COPY NO.
RM No. E9B23

NACA RM No. E9B23

RESEARCH MEMORANDUM

EFFECT OF HOT-GAS BLEEDBACK ICE PREVENTION ON PERFORMANCE OF A TURBOJET ENGINE WITH FIXED-AREA TAIL-PIPE NOZZLE

By Robert O. Dietz, Jr. and Richard P. Krebs

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

May 16, 1949

NACA RM No. E9B23

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EFFECT OF HOT-GAS BLEEDBACK ICE PREVENTION ON PERFORMANCE OF A TURBOJET ENGINE WITH FIXED-AREA TAIL-PIPE NOZZLE

By Robert O. Dietz, Jr. and Richard P. Krebs

SUMMARY

The results of an analytical investigation showed that the inlet of a turbojet engine can be protected from ice accretions by bleeding hot gases from other locations withfn the engine to the inlet without undue loss in thrust. The bleedback required and the thrust losses entafled by such a process were calculated. The analysis was made for a turbojet engine operating at rated engine speed and sea-level-pressure, zero-flight-speed condftions. The ambient-air condftions of the investigation covered a range of temperatures from -40° to 38° F at liquid-water contents of 1.0 and 2.3 grams per cubic meter. Bleedback from the combustion chamber was preferable to tail-pipe bleedback because the pressure was greater, less bleedback was required, and smaller thrust losses resulted. The thrust available at take-off from en engine protected against icing conditions in temperatures as low as -40° F with liquid-water contents as high as 2.5 grams per cubic meter exceeded the thrust available from the same engine in an ambient-air temperature of 100° F.

INTRODUCTION

A satisfactory means of preventing ice formation at the inlet of a turbojet engine must be found before the turbojet-powered aircraft can be considered an all-weather airplane, One solution that has been advanced is the ducting of hot gases from either the combustion chamber or the tail pipe of the engine to the engine inlet. The gases mix with and sufficiently heat the air to eliminate ice formations or reduce them to a safe limit.

One phase of the hot-gas bleedback problem has been analytically investigated at the NACA Lewis laboratory. A companion experimental investigation is reported in reference 1. The bleedback required and the thrust losses entailed by such a process have been calculated for three different criterions for ice prevention. The analysis was made for a turbojet engine operating at rated engine speed and sea-level-pressure, zero-flight-speed conditions. The ambient-air conditions of the investigation covered a range of temperatures from -40° to 38° F at liquid-water contents of 1.0 and 2.5 grams per cubic meter. Both the combustion chamber and the tail pipe were considered as sources of the hot gas.

ANALYSIS

Ice formation is most likely to occur in the restricted passages of the engine inlet where the air velocity is highest. This maximum velocity was assumed to be in the compressor-inlet guide or turning vanes. Icing may be encountered with moist air at an ambient temperature greater than 32° F, when the increased velocity depresses the static temperature in the restricted passages, and water droplets may condense and freeze on the guide vanes.

Criterions for ice prevention. - Ice formations in the inlet of a turbojet engine may be prevented by heating the air until the temperatures of the guide vanes and the walls exceed 32° F. If the initial air temperature is low, the addition of heat may evaporate all the free water at a temperature below 32° F. Icing might therefore be avoided by heating the air until either the wall temperatures exceed 32° F or the dew point is exceeded.

A modification of the second alternative is to heat the air until the temperature in the bound&y layer exceeds the dew point. In such a case the temperature of the air in the center of the passage will be below the dew point and subfreezing droplets of water will be thrown into the boundary layer. If the evaporation rate exceeds the rate of water impingement, no ice till form.

Some doubt exists that heating the air until the temperature of the main stream or the boundary layer exceeds the dew point will always be effective, because the time available for heating the water droplets may be insufficient for complete evaporation. An experimental investigation reported in reference 2 shows that ice accretions form at temperatures above the dew point of the boundary layer.

Because of the sparse experimental evidence available as to the conditions under which inlet icing will occur, three analyses of the use of hot bleedback gases for ice prevention based on the following criterions have been made:

1094

A. The additionof sufficient heattothe inlet air to maintain the temperature of the boundary-layer air and the compressor-inlet turning-vane wall above freezing ($T_w = 32^\circ$ F)

B. The addition of sufficient heat to the Inlet air to raise the temperature of the boundary-layer air in the compressor-inlet turning vanes to the dew point (T_w = dew-point temperature)

C. The addition of sufficient heat to the inlet air to maintain the static temperature of the air stream in the compressor-inlet turning vanes at the dew point (t_s = dew-point temperature)

Sources of heat for ice prevention. - Hot gases extracted from various locations in the turbojet engine and bled back into the engine inlet serve as a source of heat, mixing with the inlet air and preventing ice accretions. Two bleedoff locations were investigated in the analysis: (1) combustion-chamber bleedoff upstream of the turbine nozzle, and (2) tail-pipe bleedoff downstream of the turbine outlet. The hot gases were assumed to be ducted from these two bleedoff locations to the front of the engine, where they were mixed with the inlet air through high-velocity jets. The efficacy of such a method of mixing hot and cold gases is illustrated in reference 2.

The experimental data for a typical turbojet engine (fig. 1) show the pressure ratio available to force the hot gases into the inlet air. At the combustion chamber the pressure is sufficient over a wide range of engine speeds to provide penetrating jets; whereas, sonic jet velocities, necessary for good mixing, cannot be obtained at any engine speed from tail-pipe bleedback. Cases bled from the turbine inlet have a higher heat content than those bled from the tail pipe. In order to supply a given amount of heat to the inlet air, less gas would therefore be needed from combustion-chamber bleedback than from tail-pipe bleedback.

Flight and engine operating conditions. - Flight conditions 'corresponding to sea-level pressure and zero ram-pressure ratio were chosen for this analysis. Air temperatures from -40° to 38° F with two liquid-water contents of 1.0 and 2.5 grams per cubic meter at the compressor-inlet guide vanes were considered. The flight conditions approximated flight attitudes in which icing is a serious problem, that is, take-off, climb, and letdown. The two liquid-water contents chosen are those listed by Lewis (reference 3) as maximums for long and short flight conditions, respectively, increased by 25 percent to cover the effect of scooping at the engine inlet.

The following engine operating conditions were assumed:

(1) Rated engine speed 1094

(2) Constant compressor and turbine efficiency

(3) Constant combustion-chamber pressure-loss ratio

(4) Constant-area tail-pipe nozzle

(5) Zero pressure losses in diffuser and tail pipe

(6) Momentum-pressure loss due to mixing of bleedback gases and air stream neglected

(7) Enthalpy rise across compressor equal to enthalpy drop across turbine

(8) Effect of fuel weight neglected

(9) Effect on specific heat of combustion products introduced at engine inlet neglected

St should be emphasized that the results presented are for a constant-area tail-pipe nozzle. A discussion of the effect of a variable-area nozzle is included in the following section.

The methods of calculation for the analysis are given in the appendix.

RESULTS

The results of the analysis are presented in terms of the bleedback requirements and the effect of bleedback on the engine thrust ratio. The discussion centers around the variation of these two factors with the ice-protection criterion, the liquid-water content, and the location from which hot gas is bled.

Bleedback requirements. - As a result of the high air velocity in the guide vanes, the wall temperatures are 6° cooler than the ambient air. Ice protection is therefore required at ambient-air temperatures below 38° F.

In figure 2 the amount of bleedback required for maintaining the wall temperature at freezing (criterion A), the well temperature at the dew point (criterion B), and the static-air temperature in the turning vanes at the dew point (criterion C) are compared at ambient-air temperatures between -40° and 38° F. The bleedback requirements from either the combustion chamber (fig. 2(a)) or the tail pipe (fig. 2(b)) are smallest for criterion B except at temperatures in the approximate range between 26° and 38° F. As previously pointed out, however, some doubt exists that bleedback according to criterion B is sufficient to prevent icing. The bleedback required to maintain the static temperature of air, initially containing 1.0 gram of free water per cubic meter, above the dew point (criterion C) is higher than that required for criterion A, except at temperatures below approximately -15° F. At lower temperatures, the bleedback requirements for the two criterions are approximately equal. When the initial liquid-water content is 2.5 grams per cubic meter, the bleedback requirements for criterion A are less than for criterion C at all temperatures investigated.

In view of the theoretical results just given and the limited experience reported in reference 2, it is tentatively concluded that hot-gas bleedback requirements should be based on maintaining the temperature of the coldest point on the turning vanes above freezing (criterion A),

At altitudes higher than sea level, assumed in the calculation of figure 2, the relation between criterions A and C will not be significantly changed.

Increasing the liquid-water content of the air increases the bleedback requirements, as shown in figure 2. In the case where the guide-vane walls are heated above the freezing point, the water content of the air has a relatively minor effect on bleedback requirements because the heat requirements are largely convective. At 0° F, increasing the liquid-water content from 1.0 to 2.5 grams per cubic meter increases the bleedback requirements from 0.028 to 0.031 (criterion A). For those cases in which the dew point is involved, considerable increase In bleedback is required with an increase in liquid-water content.

