist method, and 18 percent for the bleedoff method with saturated air at the compressor inlet. For the same engine and flight conditions, increasing the augmented liquid ratio to 8 increases the thrust augmentation produced by the various methods to the following values: 102 percent for the combination of tail-pipe burning and water injection, 38 percent for the rocket-assist method, and 54 and 40 percent for the bleedoff method with compressor-outlet and compressor-inlet saturation, respectively. A value of augmented liquid ratio of 8 is beyond the range of the tail-pipe-burning or water-injection methods alone for the particular operating conditions. In order to obtain 102 percent augmentation with the bleedoff or rocket-assist methods, from two to two and one-half times the augmented liquid ratio is required as with the combination of tail-pipe burning and water injection.

The effect of flight Mach number can be determined by comparing the performance at sea-level static conditions (fig. 2(a)) with performance of the various methods operating at the same augmented liquid ratio and altitude but at an increased flight Mach number. In general, with all other conditions fixed, increasing the flight Mach number greatly increases the augmentation produced by the various methods. For example, for sea-level altitude, an augmented liquid ratio of 4, and a flight Mach number of 1.50, the thrust augmentation produced by the tail-pipe-burning method is 165 percent (fig. 2(c)) as compared to 55 percent at a flight Mach number of 0 (fig. 2(a)). The augmentation produced by the other methods at a flight Mach number of 1.50 and an augmented liquid ratio of 4 is 47 percent for the water-injection method and 30 percent for the rocket-assist method as compared to 32 percent and 17 percent for the water-injection and rocket-assist methods, respectively, at a flight Mach number of 0.

Increasing the flight Mach number not only increases the thrust augmentation for a given augmented liquid ratio, but with the exception of rocket assist also increases the maximum augmented liquid ratio possible, thus producing even higher values of augmentation. For example, at sea-level altitude for an engine having a low-pressure compressor and operating with the combined water-injection plus tail-pipe-burning method, increasing the flight Mach number from 0 to 1.50 increases the maximum augmentation possible from 102 to 350 percent with increase in augmented liquid ratio from 8 to 13, respectively.

In general, at a constant augmented liquid ratio, the effect of increasing altitude is to decrease somewhat the amount of thrust augmentation produced at a given flight Mach number. For example, at a flight Mach number of 0.85 and an augmented liquid ratio of 4, figure 2(b) shows the thrust augmentation produced by tail-pipe burning at sea level to be 100 percent and figure 2(d) indicates the augmentation produced for the same flight Mach number at an altitude of 35,332 feet to be 95 percent. For water injection, the thrust augmentation produced for the same conditions are 45 and 30 percent for altitudes of sea level and 35,332 feet, respectively. This decrease in the thrust augmentation with increased altitude for the methods utilizing water injection at the compressor inlet results from the decreased temperatures and decreased associated water-air ratios. Because the normal thrust and liquid consumption of the turbojet engine decreases as altitude is increased, for a given weight of liquid and amount of augmentation, operation in the augmented configuration is possible for longer periods of time at altitude than at sea level.

The effect of a flight Mach number of 2.50 at an altitude of 35,332 feet can be seen from figure 2(f). Increasing the Mach number from 1.50 (fig. 2(e)) to 2.50 increases the thrust augmentation of the tail-pipe-burning method, for an augmented liquid ratio of 4, from 140 to 350 percent. The maximum augmentation available from the tail-pipe-burning plus water-injection method at a flight Mach number of 1.50 is 234 percent at an augmented liquid ratio of 10. For a flight Mach number of 2.50 the maximum augmentation is 830 percent at an augmented liquid ratio of 22.5. Large increases in thrust augmentation are similarly obtained for the other augmentation methods considered at a Mach number of 2.50.

Comparison of figures 2 and 3 indicates that increasing the design compressor pressure ratio extends the range of application of several of the augmentation methods, especially those with water injection at the compressor inlet, by increasing the maximum value of augmented liquid ratio. This increased range of the methods using water injection at the compressor inlet associated with increased compressor pressure ratio is due to the increased water-air ratios, which are made possible by the higher compressor-outlet temperature. At the same augmented liquid ratio, however, the effect of increased compressor pressure ratio on augmentation is very slight.

In order to explain the slight effect of the compressor pressure ratio on thrust augmentation for a given augmented liquid ratio, the tail-pipe-burning method was further analyzed for a given altitude and flight speed. For a given over-all fuel-air ratio, as the compressor pressure ratio increases, the thrust of the augmented engine was found to increase faster than that of the standard engine, so that the augmentation increases with increasing pressure ratio. The specific fuel consumptions of both the standard and the augmented engines first decrease and then increase with increasing compressor pressure ratio; however, the specific fuel consumption of the augmented engine reaches a minimum at a lower value of compressor pressure ratio than the standard engine. The combined effects of these factors result in little or no change in the values of thrust augmentation obtained for a given value of the augmented liquid ratio for engines having the two compressors considered. As previously stated, however, the increased compressor pressure ratio does increase the maximum possible augmented liquid ratio and hence the maximum augmentation.

Weight Estimates

The ratio of increase in engine weight to increase in engine thrust (specific weight of the augmentation equipment) for sea-level static operation is plotted in figure 4 against thrust augmentation for each of the methods considered except rocket assist; for the rocket-assist method, the specific weight of augmentation

equipment is not a function of thrust augmentation but of time of operation and is plotted against time on an auxiliary abscissa. The increased weight is the weight of additional equipment only and does not include any additional liquids that are necessary. For all of the methods except rocket assist, the ratio of increase in 1012
engine weight to increase in thrust decreases as the thrust augmentation increases, as indicated in figure 4. For all methods, the value of the ratio of increased weight to increased thrust is approximately the same (0.05 to 0.07) at the maximum values of augmentation. For rocket assist, the ratio of increase in engine weight to increase in thrust has a minimum value for zero time of operation and increases as the operating time increases. The minimum value for rocket assist (zero time) is approximately equal to the value obtained by the various other methods when operating at maximum values of thrust augmentation. By considering all of the methods except rocket assist, at a constant amount of thrust augmentation, the water-injection method entails the least additional weight and the bleedoff method requires the most additional weight. The weight of additional equipment involved with tail-pipe burning is intermediate between that for water injection and bleedoff. The curve for bleedoff with compressor-outlet air saturated falls below that for bleedoff with compressor-inlet air saturated because greater thrust augmentation is obtained for the same weight of additional equipment.

The following table lists the calculated weights of augmentation equipment required for the various augmentation methods installed on engines with low-pressure compressors and operating at their maximum values of sea-level static thrust augmentation. The comparison is made for all methods installed on an engine having a normal thrust of 4000 pounds and for the tail-pipe-burning method installed on engines having normal thrusts of 3000, 4000, and 5000 pounds. The weight of equipment required for rocket assist is a function of time of operation as well as the value of augmentation; values of 20- and 30-second duration were therefore assumed in calculating the tabulated values. A value of thrust augmentation approximately equal to that obtainable from the bleedoff method was assumed for rocket assist.

Normal thrust (lb)	Augmentation method	Thrust augmentation	Weight of augmentation equipment (lb)
3000	Tail-pipe burning	0.55	116
4000	------------do.-----------	.55	155
5000	------------do.-----------	.55	194
4000	Water injection	.34	80
4000	Tail-pipe burning plus water injection	1.02	221
4000	Bleedoff (saturated air at compressor outlet)	1.58	352
4000	Bleedoff (saturated air at compressor inlet)	1.23	336
4000	Rocket assist (20 sec)	1.50	840
4000	Rocket assist (30 sec)	1.50	1050

In the investigation of the times of operation for which the augmented engines are more economical with regard to total propulsive weight than larger standard engines producing the same thrust, curves similar to figure 5 were obtained. The ratio of augmented-to-normal total propulsive weight (for equal thrust) is shown in figure 5 as a function of thrust augmentation for various times of operation for an engine having a low-pressure compressor and utilizing the tail-pipe-burning method of augmentation for operation at an altitude of 35,332 feet and a flight Mach number of 0.85. For certain times of augmented operation, the curves for ratio of augmented-to-normal total propulsive weight minimize as the amount of augmentation is increased, as shown in figure 5. This decrease is due to the decreased weight of the basic engine, which is greater than the increased weight of liquids. For very short times of operation, the curves of figure 5 reach a minimum value at a value of thrust augmentation greater than possible for the tail-pipe-burning method at these particular flight conditions (fig. 2(d)). The curves have therefore been discontinued at this point of maximum augmentation. For the particular flight conditions and times of operation less than 30 minutes, the total propulsive weight of the augmented engine is less than the weight of a larger standard engine producing the same thrust as indicated in figure 5. The curve through the minimum points of the family of curves presented in figure 5 indicates the amount of thrust augmentation that will give the lowest total propulsive weight (engine plus fuel, auxiliary equipment, and auxiliary liquids) for the time under consideration.

