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RESEARCH MEMORANDUM

FLIGHT INVESTIGATION OF THRUST AUGMENTATION OF A TURBOJET ENGINE BY WATER-ALCOHOL INJECTION

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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FLIGHT INVESTIGATION OF THRUST AUGMENTATION OF A TURBOJET ENGINE BY WATER-ALCOHOL INJECTION

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SUMMARY

Thrust augmentation by the injection of water-alcohol mixtures into the compressor inlets of a turbojet engine with a centrifugal-flow-type compressor was investigated in flight at altitudes of sea level, 5000 feet, and 10,000 feet. The investigation was made to determine the water-alcohol mixture and the injection rate for optimum thrust augmentation.

The mixture of 20-percent alcohol by weight and an injection rate of 1.45 pounds per second produced the maximum thrust augmentation at an altitude of 10,000 feet. This injection rate is equivalent to a water-alcohol-to-air ratio of approximately 0.05 and gave a 21-percent increase in net thrust. For altitudes below 10,000 feet, the optimum water-alcohol-to-air ratio was within the range of 0.03 to 0.05. At sea level, calculations showed that the take-off distance could be reduced about 15 percent when this mixture was injected at a rate of 1.3 pounds per second, which is equivalent to a water-alcohol-to-air ratio of 0.04.

INTRODUCTION

The injection of water into the compressor is one means of augmenting the thrust of a jet engine. Water injection, by reducing the temperature of the air flowing through the compressor, increases the mass flow and the pressure ratio through the compressor and therefore the thrust of the engine.

With the injection of water alone, an increase in fuel flow is necessary to maintain maximum engine speed. If the proper amount of additional fuel, such as alcohol, is injected with the water, a change in the throttle position is unnecessary. A mixture of water and alcohol that would give the maximum thrust increase and would not require a change in throttle setting during flight is therefore desirable.

A sea-level static investigation over a wide range of water-alcohol mixtures and injection rates has been conducted with a centrifugal-flow-type turbojet engine (reference 1) similar to that used in the flight investigation reported herein. The present flight investigation was conducted at the NACA Cleveland laboratory to measure the effect of water-alcohol injection on performance at altitudes of sea level, 5000 feet, and 10,000 feet and to determine optimum mixture and injection rate for maximum augmentation. The range of mixture and injection rates for this investigation was determined from the results of the sea-level static investigation.

SYMBOLS

The following symbols are used in this report:

F_j jet thrust, pounds

F_n net thrust, pounds

N engine speed, rpm

P total pressure, pounds per square foot absolute

p static pressure, pounds per square foot absolute

T total indicated temperature, °R

t static temperature, °R

W_a air flow, pounds per second

$W_{w,al}$ injected water-alcohol flow, pounds per second

W_f fuel (kerosene) flow, pounds per hour

Subscripts:

0 ambient

1 front compressor inlet

2 rear compressor inlet

5 tail-pipe thrust ring

7 jet-survey rake

Correction Factors

All performance data were corrected to NACA standard altitude conditions by the following correction factors:

$$\delta = \frac{\text{Compressor-inlet total pressure, } P_{1,2}, \text{ (lb)/(sq ft absolute)}}{\text{Pressure at NACA standard altitude, } P_0, \text{ (lb)/(sq ft absolute)}}$$

$$\theta = \frac{\text{Compressor-inlet total temperature, } T_{1,2}, \text{ (}^{\circ}\text{R)}}{\text{Temperature at NACA standard altitude, } t_0, \text{ (}^{\circ}\text{R)}}$$

where $P_{1,2}$ and $T_{1,2}$ are the average compressor-inlet total pressure and temperature, respectively, for the engine without augmentation.

The following correction parameters are the various performance variables corrected to NACA standard altitude:

F_j/δ	jet thrust, pounds
F_n/δ	net thrust, pounds
$N/\sqrt{\theta}$	engine speed, rpm
P/δ	pressure, pounds per square foot absolute
T/θ	temperature, $^{\circ}$R
$W_a\sqrt{\theta}/\delta$	air flow, pounds per second
$W_{w,al}\sqrt{\theta}/\delta$	water-alcohol flow, pounds per second
$W_f/\delta\sqrt{\theta}$	fuel flow, pounds per hour

APPARATUS AND PROCEDURE

A twin turbojet engine pursuit airplane (fig. 1) was instrumented to measure the fundamental characteristics of a turbojet engine in flight. The right engine was completely instrumented for performance measurement. The engine has a double-faced, centrifugal-flow-type compressor and a 12.5-inch-diameter jet nozzle. The sea-level thrust rating of the engine is 1600 pounds at a engine speed of 16,500 rpm.

The water-alcohol mixtures for thrust augmentation were introduced at the compressor inlets by means of 20 spray nozzles mounted on a common circular manifold fitted to the compressor casing. Ten nozzles were equally spaced around each compressor inlet (fig. 2). The water-alcohol mixture was pumped from two drop tanks that served as reservoirs for the mixture.

Location of the stations at which instrumentation was installed is indicated in a cross-sectional drawing of the engine (fig. 3). Ten shielded total-pressure tubes and ten iron-constantan thermocouples were evenly spaced around the periphery of each compressor inlet (stations 1 and 2). In the tail pipe, station 5, two total-pressure tubes, two static-wall orifices, and eight equally spaced chromel-alumel thermocouples served as a calibrated thrust ring. This ring was calibrated with the tail pipe and the nozzle for the measurement of jet thrust and gas flow.

The jet was surveyed by a rake that moved across the jet 1 inch downstream of the exit of the tail pipe for the purpose of determining the jet temperature and pressure distribution. The survey rake included 12 thermocouples, 20 total-head tubes, and 5 static-head tubes (fig. 4).

The fuel flow to the engine was measured by a rotating vane-type meter and was both recorded and indicated on flight instruments. The water-alcohol flow was measured in the same manner as the fuel flow. These flows were indicated on the pilot's instrument panel. The engine speed was measured by a tachometer generator that transmitted voltages to a recording and indicating instrument. A NACA standard airspeed boom and instrument were used to record the altitude and the airspeed. A calibrated resistance bulb indicated the ambient-air temperature. All instruments were accurate within ±2 percent with the exception of the fuel- and water-flow measuring units, which were accurate within ±5 percent.

A constant ram-pressure ratio was maintained at the compressor inlets by flying at a constant airspeed with the left engine used as a speed control. Several runs were made during a single flight to establish the standard performance characteristics of the engine at that altitude and thrust-augmented runs were then conducted with varied injection rates at two engine speeds, 16,500 and 15,500 rpm.

The range of water-alcohol injection rate was from 0.5 to 2 pounds per second. The alcohol in the mixture used was 50-percent ethyl, 50-percent methyl blend. The freezing point of the water-alcohol mixture was about 12° F and permitted safe operation to a NACA standard altitude of 13,000 feet. All data were recorded under a stabilized condition.

RESULTS AND DISCUSSION

Sea-level static runs over a range of water-alcohol mixtures were conducted with an engine similar to that used in the flight investigation reported herein. The static runs (reference 1) indicated that an increase of 23 percent in thrust had been achieved with water injection alone at 16,500 rpm and that a mixture of about 20-percent alcohol by weight would permit operation with injection without adjustment of the throttle from the normal operating position.