The bleedback requirements according to any of the three criterions are smaller from the combustion chamber than from the tail pipe (fig. 3), as was expected. At an ambient-air temperature of 0° F and a liquid-water content of 1.0 gram per cubic meter, the bleedbacks from combustion chamber and tail pipe required to maintain a wall temperature of 32° F (criterion A) were 0.028 and 0.040, respectively.

Engine performance. - Bleedhack ice prevention decreases thrust in two ways. The compressor-inlet temperature is raised and gas is bled from the cycle. The effects of both of these factors on jet thrust are shown in figure 4, where the compressor-inlet temperature and the gas bled from the engine have been varied independently and the tail-pipe nozzle area and the engine speed have been held fixed.

Bleeding air from the tail pipe produces a much greater thrust loss than bleeding from the combustion chamber. This difference results principally from a marked decrease in turbine-outlet temperature when gas is bled from the tail pipe; whereas bleeding from the combustion chamber *results* in an increase in turbine-outlet temperature. Calculation and experiment (reference 2, fig. 10) have shown that the momentum-pressure loss due to the mixing of the hot jets and the air stream results in less than a 0.02 decrease in the total-pressure ratio across the diffuser for bleedbacks up to 0.05. From reference 4 it was computed that such a pressure loss would reduce the jet thrust about 0.03.

Thrust losses accompanying ice protection are presented in figure 5 *as* a thrust ratio, that is, the ratio of engine thrust with bleedback to the thrust of the engine without bleedback, but operating at a compressor-inlet temperature equal to the ambient-air temperature. Figure 5 was prepared from figure 4 in conjunction with figure 2. The qualitative trends of the thrust-ratio curves may be predictedfrom the bleedback curves of figure 2. Criterion A gives smaller thrust loases than criterion C at all temperatures above -15° F, and smaller losses than criterion B at temperatures above approximately 30° F.

The effect of changes in liquid-water content on thrust ratio is also illustrated in figure 5. An increase of liquid-water content from 1.0 to 2.5 grams per cubic meter does not reduce the thrust ratio more than 0.05 for any of the criterions if' combustion-chamber bleedback is used. The change in bleedback requirements with water content is least for criterion A and the change in thrust ratio is about 0.005.

A comparison of the thrust losses with combustion-chamber and tail-pipe bleedbacks is given in figure 6. At an ambient-air temperature of 0° F and a liquid-water content of 1.0 gram per cubic meter, heating the inlet air until the wall temperature reaches 32° F results in a 13-percent thrust loss with combustion-chamber bleedback and a 23-percent thrust loss with tail-pipe bleedback.

Effect of nozzle area. - The comparison between the two bleedback systems shown in figure 6 would be somewhat different if a variable-area nozzle were used. When gas is bled from the combustion chamber of an engine with a fixed tail-pipe nozzle area, the turbine-inlet temperature must be increased to maintain constant engine speed. Because the compressor-inlet temperature is

1094

lower than that with which the limiting turbine-inlet temperature is realized (59° F), however-, bleedback is possible without exceeding the turbine-inlet temperature limit. With a compressor-inlet temperature of 38° F, a bleedoff of 0.05 can be tolerated with a fixed-area nozzle.

Tail-pip8 bleedoff lowers the turbine-inlet temperature even though engine speed is maintained. Replacement Of 8 variable-area nozzle for the fixed-area nozzle therefore yields higher temperatures and higher pressures throughout the engine for either bleedoff location. Less bleedback will be required for a given heat requirement 8t the inlet. With 8 fixed-area nozzle, however, the turbine-inlet temperature is far lower with tail-pipe bleedoff than with combustion-chamber bleedoff and much greater recoveries in thrust can be realized with 8 variable-area nozzle for tail-pipe bleedoff than for combustion-chamber bleedoff. With a variable-area nozzle, tail-pipe bleedoff will appear in a much more favorable light compared with combustion-chamber bleedoff so far as the thrust ratio is concerned.

Mixing efficiency. - Because it is impossible to have a uniform temperature profile across the engine inlet when 8 system of high-velocity jets is used to introduce the hot gases into the inlet, some areas of the engine inlet must be heated to a temperature above that computed for a given ice-protection criterion so that all areas are above the minimum allowable temperature. The data plotted in figure 7 were computed with the assumption of a 20-percent-excess hot-gas enthalpy to be required to protect all areas of the inlet. This value corresponds to the temperature deviations reported in reference 2. The data presented are for conditions corresponding to the heating of the wall to 32° F with combustion-chamber bleedback. The liquid-water content was 1.0 gram per cubic meter. The 20-percent additional enthalpy taken from the combustion chamber and put into the inlet lowers the thrust ratio 6 percent at an ambient-air temperature of -40° F. The loss ill thrust ratio decreases as the ambient-air temperature increases and becomes zero at 38° F. At 0° F the thrust ratio is 0.84.

Seriousness of thrust losses. - Flight in icing conditions is seldom of long duration (reference 3) and the seriousness of thrust losses arising from an ice-protection system should be considered in the light of the loss in maximum thrust that can be tolerated for a short period of time. The thrust loss may be no greater then that which would exist because of a change in ambient-air temperature, a factor over which the pilot has no control. For example, at take-off, the thrust loss of an engine protected according to any one of the criterions discussed herein would be less than that experienced by the engine taking off on a hot summer day at an ambient-air temperature of 100° F. The ratio of jet thrust for an ice-protected engine to the thrust of the engine at an ambient-air temperature of 100° F is plotted against ambient-air temperature of the icing condition in figure 8. The data are calculated for .a liquid-water content of 1.0 gram per cubic meter. The ratio is greater than unity for all ambient-air temperatures and for all ice-protection criterions. Further calculations show that the thrust ratio remains greater than 1.00 for liquid-water contents up to 2.5 grams per cubic meter.

SUMMARY OF RESULTS

An analytical investigation Of the thrust losses accompanying the bleedback of hot engine gases to the engine inlet for protection from ice formations gave the following results. These results were based on the use of an engine with a fixed tail-pipe area, running at constant rotational speed, and operating at sea-level pressure and zero flight speed.

1. Bleedback from the combustion chamber was superior to bleedback from the tail pip8 because of: (a) higher pressures available for mixing hot gas and inlet air, (b) lower thrust losses, and (c) smaller amounts of bleedback required to afford the same icing protection.

2. A thrust loss of 13 percent was estimated for ice protection with combustion-chamber bleedback at an ambient-air temperature of 0° F and a liquid-water content of 1.0 gram per cubic meter. Protection was afforded by heating the inlet guide vanes to 32° F. The addition Of 20 percent more enthalpy from the hot gases to take care of poor mixing entailed another J-percent loss in thrust. An increase in liquid-water content from 1.0 to 2.5 grams per cubic meter decreased the thrust ratio about 0.005 for the conditions given.

3. The thrust available at take-off for an engine protected against inlet icing conditions with liquid-water contents as high as 2.5 grams per cubic meter and temperatures as low as -40° F was greater than the thrust available on 8 hot day at an ambient-air temperature of 100° F.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

APPENDIX - METHODS OF CALCULATION

Symbols

The following symbols are used in the calculations:

A	area, sq ft
c_p	specific heat at constant pressure, Btu/(lb)(°R)
F_j	jet thrust, lb
g	acceleration due to gravity, 32.2 ft/sec^2
h	specific enthalpy, Btu/lb
J	mechanical equivalent of heat, 778 ft-lb/Btu
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft absolute
R	gas constant, 53.4 ft-lb/(lb)(°R)
T	total temperature, °R
t	static temperature, °R
V	velocity, ft/sec
W_g	gas bled off, lb/sec
W_i	inlet air flow, lb/sec
γ	ratio of specific heats at constant pressure and constant volume
η	efficiency
ρ	density, lb/cu ft

Subscripts:

0	ambient conditions
2	compressor inlet

3 compressor outlet

4 turbine inlet

5 tail-pipe-nozzle outlet

C compressor

S stream

t turbine

w wall

Analysis

The analysis was conducted in accordance with the assumptions listed in the body of the report. Efficiencies assigned to the compressor and the turbine were 0.85 and 0.80, respectively. The total-pressure ratio across the combustion chamber was assumed as 0.96. Air flow at various engine-inlet temperatures was taken from experimental data for an engine having characteristics similar to those assumed for the analysis. An axial-flow-compressor characteristic was assumed in which no change of air flow accompanied a change in compressor pressure ratio at a fixed engine-inlet air temperature and 8 fixed engine speed.

The velocity in the turning vanes was assumed. to be 700 feet per second. The dynamic enthalpy is given by

$$\frac{V^2}{2gJ} = \frac{700 \times 700}{2 \times 32.2 \times 778} = 9.8 \text{ Btu}$$

The kinetic enthalpy on the turning-vane walls was equal to the total enthalpy decreased by 9.8 X 0.15, or 1.47 Btu. The relation between enthalpies and temperatures was found by use of reference 5. A total temperature of 38° F was necessary to maintain a wall temperature of 32° F.