The ratio of augmented total propulsive weight (engine plus fuel, auxiliary equipment, and auxiliary liquids) to normal total propulsive weight (engine plus fuel) is shown in figure 6 as a function of time of operation for the various methods. The curves of figure 6 are for an engine that has a low-pressure-ratio compressor operating at an altitude of 35,332 feet and a flight Mach number of 0.85. The data contained in figure 6 were obtained using the values of thrust augmentation necessary to provide minimum total propulsive weight for each method and time of operation as determined from curves similar to figure 5. Large deviations from the assumed values for the auxiliary equipment weight have only a slight effect on the curves presented in figure 6 because the equipment weight is a very small percentage of the total propulsive weight. Several curves are presented for the rocket-assist method representing various values of augmentation. Because the engines are assumed to produce the same thrust for all cases, the augmented engine is smaller than the standard engine and it must be remembered in using figure 6 for design purposes that the normal thrust of the augmented engine is less than the maximum. In general, the longer the designated augmented operating time, the greater the ratio of augmented-to-normal total propulsive weight will be and the less the amount of thrust augmentation should be for any particular method (fig. 6). The values of thrust augmentation necessary to give the minimum ratio of augmented-to-normal total propulsive weight are shown on the curves in figure 6. Sharp breaks occur in the curves for bleedoff because for this system the augmentation for the minimum total propulsive weight shifts suddenly from the maximum to the minimum value as the time of operation increases. The approximate maximum times of augmented operation for which the total propulsive weight of the augmented engine is less than that of a normal engine producing the same thrust (ratio of augmented-to-normal total propulsive weight equal to 1.0) are 2 minutes for the rocket-assist method, 4 to 5 minutes for bleedoff, 7 minutes for water injection, and about 30 minutes for tail-pipe burning and tail-pipe burning plus water injection (fig. 6). The values of thrust augmentation corresponding to these times of operation are any value for the rocket-assist method, 0.15 for water injection, 0.43 for tail-pipe burning, 1.46 for bleedoff with compressor-inlet air saturated, and 0.40 for bleedoff with compressor-outlet air saturated.

SUMMARY OF RESULTS

An analysis of tail-pipe-burning, water-injection at the compressor inlet, tail-pipe-burning plus water-injection, bleedoff, and rocket-assist methods of thrust augmentation indicates the following results:

1. For all conditions of flight Mach number and altitude, the combination of tail-pipe burning and water injection at the compressor inlet appeared to be the most advantageous method of obtaining large amounts of thrust augmentation. For an engine having a low-pressure-ratio compressor operating at sea-level static conditions, the tail-pipe-burning plus water-injection method provided a thrust augmentation (ratio of increase in thrust to normal thrust) of 102 percent at a total liquid consumption of eight times normal. This amount of augmentation was much greater than that produced by any of the other methods, which operated at this augmented liquid ratio for these particular conditions. In order to obtain the same augmentation using the bleedoff or rocket-assist methods of augmentation, two to two and one-half times the augmented liquid ratio was required as with the combination of tail-pipe burning and water injection.

2. For moderate increases in thrust, the tail-pipe-burning method appeared best because this method had the lowest ratio of augmented-to-normal total liquid consumption for a given thrust increase of any of the methods considered. For an engine having a low-pressure-ratio compressor operating at sea-level static conditions, the maximum thrust augmentation available was approximately 55 percent at a total liquid consumption of four times normal. For these same conditions and the same augmented liquid ratio, the thrust augmentation available for the water injection method was 32 percent.

3. The principal effect of increasing the engine-design compressor pressure ratio was to increase the maximum value of augmented liquid ratio and hence the maximum augmentation; however, for a given augmented liquid ratio, increasing the compressor pressure ratio for the range of pressure ratios considered did not increase the thrust augmentation produced at a given value of augmented liquid ratio.

4. Increasing the flight Mach number at a constant augmented liquid ratio greatly increased the thrust augmentation. For example, for an engine having a low-pressure compressor operating at an augmented liquid ratio of 4, the thrust augmentation produced by the tail-pipe-burning method increased from 55 percent to 165 percent as the sea-level flight Mach number was increased from 0 to 1.50. Increasing the flight Mach number also increased the maximum ratio of augmented-to-normal total liquid consumption and thus allowed greater maximum values of thrust augmentation. For example, for an engine having a low-pressure compressor, increasing the flight Mach number at sea level from 0 to 1.50 increased the

maximum thrust augmentation produced by the combined tail-pipe-burning plus water-injection method from 102 percent to 350 percent with an increase in augmented liquid ratio of from 8 to 13.

5. Increasing the altitude of operation somewhat decreased the augmentation produced, especially by those methods using water injection at the compressor inlet.

6. For each augmentation method, there was a certain time of operation below which the total propulsive weight (engine plus fuel, auxiliary equipment, and auxiliary liquids) of an augmented engine is less than the total propulsive weight (engine plus fuel) of a standard engine producing the same thrust. At a flight Mach number of 0.85 and an altitude of 35,332 feet, these operating times were very short for the rocket-assist method (approximately 2 min) and increased for the different methods up to approximately 30 minutes for the tail-pipe-burning method. The values of thrust augmentation corresponding to these times of operation were 0.43 for the tail-pipe-burning method and any value for the rocket-assist method.

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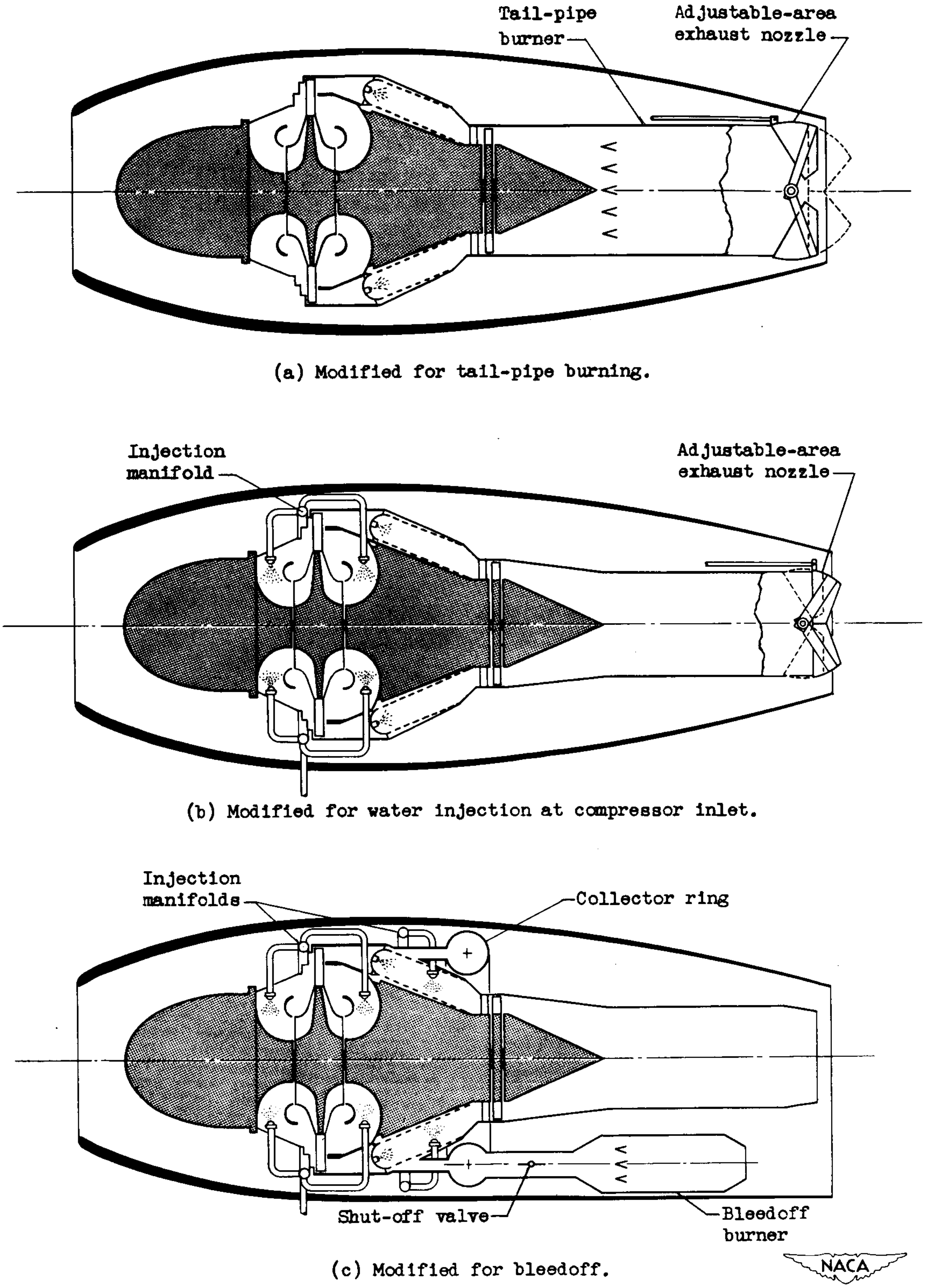

(a) Modified for tail-pipe burning.

(b) Modified for water injection at compressor inlet.

(c) Modified for bleedoff.

Figure 1. - Turbojet engine modified for thrust augmentation by various methods.