A preliminary ground investigation was made to check the static sea-level results presented in reference 1. Flight tests were then conducted at an altitude of 10,000 feet to determine the optimum mixture for maximum thrust augmentation during flight. Mixtures of 17-, 20-, and 23-percent alcohol to water by weight with varying rates of injection were used. The maximum increase in net thrust was obtained with the 20-percent alcohol mixture, as indicated in figure 5.

The subsequent flight runs were made with a 20-percent alcohol mixture. The curves presented in figures 6 to 9 represent performance data that have been corrected to NACA standard altitude conditions. These data were obtained at an airspeed corresponding to a constant compressor-inlet ram-pressure ratio of 1.095. Varied engine speeds and water-alcohol injection rates were used.

At an altitude of 10,000 feet and a corrected engine speed of 16,000 rpm, the increase in net thrust due to water-alcohol injection was about 185 pounds or about 21 percent of the normal thrust at that engine speed (fig. 6). Over the range of water-alcohol injection rates used, the variation in thrust with injection rates was very slight; figure 7 shows an increasing amount of thrust augmentation with increasing water-alcohol injection to a rate of approximately 1.45 pounds per second and then very little change with additional water-alcohol injection. This rate was equivalent to a water-alcohol-to-air ratio of approximately 0.05.

With the injection of the water-alcohol mixture, the fuel flow increased slightly, as indicated in figure 8. A 4-percent increase in fuel flow occurred during the augmented runs, which was about 1 pound per minute more than normal at 16,000 rpm. Inasmuch as this difference in flow rates was beyond the accuracy of the flow-measuring instruments, no further attempt was made to maintain a constant fuel flow when the water-alcohol mixture was added to the engine. A slight throttle adjustment was sometimes required to maintain the same engine speed. In most of the runs the engine speed dropped slightly with water-alcohol injection, then increased and stabilized at the original value.

The tail-pipe temperature was noticeably cooler during the augmented runs; the difference in tail-pipe temperatures of the normal dry run and the augmented run increased with increasing injection rate (fig. 9). More thrust could be obtained if the tail-pipe temperature was maintained at its maximum design limit during water-alcohol injection. The use of an adjustable-area exhaust nozzle in conjunction with water-alcohol injection would increase the amount of thrust augmentation (reference 1) by maintaining the maximum tail-pipe temperature permitted.

The effect of various water-alcohol-to-air ratios upon thrust augmentation at three altitudes is indicated in figure 10. At sea level, 5000 feet, and 10,000 feet, the curves proved to be rather flat above the water-alcohol-to-air ratio of approximately 0.04. These curves indicate that the optimum water-alcohol-to-air ratio was within the range of 0.03 to 0.05 and the higher the altitude, the less water-alcohol injection is required for maximum augmentation because at a constant engine setting the air flow decreases with altitude. The specific liquid consumption based on net thrust was raised about 250 percent during operation at a water-alcohol-to-air ratio of about 0.04. This high specific liquid consumption limits operation with water-alcohol injection to short periods of time.

Thrust augmentation by water-alcohol injection would be most applicable for take-off by reducing the take-off distance. A series of ground runs were therefore made to determine the injection rate for maximum thrust augmentation at sea level, using a 20-percent alcohol-water mixture. The results presented in figure 11 indicate that at a corrected engine speed of 16,525 rpm this injection rate would be somewhat higher than 1.3 pounds per second.

Calculations for the optimum rate of water-alcohol injection for a twin-engine take-off were made. The take-off distance for lift-off at several injection rates were calculated, assuming an idealized airplane having a maximum lift-drag ratio of 12, a wing loading of 28.5 pounds per square foot, a take-off weight of 12,000 pounds plus 30 pounds of augmentation equipment with a 1-minute supply of water-alcohol mixture. The optimum rate of water-alcohol injection was about 1.3 pounds per second (fig. 12). This injection rate was equivalent to a water-alcohol-to-air ratio of 0.04, and decreased the take-off distance about 15 percent for an increase in the aircraft weight of only 2 percent. The reduction in the take-off distance was effected by an increase of 14 percent in thrust.

The use of water alcohol as a means of thrust augmentation presented several installation problems. The greatest problem was the contamination of the lubricating oil with water-alcohol mixture, which resulted in corrosion and breakdown of engine bearings. In some jet engines, filtered air for atomization and cooling of bearing oils is taken from the compressor. When water-alcohol mixture is injected into the compressor, the bearing air, which should be relatively dry, carries vapors of water and alcohol that condense out in the bearing oil. Cooling coils and traps were designed to rid the bearing air of excessive moisture. These methods were ineffective and the air for the bearings had to be taken from the left engine during the augmented runs.

SUMMARY OF RESULTS

From the investigations in which water-alcohol mixtures were injected into the inlets of a centrifugal-flow-type turbojet engine in flight, the following results were obtained:

1. At a NACA standard altitude of 10,000 feet and an engine speed of 16,000 rpm, the mixture and injection rate for optimum thrust augmentation was found to be 20-percent alcohol to water by weight injected at a rate of approximately 1.45 pounds per second, which was equivalent to a water-alcohol-to-air ratio of 0.05. This mixture gave a 21-percent increase in net thrust.

2. The optimum water-alcohol-to-air ratio for thrust augmentation was within the range of 0.03 to 0.05 at altitudes up to 10,000 feet and engine speeds from 15,960 to 16,525 rpm.

3. Calculations showed that it was possible to decrease the take-off distance of an idealized airplane at sea level approximately 15 percent by the use of a 20-percent alcohol-water mixture injected at a water-alcohol-to-air ratio of 0.04.

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

REFERENCE

1. Jones, William L., and Dowman, Harry W.: Experimental Investigation of Thrust Augmentation of a 1600-Pound Thrust Centrifugal-Flow-Type Turbojet Engine by Injection of Refrigerants at Compressor Inlets. NACA RM No. E7G23, 1947.