General procedure. - The analysis was based on the assumption that the gases bled from the combustion chamber or the tail pipe were ejected from the engine at the location in question. The effect of injecting the hot gases into the engine inlet was affected by the assumption of various inlet-air temperatures.

Critical flow was assumed through the turbine nozzle and the corrected gas flow at the turbine inlet was assumed constant. For each bleedoff, calculations were made at various assumed turbine-inlet temperatures to determine temperatures and pressures throughout the engine and the corresponding value of tail-pfpe-nozzle area. The turbine-inlet temperature corresponding to the fixed-area tail-pipe nozzle was then determined. Coincident values of tail-pipe pressure and temperature were used in calculating the jet thrust.

Combustion-chamber bleedoff. - Details of the calculation for combustion-chamber bleedoff follow. Critical flow in the turbine nozzle was expressed by

$$\frac{W_1\sqrt{T_4\gamma_4}}{\gamma_4 P_4} = \text{constant} \tag{1}$$

The constant *0.334* was experimentally determined from an engine having characteristics similar to those used for the analysis. The air flow was determined from the corrected engine speed corresponding to the engine-inlet air temperature. A series of turbine-inlet temperatures was assumed. For each temperature the turbine-inlet pressure Was calculated from

$$P_4 = \frac{W_1\sqrt{T_4\gamma_4}}{\gamma_4\, 0.334} \tag{2}$$

The compressor-outlet pressure Was calculated by assuming a C-percent loss in total pressure across the combustion chamber.

$$P_3 = \frac{P_4}{0.96} \tag{3}$$

Turbine-outlet pressure P_5 or tail-pipe-nozzle pressure was calculated from the following equation:

$$c_{p,t}T_4\left[1-\left(\frac{P_5}{P_4}\right)^{\frac{\gamma_t-1}{\gamma_t}}\right]\eta_t = \frac{c_{p,c}T_2\left(1+\frac{W_g}{W_1}\right)\left[\left(\frac{P_3}{P_2}\right)^{\frac{\gamma_c-1}{\gamma_c}}-1\right]}{\eta_c} \tag{4}$$

which is the energy balance between th8 compressor and the turbine if the weight of fuel added is neglected. Manipulating the equationto obtain P_5 gives

1094

$$p_5 = p_4 \left\{ 1 - \frac{c_{p,c} T_2 \left(1 + \frac{W_g}{W_i}\right) \left[\left(\frac{P_3}{P_2}\right)^{\frac{\gamma_c - 1}{\gamma_c}} - 1 \right]}{\eta_c \eta_t c_{p,t} T_4} \right\}^{\frac{\gamma_t}{\gamma_t - 1}} \tag{5}$$

Static pressure at the tail-pipe-nozzle outlet p_5 was equal to an ambient-air pressure of 2116 pounds per square foot, or the total pressure at the tail-pipe-nozzle outlet divided by the critical pressure ratio, depending on the existence of subsonic or sonic velocity in the nozzle. The static pressure with subsonic velocity in the tail-pipe nozzle was

$$p_5 = 2116 \tag{6a}$$

or with sonic velocity in the tail-pipe nozzle

$$p_5 = \frac{P_5}{\left(\frac{\gamma_5 + 1}{2}\right)^{\frac{\gamma_5}{\gamma_5 - 1}}} \tag{6b}$$

Total temperature in the tail pipe was calculated by subtracting the temperature drop across the turbine from the assumed turbine-inlet temperature. The temperature drop across the turbine was

$$\Delta T_t = \frac{c_{p,c}}{\eta_c c_{p,t}} T_2 \left(1 + \frac{W_g}{W_i}\right) \left[\left(\frac{P_3}{P_2}\right)^{\frac{\gamma_c - 1}{\gamma_c}} - 1 \right] \tag{7}$$

and the temperature in the tail pipe was found by

$$T_5 = T_4 - \Delta T_t \tag{8}$$

1094

Static temperature at the tail-pipe-nozzle outlet was obtained from the adiabatic relation

$$t_5 = T_5 \left(\frac{p_5}{P_5}\right)^{\frac{\gamma_5-1}{\gamma_5}} \tag{9}$$

The area of the tail-pipe nozzle was determined by use of the following equation for the continuity of flow:

$$A_5 = \frac{W_i}{\rho_5 V_5} = \frac{W_i t_5}{p_5\sqrt{c_{p,5}(T_5-t_5)}}\,\frac{R}{\sqrt{2Jg}} \tag{10}$$

The calculated values of tail-pipe-nozzle-outlet area were plotted against turbine-inlet temperature for one value of bleedoff. From this plot the temperature corresponding to the assumed tail-pipe-nozzle-outlet area of 1.42 square feet was determined. From this value of T_4, corresponding values of P_5, p_5, and T_5 were found and used to calculate the jet thrust of the engine with the equation

$$F_j = \frac{W_i}{g}\sqrt{2Jgc_{p,5}(T_5-t_5)} \tag{11}$$

This process was repeated for various amounts of bleedoff over a range of engine-inlet air temperatures. A plot of the variation of jet thrust with air temperatures for various amounts of bleedoff was constructed from the data (fig. 4).

Tail-pipe bleedoff. - Equations similar to those for combustion-chamber bleedoff were used to compute engine performance with tail-pipe bleedoff, with the exception that in equations (1) and (2) the air flow Wi must be multiplied by $\left(1 + \frac{W_g}{W_i}\right)$ and the factor $\left(1 + \frac{W_g}{W_i}\right)$ must be eliminated from equations (4), (5), and (7).

Mollier diagram for water-air mixtures. - A Mollier diagram for water-air mixtures (reference 5) was used to calculate the heat to be added to the engine-inlet air to satisfy the various ice-prevention conditions. The compressor-inlet air temperature after the heat was added to the inlet air was also obtained from the Mollier diagram. With the amount of heat required at the engine inlet known, the amount of bleedback from either bleedoff station was calculated from

$$\frac{W_g}{W_i} = \frac{h_2-h_0}{h_4-h_2} \qquad (12a)$$

for combustion chamber bleedoff or

$$\frac{W_g}{W_i} = \frac{h_2-h_0}{h_5-h_2} \qquad (12b)$$

for tail-pip8 bleedoff. Results of these calculations are plotted in figure 2.

Thrust losses. - Values shown in figures 2(a) and 4(a) were used to calculate the thrust losses caused by combustion-chamber bleedback ice prevention. For example, at an ambient-air temperature of 20° F and a liquid-water content of 1.0 gram per cubic meter, 0.015 bleedback from the combustion chamber was mixed with the inlet air to raise the total temperature at the engine inlet to 38° F (T_w = 32° F). Normal jet thrust of the engine (4340 lb) was obtained from figure 4 for zero bleedoff and a temperature of 20° F. Jet thrust of the engine with combustion-chamber bleedback (4080 lb) was obtained from figure 4(a) for 0.025 bleedoff and a temperature of 38° F. The ratio of the jet thrust with bleedback to the normal jet thrust was 4080/4340 = 0.94 (fig. 5(a)).

A similar method using figures 2(b) and 4(b) was used to determine the thrust ratio for tail-pipe-bleedback ice prevention.

REFERENCES

1. Fleming, William A., and Saari, Martin J.: Inlet Icing and Effectiveness of Hot-Gas Bleedback for Ice Protection of Turbojet Engine. NACA RM No. E8J25c, 1948.

2. Callaghan, Edmund E., Ruggeri, Robert S., and Krebs, Richard P.: Experimental Investigation of Hot-Gas Bleedback for Ice Protection of Turbojet Engines. I - Nacelle with Offset Air Inlet. NACA RM No. E8D13, 1948.

3. Lewis, William: A Flight Investigation of the Meteorological Condition6 Conducive to the Formation Of Ice on Airplanes. NACA TN No. 1393, 1947.

4. Hanson, Frederick H., Jr., and Mossman, Emmet A.: Effect of Pressure Recovery on the Performance of a Jet-Propelled Airplane. NACA TN No. 1695, 1948.