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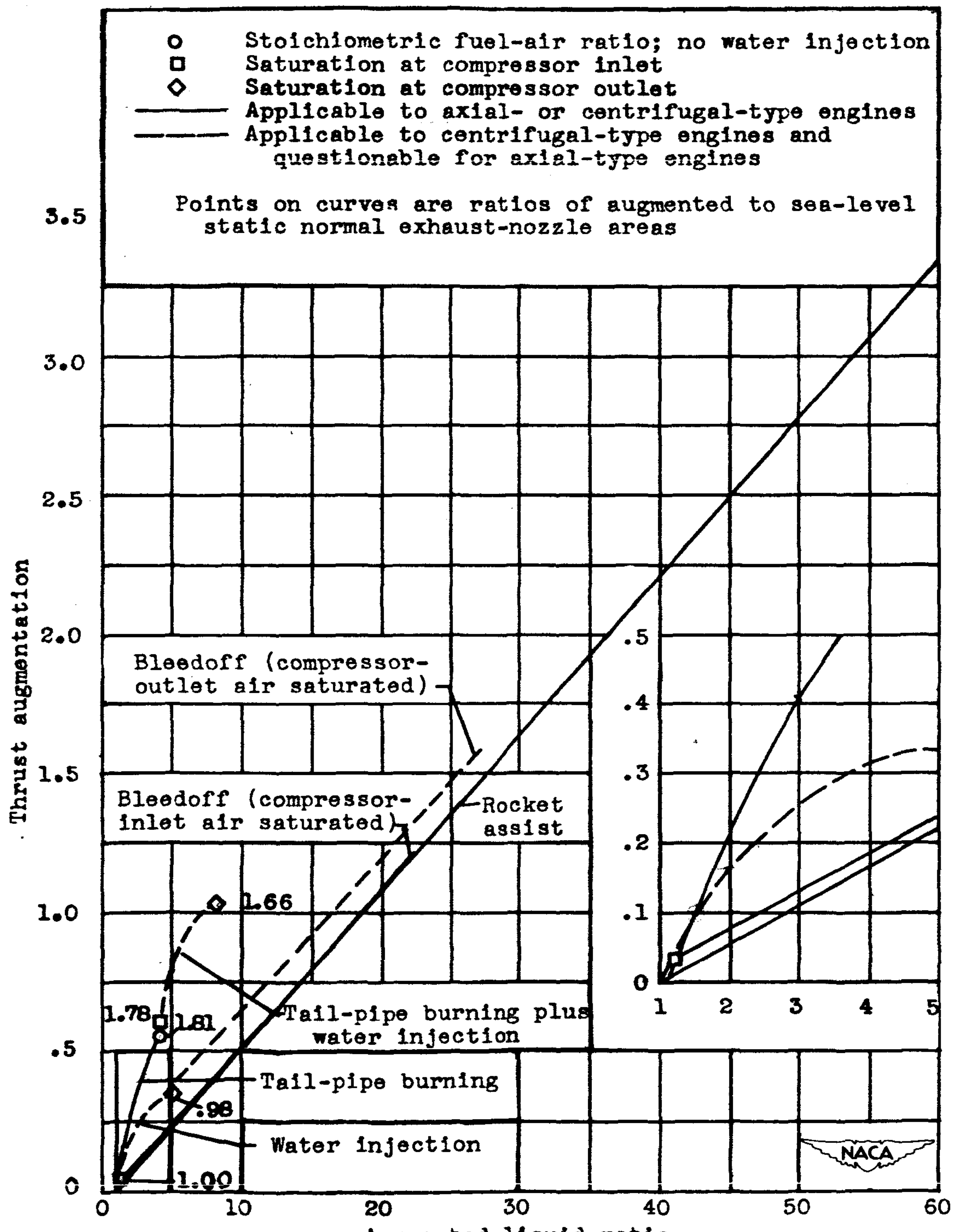
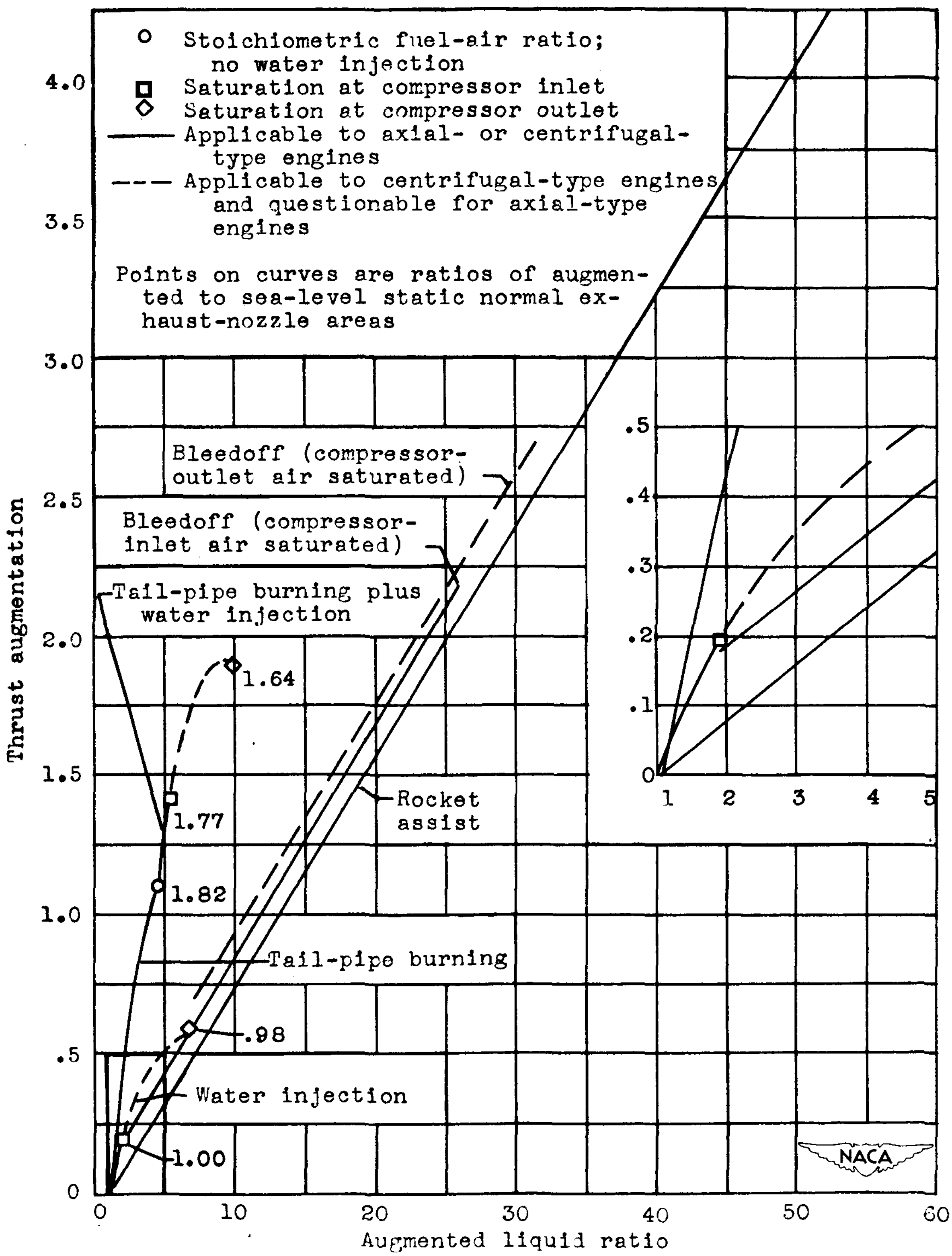


(a) Altitude, sea level; flight Mach number, 0.

Figure 2. - Thrust augmentation of turbojet engine with low-pressure-ratio compressor.



(b) Altitude, sea level; flight Mach number, 0.25.

Figure 2. - Continued. Thrust augmentation of turbojet engine with low-pressure-ratio compressor.