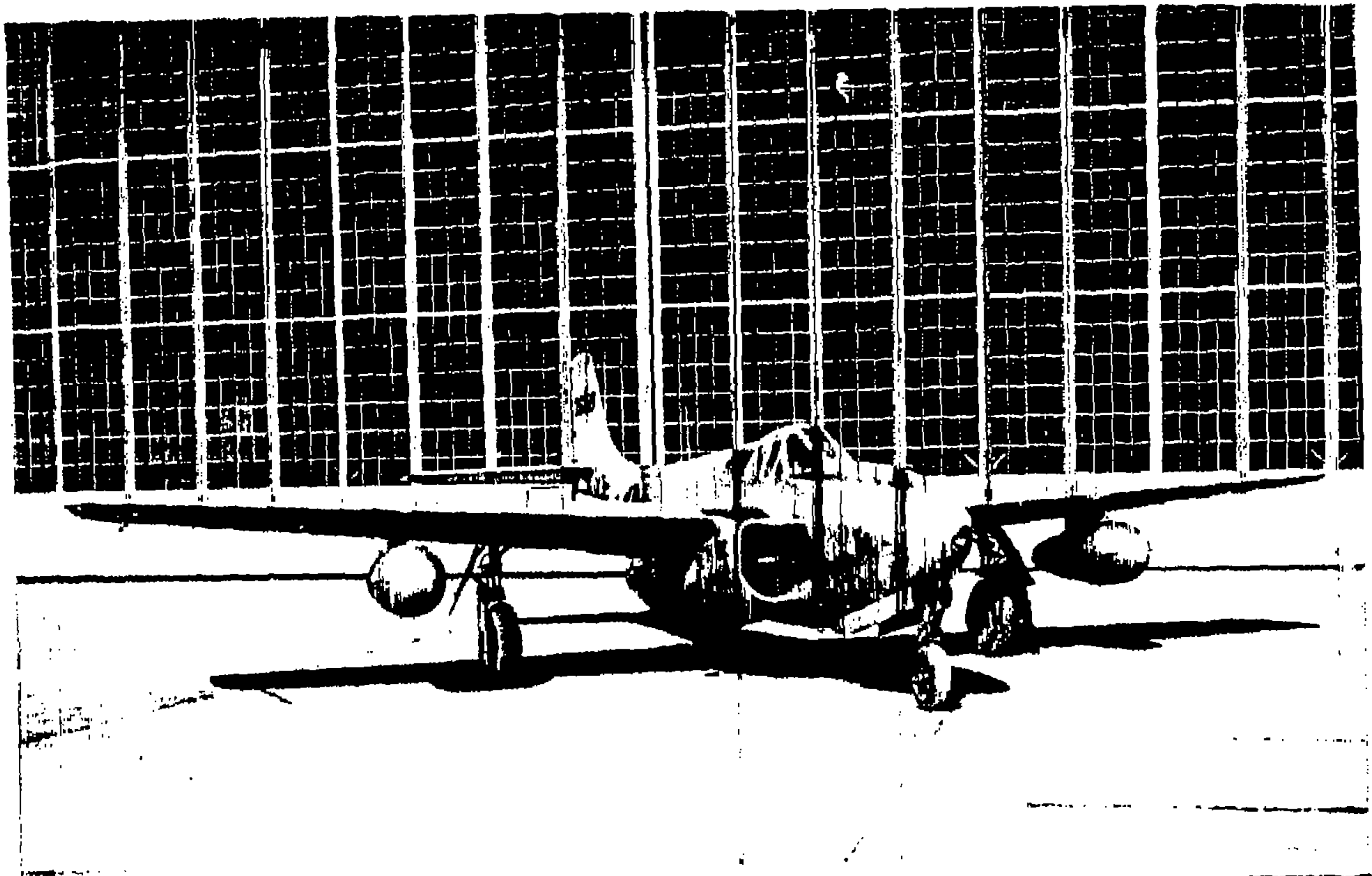

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Figure 1. - Twin turbojet engine pursuit airplane used in flight investigation of thrust augmentation.

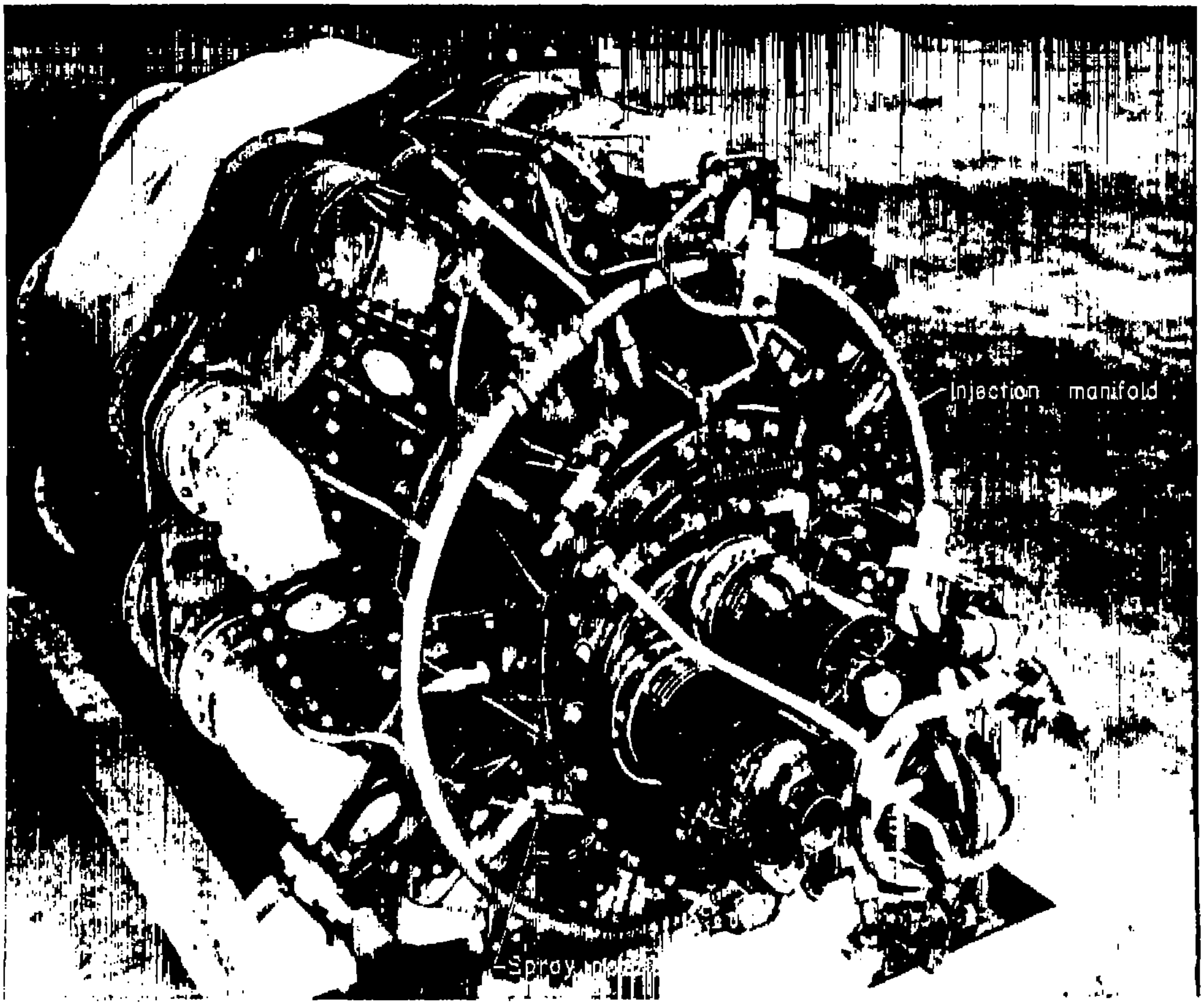

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Figure 2. - Water-alcohol-injection spray ring fitted to compressor casing.

