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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF THRUST AUGMENTATION OF 4000-POUND-THRUST CENTRIFUGAL-FLOW-TYPE TURBOJET ENGINE BY INJECTION OF WATER AND ALCOHOL AT COMPRESSOR INLETS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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EXPERIMENTAL INVESTIGATION OF THRUST AUGMENTATION OF 4000-POUND-THRUST CENTRIFUGAL-FLOW-TYPE TURBOJET ENGINE BY INJECTION OF WATER AND ALCOHOL AT COMPRESSOR INLETS

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SUMMARY

An experimental investigation was conducted at zero flight speed and sea-level conditions on a 4000-pound-thrust centrifugal-flow-type turbojet engine to determine the amount of thrust augmentation obtainable at maximum rotor speed (11,500 rpm) by the injection of water, alcohol, and water-alcohol mixtures at the compressor inlets. Injected mixtures comprised up to 4.5 pounds of water and 2.5 pounds of alcohol per second. A fixed-area exhaust nozzle, 19 inches in diameter, was used for this investigation. The inlet-air-temperature range was from 505° to 530° R.

A maximum thrust augmentation of 26 percent was obtained by the injection of 4.5 pounds per second of water and 2.0 pounds per second of alcohol. With this injected mixture (representing 31 percent alcohol by weight), the fuel flow was the same as for no injection; no change in throttle setting was therefore required for constant rotor speed. The tail-pipe gas temperature for this injected flow rate was also the same as for no injection.

INTRODUCTION

Augmentation of the normal thrust of turbojet engines is of importance in improving the take-off, climb, and high-speed flight characteristics of jet-propelled aircraft. A general research program is being conducted at the NACA Cleveland laboratory in order to investigate various methods of thrust augmentation.

One simple method of thrust augmentation is the injection of refrigerants at the compressor inlets. The increase in thrust produced by the injection of liquids is the result of the increased mass flow of air and liquids and the increased jet velocity provided by the higher compressor-outlet pressure. An experimental investigation in which substantial thrust increases were achieved with a 1600-pound normal-thrust engine by the injection of water and alcohol as the refrigerant liquids is described in reference 1.

A similar investigation conducted at the NACA Cleveland laboratory during December 1945 to determine the amount of thrust augmentation possible for a 4000-pound-thrust centrifugal-flow-type turbojet engine at maximum rotor speed, zero ram, and sea-level conditions by the injection of water, alcohol, and water-alcohol mixtures at the compressor inlets is described herein. The mixture was injected at rates up to 4.5 pounds of water per second at 2.5 pounds of alcohol per second. A fixed-area exhaust nozzle, 19 inches in diameter, was used for the entire investigation. The inlet-air temperature ranged from 505° to 530° R.

APPARATUS

The thrust-augmentation investigation was conducted on a double-entry centrifugal-flow-type turbojet engine (I-40) having straight-through combustion chambers and a nominal thrust rating of 4000 pounds. The engine used for the investigation produced a net thrust of 3850 pounds at a rated maximum rotor speed of 11,500 rpm with a 19-inch-diameter exhaust nozzle and NACA standard inlet-air conditions (519° R and 14.7 lb/sq in. absolute). For these conditions, the normal air flow was 80.4 pounds per second, the fuel flow was 4900 pounds per hour, and the tail-pipe gas temperature was 1686° R.

The general arrangement of the engine installation is shown in figure 1. The air supply to the engine entered the test cell through two air-measuring nozzles. Cell leakage was determined by calibration of the test cell and was of the order of 2 percent of the metered air flow.

The engine was rigidly mounted on a frame that was suspended from the ceiling of the test cell by four rods swinging on ball-bearing pivots. Lateral restraint was provided by guide rollers; longitudinal restraint was provided by the thrust-measuring device. All instrumentation and control lines were flexible and a special seal (detail A in fig. 1) was installed where the tail pipe passes through the wall of the cell in order to reduce frictional forces.

The engine thrust was transmitted through a linkage to the diaphragm of an air-pressure cell. A pilot valve, directly connected to the thrust linkage, controlled the air pressure in the diaphragm cell to balance the thrust force. The thrust was read from a manometer connected to the diaphragm cell. The thrust device was calibrated by means of dead weights.

The engine fuel (kerosene) flow and the water and alcohol injection rates were measured with calibrated rotameters and thin-plate orifices, respectively. The alcohol used for the investigation was 50-percent methyl and 50-percent ethyl alcohol by weight. The alcohol and water were measured separately and then combined in a mixing chamber and distributed to the injection nozzles through a single manifold, which is shown in figure 2. Fourteen flat-spray-type nozzles, each rated at 2.05 gallons per minute at a pressure of 100 pounds per square inch, were directed into each inlet of the compressor. The nozzles were equally spaced circumferentially 4 inches from the inlet screens, but were so placed that the outer diameter of the impeller inlets would receive almost all the injected liquid in order to prevent water from reaching the bearings (fig. 2).

The temperatures and the pressures were measured at the points indicated in figure 2 with the following arrangements of thermocouples and pressure tubes:

(1) Inlet-air temperature T_0; average of three groups of four thermocouples in parallel in cowling inlet

(2) Inlet-air total pressure P_0; one open-end tube in quiescent zone of cell

(3) Compressor-outlet total temperature T_2; average of three separately read unshielded thermocouples, each located in a different diffuser elbow

(4) Compressor-outlet total pressure P_2; average of two separately read total-pressure tubes each in a different diffuser elbow

(5) Tail-pipe gas temperature T_7; four strut-type thermocouples connected in parallel and located slightly upstream of exhaust nozzle

Potentiometers were used to measure temperatures and manometers were used to measure pressures.

PROCEDURE

Runs were made at each liquid injection rate over a range of rotor speeds from 10,000 to 11,500 rpm to obtain data for the plotting of curves from which the corrected values of the performance variables at the rated maximum rotor speed of 11,500 rpm could be cross-plotted. The range of liquid injection rates covered in the investigation is shown in the following table: 847

Run	Approximate water-flow rate (lb/sec)	Approximate alcohol-flow rate (lb/sec)
A	0.8	0, 0.75, 1.5, 2.5
B	1.5	0, 0.75, 1.5, 2.5
C	3.0	[a]0, 0.75, 1.5, 2.5
D	4.5	[a]0, 0.75, 1.5, 2.5
E	0	0.75, 1.5

[a]11,500 rpm not attainable.

The cowling inlet-air temperature ranged from 505° to 530° R. Checks of normal performance were run at frequent intervals during the investigation in order to take into account the deterioration of the engine with time. The normal thrust decreased from 3850 to 3725 pounds, a change of 3 percent, and the tail-pipe gas temperature increased 50° R during the course of the investigation.

Several of the tail-pipe gas-temperature thermocouples failed during the investigation, which led to some erroneous readings. In order to determine accurately the trends of the tail-pipe gas temperature with liquid injection, a part of the program was rerun.