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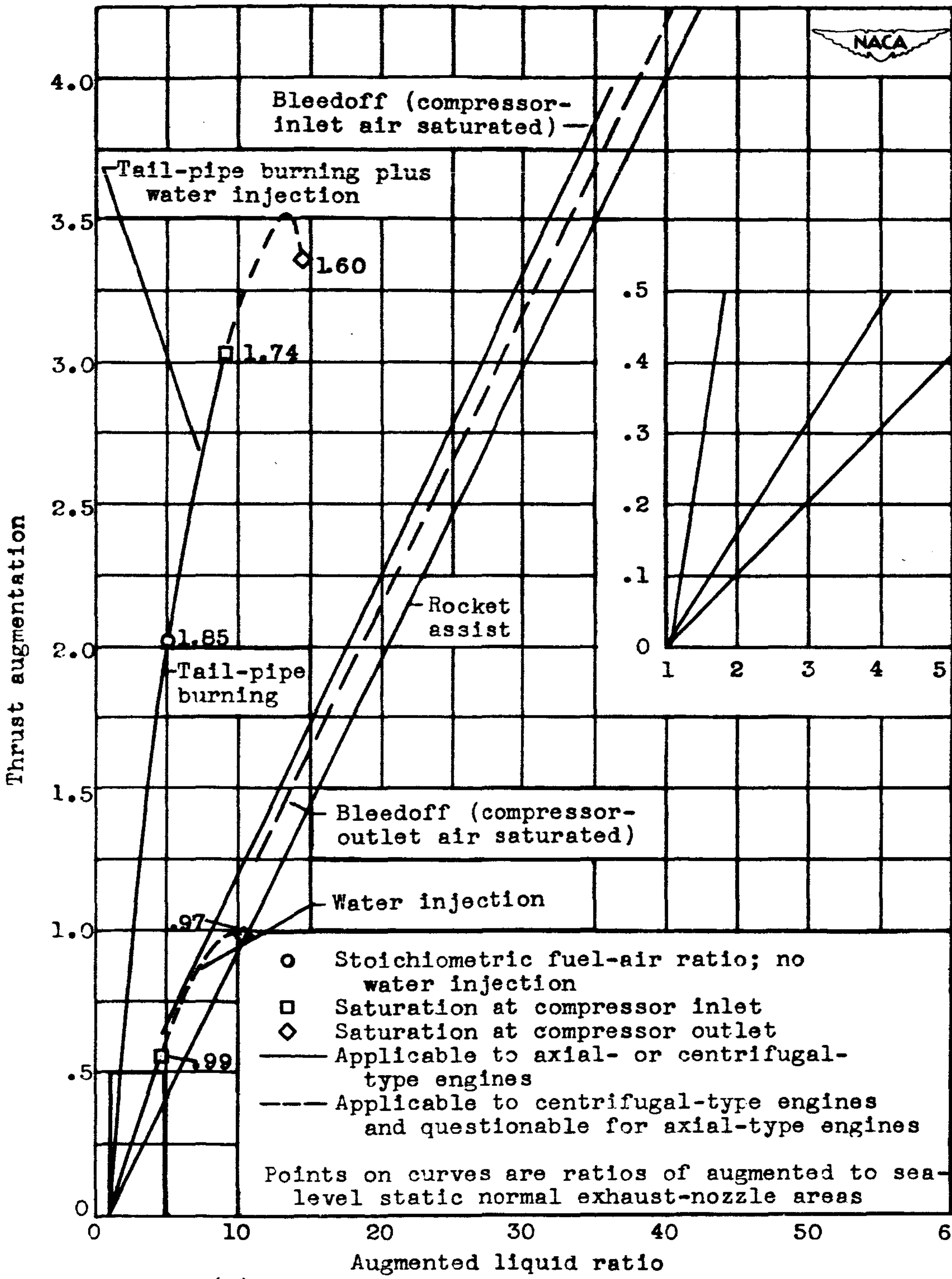
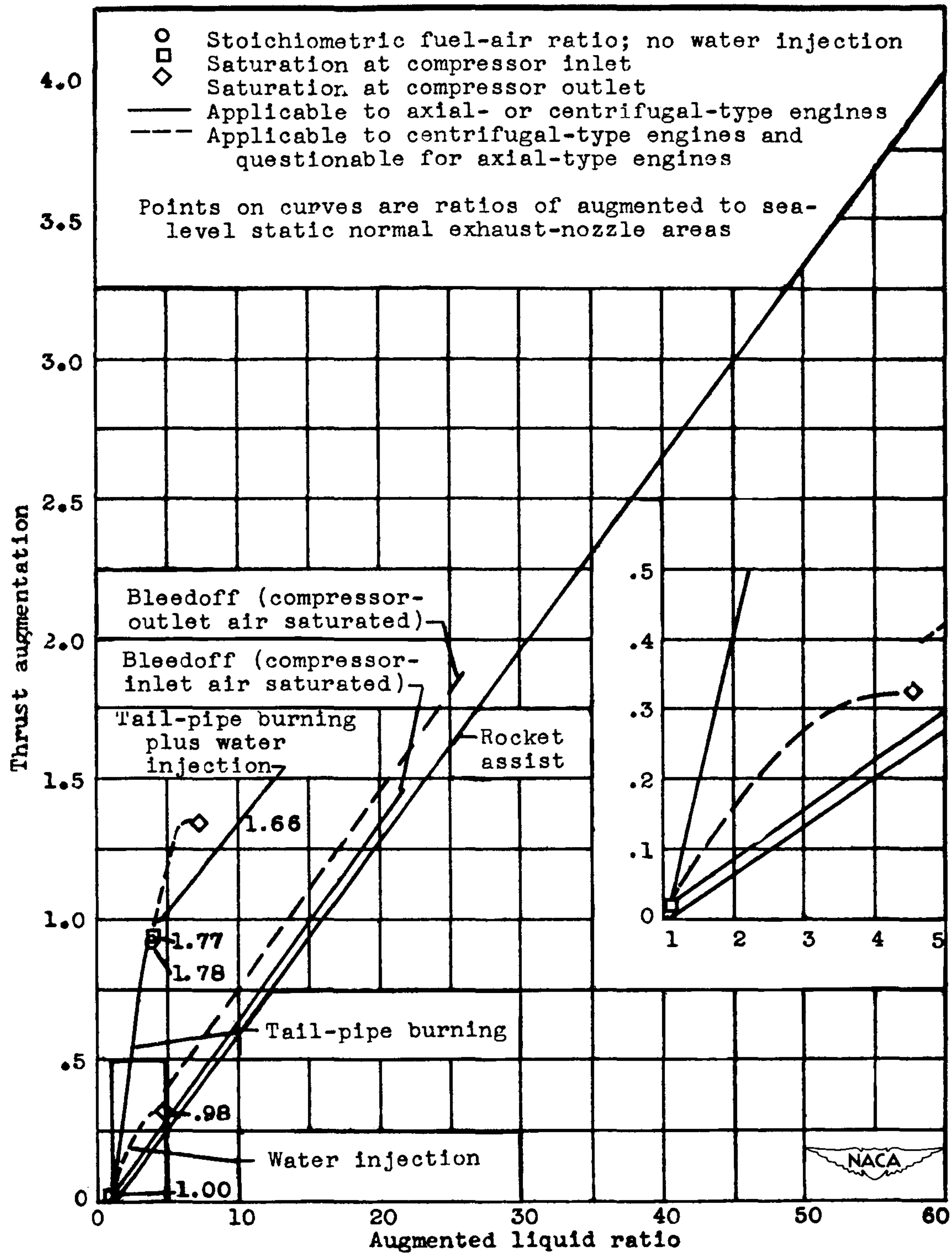


(c) Altitude, sea level; flight Mach number, 1.50.

Figure 2. - Continued. Thrust augmentation of turbojet engine with low-pressure-ratio compressor.



(d) Altitude, 35,332 feet; flight Mach number, 0.85.

Figure 2. - Continued. Thrust augmentation of turbojet engine with low-pressure-ratio compressor.

