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RESEARCH MEMORANDUM

INVESTIGATION OF THRUST AUGMENTATION OF A 1600-POUND THRUST CENTRIFUGAL-FLOW-TYPE TURBOJET ENGINE BY INJECTION OF REFRIGERANTS AT COMPRESSOR INLETS

By William L. Jones and Harry W. Dowman

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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INVESTIGATION OF THRUST AUGMENTATION OF A 1600-POUND THRUST CENTRIFUGAL-FLOW-TYPE TURBOJET ENGINE BY INJECTION OF REFRIGERANTS AT COMPRESSOR INLETS

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SUMMARY

The performance of a centrifugal-flow-type turbojet engine (having a normal military rating of 1600-lb thrust at a rotor speed of 16,500 rpm), has been investigated at zero flight speed with injection of refrigerants at the compressor inlets. The largest part of these investigations was devoted to the injection of water and water-alcohol mixtures; brief investigations were also conducted with the injection of kerosene and carbon dioxide.

The engine performance with the injection of water was investigated over a range of rotor speeds. Three different exhaust-nozzle sizes were used in order to evaluate the thrust augmentation possible when an adjustable-area exhaust nozzle is used. Various mixtures of water and alcohol were injected for a range of total flows up to 2.2 pounds per second. The runs with kerosene injected into the compressor inlets covered a range of injected flows up to approximately 30 percent of the normal engine fuel flow and were conducted over a range of rotor speeds. The carbon dioxide was injected in snow form from standard 75-pound fire-extinguisher bottles and its use was investigated both alone and with the injection of water and alcohol.

The injection of 2.0 pounds per second of water alone would provide a thrust augmentation of 35.8 percent at rated engine conditions for operation with an adjustable-area exhaust nozzle. A maximum thrust augmentation at zero flight speed of 40 percent was indicated at rated engine conditions for operation with an adjustable-area exhaust nozzle by injection of 1.6 pounds per second of water and 0.4 pound of alcohol per second. The injection of kerosene produced a negligible increase in thrust. A thrust augmentation of 23.5 percent was obtained with the injection

of 4.6 pounds per second of carbon dioxide alone. The injection of 3.5 pounds per second of carbon dioxide with a mixture of water and alcohol provided a thrust augmentation of 36 percent, 16 percent of which was contributed by the carbon dioxide.

INTRODUCTION

Thrust augmentation of turbojet engines to provide improved take-off, climb, and high-speed flight characteristics is of importance in increasing the effectiveness of the application of turbojet engines to both civilian and military aircraft. One of the methods of increasing the thrust of the turbojet engine is by the injection of refrigerants at the compressor inlets. This method increases the density of the air and the compressor Mach number. The increased density gives a higher mass flow through the engine and the increased compressor Mach number yields a higher pressure ratio across the compressor. Both of these factors increase the thrust of the engine.

As part of a general research program being conducted at the NACA Cleveland laboratory to investigate various methods of thrust augmentation, the performance of a centrifugal-flow-type turbojet engine at zero flight speed and sea-level conditions with injection of water and water-alcohol mixtures has been determined. For the investigation reported, which was conducted during the fall of 1944, various mixtures of water and alcohol were used over a range of injected liquid flows. The engine performance with injection of water was determined over a range of rotor speeds; the use of water-alcohol mixtures was investigated at two rotor speeds. Three different exhaust-nozzle sizes were used in order to evaluate the thrust augmentation possible if an adjustable-area exhaust nozzle were used.

The investigation with injection of water-alcohol mixtures was of importance because of: (a) the provision in the injected mixture of the extra fuel that is required for operation with water injection; (b) the possibility of choosing a mixture that would eliminate the need for adjustment of the fuel throttle during injection; and (c) the low freezing temperature of water-alcohol mixtures.

In addition to the investigation of engine performance with water and alcohol injection, brief investigations were also conducted with the injection of kerosene and carbon dioxide. The investigations with kerosene injection covered a range of injected flows up to approximately 30 percent of the normal fuel flow and were conducted over a range of rotor speeds. The carbon dioxide was injected in snow form from standard 75-pound fire-extinguisher bottles and its use was investigated both alone and in conjunction with the injection of water and alcohol.

APPARATUS

General Setup

The general arrangement of the test setup is shown in figure 1. The investigations were conducted on an I-16 turbojet engine (normal rating, 1600-lb thrust) that was rigidly mounted on a framework suspended from the ceiling of the test cell by four rods supported by ball-bearing pivots. The tail pipe of the engine extended through an air seal in the outside wall of the test chamber. All supply lines to the engine were of flexible hose in order that restraining forces would be at a minimum. Lateral movement of the engine and the frame was prevented by means of ball-bearing guide rollers. The thrust exerted by the suspended engine was transmitted by a cranklever arrangement to the diaphragm of a calibrated balanced pressure cell. Measurement of the balancing pressure provided an indication of the engine thrust. The fuel flow (kerosene) to the engine was measured by calibrated rotameters. A chronometric tachometer was used to measure the rotor speed. The air supply to the engine entered the nearly airtight test chamber through an 18-inch throat-diameter A.S.M.E. standard air-measuring nozzle. A diffuser, which had an area ratio of 4, was connected to the nozzle in order to convert the velocity pressure at the nozzle throat to static pressure in the test cell. The cell leakage, which was found by calibration to be less than 0.3 percent of the total air flow, was added to the measured air flow.

An aluminum cowl and a wooden inlet-air nozzle were installed on the engine to restrict the inlet-air flow to an area in which the temperature could be accurately measured.

Injection Equipment

Water and alcohol injection. - Water and alcohol mixtures were injected through twenty 37.5-gallon-per-hour spray nozzles connected to a common manifold, as shown in figure 2. Ten nozzles were equally spaced around each compressor-inlet screen. Water and alcohol flows were measured by calibrated orifices. The alcohol used in these investigations was approximately 50-percent methyl and 50-percent ethyl by weight.