5. Hensley, Reece V.: Mollier Diagram% for Air Saturated with Water Vapor at Low Temperatures. NACA TN No. 1715, 1948.

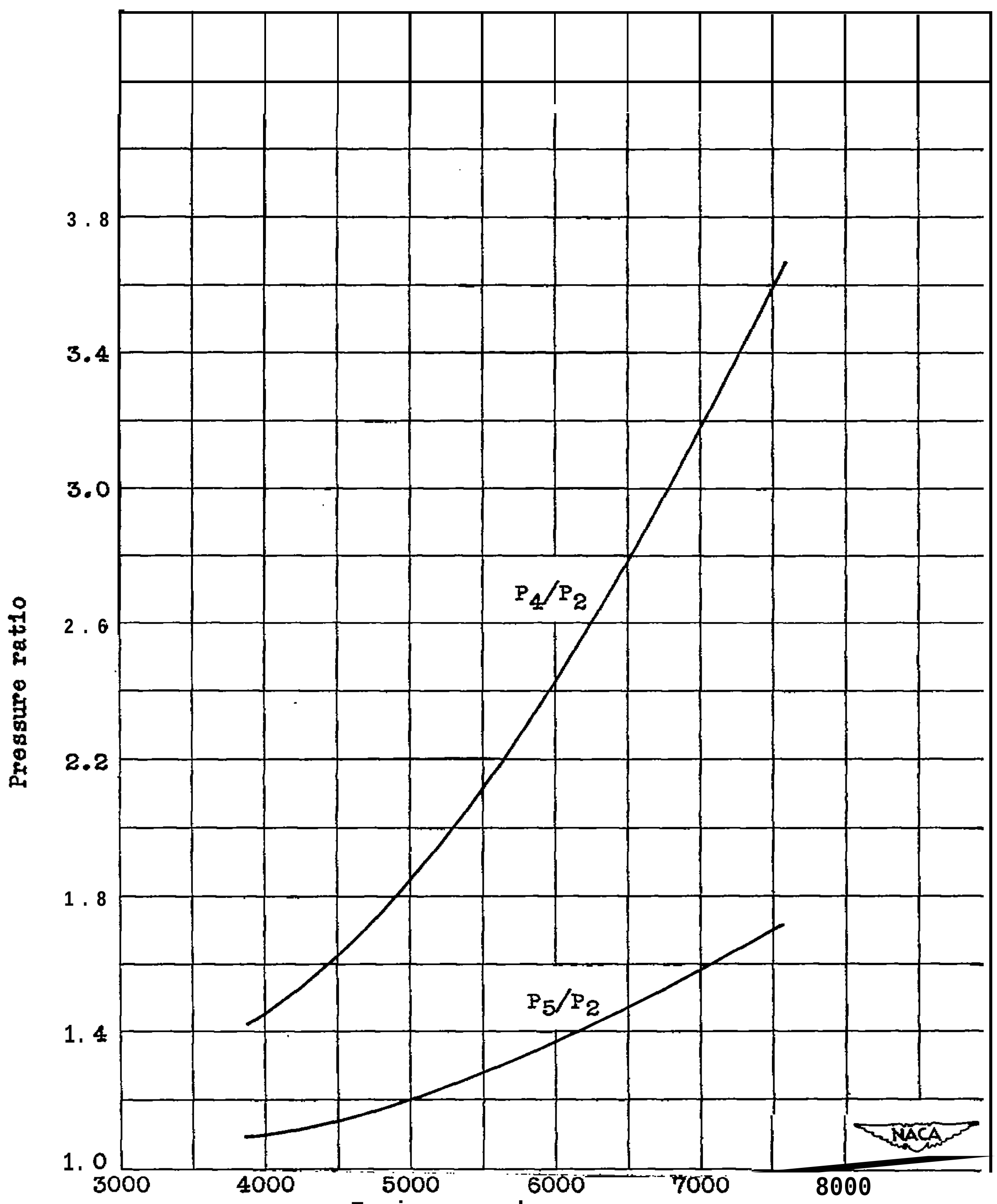
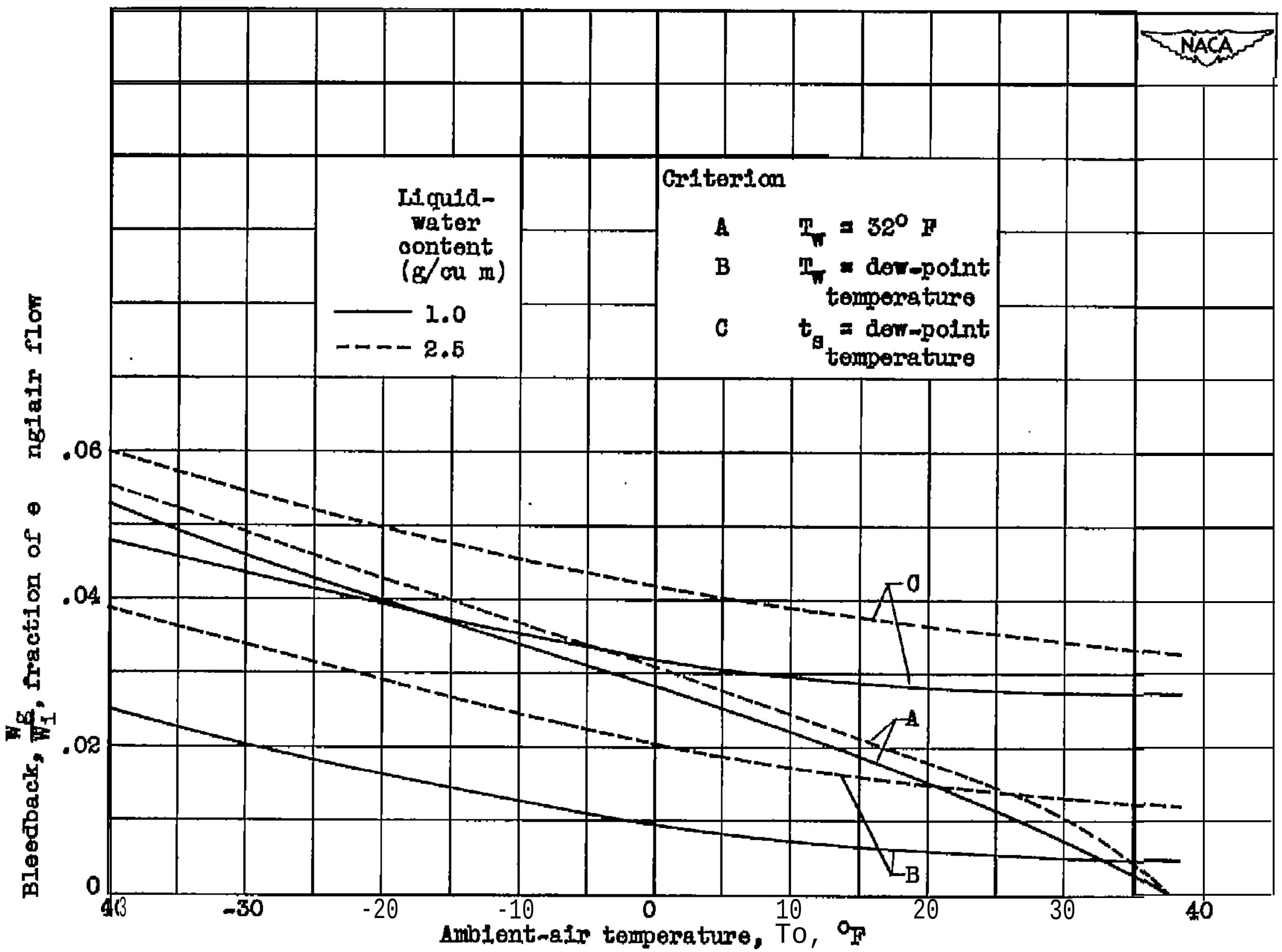
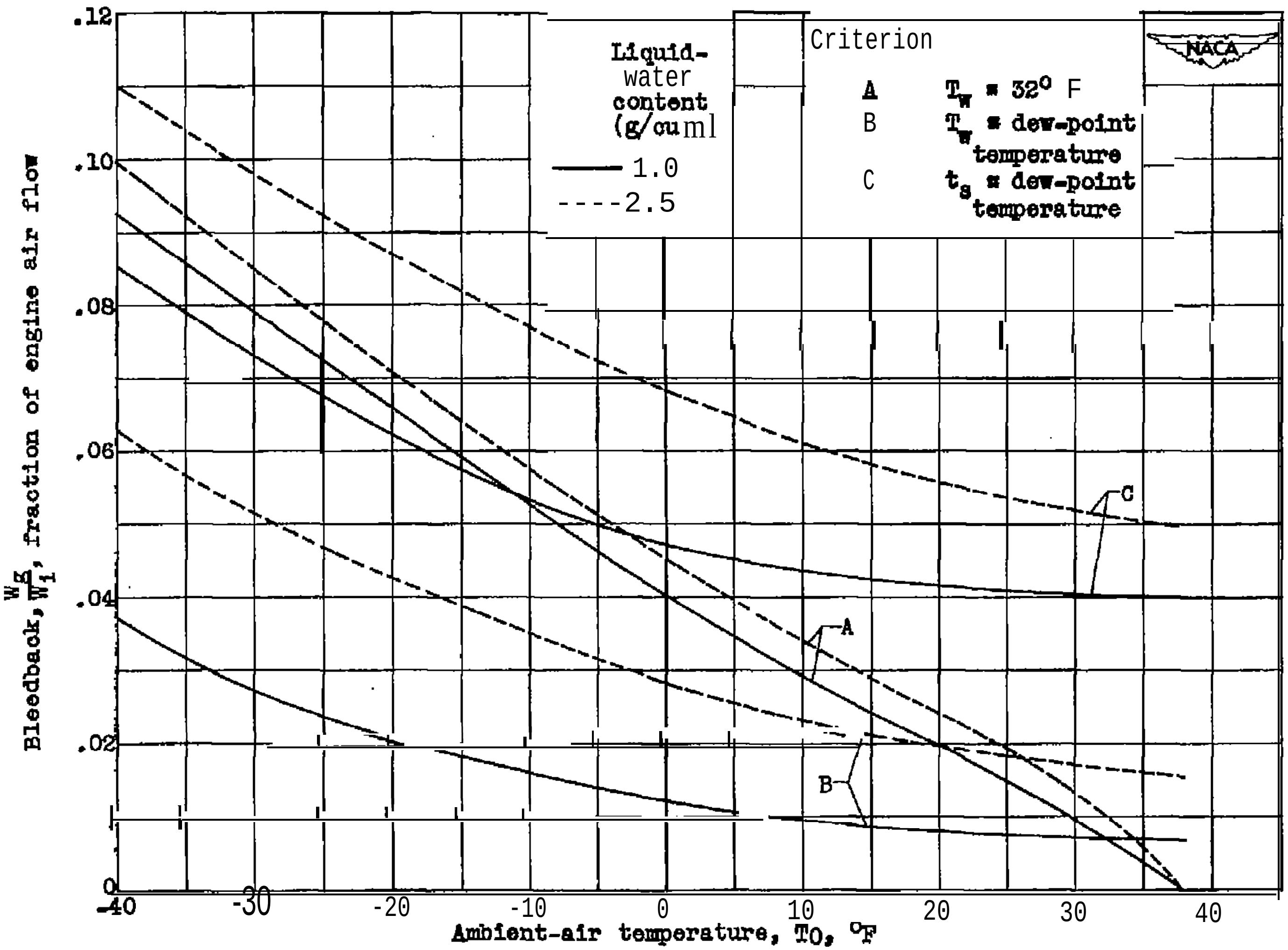