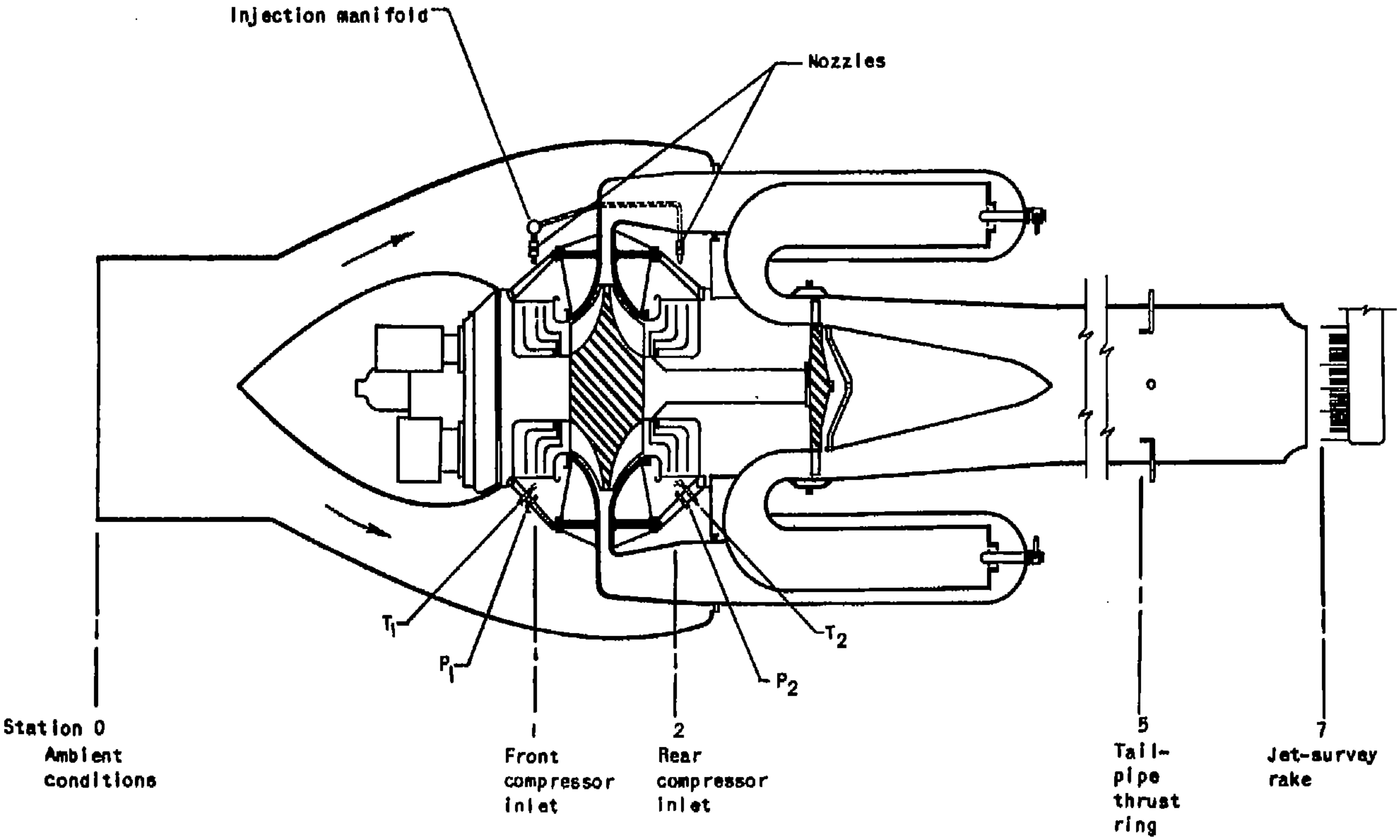

Figure 3. - Instrumentation and injection equipment for turbojet engine.

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Figure 4. - Survey rake installed behind tail-pipe exhaust nozzle.

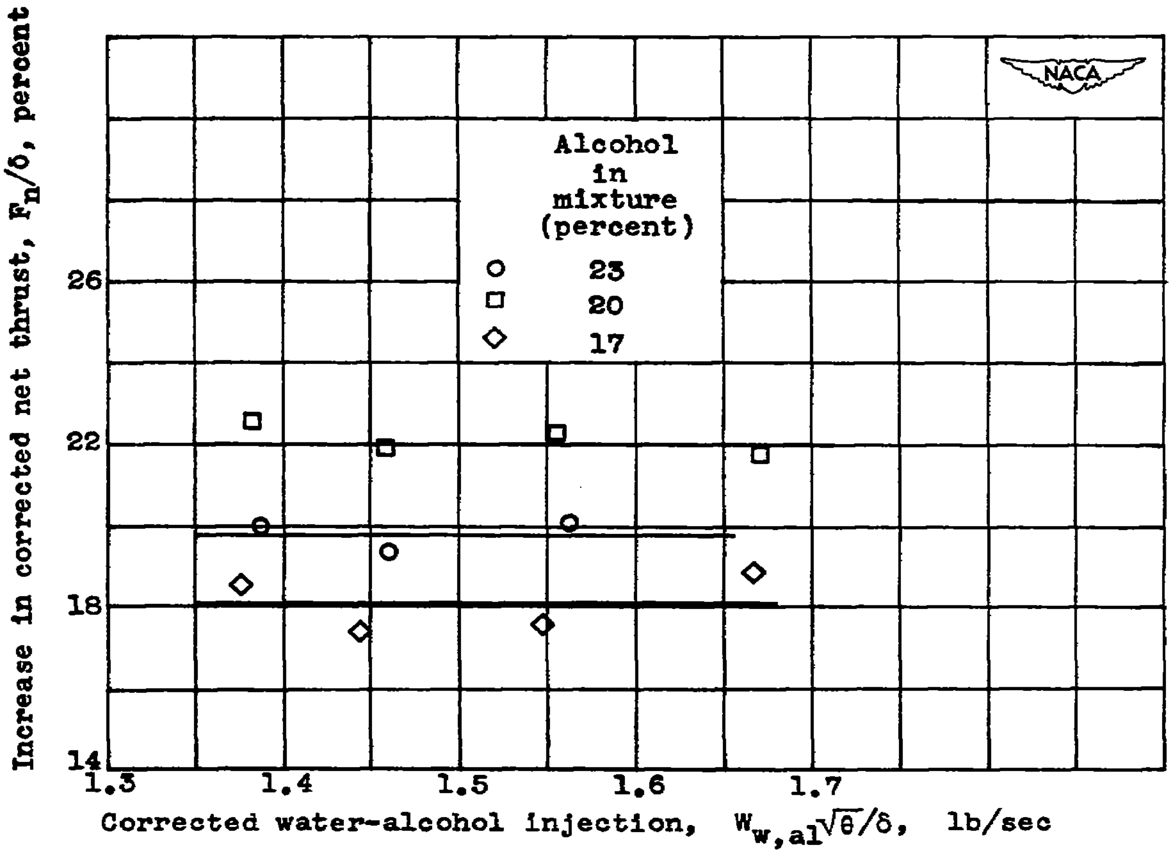

Figure 5. - Increase in corrected net thrust for three water-alcohol mixtures at NACA standard altitude of 10,000 feet and ram-pressure ratio of 1.095. Corrected engine speed, $N/\sqrt{\theta}$, 16,000 rpm.