Kerosene injection. - For the injection of kerosene, the engine fuel system was so revised that both the fuel injected into the compressor and the fuel supplied to the engine burner nozzles passed through the overspeed governor. Separate throttles were provided for each fuel line. The kerosene was injected into the compressor inlets through twenty 6.5-gallon-per-hour spray nozzles installed in the same manner as the water-alcohol injection nozzles. The total flow of kerosene to the engine was measured by a calibrated rotameter. The injected kerosene flows at the compressor inlets were determined by a flow calibration of the injection nozzles.

Carbon-dioxide injection. - The additional equipment required for the injection of carbon dioxide is shown in the foreground of the photograph presented in figure 3. (The injection manifold shown mounted on the inlet nozzle was not used during these runs.) Carbon dioxide from 75-pound-capacity fire extinguishers was injected into the inlet-air stream in snow form.

Several bottles of carbon dioxide were discharged to obtain weight-flow calibrations. The results of five such calibrations are presented in figure 4 from which carbon-dioxide flows have been determined for these investigations. Although the data for these curves scatter somewhat, the trends indicate that the flow rate of carbon dioxide is dependent on its initial temperature with the greatest flow rates occurring at the highest temperature.

Pressure and Temperature Instrumentation

The stations at which the engine was instrumented for temperature and pressure measurements are shown in figure 2. The variables measured and the number, type, and location of instruments are:

(a) Cowl-inlet total temperature T_0, average of six unshielded thermocouples in inlet-air nozzle

(b) Cowl-inlet total pressure P_0, one open-end tube in test cell

(c) Compressor-outlet total temperature (inlet of burner 10) T_2, one unshielded thermocouple

(d) Compressor-outlet total temperature (inlet of burner 5) T_2, one stagnation-type thermocouple

(e) Compressor-outlet static pressure (inlet of burner 9) p_2, four static wall taps connected to a piezometer ring

(f) Compressor-outlet total pressure (inlet of burner 9) P_2, one five-tube total pressure rake with all tubes connected to a common line

(g) Tail-pipe gas temperature T_7, six aspirating-type thermocouples connected in parallel

These measurements were read on potentiometers and manometers.

PROCEDURE

Water and Water-Alcohol Injection

Five separate series of runs were conducted, three with water injection and two with water-alcohol injection. The conditions for the five runs are presented in the following table:

Run	Injected liquid	Exhaust nozzle diameter (in.)	Injected water flow W_w (lb/sec)	Injected alcohol flow W_{al} (lb/sec)	Total injected liquid flow $W_w + W_{al}$ (lb/sec)	Rotor speed N (rpm)	Cowl inlet-air temperature range (°R)
A	Water	12.5	0-1.9	0	0-1.9	11,000-16,500	526 - 540
B	Water	12.0	0-1.9	0	0-1.9	11,000-16,500	529 - 540
C	Water	11.5	0-1.9	0	0-1.9	[a]11,000-16,000	533 - 555
D	Water-alcohol	12.0	0.5-0	0-0.5	0.5	[a]16,000	537 - 543
E	Water-alcohol	12.0	1.5	0-0.6	1.5-2.1	16,000, 16,500	541 - 547

[a]Top speed limited by allowable tail-pipe gas temperature.

Water-injection runs A, B, and C differed only in the size of the exhaust nozzle used on the engine. Water-alcohol injection runs D and E were run with a 12-inch-diameter exhaust nozzle and differed in the manner in which the proportion of water and alcohol were varied. In run D, the total injected flow of water and alcohol was held constant at approximately 0.5 pound per second and the proportions of each were varied. In run E, the injected water flow was held constant at 1.5 pounds per second and the alcohol rate was progressively increased from 0 to 0.6 pound per second.

Prior to each run, engine performance was determined without injection in order to provide a basis for evaluating the thrust augmentation.

Kerosene and Carbon-Dioxide Injection

The investigation of the performance of a centrifugal-flow-type turbojet engine, which had a 12-inch-diameter exhaust nozzle, during injection of kerosene, carbon dioxide, and carbon dioxide with a water-alcohol mixture was conducted according to the following procedure:

Kerosene injection. - The normal performance of the engine was determined prior to the injection of kerosene. Kerosene was injected into the compressor inlets of the turbojet engine in the same manner as the water and alcohol and the injected flows were varied from 0 to 603 pounds per hour. The rotor speed was varied from 14,000 rpm to 16,500 rpm; the inlet-air temperature was approximately 535° R.

Carbon-dioxide injection. - The normal performance of the engine without injection was first established. The injection of carbon dioxide into the compressor inlets was then accomplished by simultaneously opening the valves on four 75-pound capacity carbon-dioxide bottles. The injected flow of carbon dioxide varied from 4.6 pounds per second at the beginning of the run to almost zero at the end of the run. The engine was first operated at 16,500 rpm but the speed abruptly decreased when the injection valves were opened. When the rotor speed was stablized at 16,100 rpm, data were taken in quick succession until the contents of the bottles were depleted. The ambient cell temperature varied from 526° to 530° R.

Carbon-dioxide injection with water-alcohol mixture. - The normal engine performance was first established. This determination was followed by an investigation of engine performance for the injection of a 9:8 mixture of water and alcohol. Then, while the water and alcohol mixture was being injected at a rotor speed of approximately 16,500 rpm, the valves on three 75-pound capacity carbon-dioxide bottles were simultaneously opened. Readings were started 6 seconds after opening of the valves and were taken at 12-second intervals until the contents of the bottles were depleted. The variation in rotor speed was about 60 rpm for the run and the ambient cell temperature varied from 507° to 514° R.