Figure 1. - Variation of ratio of combustion-chamber-outlet total pressure to compressor-inlet total pressure P_4/P_2 and ratio of tail-pipe total. pressure to compressor-inlet total pressure P_5/P_2 with engine speed for turbojet engine.



(a) Combustion-chamber bleedback.

Figure 2. - Effect of liquid-water content and ambient-air temperature on amount of hot gas bled back for ice prevention in turbojet engine. Fixed-area tail-pipe nozzle; constant engine speed.



(b) Tail-pipe bleedback.

Figure 2. - Concluded. Effect of liquid-water content and ambient-air temperature on amount of hot gas bled back for ice prevention in turbojet engine. Fixed-area tail-pipe nozzle; constant engine speed.

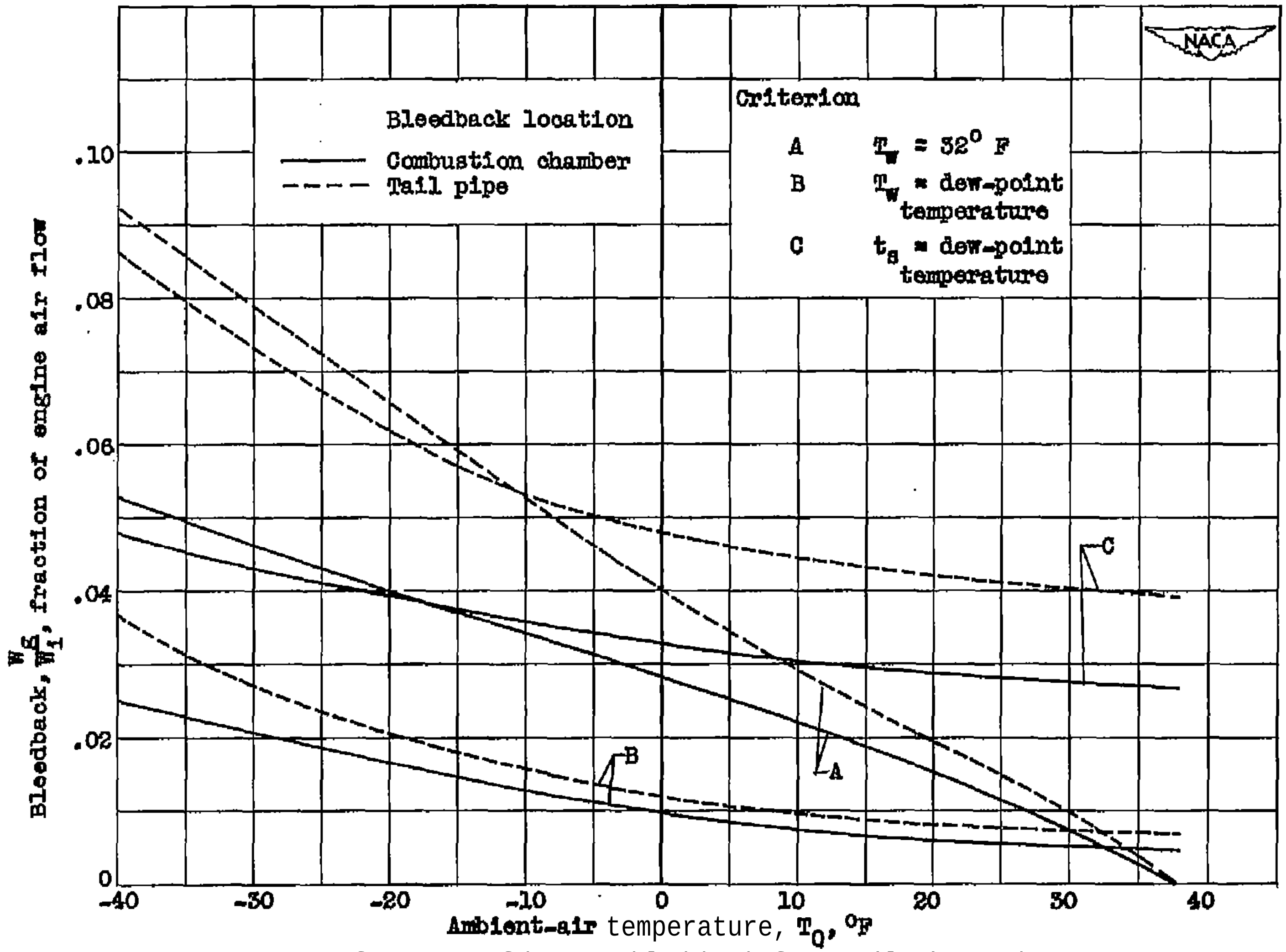
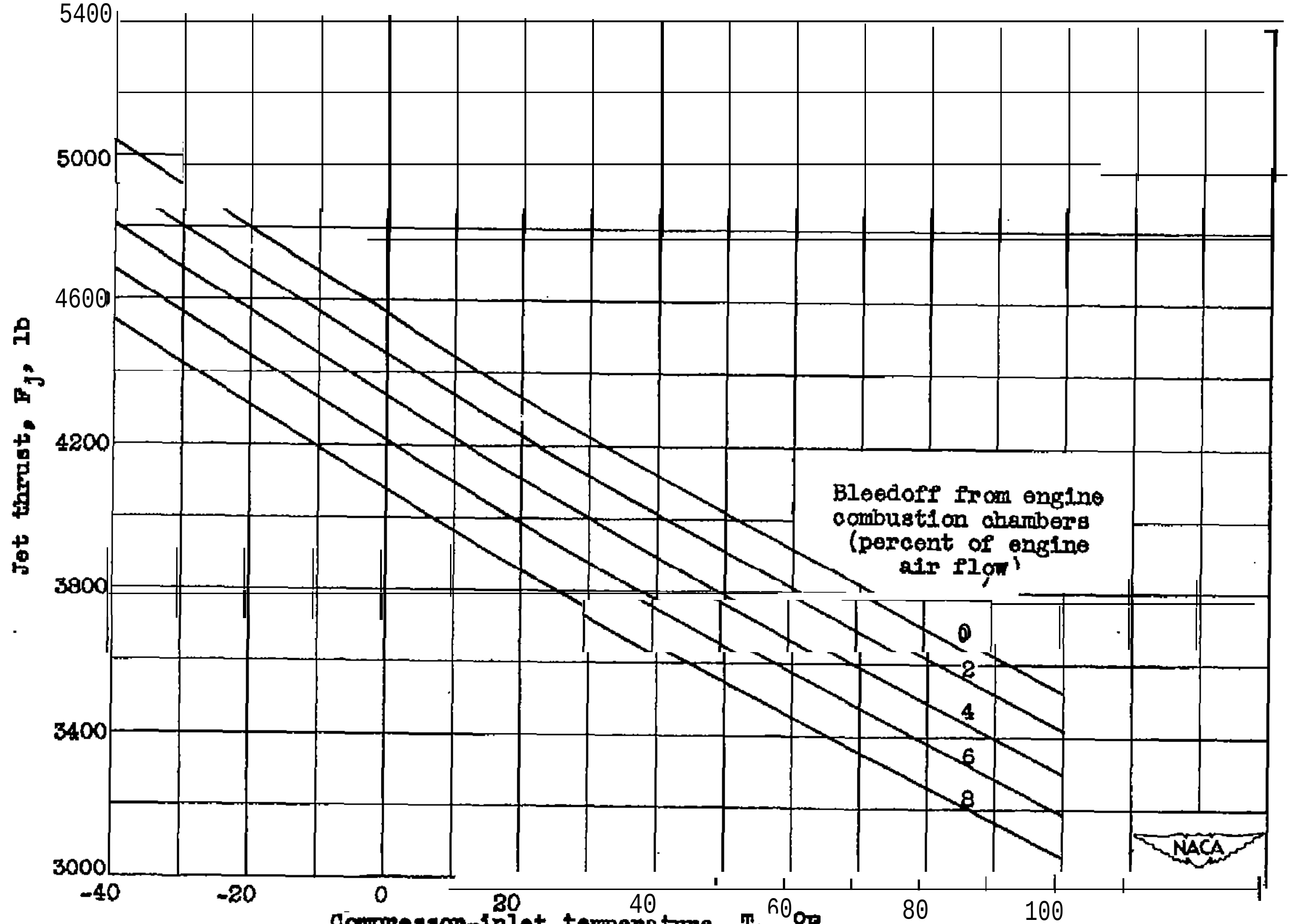
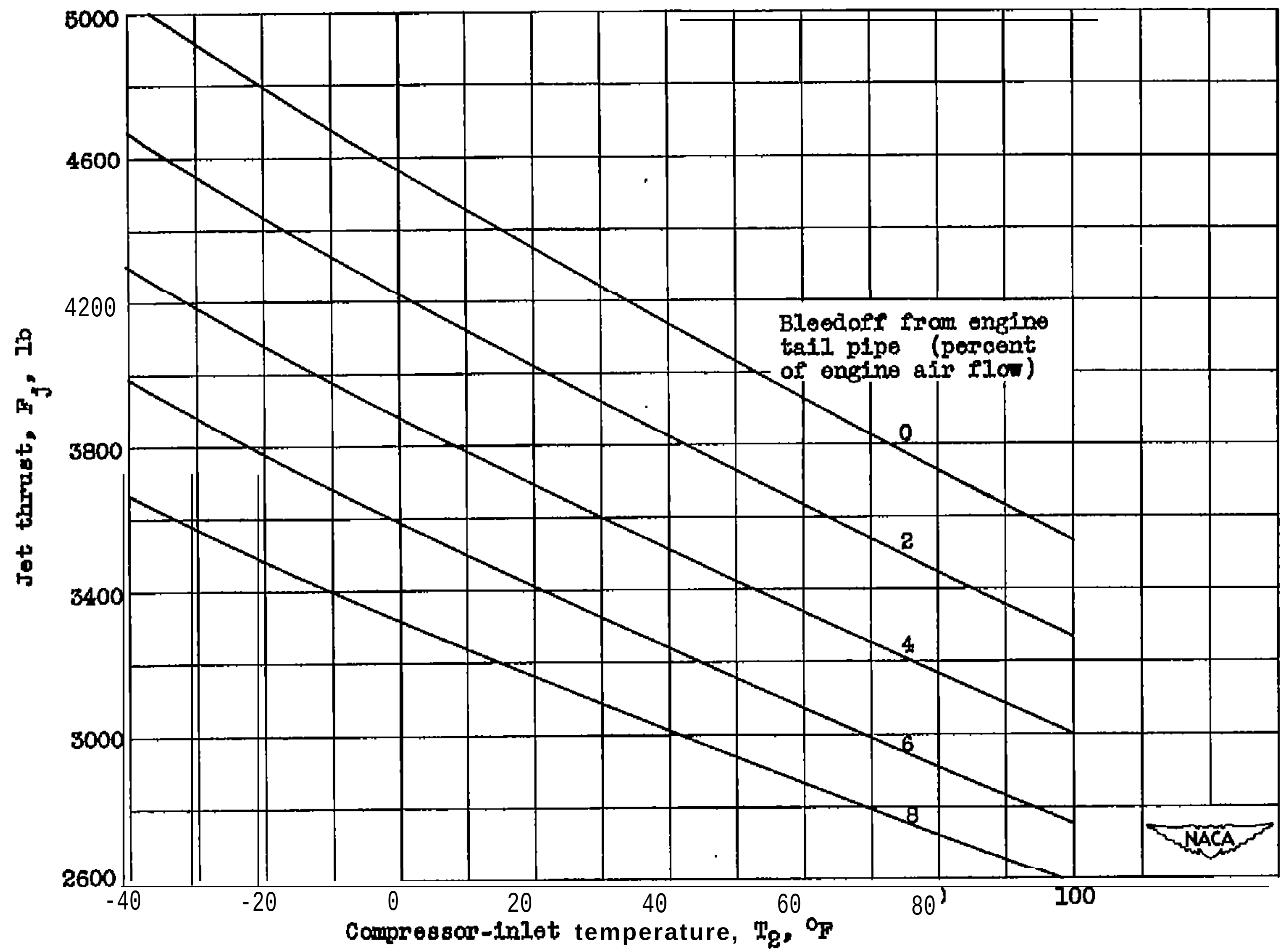