SYMBOLS

The following symbols are used in this report:

F static thrust, (lb)

f total specific liquid consumption including fuel, water, and alcohol, (lb)/(hr)(lb thrust)

N rotor speed, (rpm)

P total pressure, (lb)/(sq in. absolute)

p static pressure, (lb)/(sq in. absolute)

T indicated total temperature, (°R)

W_a air flow, (lb/sec)

W_{al} injected alcohol flow, (lb/sec)

W_f fuel (kerosene) flow, (lb/hr)

W_t total liquid consumption including fuel, water, and alcohol, (lb/sec)

W_w injected water flow, (lb/sec)

Subscripts:

corr corrected

0 cowling

2 compressor outlet

7 tail pipe

ANALYSIS OF DATA

Correction for Inlet Conditions

In order to facilitate evaluation of the thrust-augmentation method, the performance data were corrected to NACA standard inlet-air pressure and temperature conditions of 14.7 pounds per square inch absolute and 519° R, respectively, by means of the following correction factors:

$\frac{F}{\delta}$ corrected thrust

$\frac{N}{\sqrt{\theta}}$ corrected engine speed

$\frac{P}{\delta}$ corrected pressure

$\frac{T}{\theta}$ corrected temperature

$\frac{W_a\sqrt{\theta}}{\delta}$ corrected air flow

$\frac{W_{al}\sqrt{\theta}}{\delta}$ corrected alcohol flow

$\frac{W_w\sqrt{\theta}}{\delta}$ corrected water flow

$\frac{W_f K}{\delta\sqrt{\theta}}$ corrected fuel flow

$$\delta = \frac{\text{cowling-inlet total pressure, } P_0, \text{ (lb/sq in. absolute)}}{\text{NACA standard sea-level pressure, 14.7 (lb/sq in. absolute)}}$$

$$\theta = \frac{\text{cowling-inlet total temperature, } T_0, \ {}^{\circ}R}{\text{NACA standard sea-level temperature, } 519^{\circ} R}$$

$$K = 1 + \frac{3600}{W_f}(0.25\, W_{al})(1-\theta)$$

Except for the factors for corrected water, alcohol, and fuel flows, this method of correction is the same as discussed in references 2 and 3. The correction factors for the water and alcohol flows are the same as the air-flow correction so that the water-air and alcohol-air ratios are the same before and after correction. This correction of $\frac{\sqrt{\theta}}{\delta}$ for the alcohol flow is therefore different from the normal fuel-flow correction of $\frac{1}{\delta\sqrt{\theta}}$. Because the alcohol also supplies heat in the combustion process, an additional factor K is included in the fuel-flow correction to maintain a heat balance after the values of engine performance are corrected. The constant of 0.25 appearing in this expression for the K factor represents the ratio of the effective heating value of the alcohol to the engine fuel (kerosene) and was evaluated from engine performance data.

As a check on the validity of this correction method, a theoretical analysis of the wet-compression process was made. The analysis indicated that over a limited range of inlet conditions for a given compressor Mach number and water-air or alcohol-air ratio, the compressor-outlet pressure and temperature are nearly proportional to inlet pressure and temperature. The correction factors P/δ and T/θ are therefore satisfied.

The correction factors used are applicable to centrifugal compressors only. They are also known to be inexact for data adjustment over large ranges of inlet conditions and no attempt should be made to use them for extrapolation to altitude conditions. For small variations in inlet temperature and pressure, as in the data presented, the error in the method of correction is believed to be negligible. The initial relative humidity of the inlet air may also be of importance but no attempt was made to measure or control it in this investigation.

Adjustment for Engine Running Time

In addition to the corrections for inlet-air conditions, all experimental results were adjusted to account for the change in normal engine performance with running time. After correction for inlet-air conditions, the data were plotted against engine speed and the values of the performance variables at 11,500 rpm were taken from the curves. The data for the normal performance check runs were then plotted against engine running time for a rotor speed of 11,500 rpm. Each value for 11,500 rpm taken from the injection data was then adjusted according to the ratio by which the normal performance had changed. The curves presented are based on these adjusted values.

RESULTS AND DISCUSSION

The thrust increase attendant with injection of water and alcohol mixtures at the compressor inlets of a turbojet engine is due primarily to evaporative cooling of the inlet air and, to a lesser extent, to the additional liquid mass flow through the engine. The cooling effect of the injected water and alcohol results in both a greater jet velocity provided by the higher compressor-discharge pressures and an increase in the air flow.

Thrust. - The variation of thrust with water and alcohol injection is presented in figure 3 for a corrected rotor speed of 11,500 rpm. With a water injection rate of 3 or more pounds per second, the engine fuel pump did not have sufficient capacity to maintain a rotor speed of 11,500 rpm and alcohol injection was therefore necessary to maintain the rotor speed. Alcohol injection alone was limited to 1.5 pounds per second because of excessive temperature in the tail pipe and large glowing hot spots in the vicinity of the turbine.

The thrust increased fairly rapidly with an increase in the injection rate of both water and alcohol up to a flow of about 1.5 pounds per second of alcohol and 3 pounds per second of water. Further increases in the injection rate of both water and alcohol resulted in only small additional thrust gains. A maximum thrust of 4850 pounds was reached with injection of 4.5 pounds per second of water and approximately 2.0 pounds per second of alcohol.

The data of figure 3 are replotted in figure 4(a) to show the variation of thrust with injected liquid flow (water plus alcohol). For an injected flow of 4 pounds per second, the thrust was 4700 pounds, which is a thrust augmentation of 22 percent. For values of total injected liquid up to approximately 4 pounds per second, the thrust increase is nearly proportional to the injected flow.

The variation of thrust with total liquid consumption (water, alcohol, and fuel) at a rated rotor speed of 11,500 rpm is shown in figure 4(b). For any constant thrust increase, the total liquid consumption of the engine is smallest for the injected mixtures containing the greatest proportion of alcohol. This advantage of injecting mixtures rich in alcohol is due primarily to the replacement of the primary engine fuel (kerosene) by the injected alcohol, as will be subsequently illustrated.

Tail-pipe gas temperature. - The corrected tail-pipe gas temperatures varied from about 50° R above to 45° R below the normal value of 1686° R throughout the range of injected flow rates (fig. 5). No attempt was made to correct the results of this investigation to a constant tail-pipe gas temperature. The gas temperatures were approximately normal at the injection rates for maximum thrust, and were lower than normal only when the injected flow rates of both water and alcohol were very high. It is consequently believed that the use of a variable-area exhaust nozzle, as suggested for the engine investigation in reference 1, would result in only small additional thrust increases for the engine used in the present investigation at the water-alcohol injection rate for maximum augmentation.

Air-flow and compressor-outlet pressure. - The compressor-outlet total pressure (fig. 6) increased with liquid injection rate in the low range of injection and tended toward a maximum value in the high injection range because of the approach to saturation of the air in the compressor.

The air flow (fig. 7) was greater than normal at all liquid injection rates and reached a maximum value at a water injection rate of 1.5 pounds per second with an alcohol injection rate of 2.5 pounds per second. At water injection rates below 3 pounds per second, the injection of alcohol caused an increase in air flow; however, at water-injection rates of 3.0 and 4.5 pounds per second, the injection of alcohol did not appreciably change the air flow. An increase in water injection rate from 3.0 to 4.5 pounds per second resulted in a reduction in air flow. Because the compressor-outlet total pressure was approximately constant at the high water and alcohol injection rates (fig. 6) and because the turbine-inlet temperature is nearly constant, the total mass flow through the engine is limited to a constant value. An increase in the injected liquid flow rate in this range of operation therefore results in a decrease in the air flow.

Fuel flow. - The corrected fuel-flow data for the various water and alcohol injection rates are plotted in figure 8. The fuel flow required for constant rotor speed or to maintain the turbine-inlet temperature, is increased by the injection of water because of the additional heat required to vaporize the water and to heat the higher air-flow rate. An increase in the alcohol injection rate decreases the required fuel flow because the alcohol burns in the combustion chambers and thus serves as a fuel itself.

The dashed line in figure 8 indicates the mixtures of water and alcohol that may be injected without a change in fuel flow and hence without changing the throttle setting. These constant throttle mixtures contain from 32 to 40 percent alcohol; the percentage of alcohol increased as the injection rate decreased. The injection of 2 pounds per second of alcohol resulted in a decrease of about 0.5 pound per second in the fuel flow, which varies slightly with the water injection rate. If lower heating values of 18,700 and 10,900 Btu per pound are assumed for the kerosene and alcohol, respectively, and if a combustion efficiency of 95 percent is assigned to the kerosene fuel, it is calculated that about 40 percent of the injected alcohol burns in the engine combustion chambers.