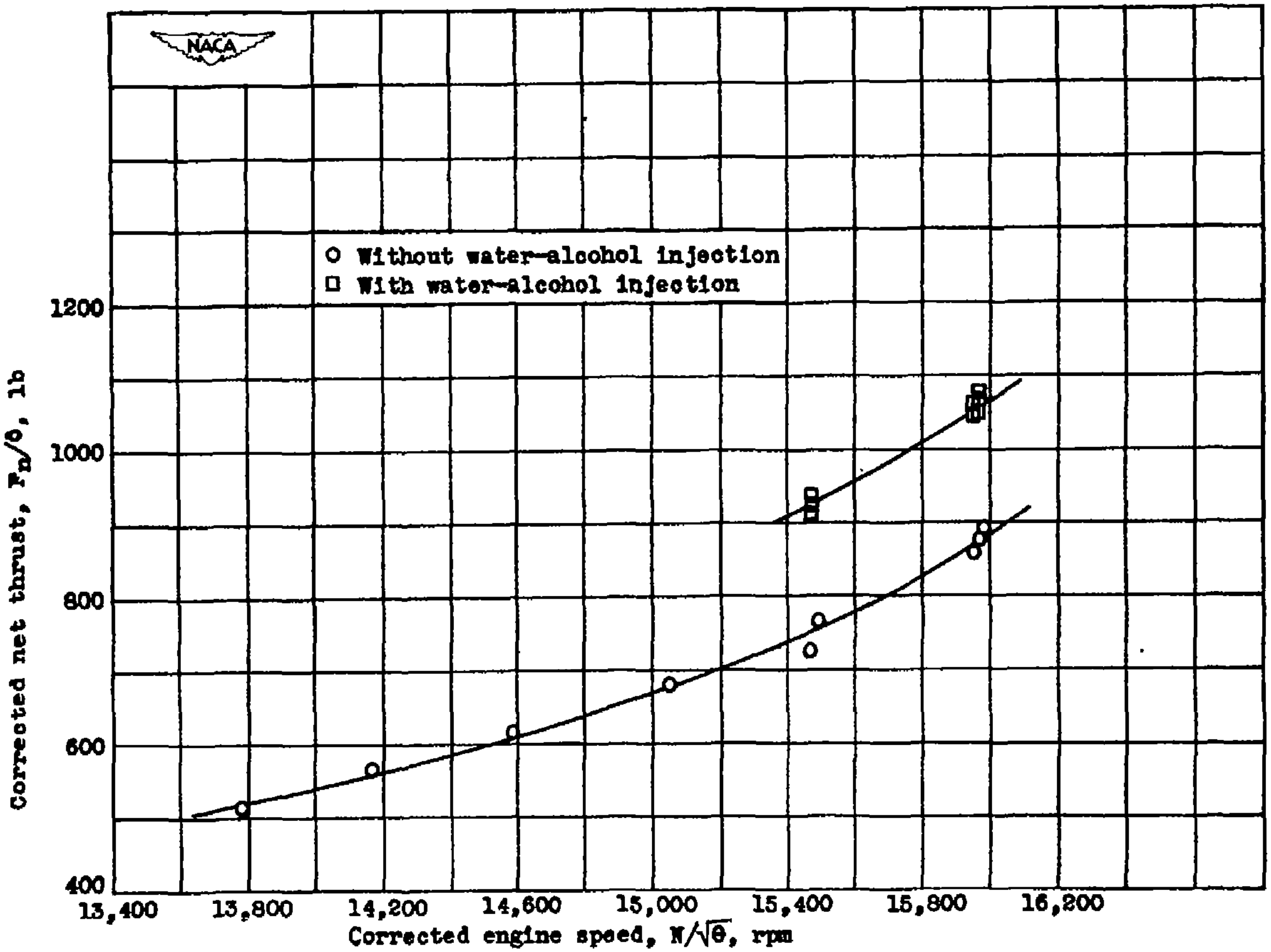

Figure 6. - Comparison of corrected net thrust with and without water-alcohol injection at NACA standard altitude of 10,000 feet and ram-pressure ratio of 1.095. Water-alcohol injection, 1.2 to 1.7 pounds per second; alcohol, 20 percent by weight.

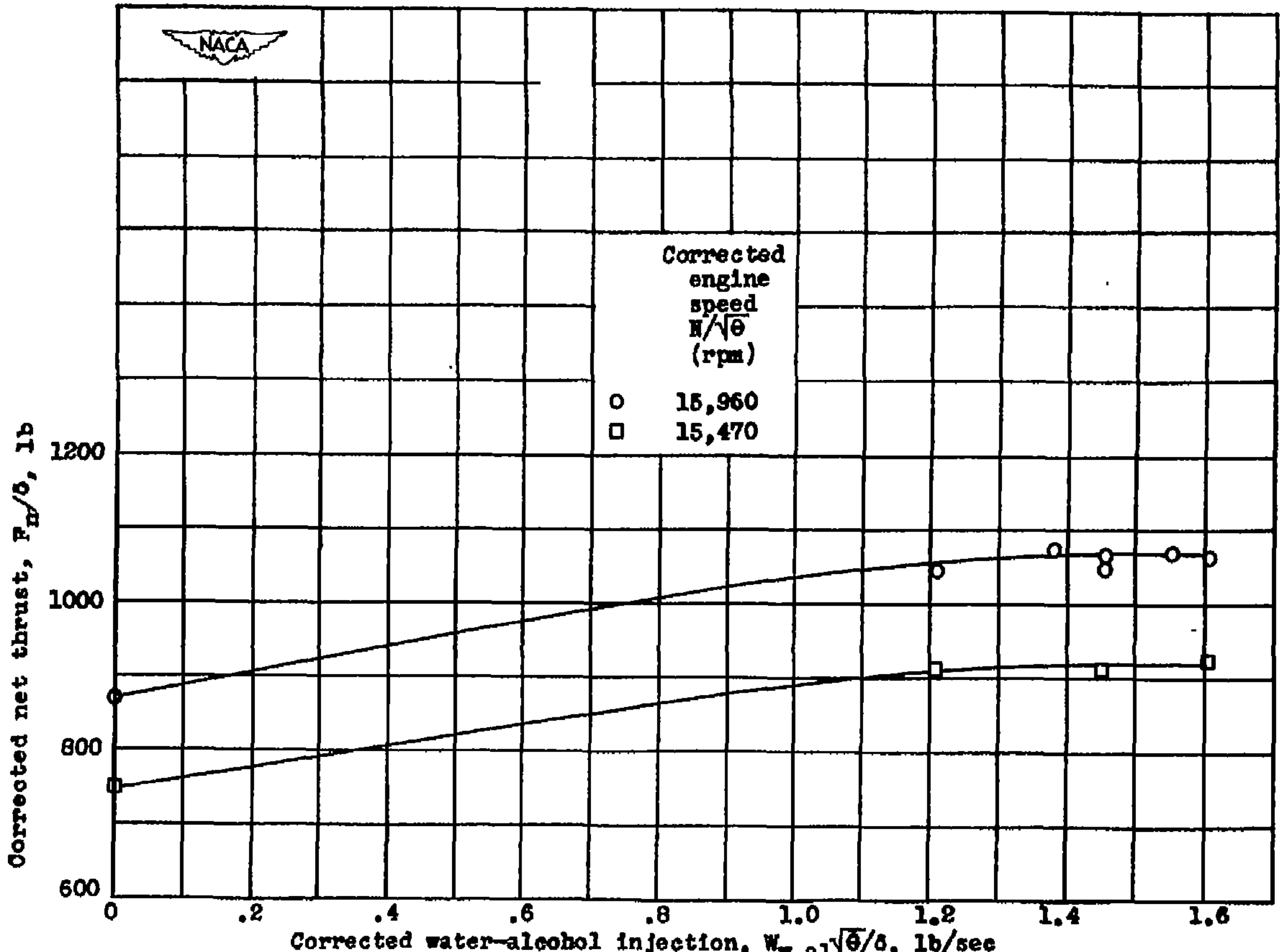

Figure 7. - Comparison of corrected net thrust for various water-alcohol injection rates and two corrected engine speeds at NACA standard altitude of 10,000 feet and ram-pressure ratio of 1.095. Alcohol, 20 percent by weight.