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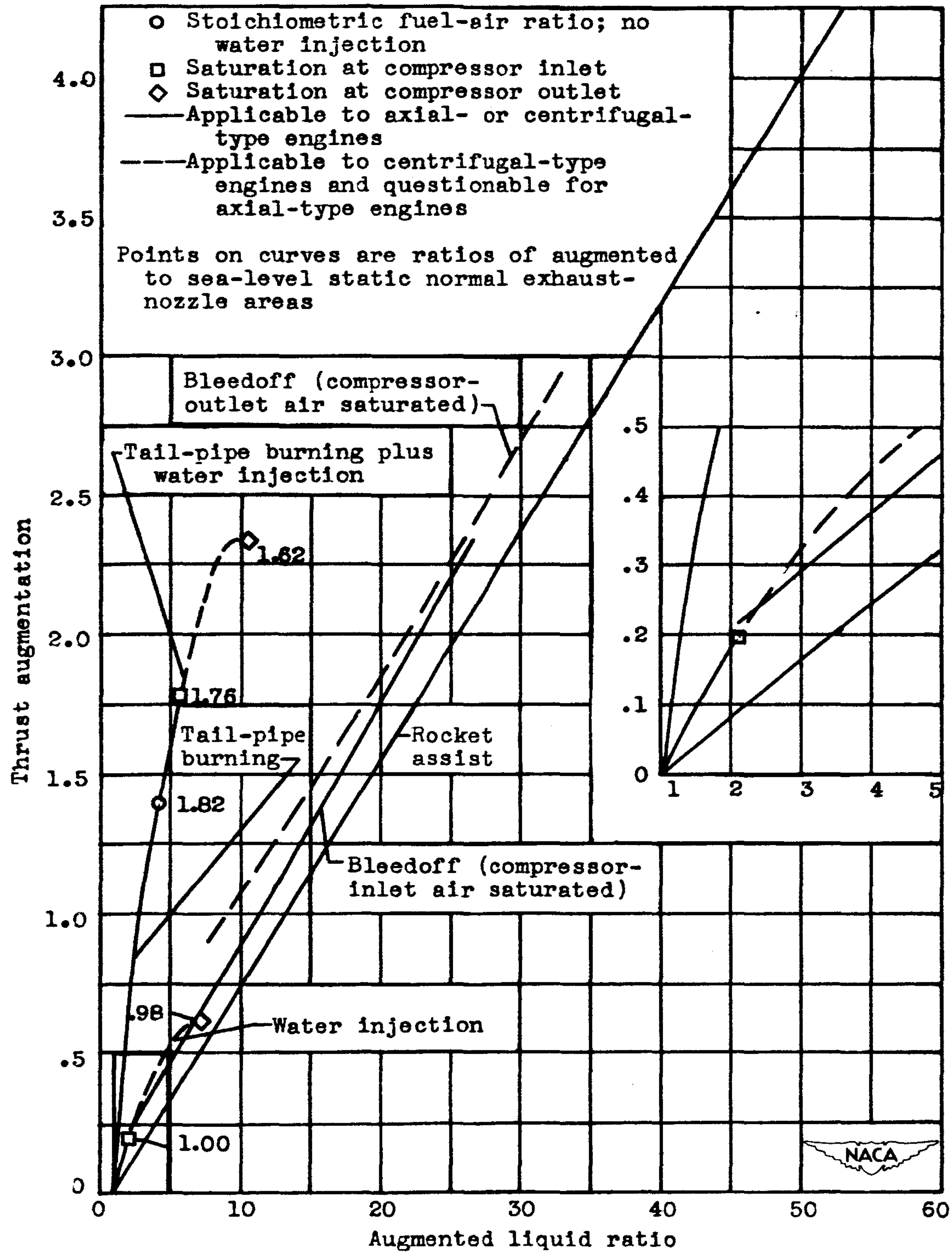
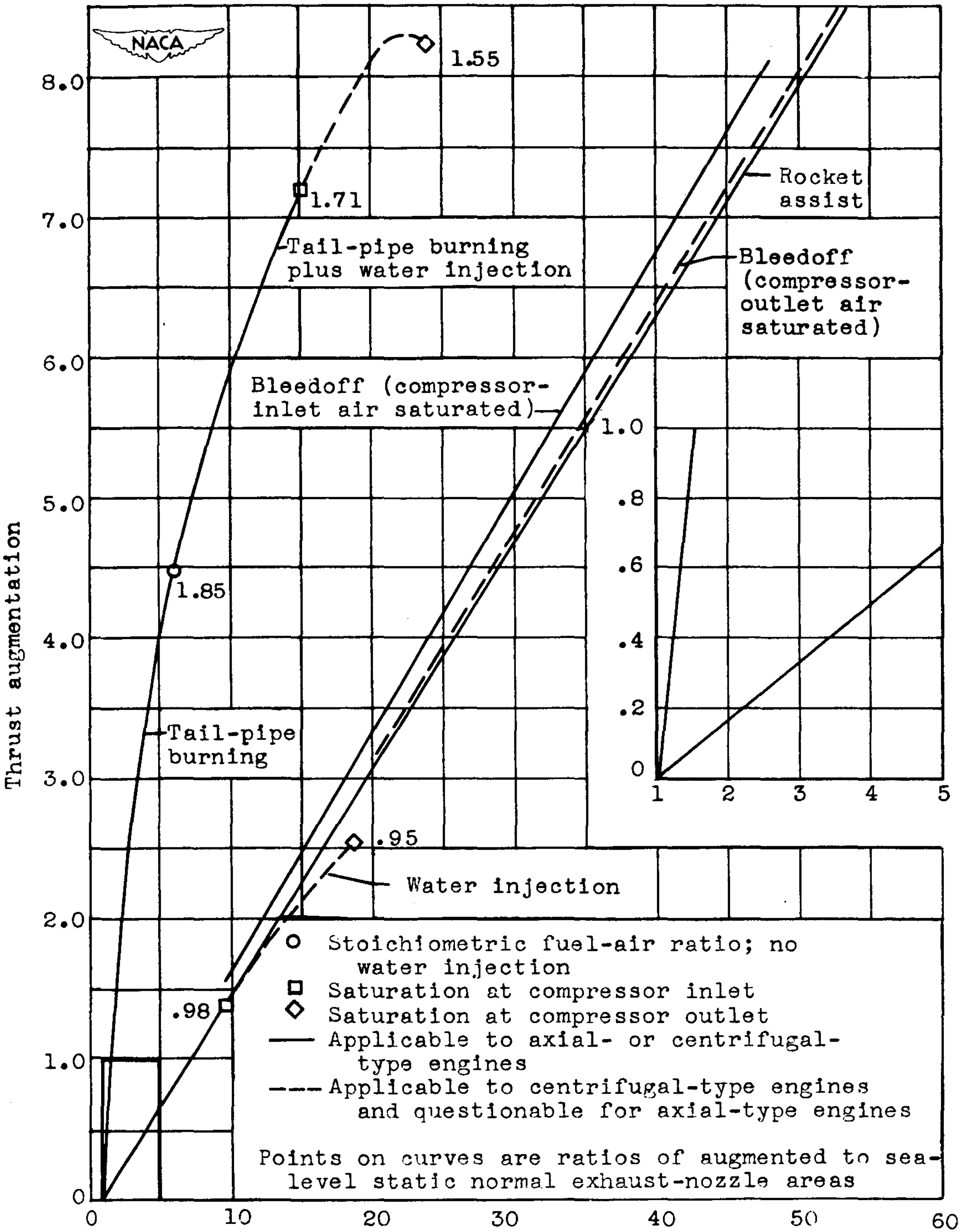


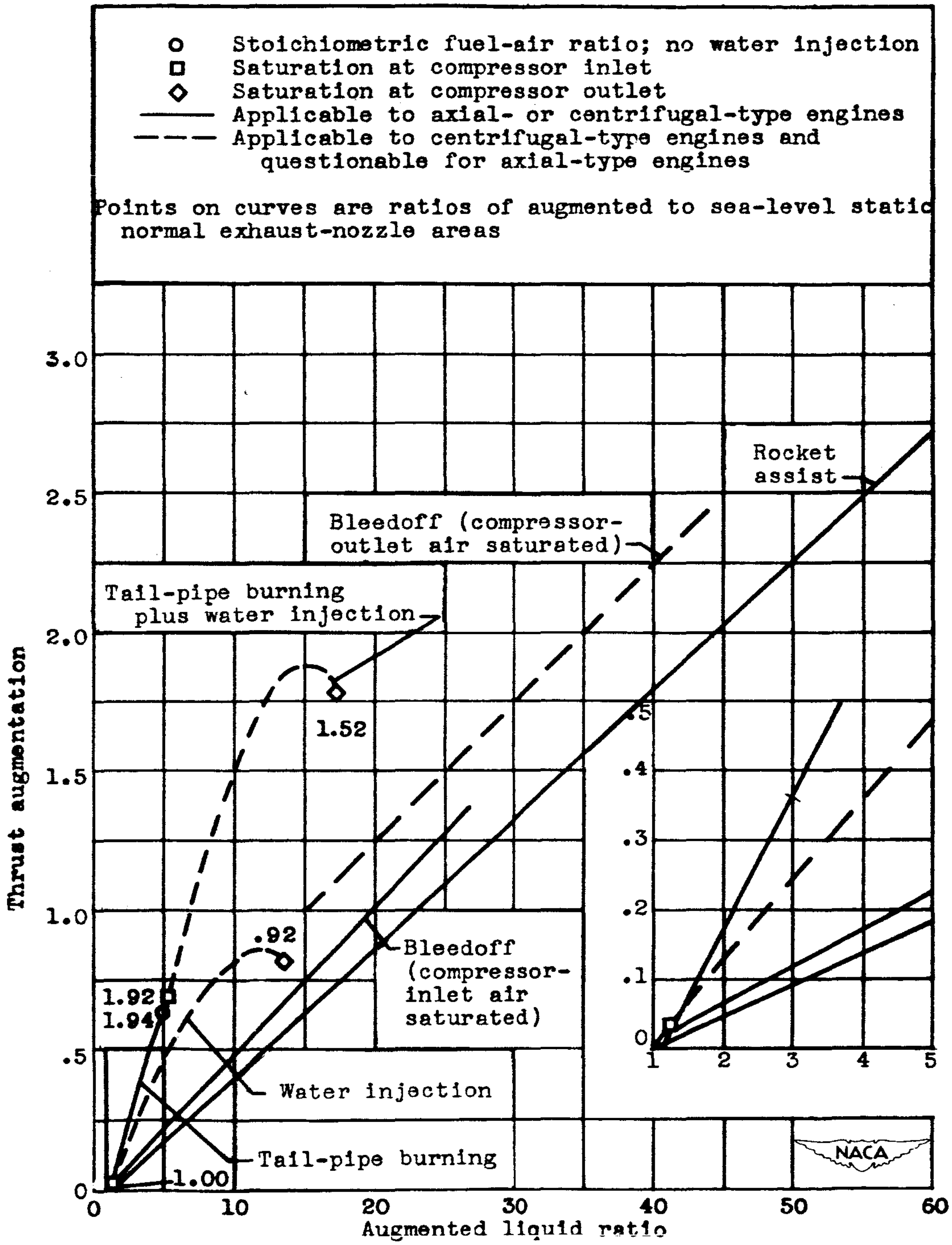
(e) Altitude, 35,332 feet; flight Mach number, 1.50.

Figure 2. - Continued. Thrust augmentation of turbojet engine with low-pressure-ratio compressor.