Specific liquid consumption. - The corrected total specific liquid consumption including fuel, water, and alcohol is shown by the solid lines in figure 9. The total specific liquid consumption is increased by both water and alcohol injection, but is increased more by the injection of water than by the injection of alcohol because the alcohol replaces some of the kerosene fuel, as previously discussed. Lines of constant corrected thrust are included to show optimum injected water and alcohol mixtures for several augmented thrust values. Lower total specific liquid consumption rates are obtained at all but the highest thrust values at the highest alcohol injection rates. The total liquid consumption rate for the highest thrust (4800 pounds) reaches a minimum at approximately 2.0 pounds per second alcohol flow with 3.0 pounds per second of water flow.

Thrust augmentation. - The thrust increase (augmentation) as a percentage of the normal thrust at a corrected rotor speed of 11,500 rpm plotted against alcohol injection rate for various water injection rates is presented in figure 10. Curves of constant water-alcohol mixture are shown, as well as a curve for the mixture at constant throttle setting. These curves were obtained from the data of figures 3 and 8.

The maximum thrust augmentation of 26 percent was obtained by the injection of 4.5 pounds of water per second and 2.0 pounds of alcohol per second. This mixture, which contains 31 percent of alcohol by weight, also provides constant throttle setting.

SUMMARY OF RESULTS

The following results were obtained from a thrust-augmentation investigation of a 4000-pound-thrust centrifugal-flow-type turbojet engine with a fixed-area exhaust nozzle 19 inches in diameter by injection of water and alcohol at the compressor inlets at zero flight velocity, sea-level conditions (average inlet-air temperature from 505° to 530° R), and a rotor speed of 11,500 rpm:

1. The maximum thrust augmentation was found to be 26 percent and was obtained by the injection of 4.5 pounds per second of water and 2.0 pounds per second of alcohol. With this injected mixture (representing 31 percent alcohol by weight), the fuel flow was the same as for no injection; no change in throttle setting was therefore required for constant rotor speed. The tail-pipe gas temperature for this injected flow rate was normal.

2. For slightly less than maximum augmentation the necessary injection rate is much lower. For example, an augmentation of 22 percent requires an injection rate of only 4.0 pounds per second as compared with 6.5 pounds per second for an augmentation of 26 percent.

3. For constant augmentation, the total specific liquid consumption decreased as the injected mixture was enriched with alcohol, due to the replacement of the engine fuel with alcohol.

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847

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2. Warner, D. F., and Auyer, E. L.: Contemporary Jet-Propulsion Gas Turbines for Aircraft. Mech. Eng., vol. 67, no. 11, Nov. 1945, pp. 707-714.

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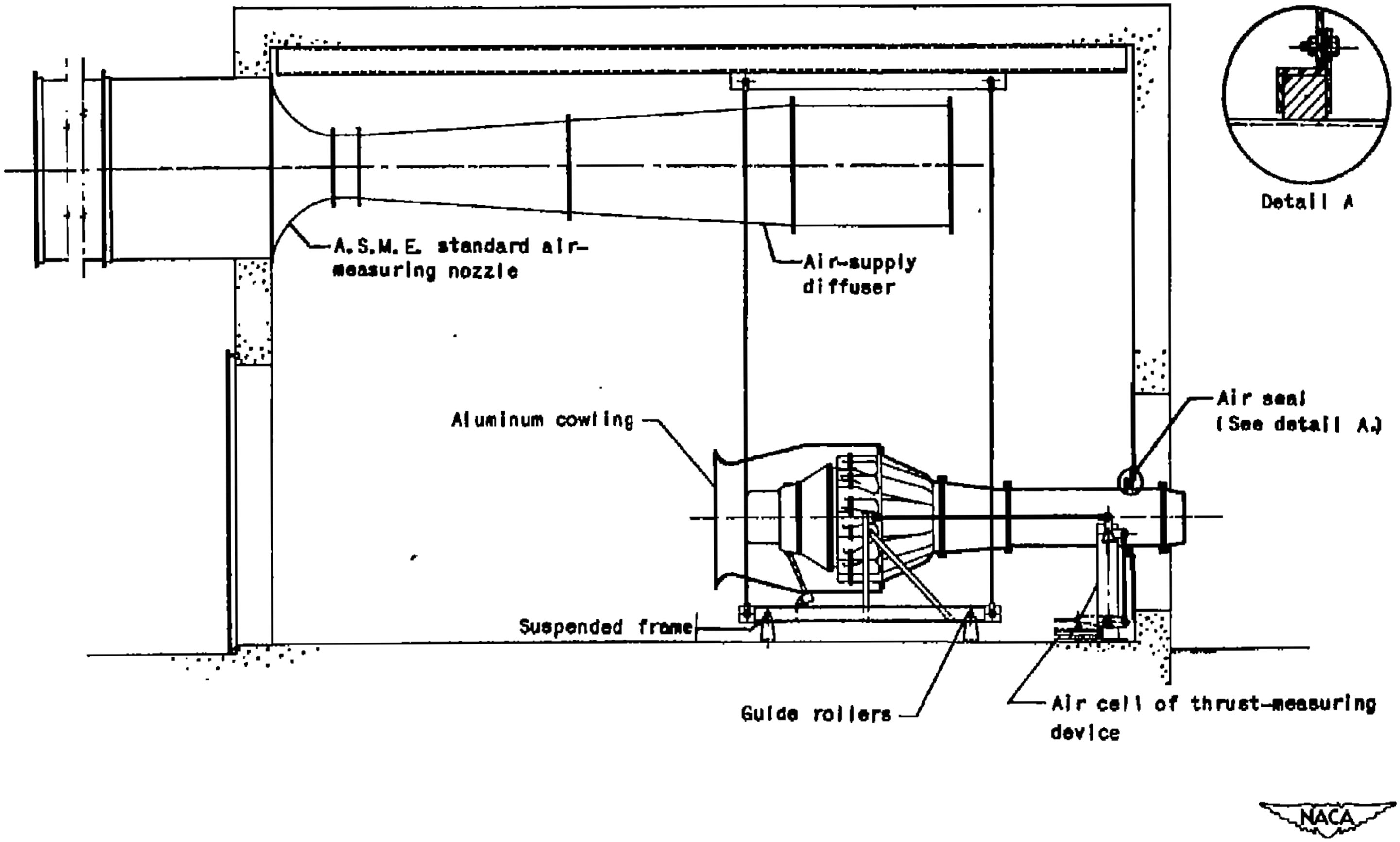


Figure 1. - Diagram of setup for investigation of engine performance with water and alcohol injection on 4000-pound-thrust centrifugal-flow-type turbojet engine.