SYMBOLS

The following symbols are used in this report:

F	thrust, (lb)
h	lower heating value of fuel, (Btu)/(lb)
K	fuel-flow correction factor
N	rotor speed, (rpm)
P	total pressure, (lb)/(sq in. absolute)
p	static pressure, (lb)/(sq in. absolute)
T	indicated temperature, (°R)
t	time, (sec)
W_a	air flow, (lb)/(sec)
W_{al}	injected alcohol flow, (lb)/(sec)
W_c	injected carbon-dioxide flow, (lb)/(sec)
W_f	fuel flow, (lb)/(hr)
W_k	injected kerosene flow, (lb)/(hr)
W_w	injected water flow, (lb)/(sec)
W_t	total liquid consumption, (lb of fuel, water, alcohol, and carbon dioxide)/(sec) or (lb)/(hr)

Subscripts:

0 cowl inlet

2 compressor outlet

7 tail pipe

corr corrected

METHODS OF CORRECTION

All performance data from water and water-alcohol injection runs were corrected to standard conditions at the cowl inlet by the following equations (the values without the subscript corr are observed data):

$$F_{corr} = \frac{F}{\delta} \qquad (1)$$

$$N_{corr} = \frac{N}{\sqrt{\theta}} \qquad (2)$$

$$P_{corr} = \frac{P}{\delta} \qquad (3)$$

$$p_{corr} = \frac{p}{\delta} \qquad (4)$$

$$T_{corr} = \frac{T}{\theta} \qquad (5)$$

$$W_{a\ corr} = \frac{W_a \sqrt{\theta}}{\delta} \qquad (6)$$

$$W_{al\ corr} = \frac{W_{al} \sqrt{\theta}}{\delta} \qquad (7)$$

$$W_{w\ corr} = \frac{W_w \sqrt{\theta}}{\delta} \qquad (8)$$

$$W_{t\ corr} = \frac{W_{a1}\sqrt{\theta}}{\delta} + \frac{W_v\sqrt{\theta}}{\delta} + \frac{W_f\ K}{\delta\sqrt{\theta}\ 3600} \tag{9}$$

$$W_{f\ corr} = \frac{W_f\ K}{\delta\sqrt{\theta}} \tag{10}$$

where the correction factors

$$\delta = \frac{\text{cowl-inlet total pressure } P_0}{\text{pressure of NACA standard atmosphere at sea level}}$$

$$\theta = \frac{\text{cowl-inlet total temperature } T_0}{\text{temperature of NACA standard atmosphere at sea level}}$$

$$K = 1 + \left(3600 \times 0.4\ \frac{W_{a1}}{W_f}\right)\left(1 - \theta\right)$$

The accuracy of the correction of engine performance data with liquid injection to standard inlet conditions is somewhat questionable because of unknown effects of inlet-air temperature on the vaporization of the injected liquid. The corrections applied are therefore only approximate and probably limited to small ranges of inlet temperature such as contained in the present data.

The correction equations are all valid if the corrected pressures and temperatures throughout the engine are related to the corresponding uncorrected values by the factors δ and θ. A theoretical analysis of the wet compression process indicates that if liquid-air ratio and compressor Mach number are held constant, the corrected pressures and temperatures will be related to the uncorrected values by the factors δ and θ, provided that: (1) the liquid is completely vaporized in the compressor, and (2) the variations in inlet conditions are small.

The corrections are based on maintaining corrected values of water-air and alcohol-air ratios and Mach numbers the same as the uncorrected values. The water-air and alcohol-air ratios are maintained constant by correcting water and alcohol flows in the same manner as the air flow. Corrected and uncorrected Mach numbers of the flow through the engine are the same except for variations in the thermodynamic properties of the gases arising from

(1) small changes (with correction) in fuel-air ratio (and, hence fuel-water and fuel-alcohol ratios), and (2) small changes in the vaporization processes in the compressor (with inlet conditions).

The total liquid consumption of the engine consists of fuel (kerosene), water, and alcohol, which provide or absorb heat in the engine combustion process. Because both the engine fuel and the injected alcohol provide heat during combustion, the resultant fuel flow must be corrected in a manner that accounts for the changes in alcohol flows arising from correction. The correction factor K, which takes into consideration the action of fuel and injected alcohol, is derived from a simple heat-balance equation. The value 0.4 in definition of K is an approximate ratio of the effective heating value of alcohol to the effective heating value of kerosene based on data from the water-alcohol injection runs.

The performance data from runs with kerosene and carbon-dioxide injection are presented directly as read without correction for inlet conditions.

RESULTS AND DISCUSSION

Water and Water-Alcohol Injection

The greater part of the investigation of engine performance was conducted with injection of the refrigerants that were considered of primary importance, namely, water and water-alcohol mixture.

Water injection. - The observed and the corrected data of water-injection runs A, B, and C are presented in table I. The curves presented in figure 5 show the variation in engine performance with injected water flow at a corrected rotor speed of 16,500 rpm and a cowl-inlet air temperature of from 534° to 540° R for 12.0- and 12.5-inch-diameter exhaust nozzles. (Data for 11.5-in.-diameter exhaust nozzle, run C, was not obtained at 16,500 rpm because of excessive tail-pipe gas temperature.) These curves were obtained by cross-plotting curves of engine performance against rotor speed from the data in table I. Figure 5(a) shows a graph of thrust plotted against injected water flow. For an injected water flow of 2.0 pounds per second, a thrust of 1755 pounds, or an increase of 330 pounds, was obtained using the 12.5-inch-diameter exhaust nozzle; and a thrust of 1935 pounds, or an increase of 345 pounds, was obtained with the 12.0-inch-diameter exhaust nozzle. These values represent a 23.2-percent thrust increase for the 12.5-inch-diameter exhaust nozzle and a 21.7-percent increase for the 12.0-inch-diameter exhaust nozzle. The dashed line in figure 5(a) represents the thrust with an adjustable-area exhaust nozzle and will be discussed in the following paragraph.