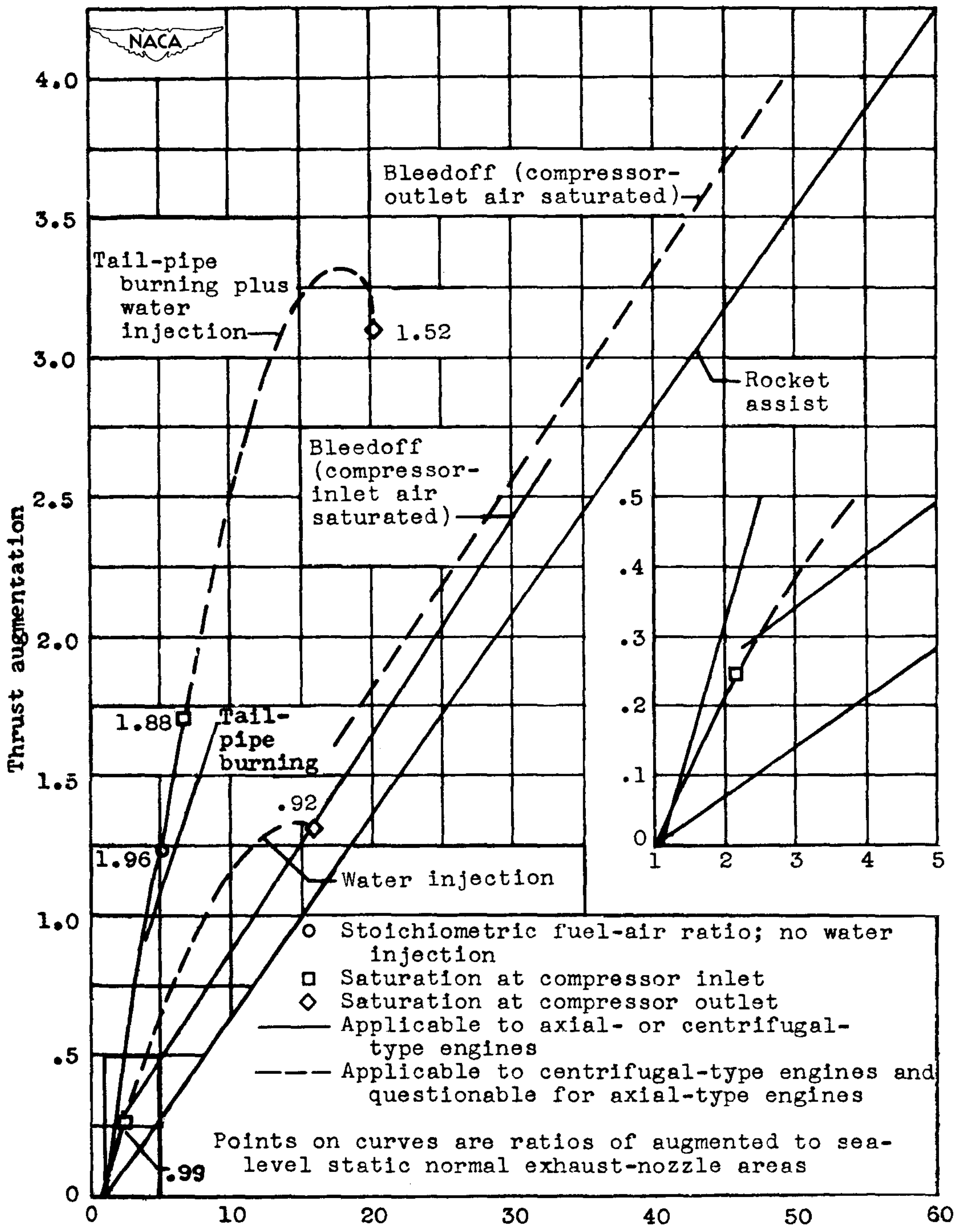
(f) Altitude, 35,332 feet; flight Mach number, 2.50.

Figure 2. - Concluded. Thrust augmentation of turbojet engine with low-pressure-ratio compressor.



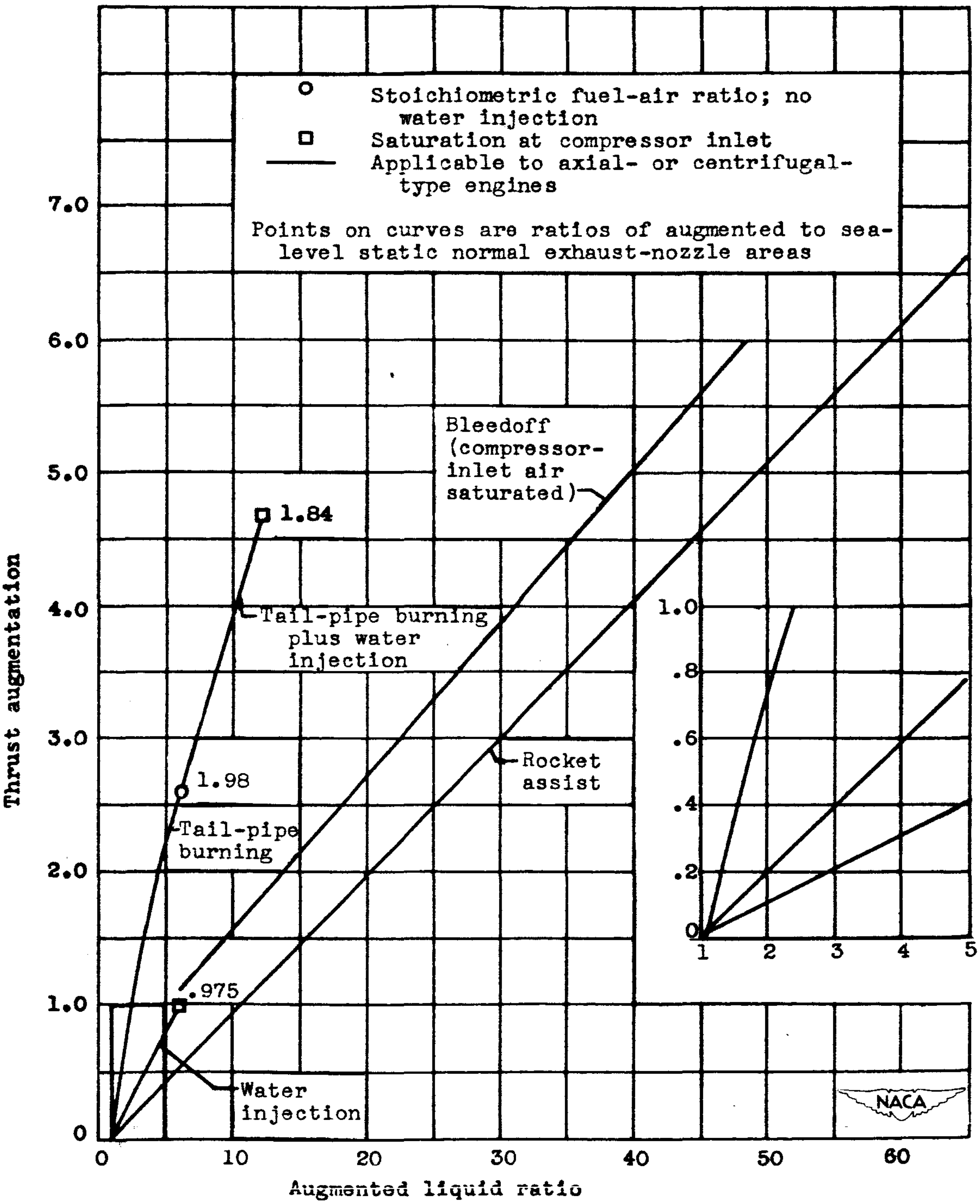
(a) Altitude, sea level; flight Mach number, 0.

Figure 3. - Thrust augmentation of turbojet engine with high-pressure-ratio compressor.



(b) Altitude, sea level; flight Mach number, 0.85.

Figure 3. - Continued. Thrust augmentation of turbojet engine with high-pressure-ratio compressor.



(c) Altitude, sea level; flight Mach number, 1.50.

Figure 3. - Continued. Thrust augmentation of turbojet engine with high-pressure-ratio compressor.