Figure 3. - Comparison of amounts of hot gas bled back from tail pipe and from combustion chamber for turbojet engine. Fixed-area tail-pipe nozzle; constant engine speed; liquid-water content, 1.0 gram per cubic meter.



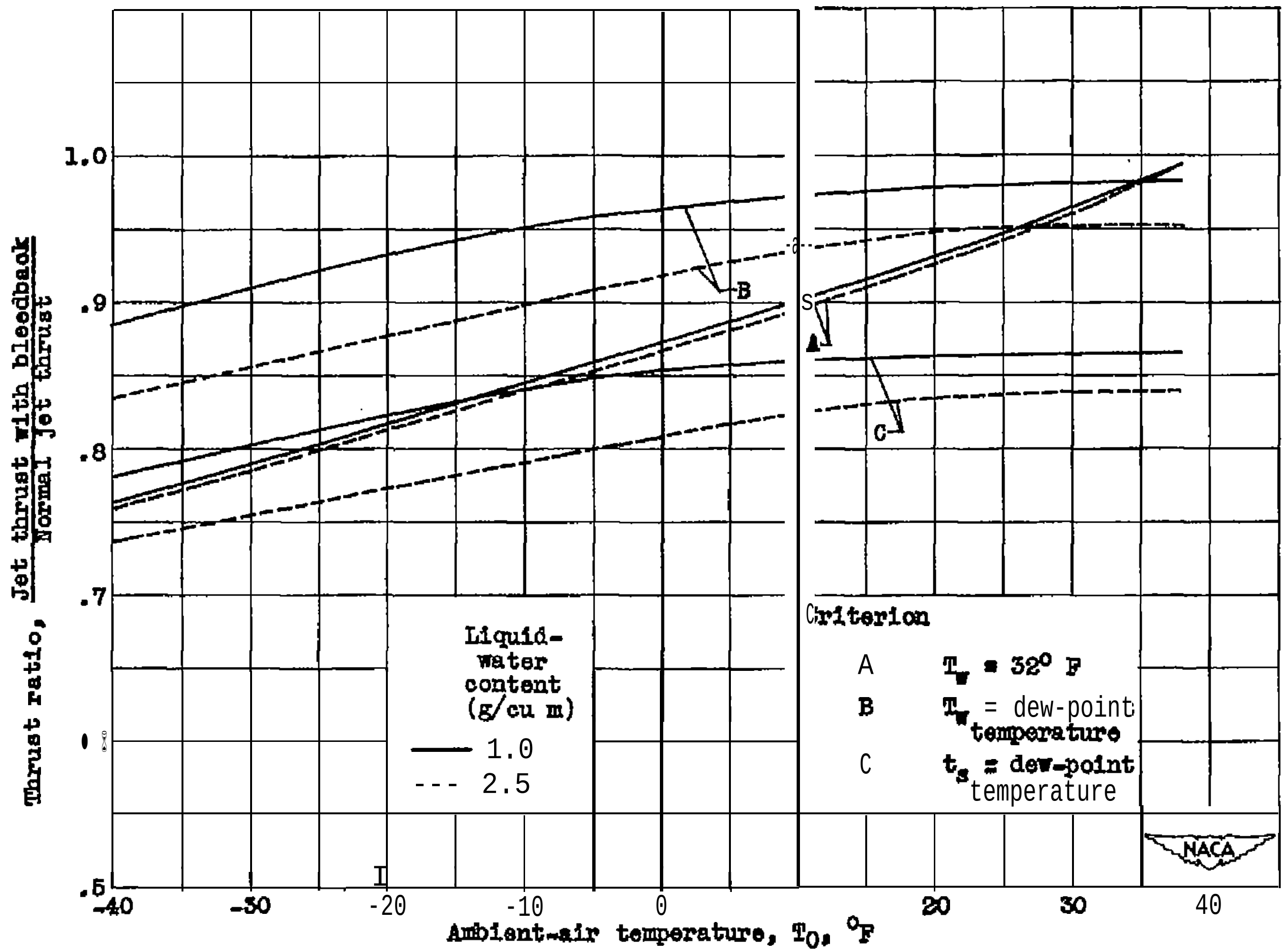
(a) Combustion-chamber bleedoff.