The tail-pipe gas temperatures decreased appreciably with injection of water for both exhaust nozzle sizes (fig. 5(b)). The excessive tail-pipe gas temperatures obtained with the 12.0-inch-diameter exhaust nozzle at points of low injection are reduced to the rated value of 1640° R by the injection of 2.0 pounds per second of water. The reduction in temperature with injection together with the higher thrust provided by the use of the smaller exhaust nozzle (fig. 5(a)), indicates that in order to realize fully the benefits of water injection the engine should be equipped with a variable-area exhaust nozzle. The thrust available when the exhaust-nozzle area is reduced sufficiently during injection to maintain the rated tail-pipe gas temperature, as shown by the dashed line in figure 5(a), was obtained by cross-plotting curves of thrust and tail-pipe gas temperature against exhaust-nozzle size. This curve for constant tail-pipe gas temperature shows that the thrust increases from 1425 pounds for no injection to 1935 pounds for injection of 2.0 pounds per second, representing a thrust augmentation of 35.8 percent. The leveling off of the curves of figures 5(a) and 5(b) indicates that both the increase in thrust and the reduction in tail-pipe gas temperature, and hence the effectiveness of the water injection, are reduced as the injection rate is increased.

The changes in fuel flow, total liquid consumption, air flow, and compressor-outlet total pressure caused by water injection are shown in figures 5(c) to 5(f), respectively. Both the fuel flow (fig. 5(c)) and the total liquid consumption (fig. 5(d)) increase appreciably for both exhaust-nozzle sizes with injected water flow. The injection of 2.0 pounds per second of water resulted in an increase of roughly 500 pounds per hour in the fuel flow and the total liquid consumption at this injection rate was about five times as high as for no injection. The air flow (fig. 5(e)) reaches a maximum (with an increase of about 2.5 lb/sec) at an injected water flow of approximately 1.0 pound per second for both exhaust-nozzle sizes. Although the air flow reaches a maximum at an injected water flow of 1.0 pound per second, the total mass flow (air plus liquid) through the engine continues to rise with injected water flow throughout the range investigated. The compressor-outlet total pressure (fig. 5(f)) increased over a larger range of injected water flows than did the air flow, leveling off at about the same injected water flow as did the thrust and the tail-pipe gas temperature.

Water-alcohol injection. - The results of run D, in which the proportions of water and alcohol were varied while the total injection rate was held constant at 0.52 pound per second (corrected value) are presented in figure 6. These data were obtained for inlet-air temperature from 537° to 543° R and are presented for a corrected rotor speed of 16,000 rpm. Figures 6(a) and 6(b) show that at this low total injected flow small amounts of alcohol (up to 0.15 lb/sec, or 30-percent alcohol) in the injected mixture produces about the same thrust and tail-pipe gas temperature as are produced by the injection of 0.52 pound per second of water alone. Injection of mixtures richer than 0.15 pound per second of alcohol, however, resulted in less thrust augmentation and higher tail-pipe gas temperatures than the injection of the same amount of water. Because alcohol acts as additional fuel, replacing some of the extra engine fuel required during water injection, the proportion of alcohol in the injected liquid has a marked effect on the engine fuel flow (fig. 6(c)). For injection of 0.10 pound per second of alcohol and 0.42 pound per second of water, the same fuel flow is required as with no injection, and therefore no adjustment of the fuel throttle is necessary. The composition of the injected mixture for constant throttle setting, (with constant nozzle size) from the previous observation, is approximately 20-percent alcohol by weight.

Figure 6(d) shows that total liquid consumption decreases as the proportion of alcohol is increased for a constant total injected mixture flow of 0.52 pound per second. This decrease in total liquid consumption is caused by the replacement of some of the engine fuel with alcohol as the injected mixture is enriched with alcohol.

Both the air flow (fig. 6(e)) and the compressor-outlet total pressure (fig. 6(f)) were higher for mixtures containing small amounts of alcohol than for mixtures rich in alcohol. These higher air flows and pressures indicate that the greatest cooling of the intake air occurred for mixtures containing a small amount of alcohol. The more rapid vaporization of mixtures rich in alcohol is apparently counteracted by the reduction in the heat of vaporization as the alcohol content is increased.

The results of run E, in which the injected water flow was held constant at 1.6 pounds per second (corrected value) and the injected alcohol flow was varied, are presented in figure 7. These data were obtained for inlet-air temperatures from 541° to 547° R and are presented for corrected rotor speeds of 16,000 and 16,500 rpm. Although the thrust values for no injection from figure 7(a) do not agree with those of figure 5(a) because of a change in normal engine performance, the percentage thrust increases brought about by injection of 1.6 pounds of water per second are about the same for both runs.

A comparison of the thrust augmentation in figures 5(a) and 7(a) shows that the addition of alcohol to an injected water flow of 1.6 pounds per second results in a greater increase in thrust than the injection of the same total flow of water alone. Moreover, the addition of alcohol to an injected water flow of 1.6 pounds per second produces a slightly lower tail-pipe gas temperature (approximately 30° F for 0.4 lb/sec alcohol) than was produced by the same total injected flow of water alone (fig. 7(b)).

The curve of fuel flow against injected alcohol flow (fig. 7(c)) indicates that the engine can be operated without adjustment of the fuel throttle with injection of 1.6 pounds per second of water and approximately 0.4 pound per second of alcohol for both rotor speeds. This mixture is in agreement with the constant-throttle-setting injection mixture of run D (approximately 20-percent alcohol by weight). Comparison of figures 5(d) and 7(d) show that the total liquid consumption is less for the injection of 1.6 pounds of water per second plus various amounts of alcohol than for the injection of an equal amount of water alone. A similar comparison of figures 5(e) and 5(f) with 7(e) and 7(f) shows that both the air-flow and compressor-outlet pressure increase more for the injection of mixtures containing alcohol than for the injection of water alone.