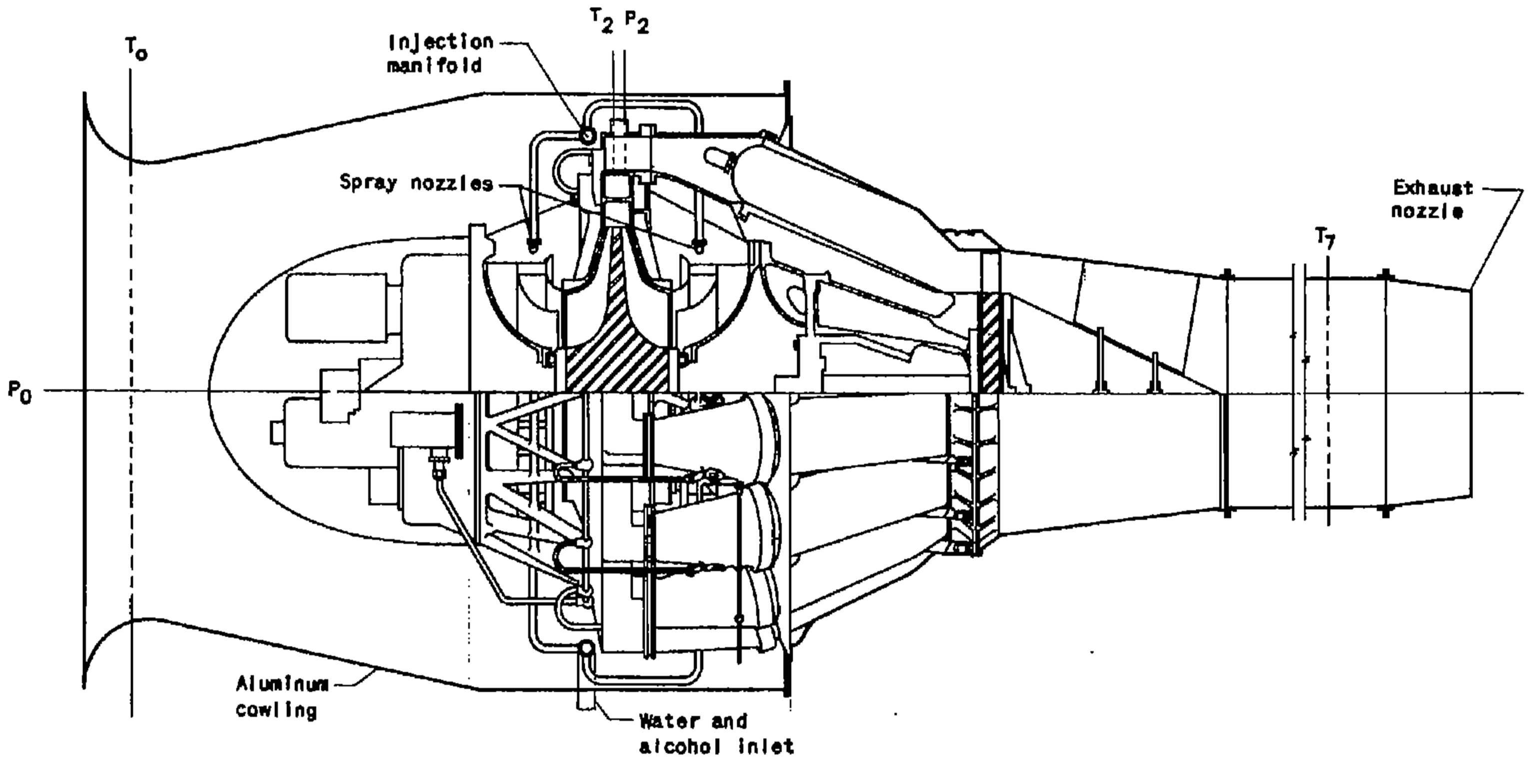


Figure 2. - Instrumentation and injection equipment for investigation of engine performance with water and alcohol injection on 4000-pound-thrust centrifugal-flow-type turbojet engine.