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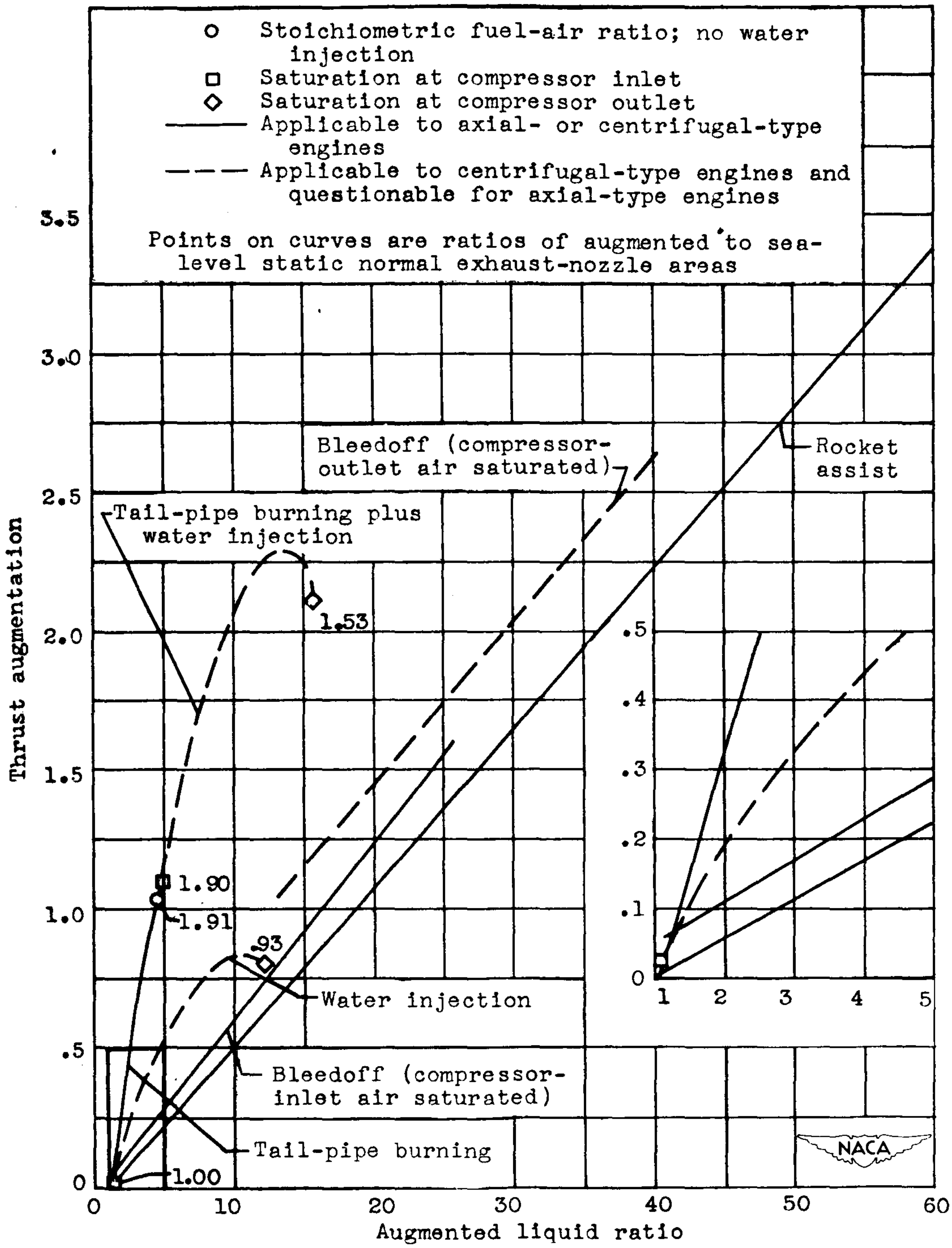

(d) Altitude, 35,332 feet; flight Mach number, 0.85.

Figure 3. - Continued. Thrust augmentation of turbojet engine with high-pressure-ratio compressor.

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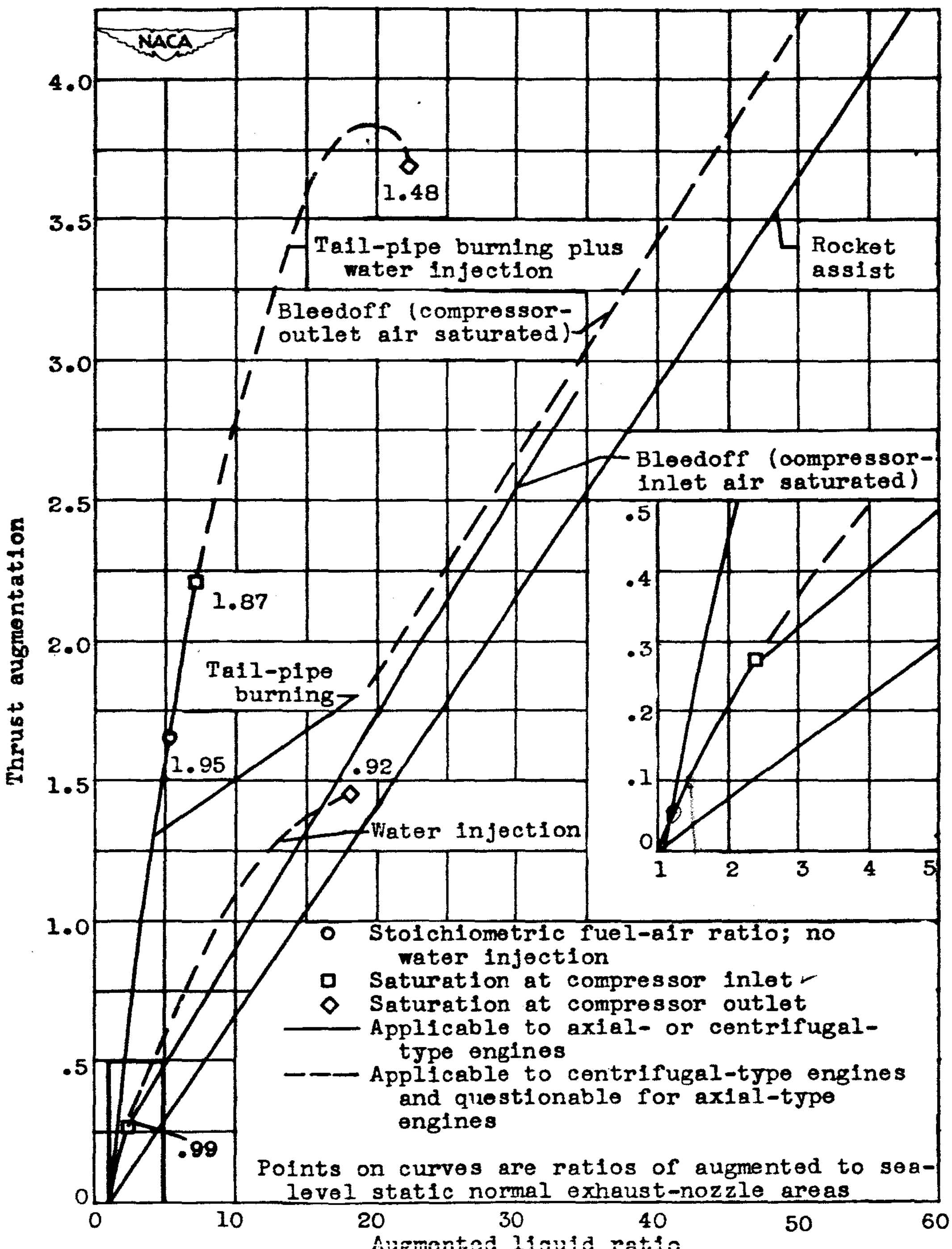

(e) Altitude, 35,332 feet; flight Mach number, 1.50.

Figure 3. - Concluded. Thrust augmentation of turbojet engine with high-pressure-ratio compressor.

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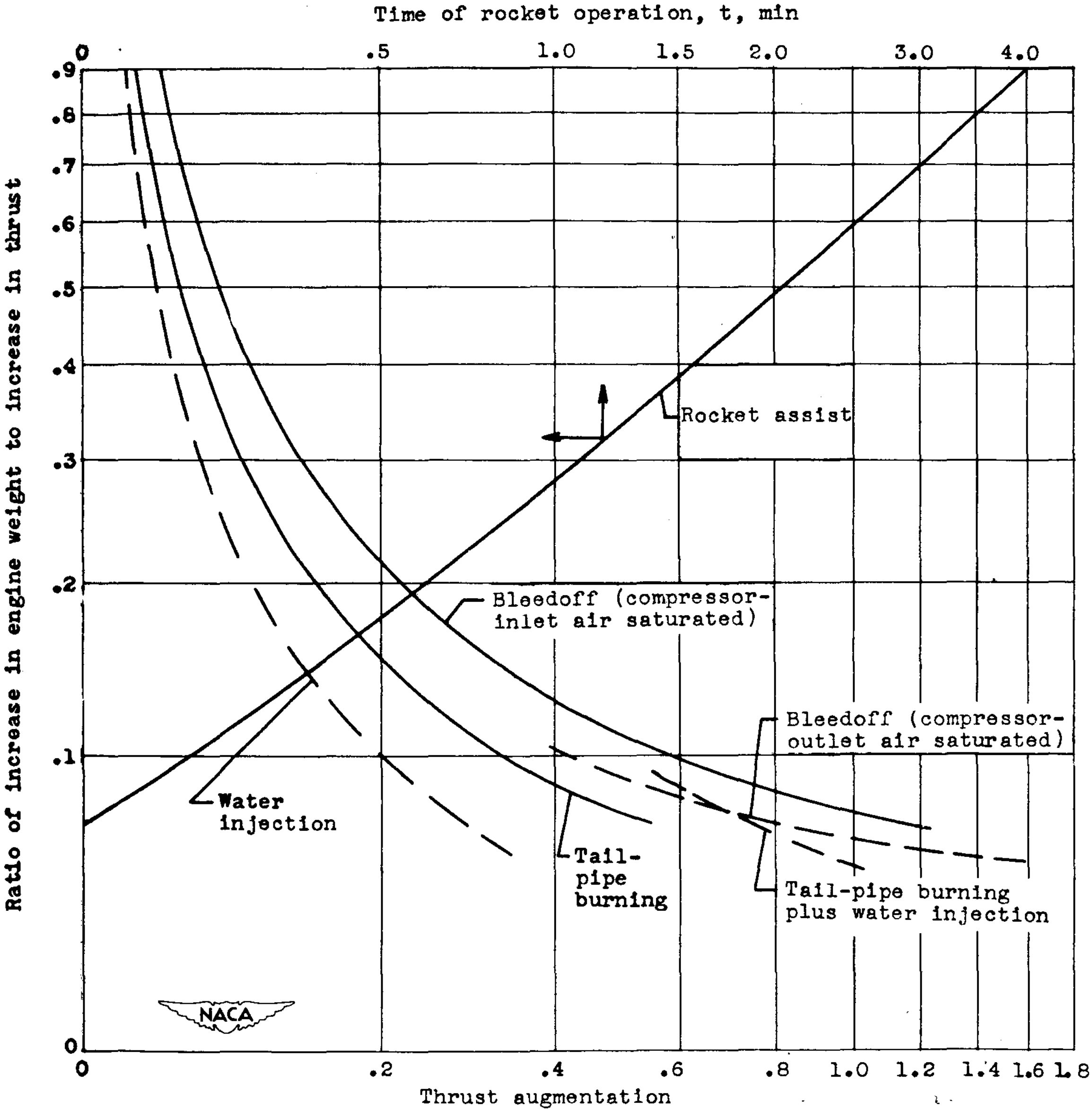

Figure 4. - Ratio of increase in engine weight to increase in engine sea-level static thrust.