The foregoing comparison of the performance data presented in figures 5 and 7 indicated that the addition of alcohol to the injected liquid at high injected water flows (approximately 1.6 lb/sec) is more effective in increasing the thrust and reducing the tail-pipe gas temperature than the addition of more water. The maximum possible thrust augmentation with water-alcohol injection was not obtained, however, because run E was conducted with only one size exhaust nozzle, which permitted the gas temperatures to decrease as the injected flow was increased. In order to illustrate the maximum thrust augmentation that may be expected with water-alcohol injection, figure 8 is presented. The data from figure 5(a) for water injection at a constant tail-pipe gas temperature of 1640° R (at 16,500 rpm) is replotted in figure 8 as percentage thrust augmentation against total injected liquid flow. A curve of the thrust augmentation available by water injection for the 12.0-inch-diameter exhaust nozzle is included for comparison. The thrust augmentation possible by water-alcohol injection is shown by dashed curves for both conditions, that is: (1) tail-pipe gas temperature maintained constant by exhaust nozzle adjustment and (2) exhaust-nozzle diameter maintained constant at 12.0 inches. This thrust augmentation for constant tail-pipe gas temperatures was obtained by multiplying the augmentation provided by 1.6 pounds per second of water alone (from fig. 5(a)) by both the ratio of the thrust increase with alcohol injection shown in figure 7(a) and the ratio of the estimated thrust increase obtained when the exhaust-nozzle size was sufficiently reduced to raise the gas temperatures of figure 7(b) to a constant value. This adjustment of the data to a common exhaust-gas temperature was based on cross plots of thrust and temperature against exhaust-nozzle size obtained from the data without injection. A maximum possible thrust augmentation of 40 percent for injection of 1.6 pounds per second of water and 0.4 pound per second of alcohol for a rotor speed of 16,500 rpm and a cowl-inlet-air temperature from 534° to 543° R is indicated by the curve obtained from this analysis of the data.

Kerosene and Carbon-Dioxide Injection

The investigation of engine performance with injection of refrigerants that were considered of secondary importance were the injection of kerosene and carbon dioxide.

Kerosene injection. - The uncorrected performance data for runs with kerosene injection are presented in figure 9 for a rotor speed of 16,500 rpm, an ambient cell temperature of about 535° R, and a 12.5-inch-diameter exhaust nozzle. Figure 9(a) shows that the injection of kerosene increases the thrust only 17 pounds for an injection rate of 603 pounds per hour. The tail-pipe gas temperature (fig. 9(b)) was found to be higher for the injection of kerosene than for no injection. The total kerosene flow (fig. 9(c)) was increased 235 pounds per hour at an injection rate of 603 pounds per hour into the compressor inlets at a rotor speed of 16,500 rpm. Figure 9(d) indicates that the air flow for the injection of kerosene was slightly lower than for no injection.

Carbon-dioxide injection. - The uncorrected performance data from runs with carbon-dioxide injection have been plotted in figure 10 against the time elapsed from the opening of the valves on the carbon-dioxide bottles. Curves of engine performance without injection have been included in the figure for comparison. The thrust increase for the injection of carbon dioxide alone was 320 pounds, representing a thrust augmentation of 23.5 percent, for an injected carbon-dioxide flow of 4.6 pounds per second (indicated rotor speed, 16,150 rpm; ambient cell temperature, 526° to 530° R). Injection of carbon dioxide resulted in a slight decrease in tail-pipe gas temperature and considerable increase in fuel flow.

Carbon-dioxide injection with water-alcohol mixture. - The uncorrected performance data for runs of the engine with injection of carbon dioxide with 1.7 pounds per second of a 9:8 mixture of water and alcohol by weight are presented in figure 11. Curves of engine performance with injection of 1.7 pounds per second of the water-alcohol mixture alone (at speeds corresponding to those during injection of carbon dioxide) as well as curves of performance without injection are included for comparison. Because of difficulty with the instrumentation, no tail-pipe gas temperature measurements were made during this run. A thrust increase for injection of 3.5 pounds per second of carbon dioxide with 1.7 pounds per second of the 9:8 mixture of water and alcohol was 575 pounds representing a thrust augmentation of 36 percent. Of this thrust increase, which was obtained at an indicated rotor speed of 16,450 rpm, an ambient cell temperature from 507° to 514° R, and with an engine fitted with a constant-size exhaust nozzle, the water and alcohol contributed about 315 pounds, or about 20-percent augmentation. Thus, the injection of 3.5 pounds per second of carbon dioxide with 1.7 pounds per second of a mixture of water and alcohol provided a thrust augmentation 16 percent higher than obtained with injection of the water and alcohol alone.

SUMMARY OF RESULTS

The following results were obtained from the investigation of the performance of a 1600-pound-thrust centrifugal-flow-type turbojet engine at zero flight speed, sea-level conditions, and with injection of various refrigerants at the compressor inlets:

Water and Water-Alcohol Injection

1. A thrust augmentation of 23.2 percent was obtained by the injection of 2.0 pounds of water per second at a corrected rotor speed of 16,500 rpm and for an inlet-air temperature of 534° to 540° R using a constant exhaust-nozzle diameter of 12.5 inches. This thrust augmentation was increased to 35.8 percent by adjustment of the exhaust-nozzle size to maintain a constant rated tail-pipe gas temperature of 1640° R.

2. In the low flow range of water-alcohol injection (approximately 0.52 lb/sec of mixture), the thrust augmentation decreased slightly as the injected mixture was enriched with alcohol.

3. At high injected water flows (approximately 1.6 lb/sec), the addition of alcohol to the injected liquid was more effective than the addition of more water. A maximum thrust augmentation of 40 percent is available by the injection of 1.6 pounds of water

per second and 0.4 pound of alcohol per second when the tail-pipe gas temperature is maintained constant at the rated value of 1640° R by exhaust-nozzle adjustment.