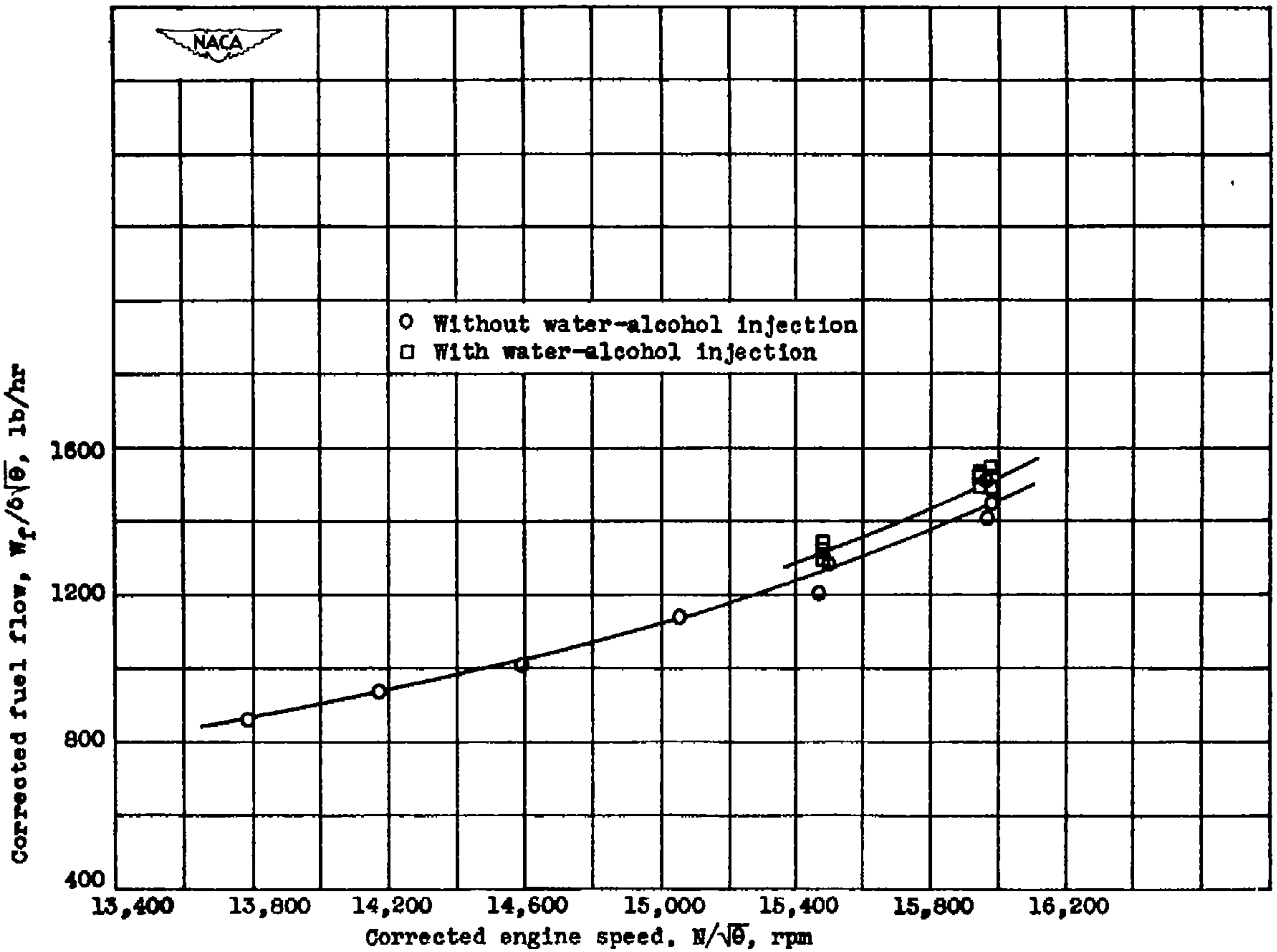

Figure 8. - Fuel consumption with and without water-alcohol injection at NACA standard altitude of 10,000 ft and ram-pressure ratio of 1.095. Water-alcohol injection, 1.2 to 1.7 pounds per second; alcohol, 20 percent by weight.

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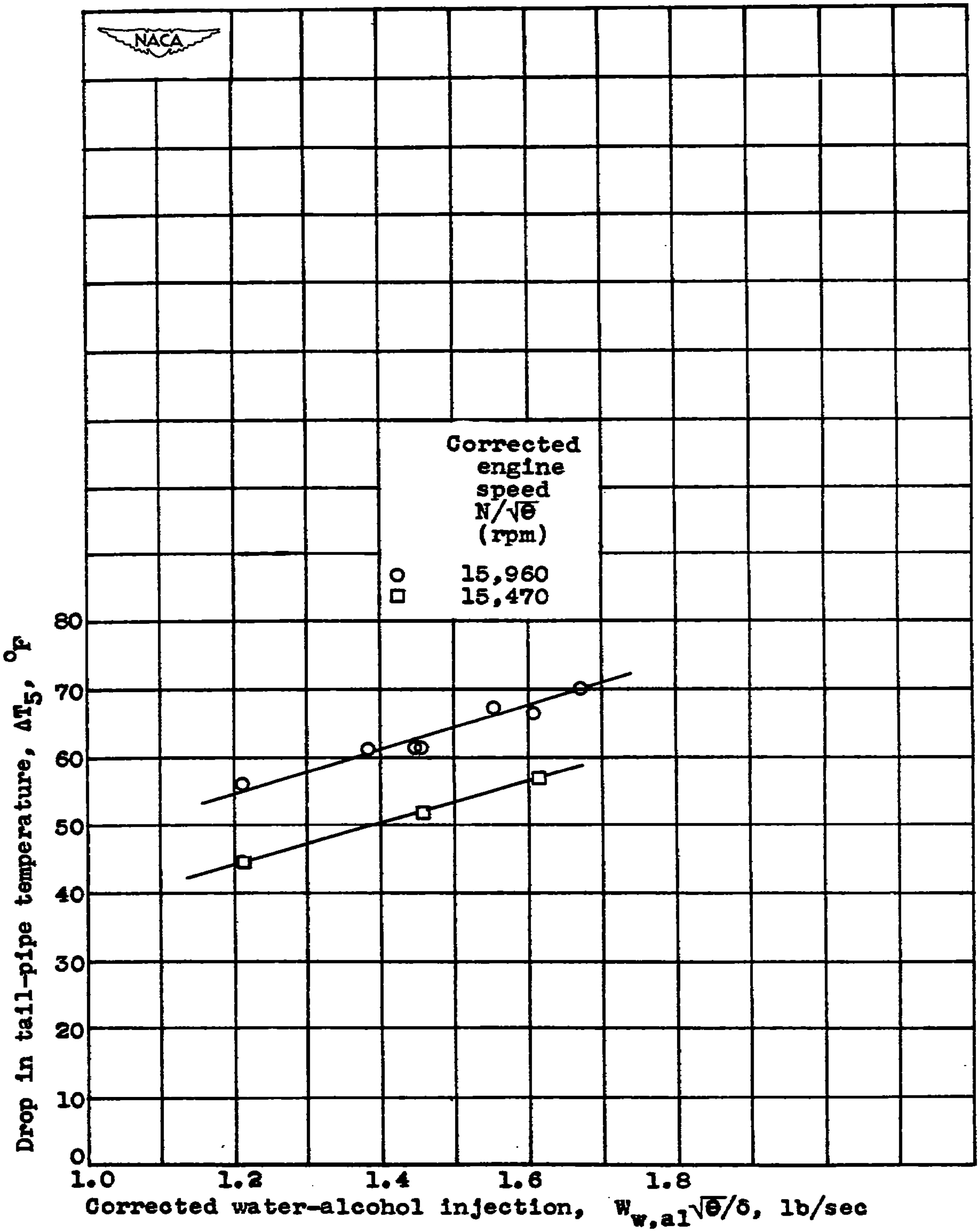