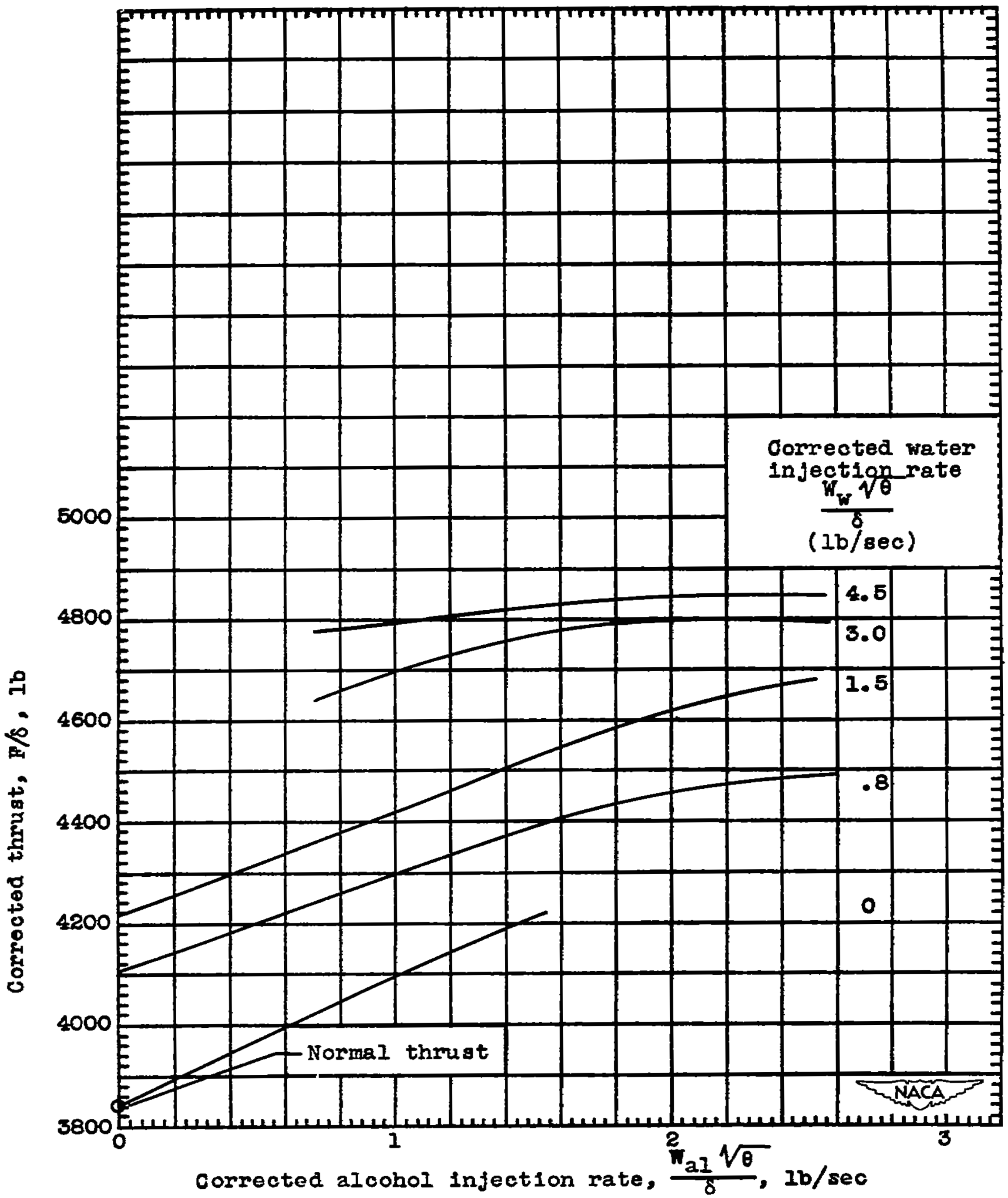
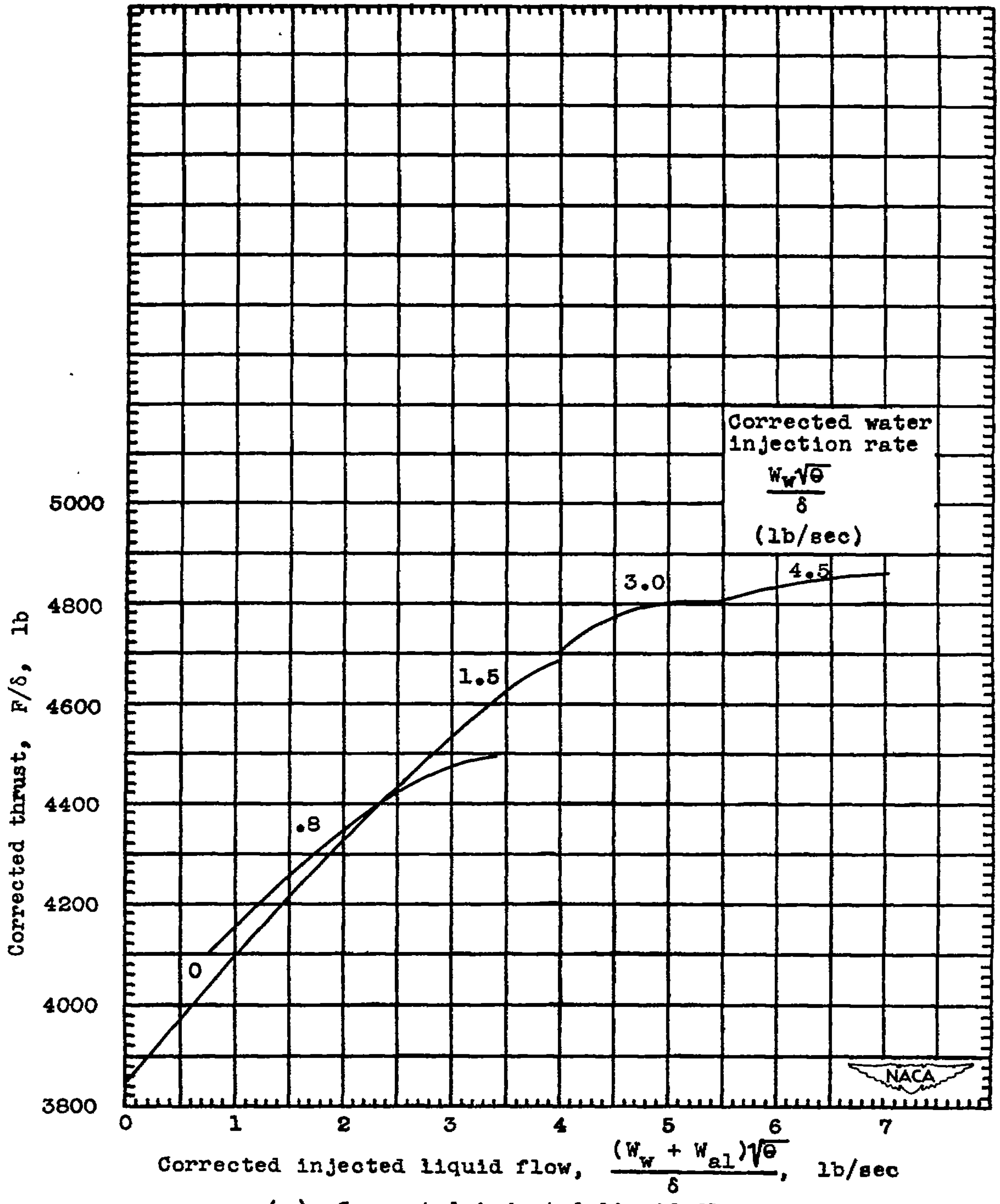
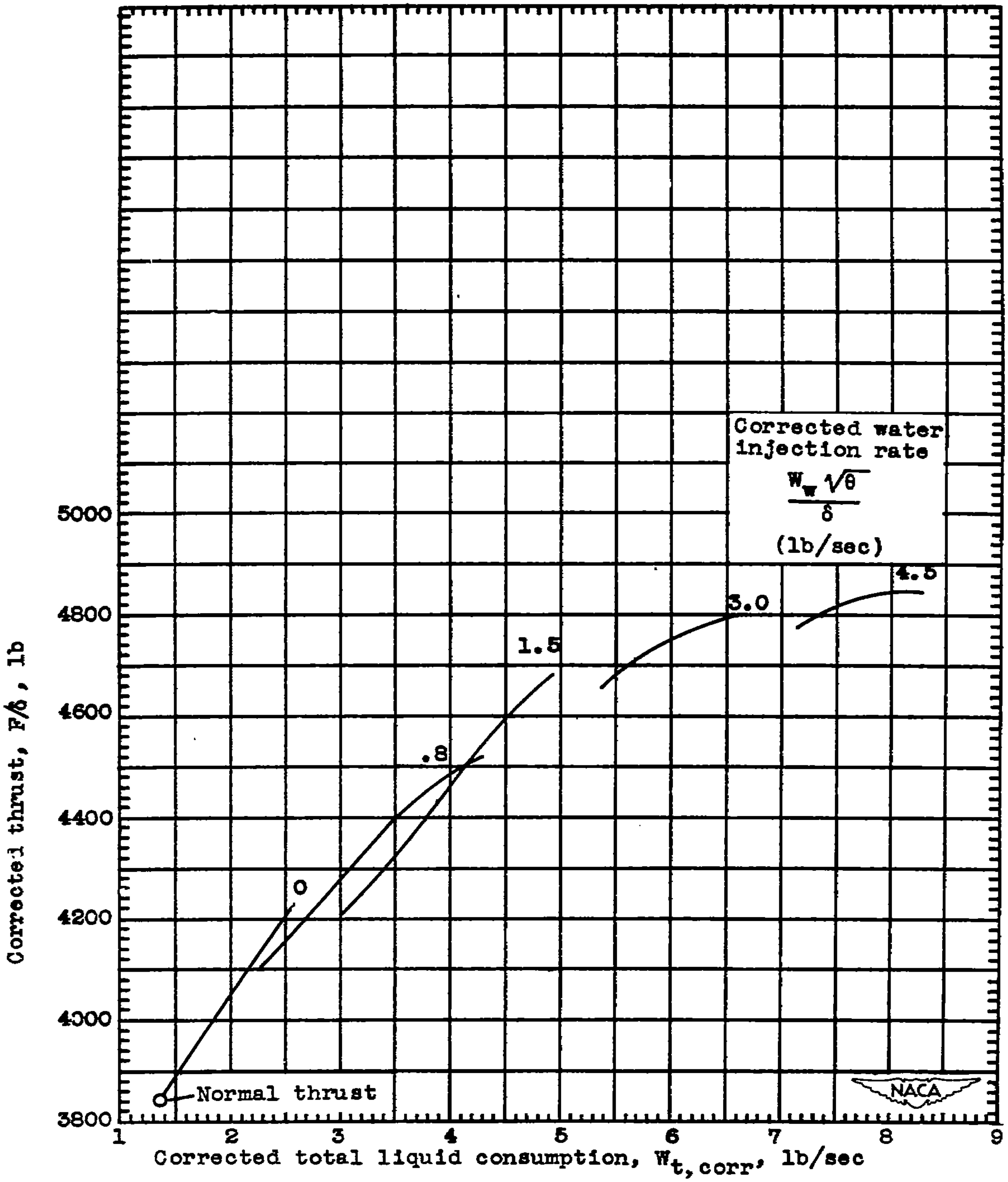


Figure 3. - Effect of alcohol injection rate on thrust of 4000-pound-thrust centrifugal-flow-type turbojet engine at several water injection rates. Corrected rotor speed, 11,500 rpm.



(a) Corrected injected liquid flow.

Figure 4. - Variation of thrust with corrected injected liquid flow and corrected total liquid consumption for several constant water injection rates on 4000-pound-thrust centrifugal-flow-type turbojet engine. Corrected rotor speed, 11,500 rpm.



(b) Corrected total liquid consumption.

Figure 4. – Concluded. Variation of thrust with corrected injected liquid flow and corrected total liquid consumption for several constant water injection rates on 4000-pound-thrust centrifugal-flow-type turbojet engine. Corrected rotor speed, 11,500 rpm.