4. Operation of the engine without adjustment of the fuel throttle from the normal operating position (at the same speed) is possible by selecting an injection mixture of alcohol and water that is roughly 20-percent alcohol by weight.

Kerosene and Carbon-Dioxide Injection

1. The increase in thrust with injection of kerosene was very slight reaching a maximum of 17 pounds for an injection rate of 603 pounds per hour at an indicated rotor speed of 16,500 rpm, an inlet-air temperature of 535° R, and a constant-area exhaust nozzle of 12.0-inch diameter. The accompanying increase in total fuel flow was 235 pounds per hour.

2. Thrust increase for the injection of 4.6 pounds per second of carbon dioxide alone was 320 pounds, representing a thrust augmentation of 23.5 percent at an indicated rotor speed of 16,150 rpm, an inlet-air temperature of 526° to 530° R, and with a 12.0-inch-diameter exhaust nozzle.

3. Thrust increase for the injection of 3.5 pounds per second of carbon dioxide with 1.7 pounds per second of a 9:8 mixture of water and alcohol, at an indicated rotor speed of 16,450 rpm, an inlet-air temperature of 507° to 514° R, and with a 12.0-inch-diameter

exhaust nozzle was 575 pounds. This increase represents a total thrust augmentation of 36 percent of which 16 percent was contributed by the carbon dioxide.

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

792

TABLE I - PERFORMANCE OF CENTRIFUGAL-FLOW-TYPE TURBOJET ENGINE WITH

[Data as observed and corrected to standard sea-level conditions at

Run	Barometric pressure (lb/sq in. absolute)	Exhaust-nozzle diameter (in.)	Water flow, W_w (lb/sec)		Rotor speed, N (rpm)		Thrust, F (lb)		Air flow, W_a (lb/sec)		Fuel flow, W_f (lb/hr)	
			Read	Corrected	Read	Corrected	Read	Corrected	Read	Corrected	Read	Corrected
(a) Injection of water												
A1	14.42	12.5	0	0	10,990	10,906	423	431	17.57	18.07	802	812
A2	14.42		0	0	11,978	11,854	519	530	19.41	20.03	897	906
A3	14.42		0	0	13,004	12,680	639	652	21.69	22.37	1010	1022
A4	14.42		0	0	14,038	13,892	790	807	23.85	24.64	1149	1162
A5	14.42		0	0	15,040	14,856	974	996	26.21	27.13	1315	1328
A6	14.42		0	0	15,530	15,311	1074	1098	27.30	28.32	1419	1431
A7	14.42		0	0	15,957	15,687	1164	1191	28.18	29.33	1527	1536
A8	14.42		0	0	16,483	16,220	1309	1340	29.54	30.73	1692	1704
A9	14.42		.50	.515	11,977	11,896	568	560	20.12	20.69	998	1013
A10	14.42		.50	.515	14,007	13,861	867	867	25.11	25.95	1230	1245
A11	14.42		.50	.520	15,042	14,843	1073	1098	27.65	28.67	1413	1427
A12	14.42		.50	.520	15,912	15,686	1288	1318	29.77	30.91	1644	1659
A13	14.42		.50	.520	16,508	16,243	1461	1496	31.15	32.41	1849	1863
A14	14.39		.60	.620	11,970	11,834	558	571	19.84	20.54	1015	1027
A15	14.39		.60	.620	12,964	12,805	694	710	22.31	23.13	1111	1124
A16	14.39		.60	.625	14,000	13,601	863	884	24.88	25.85	1241	1253
A17	14.39		.60	.625	14,994	14,768	1072	1099	27.52	28.65	1426	1440
A18	14.39		.60	.625	16,008	15,723	1331	1365	30.02	31.35	1700	1712
A19	14.39		.60	.625	16,517	16,220	1460	1519	31.20	32.60	1882	1897
A20	14.39		.63	.660	13,991	13,532	875	897	24.85	25.76	1268	1305
A21	14.39		.63	.665	14,995	14,784	1092	1119	27.65	26.76	1479	1495
A22	14.39		.83	.865	15,972	15,702	1356	1391	30.24	31.55	1751	1766
A23	14.39		.83	.670	16,511	16,167	1526	1565	31.63	33.10	1954	1966
A24	14.39		1.335	1.385	15,007	14,829	1112	1140	27.41	28.42	1620	1641
A25	14.39		1.335	1.390	15,528	15,314	1246	1278	28.37	30.03	1729	1749
A26	14.39		1.335	1.390	16,009	15,757	1399	1436	30.23	31.50	1882	1900
A27	14.39		1.335	1.395	16,498	16,190	1568	1608	31.61	33.05	2060	2074
A28	14.39		1.92	2.000	15,967	15,747	1404	1441	30.81	32.05	2043	2067
A29	14.39		1.92	2.000	16,365	16,159	1556	1596	31.05	32.31	2200	2226
B1	14.36	12.0	0	0	11,135	11,021	477	489	17.35	17.97	850	862
B2			0	0	11,934	11,906	561	575	18.98	19.67	937	950
B3			0	0	12,977	12,618	694	712	20.97	21.78	1063	1077
B4			0	0	13,949	13,767	846	868	23.02	23.94	1202	1218
B5			0	0	14,539	14,323	953	978	24.36	25.39	1202	1317
B6			0	0	15,019	14,798	1054	1082	25.38	26.46	1402	1418
B7			0	0	15,503	15,248	1165	1199	26.60	27.77	1523	1538
B8			0	0	16,032	15,739	1304	1340	27.79	29.08	1678	1693
B9			0	0	16,475	16,174	1435	1475	28.84	30.19	1835	1851
B10			.50	.520	11,062	10,955	501	514	17.48	18.10	962	977
B11			.50	.520	11,993	11,859	611	627	19.56	20.29	1042	1057
B12			.50	.520	12,999	12,849	764	784	22.07	22.92	1159	1176

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

792

INJECTION OF WATER AND WATER-ALCOHOL MIXTURES AT COMPRESSOS INLETS

seul inlet: temperature T_0, 512° R; pressure P_0, 14.70 lb/sq in.]