Figure 4. - Variation of jet thrust with compressor-inlet temperature for various amounts of bleedoff. Fixed-area tail-pipe nozzle; constant engine speed.



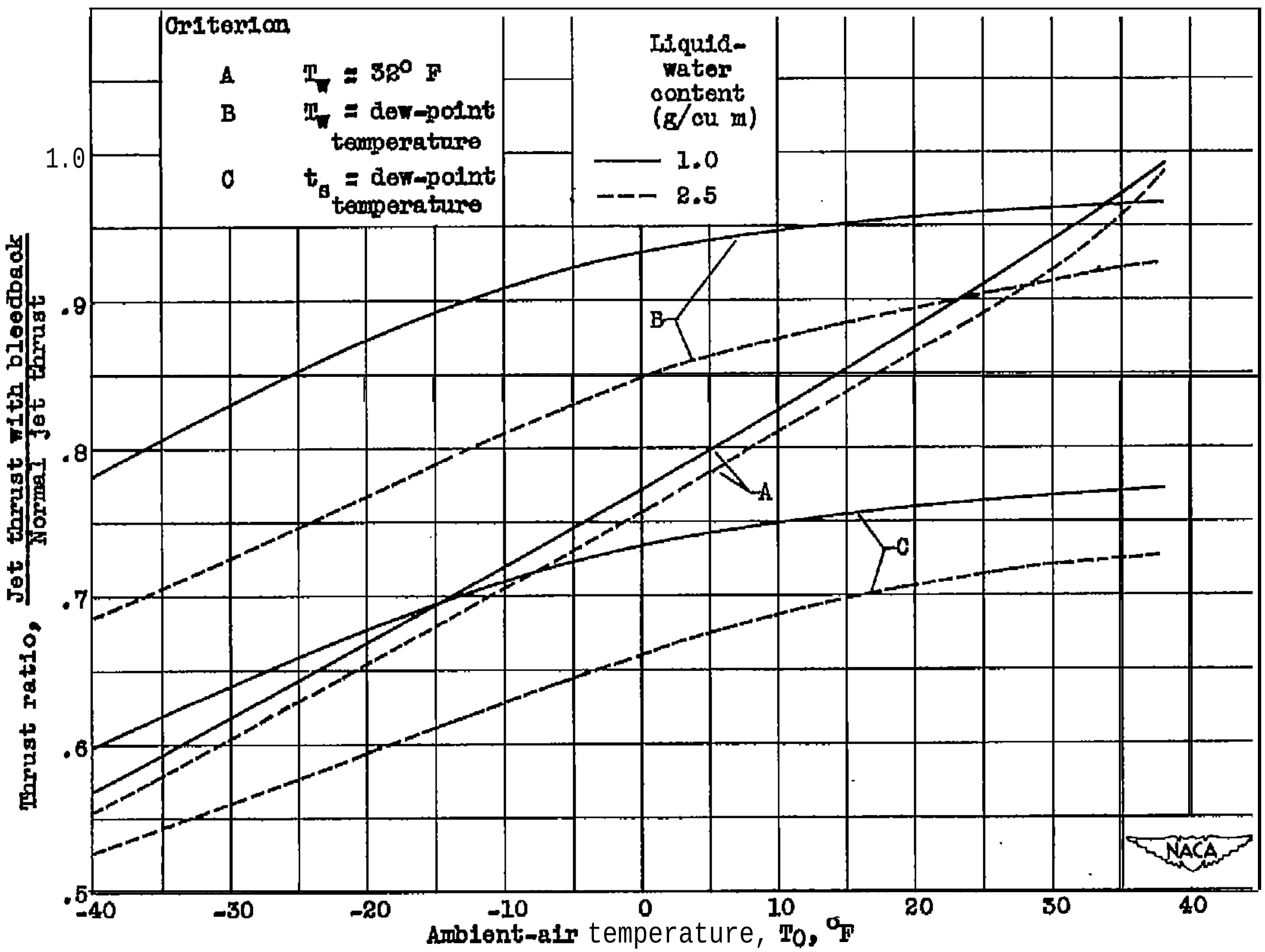
(b) Tail-pipe bleedoff.

Figure 4. - Concluded. Variation of jet thrust with compressor-inlet temperature for various amounts of bleedoff. Fixed-area tail-pipe nozzle; constant engine speed.



(a) Combustion-chamber bleedback.

Figure 5. - Effect of liquid-water content and ambient-air temperature on thrust losses with bleedback ice prevention for turbojet engine. Fixed-area tail-pipe nozzle; constant engine speed.



(b) Tail-pipe bleedback.

Figure 5. - Concluded. Effect of liquid-water content and ambient-air temperature on thrust losses with bleedback ice prevention for turbojet engine. Fixed-area tail-pipe nozzle; constant engine speed.

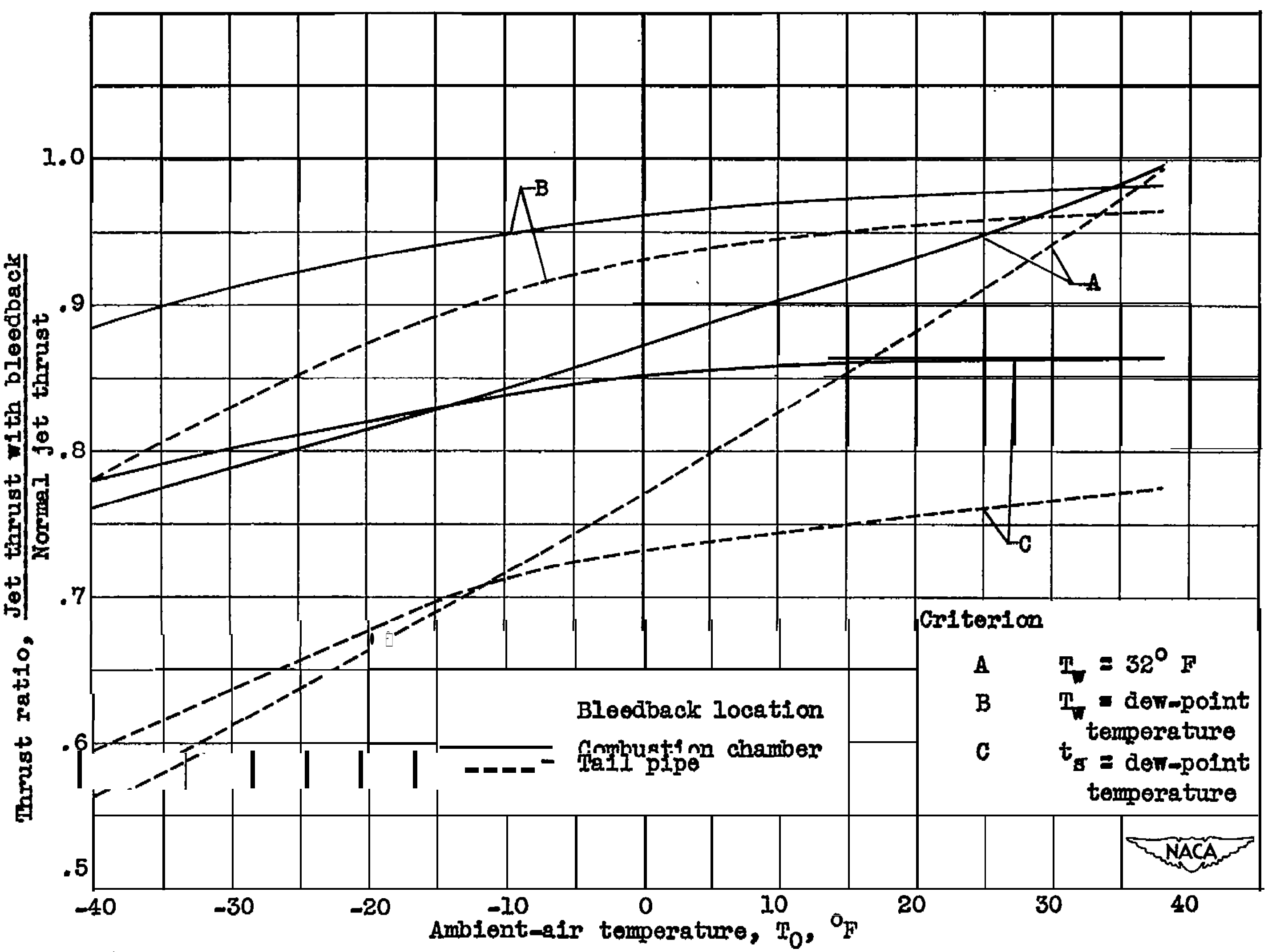


Figure 6. - Comparison of thrust losses with combustion chamber and tail-pipe bleedback ice prevention for turbojet engine. Fixed-area tail-pipe nozzle; constant engine speed; liquid-water content, 1.0 gram per cubic meter.