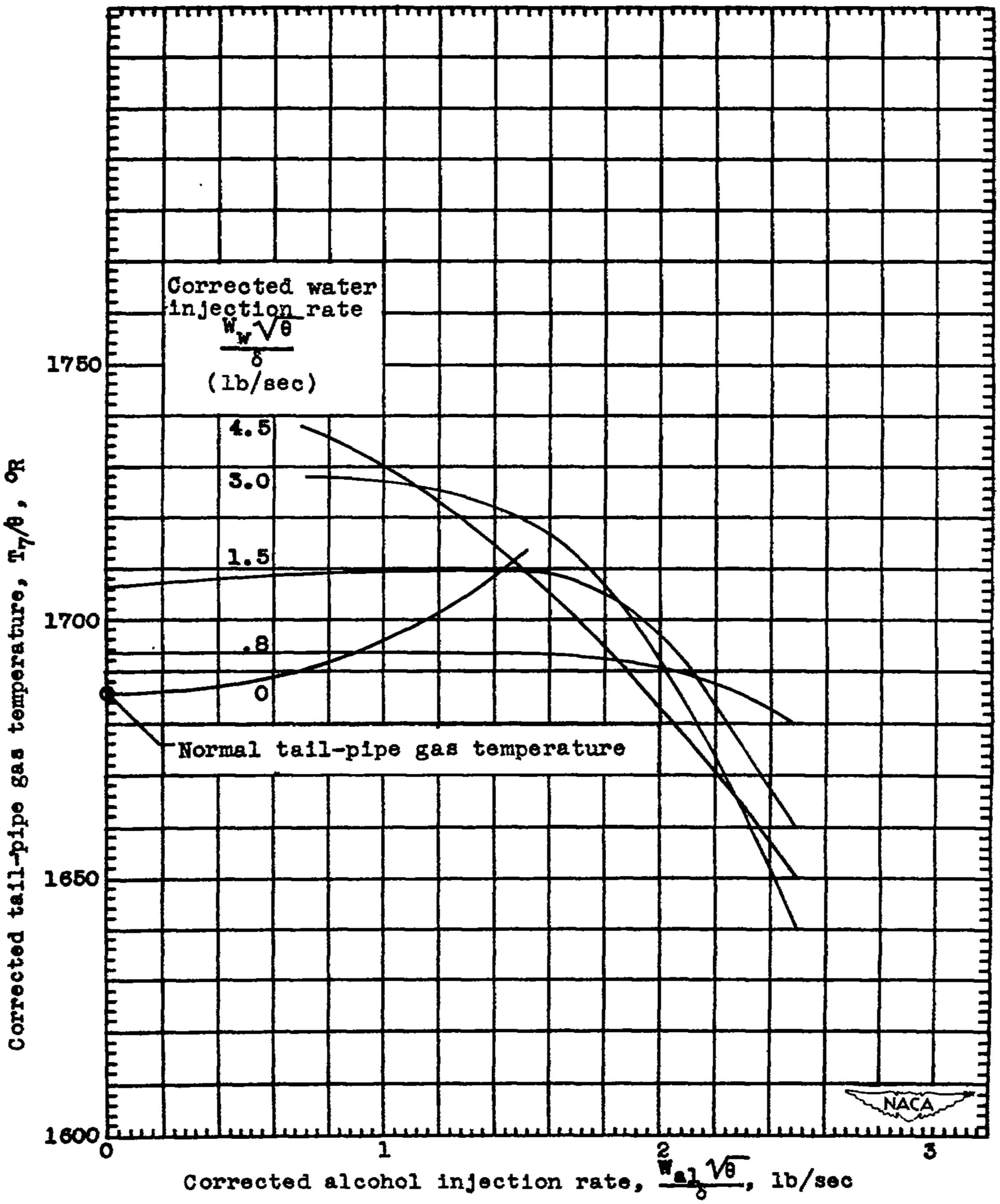


Figure 5. - Effect of alcohol injection rate on tail-pipe gas temperature of 4000-pound-thrust centrifugal-flow-type turbojet engine at several constant water injection rates. Corrected rotor speed, 11,500 rpm.

847

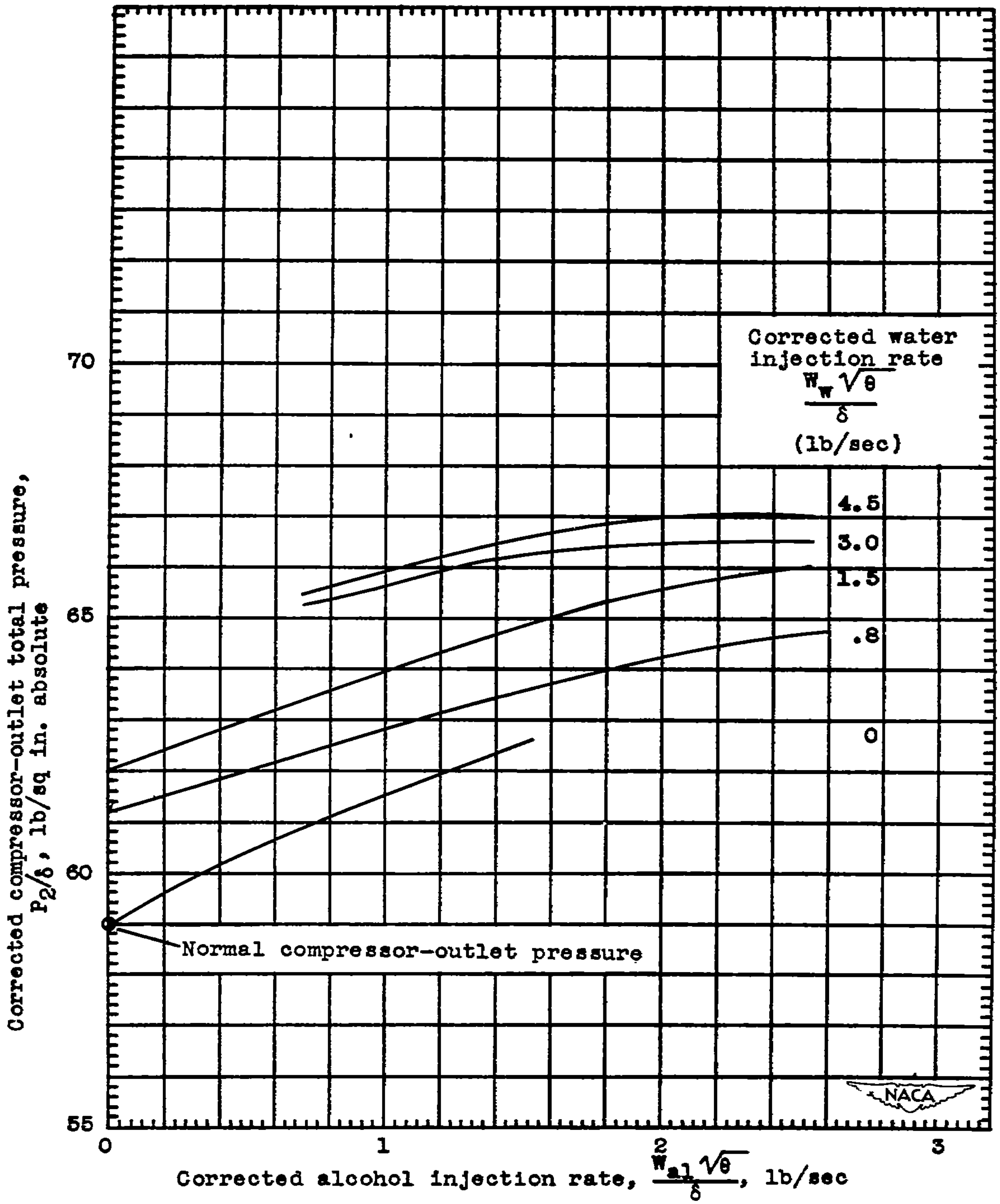


Figure 6. - Effect of alcohol injection rate on compressor-outlet total pressure of 4000-pound-thrust centrifugal-flow-type turbojet engine at several constant water injection rates. Corrected rotor speed, 11,500 rpm.