Total liquid consumption, W_t (lb/sec)		Cowl-inlet total temperature, T_0 (°R)	Cowl-inlet total pressure, P_0 (lb/sq in. absolute)	Compressor-outlet total temperature, T_2 (°R)				Compressor-outlet total pressure, P_2 (lb/sq in. absolute)		Tail-pipe indicated gas temperature, T_7 (°R)	
				Unshielded type		Stagnation type					
Read	Corrected	Read	Read	Read	Corrected	Read	Corrected	Read	Corrected	Read	Corrected
(a) Injection of water											
0.223	0.226	327	14.40	675	665	670	660	26.01	26.55	1399	1378
.249	.232	530	14.32	705	590	702	687	28.91	29.52	1415	1387
.281	.284	529	14.39	736	722	731	717	32.35	35.04	1433	1406
.519	.323	530	14.36	756	752	762	746	36.23	37.03	1473	1444
.365	.362	552	14.37	808	788	799	780	40.84	41.77	1524	1487
.394	.398	534	14.57	625	803	817	794	45.27	44.27	1561	1317
.424	.427	537	14.36	547	812	833	807	45.44	46.49	1506	1332
.470	.473	336	14.36	887	840	854	827	48.36	49.30	1534	1601
.777	.796	526	14.32	580	372	580	572	30.09	30.74	1336	1318
.842	.861	530	14.37	578	664	673	532	36.19	32.05	1362	1353
.892	.215	533	14.36	740	721	727	706	45.27	44.28	1444	1406
.937	.981	534	14.35	778	756	765	742	47.92	42.06	1343	1300
1.014	1.058	636	14.33	808	782	794	762	51.36	52.62	1611	1560
-.882	.903	531	14.36	578	363	578	363	29.86	30.37	1342	1312
.909	.232	532	14.33	523	679	586	574	33.74	34.55	1343	1312
.243	.273	334	14.33	635	615	630	612	38.26	32.19	1372	1333
.296	1.023	535	14.33	714	593	707	686	43.22	44.32	1434	1391
1.072	1.101	538	14.33	758	741	734	727	48.82	60.08	1530	1475
1.123	1.152	538	14.32	792	764	780	752	51.72	53.07	1596	1540
1.188	1.222	531	14.34	395	582	598	584	38.45	39.41	1354	1523
1.241	1.280	534	14.33	635	517	647	622	43.55	44.77	1410	1370
1.315	1.356	537	14.33	710	586	706	582	49.31	50.58	1505	1433
1.373	1.415	340	14.32	756	726	741	712	52.61	53.97	1570	1509
1.785	1.841	533	14.34	504	589	605	690	44.01	45.11	1394	1360
1.513	1.575	334	14.33	510	593	518	601	47.20	45.42	1440	1400
1.850	1.218	336	14.33	516	596	533	613	50.39	51.62	1490	1443
1.907	1.271	532	14.52	523	500	551	536	53.42	34.89	1554	1496
2.488	2.674	534	14.33	515	528	515	598	50.44	51.75	1466	1425
2.531	2.629	534	14.32	521	604	590	603	53.24	54.53	1312	1476
0.236	0.239	530	14.34	584	570	675	664	26.52	27.26	1465	1433
.260	.264	530	14.33	706	690	701	686	28.93	22.66	1460	1429
.293	.299	532	14.33	742	724	734	715	32.48	33.33	1496	1460
.334	.338	533	14.32	774	734	753	745	36.17	37.12	1535	1423
.362	.365	535	14.32	793	770	724	761	38.77	39.80	1565	1519
.362	.394	533	14.31	812	787	804	780	40.98	42.09	1525	1575
.423	.427	536	14.31	833	806	822	725	43.32	44.55	1843	1521
.466	.470	538	14.30	855	824	843	814	45.19	47.45	1720	1658
.510	.514	538	14.30	872	840	862	831	48.74	50.09	1766	1702
.757	.721	529	14.33	568	537	567	556	27.18	27.87	1390	1363
.789	.513	531	14.33	575	563	575	563	30.32	31.10	1404	1373
.822	.847	351	14.32	522	578	396	582	34.43	35.35	1406	1376