Figure 9. - Decrease in tail-pipe temperature from normal for various water-alcohol injection rates and two corrected engine speeds at NACA standard altitude of 10,000 feet and ram-pressure ratio of 1.095. Alcohol, 20 percent by weight.

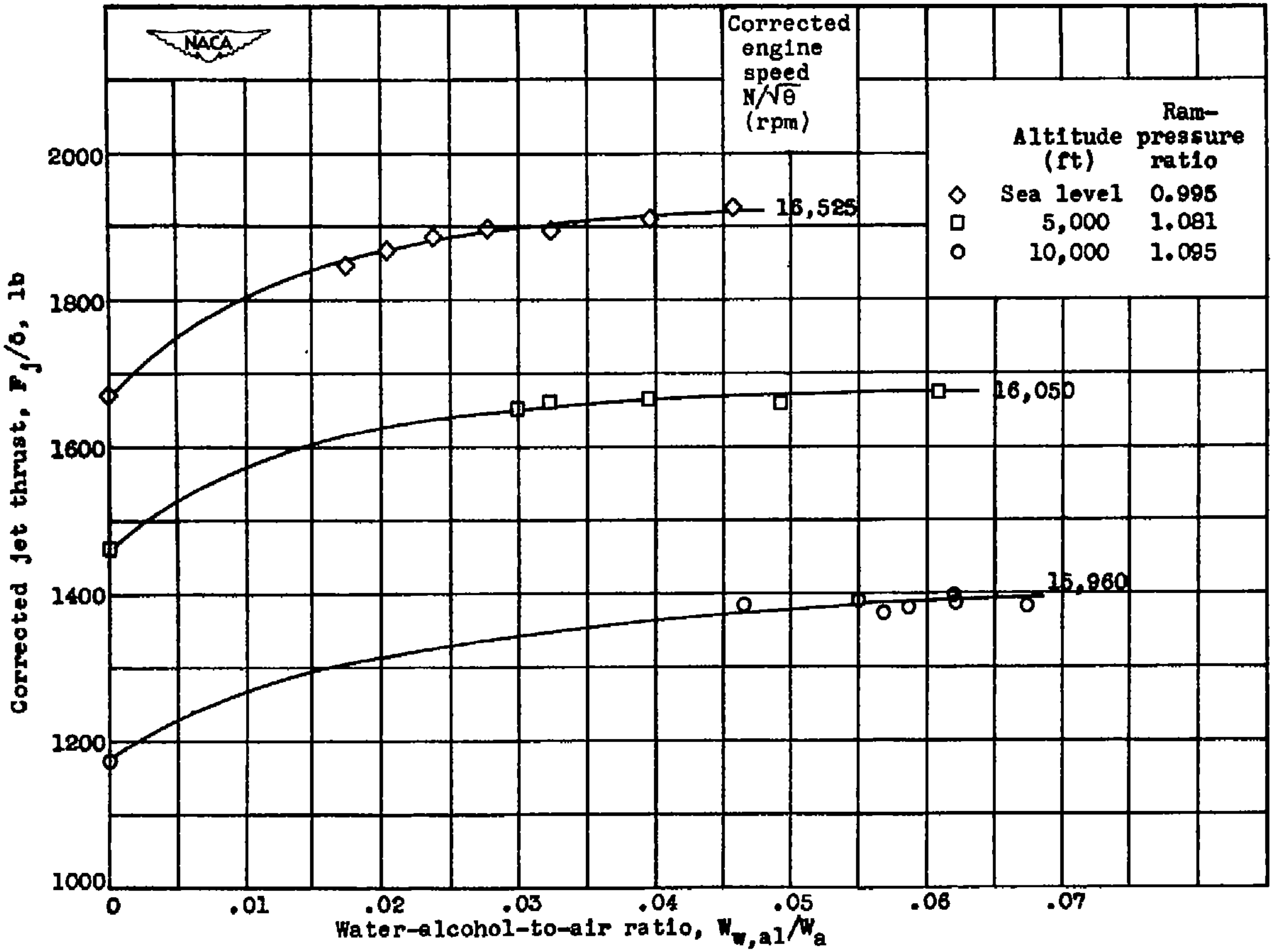

Figure 10. - Effect of water-alcohol-to-air ratio on corrected jet thrust at three altitudes and engine speeds. Alcohol, 20 percent by weight.