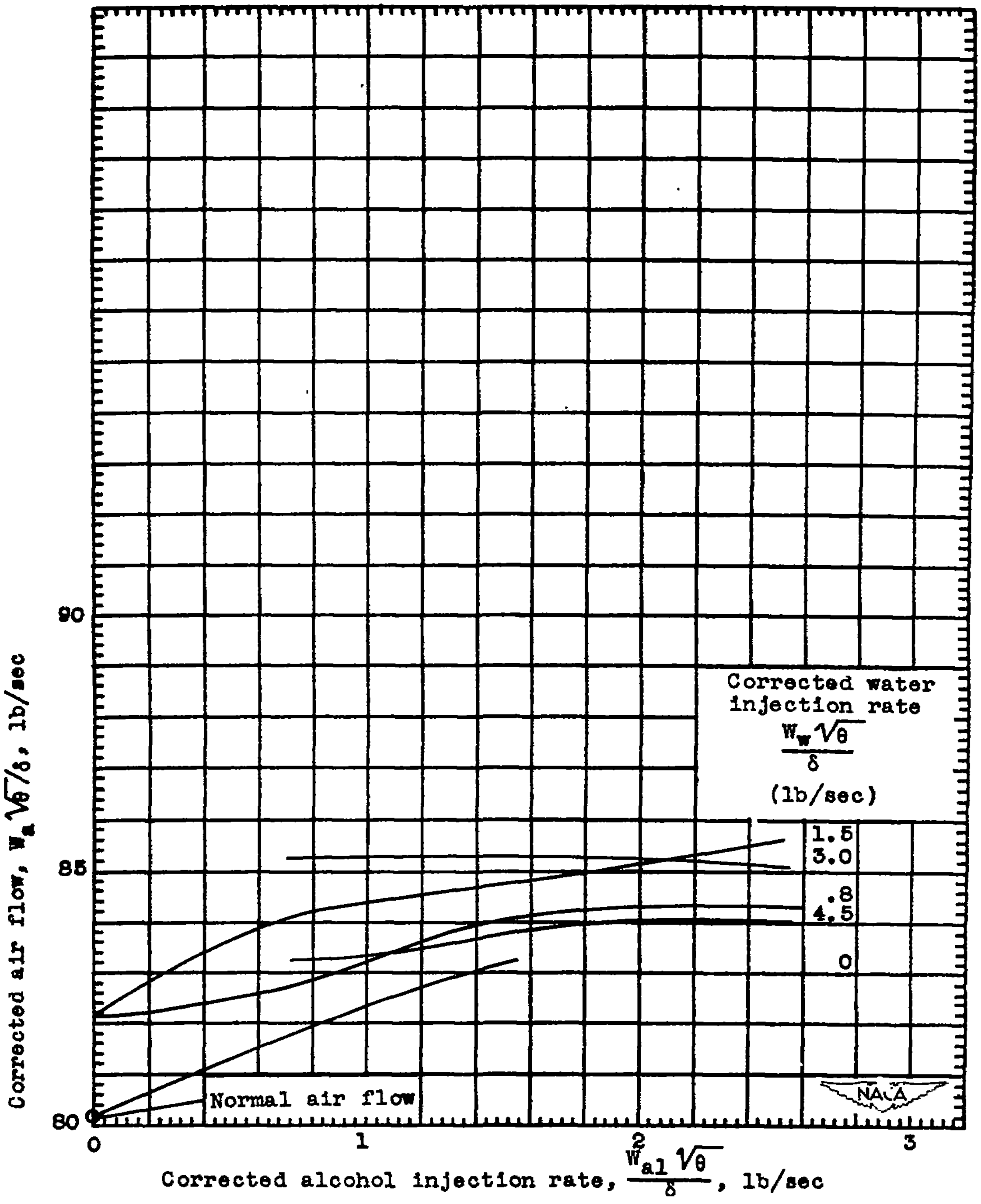


Figure 7. - Effect of alcohol injection rate on air flow of 4000-pound-thrust centrifugal-flow-type turbojet engine at several constant water injection rates. Corrected rotor speed, 11,500 rpm.

847

847

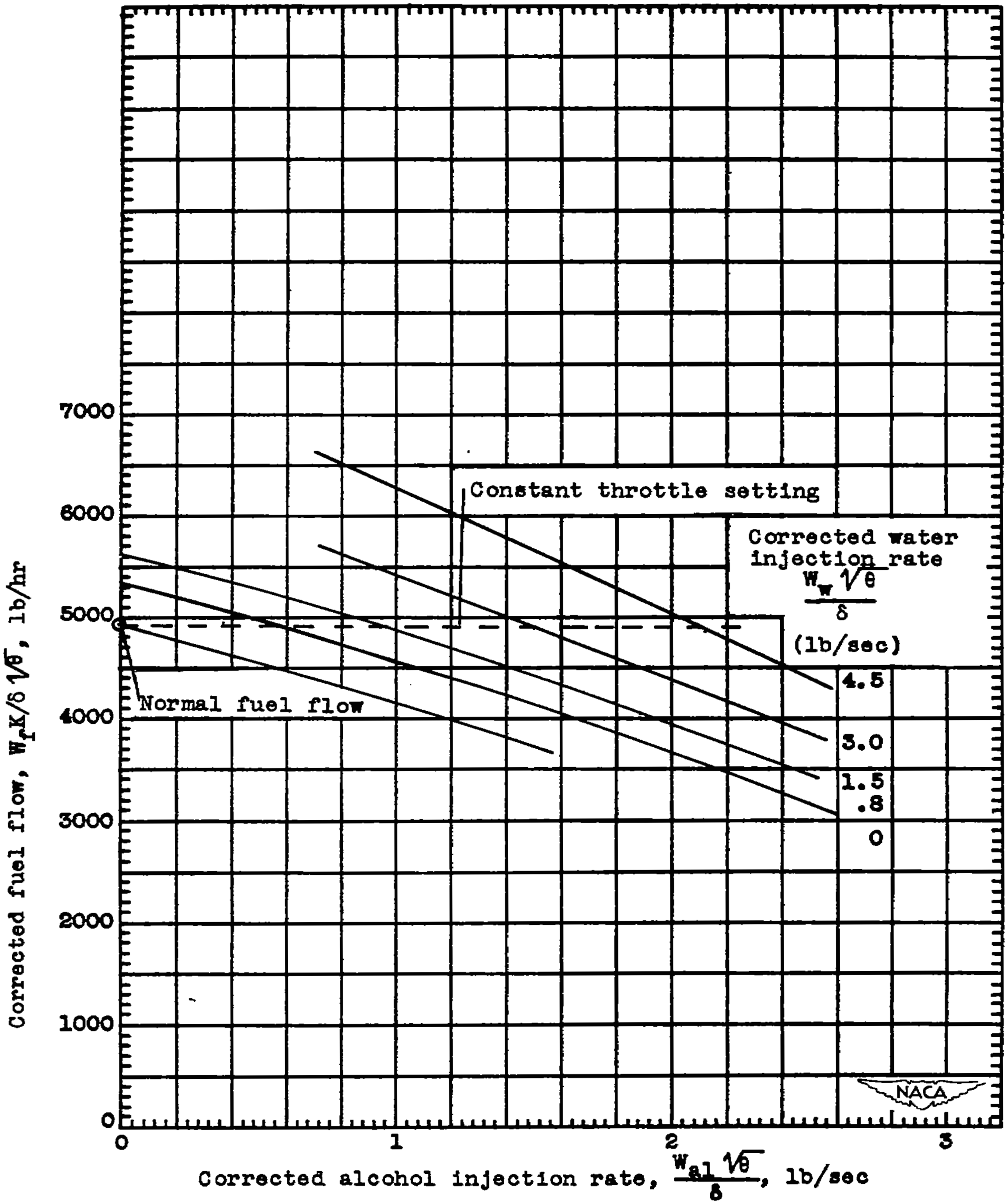


Figure 8. - Effect of alcohol injection rate on fuel flow of 4000-pound-thrust centrifugal-flow-type turbojet engine at several constant water injection rates. Corrected rotor speed, 11,500 rpm.