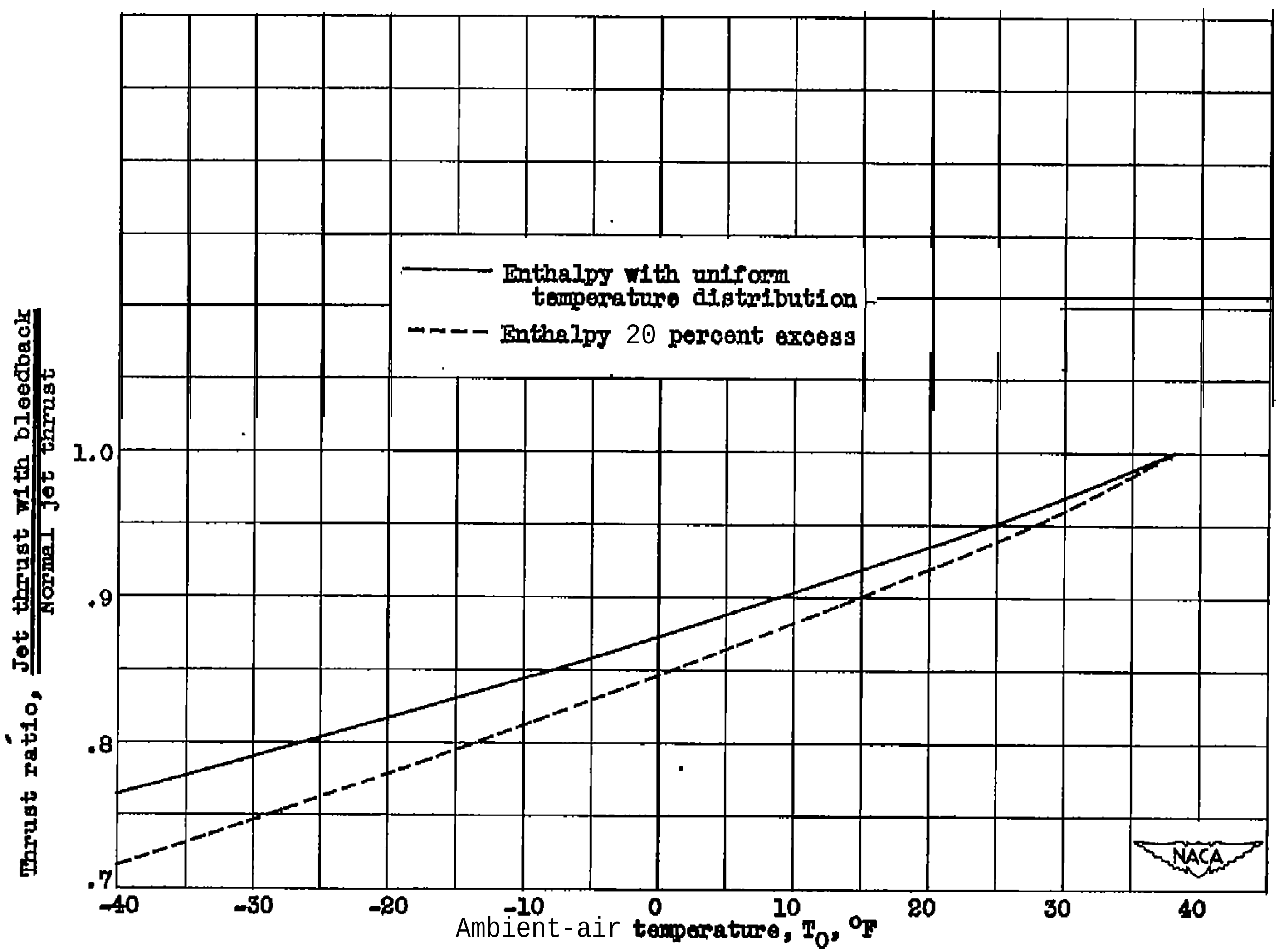


Figure 7. - Effect or mixing efficiency between gases bled from combustion chamber and inlet air on thrust losses encountered with bleedback ice prevention for turbojet engine. Wall temperature, 32° F; fixed-area tall-pipe nozzle; constant engine speed; liquid-rater content, 1.0 gram per cubic meter.

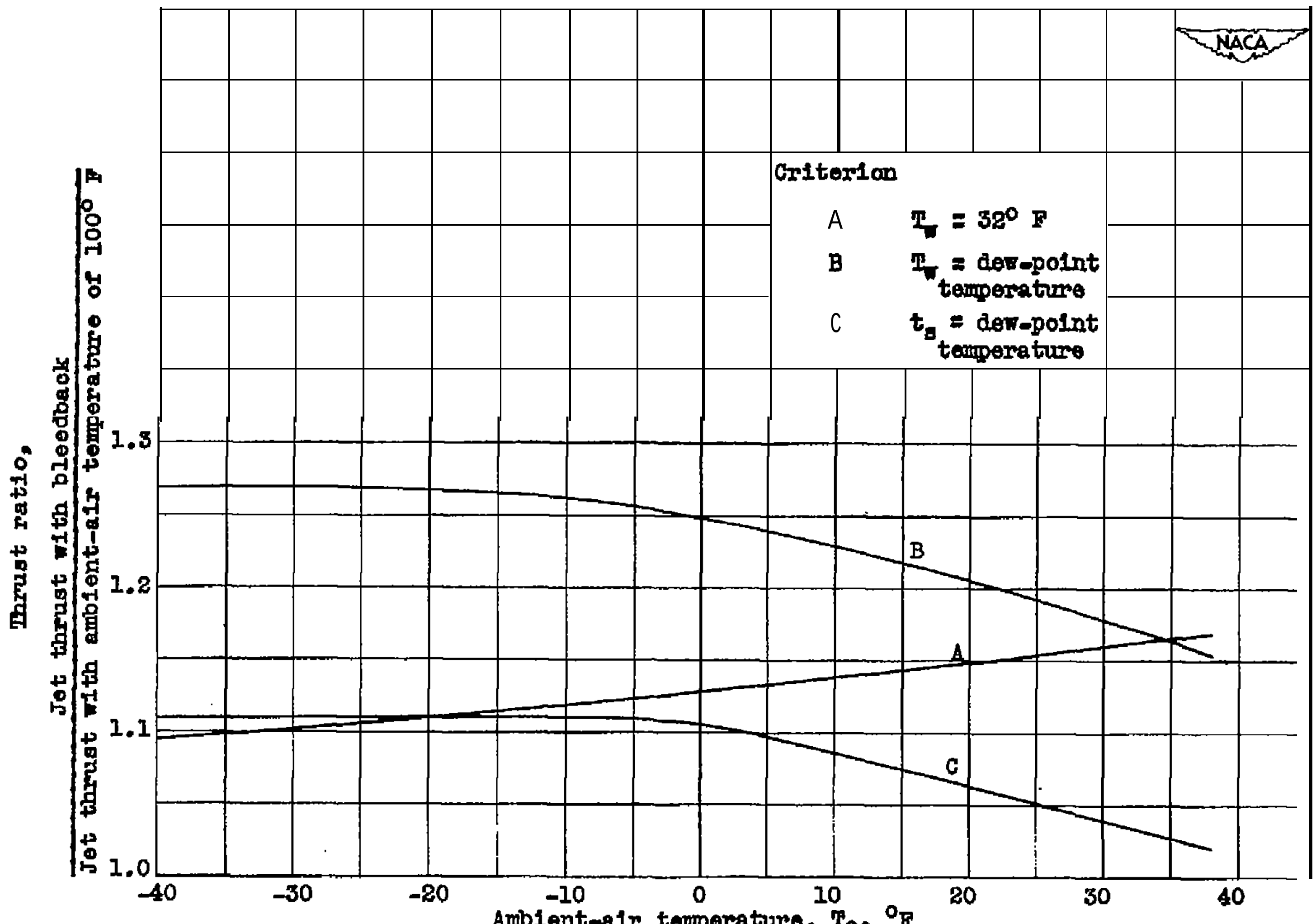


Figure 8. - Comparison of thrust available with combustion-chamber bleedback ice prevention and thrust available under normal operation at ambient-air temperature of 100° F for turbojet engine. Fixed-area tail-pipe nozzle; constant engine speed; liquid-water content, 1.0 gram per cubic meter.