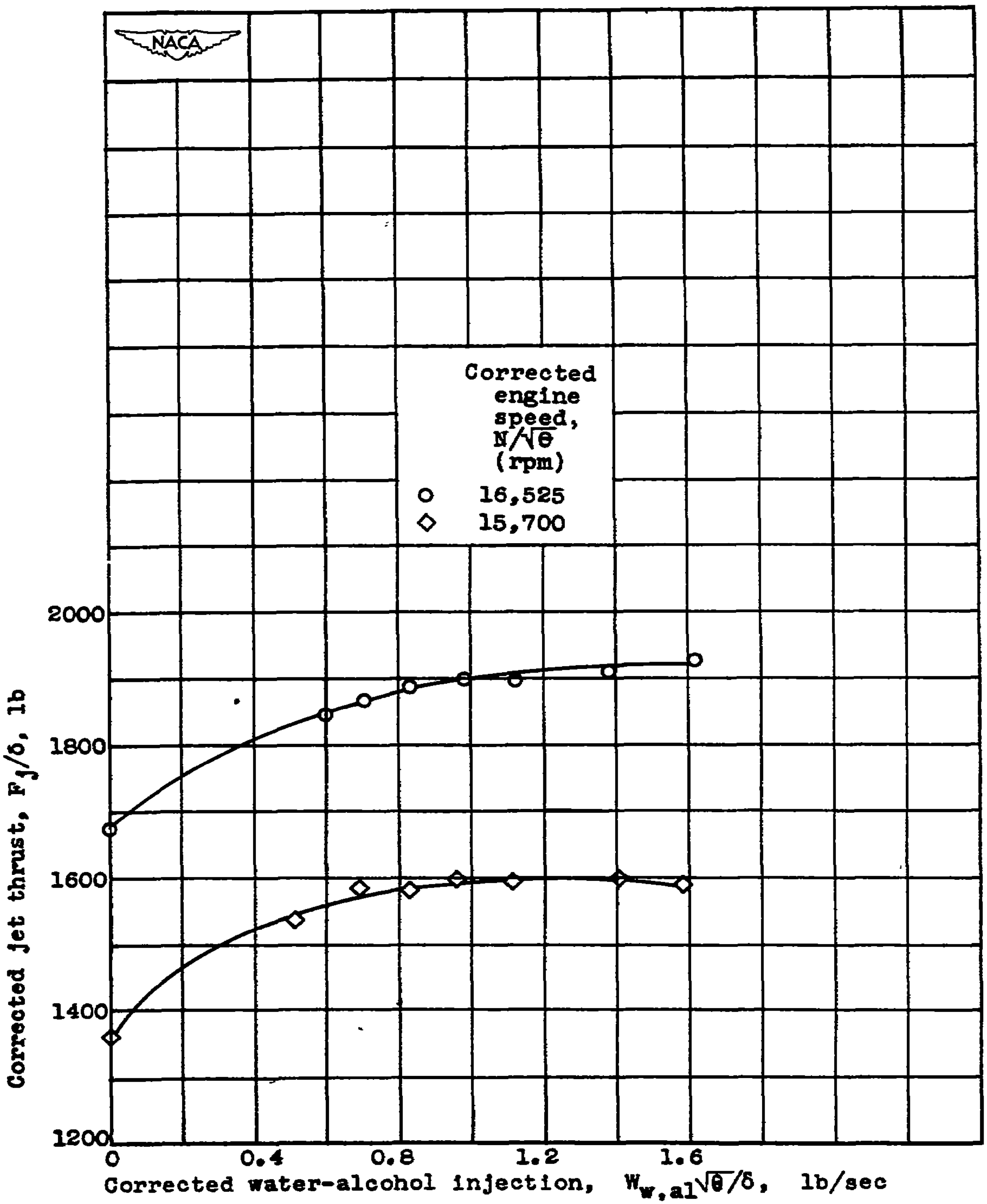

Figure 11. - Effect of water-alcohol injection rate on corrected jet thrust for two engine speeds at standard sea level and ram-pressure ratio of 0.995. Alcohol, 20 percent by weight.

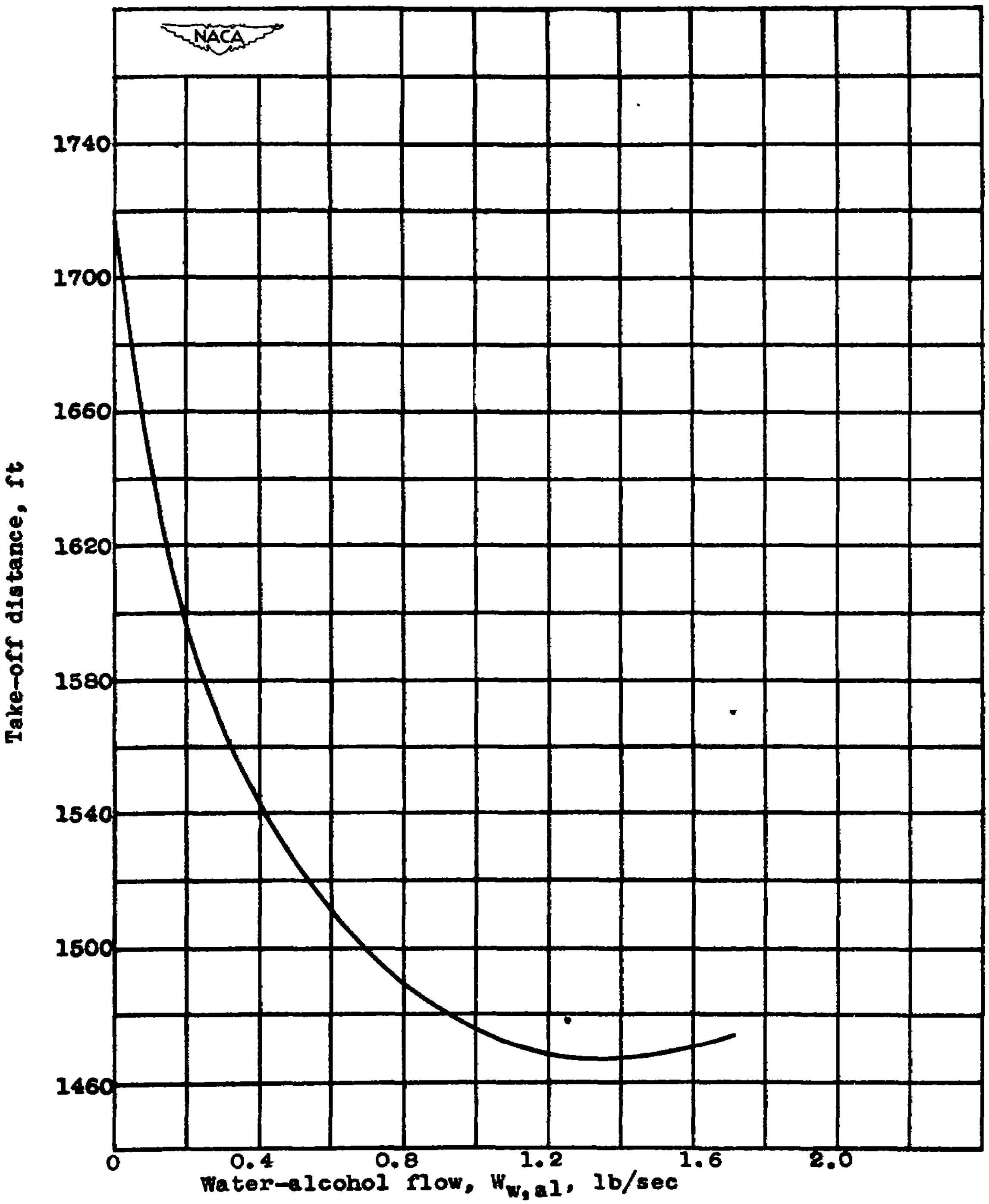

Figure 12.- Thrust-augmented sea-level take-off distances for idealized twin-engine airplane as affected by various water-alcohol (20-percent alcohol by weight) injection rates. Maximum lift-drag ratio, 12; wing loading, 28.5 pounds per square foot; take-off weight, 12,000 pounds.