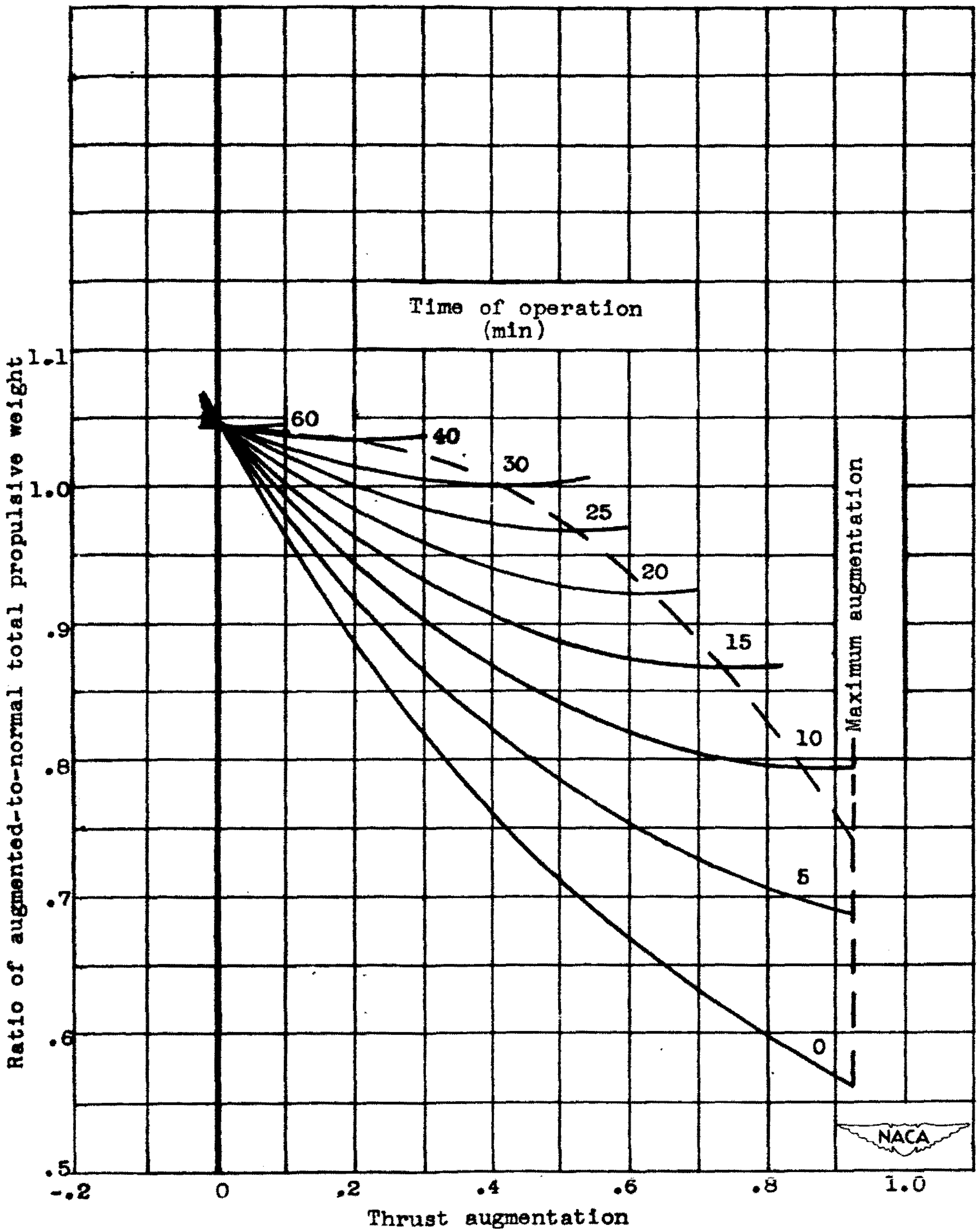

Figure 5. - Ratio of total propulsive weight (engine plus auxiliary equipment and fuel) of an engine augmented by tail-pipe burning to total propulsive weight (engine plus fuel) of the larger standard engine producing the same thrust for various operating times. Altitude, 35,332 feet; flight Mach number, 0.85; low-pressure-ratio compressor.

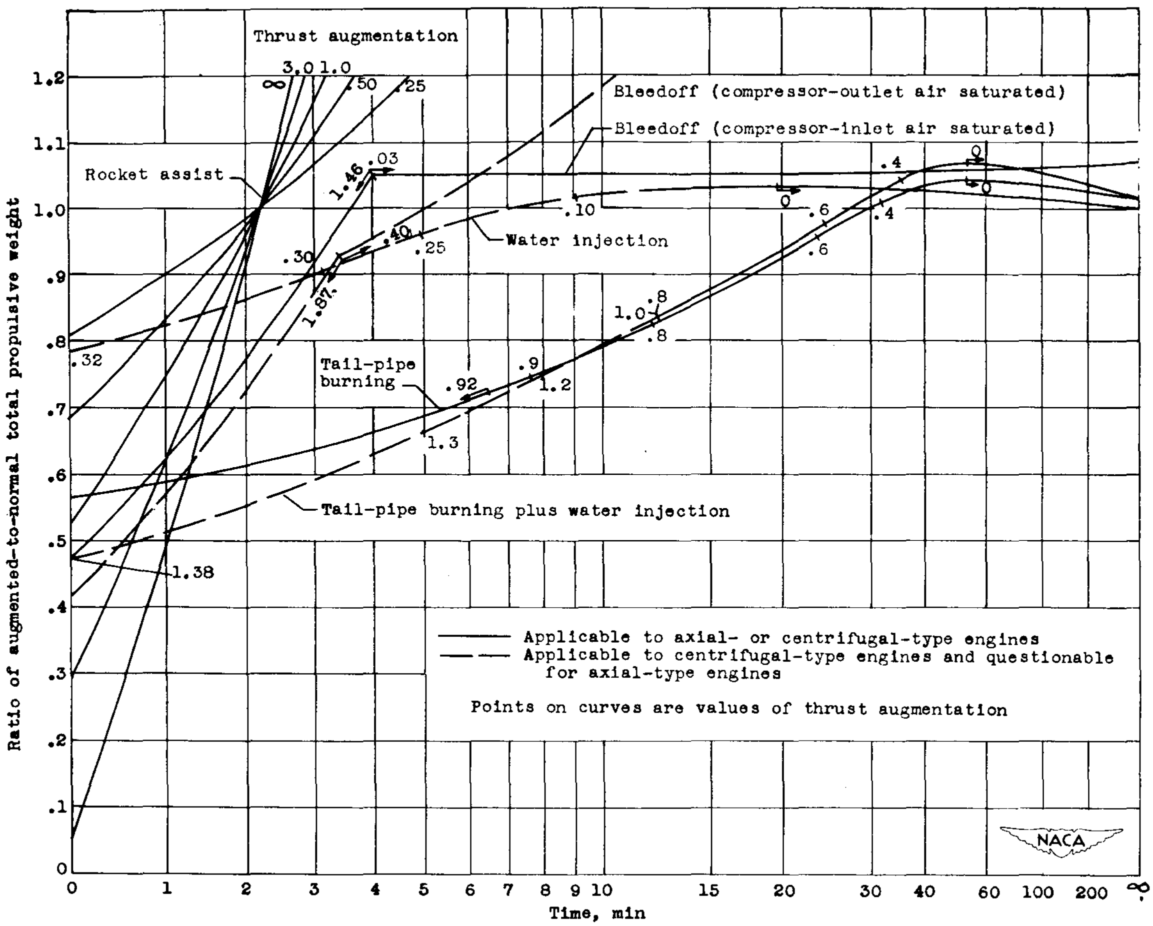

Figure 6. - Comparison of minimum ratio of total propulsive weight (engine plus auxiliary equipment, fuel, and auxiliary liquids) of an augmented engine to total propulsive weight (engine plus fuel) of a larger standard engine producing the same thrust for various operating times. Altitude, 35,332 feet; flight Mach number, 0.85; low-pressure-ratio compressor.