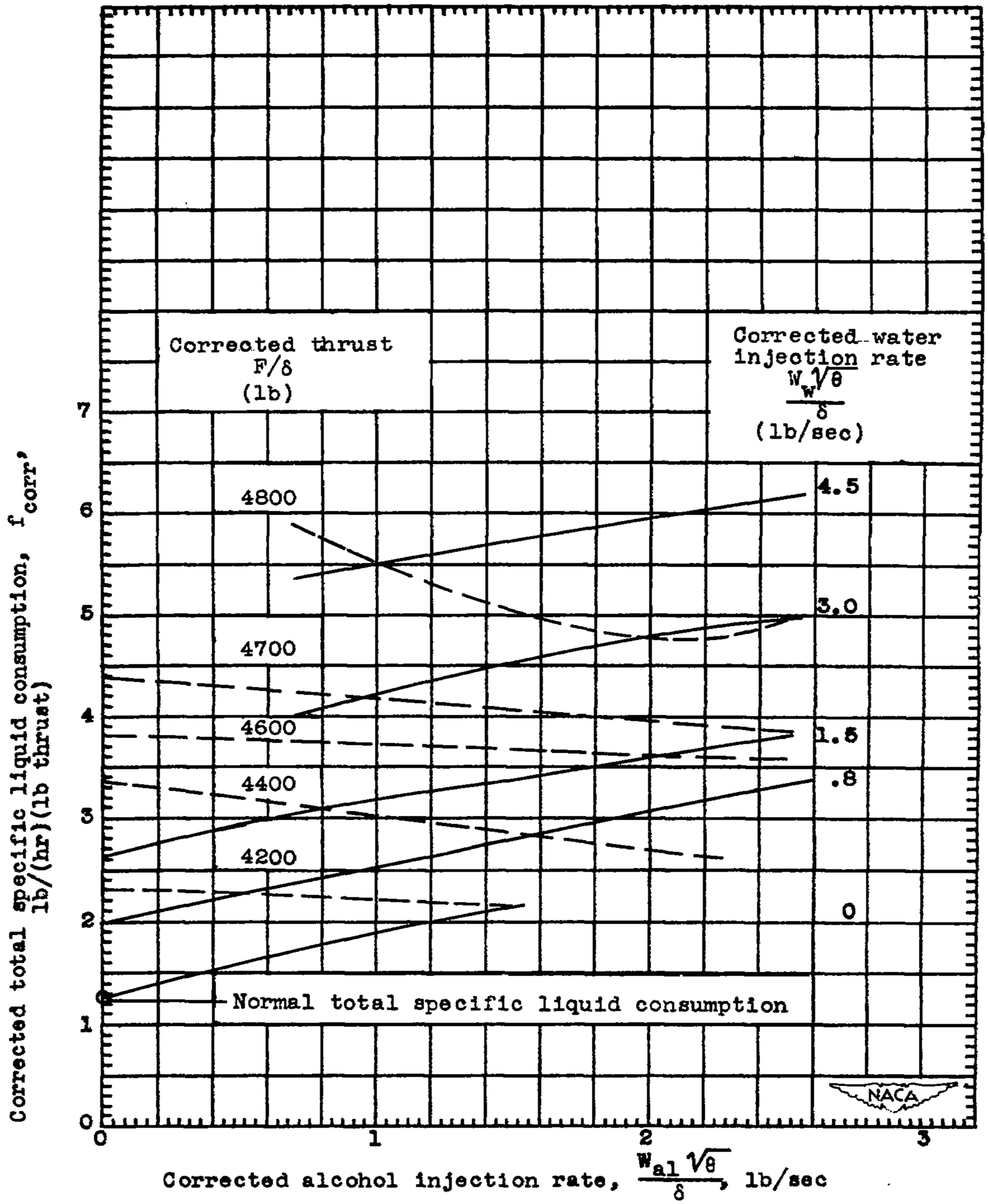


Figure 9. - Effect of alcohol injection rate on total specific liquid consumption of 4000-pound-thrust centrifugal-flow-type turbojet engine at several constant water injection rates. Corrected rotor speed, 11,500 rpm.

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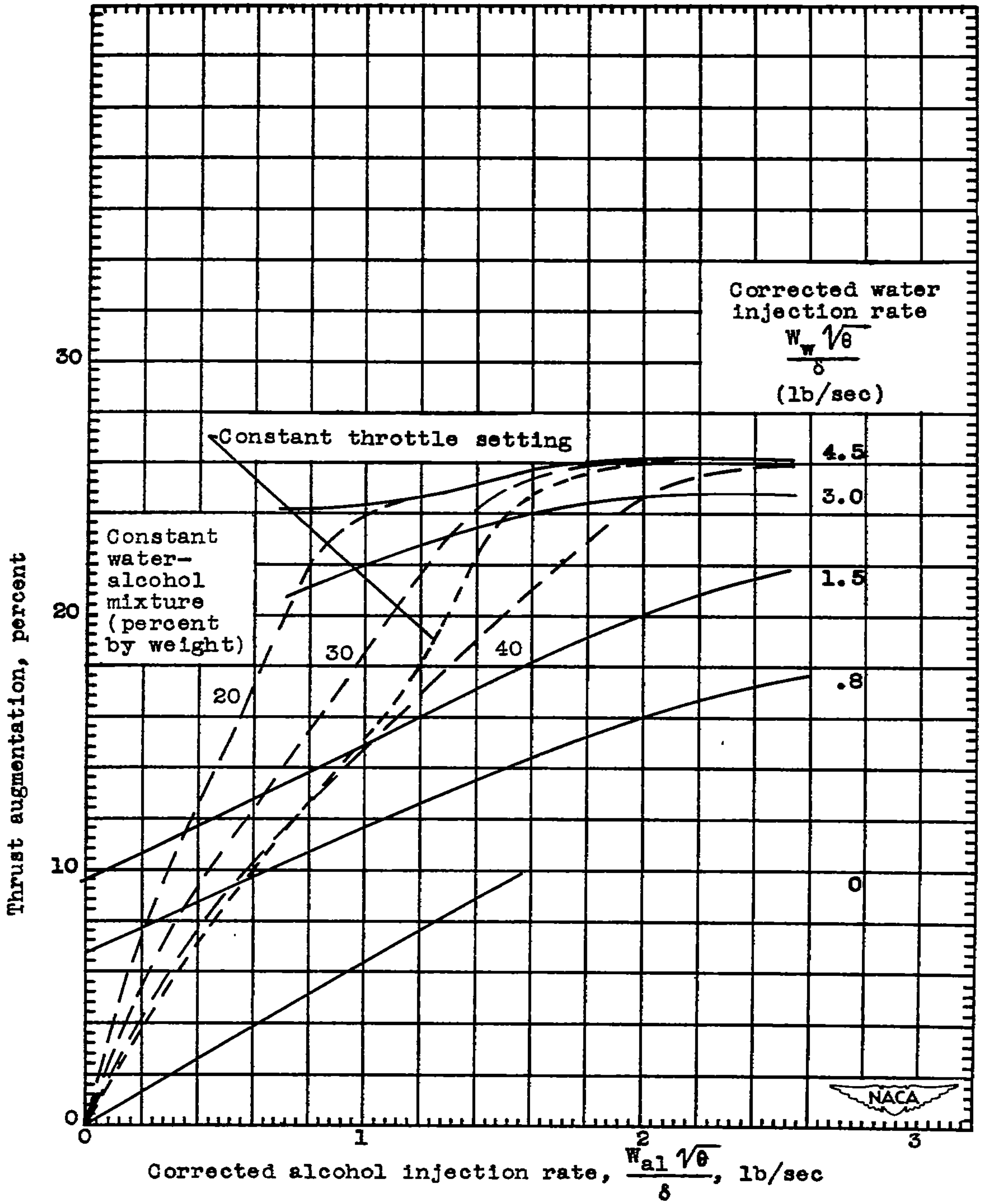

Figure 10. – Effect of alcohol injection rate on thrust augmentation of 4000-pound-thrust centrifugal-flow-type turbojet engine for several constant water injection rates. Curves of augmentation for constant percentage alcohol and constant throttle setting included. Corrected rotor speed, 11,500 rpm.