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

TABLE I - PERFORMANCE OF CENTRIFUGAL-FLOW-TYPE TURBOJET ENGINE WITH

Run	Barometric pressure (lb/sq in. absolute)	Exhaust-nozzle diameter (in.)	Water flow, W_w (lb/sec)		Rotor speed, N (rpm)		Thrust, F (lb)		Air flow, W_a (lb/sec)		Fuel flow, W_f (lb/hr)	
			Read	Corrected	Read	Corrected	Read	Corrected	Read	Corrected	Read	Corrected
(e)	Injection of water - continued											
B13	14.36	12.0	0.30	0.320	14,039	13,873	961	987	24.84	25.84	1311	1328
B14			.30	.320	13,030	14,796	1183	1213	27.11	28.30	1522	1539
B15			.50	.320	13,501	13,260	1303	1339	28.17	29.40	1633	1674
B16			.50	.623	16,042	16,754	1456	1497	29.44	30.81	1832	1849
B17			.30	.625	16,511	16,205	1606	1651	30.42	31.86	2004	2022
B18			.60	.620	11,960	11,847	611	627	19.42	20.14	1064	1079
B19			.60	.620	12,961	12,849	765	785	21.98	22.78	1177	1196
B20			.60	.625	13,961	13,783	947	972	24.49	25.47	1317	1333
B21			.60	.623	16,034	14,819	1195	1228	27.31	28.46	1550	1570
B22			.60	.625	16,039	16,760	1479	1320	29.64	30.96	1853	1874
B23			.60	.630	16,540	16,222	1644	1690	30.82	32.31	2043	2060
B24			.83	.860	13,279	13,823	939	965	24.44	25.37	1360	1361
B25			.83	.866	16,035	14,798	1221	1234	27.30	28.60	1693	1613
B26			.83	.870	16,029	13,743	1523	1566	30.03	31.45	1908	1923
B27			.83	.870	16,323	16,213	1685	1734	31.13	32.64	2106	2123
B28			1.336	1.390	14,980	14,772	1213	1246	26.79	27.91	1690	1712
B29			1.335	1.393	13,327	13,288	1380	1416	28.32	29.56	1830	1872
B30			1.333	1.393	16,030	13,776	1656	1600	29.89	31.27	2033	2033
B31			1.335	1.393	16,535	16,249	1739	1788	31.19	32.64	2242	2266
B32			1.90	1.980	16,002	13,748	1549	1392	29.19	30.48	2200	2223
B33			1.91	1.993	16,491	16,227	1751	1801	32.30	33.76	2401	2429
C1	14.34	11.5	0	0	10,887	10,768	488	601	16.70	17.34	861	873
C2			0	0	11,984	11,830	616	632	16.73	19.47	969	1002
C3			0	0	13,018	12,626	768	769	20.76	21.66	1137	1160
C4			0	0	14,001	13,767	939	964	22.80	23.62	1306	1319
C5			0	0	14,323	14,252	1046	1076	23.98	23.11	1412	1424
C6			0	0	13,044	14,736	1163	1197	25.03	26.29	1546	1656
C7			0	0	15,556	13,236	1303	1339	26.16	27.45	1696	1707
C8			.50	.520	11,997	11,843	669	687	19.27	20.04	1093	1108
C9			.60	.620	13,996	13,776	1043	1074	24.22	25.20	1407	1423
C10			.30	.525	14,635	14,292	1176	1209	25.49	26.65	1338	1554
C11			.60	.323	13,014	14,734	1302	1339	26.68	27.93	1670	1685
C12			.50	.325	16,548	16,243	1458	1500	27.72	29.08	1846	1861
C13			.50	.325	16,046	16,716	1616	1662	28.81	30.23	2040	2055
C14			.50	.623	11,994	11,828	667	685	19.27	20.07	1119	1133
C15			.50	.625	13,006	12,800	840	863	21.62	22.56	1249	1263
C16			.60	.630	13,999	13,731	1033	1082	24.24	26.35	1430	1443
C17			.60	.630	14,617	14,260	1187	1220	23.58	26.77	1563	1578
C18			.60	.630	14,973	14,666	1313	1330	26.73	28.06	1680	1692
C19			.60	.630	13,602	16,168	1473	1517	27.93	29.38	1863	1877
C20			.60	.633	16,032	13,641	1646	1694	29.02	30.61	2063	2071

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

742

INJECTION OF WATER AND WATER-ALCOHOL MIXTURES AT COMPRESSOR INLETS - Continued

Total liquid consumption, W_t (lb/sec)		Cowl-inlet total temperature, T_0 (°R)	Cowl-inlet total pressure, P_0 (lb/sq in. absolute)	Compressor-outlet total temperature, T_2 (°R)				Compressor-outlet total pressure, P_2 (lb/sq in. absolute)		Tail-pipe indicated gas temperature, T_7 (°R)	
				Unshielded type		Stagnation type					
Read	Corrected	Read	Read	Read	Corrected	Read	Corrected	Read	Corrected	Read	Corrected
(e) Injection of water - continued											
0.864	0.889	533	14.31	663	646	660	643	39.11	40.16	1455	1417
.923	.947	536	14.31	732	709	720	698	43.88	45.00	1522	1475
.960	.985	536	14.31	752	729	741	718	46.46	47.76	1560	1512
1.009	1.039	538	14.30	779	751	768	741	49.38	50.76	1644	1585
1.057	1.087	539	14.30	801	772	790	761	52.03	53.50	1711	1648
.896	.920	531	14.33	574	561	574	561	30.17	30.95	1392	1361
.927	.952	530	14.32	585	573	583	571	34.25	35.15	1400	1371
.966	.996	532	14.31	620	604	612	596	38.57	39.61	1436	1400
1.031	1.061	534	14.30	710	690	699	679	44.12	45.33	1514	1471
1.115	1.145	536	14.30	764	739	750	726	49.72	51.11	1625	1573
1.168	1.202	540	14.29	791	761	776	748	52.82	54.31	1705	1640
1.208	1.243	531	14.32	594	581	594	581	38.82	39.85	1424	1392
1.273	1.313	536	14.31	622	603	631	611	44.57	45.78	1495	1448
1.360	1.404	539	14.30	708	682	702	676	50.58	51.96	1612	1553
1.413	1.460	539	14.29	752	724	738	710	53.60	55.15	1690	1633
1.804	1.866	534	14.31	604	587	606	589	44.32	45.53	1476	1435
1.849	1.915	535	14.30	609	590	614	595	47.81	49.13	1529	1482
1.900	1.966	537	14.29	616	595	624	603	51.20	52.64	1598	1544
1.958	2.024	538	14.29	623	602	645	623	55.96	57.55	1661	1604
2.511	2.598	536	14.30	615	596	614	595	50.90	52.31	1570	1621
2.577	2.670	536	14.29	620	600	620	600	54.83	56.38	1660	1607
0.239	0.242	532	14.32	680	663	674	658	26.03	26.71	1525	1488
.275	.278	533	14.32	710	691	706	687	29.32	30.10	1553	1512
.316	.319	535	14.31	744	722	733	711	32.86	33.74	1600	1552
.363	.366	537	14.31	779	753	772	746	36.74	37.74	1636	1581
.392	.396	539	14.30	799	769	791	762	39.00	40.07	1673	1611
.429	.432	541	14.30	821	786	812	779	43.03	44.22	1722	1652
.471	.474	541	14.30	----	----	----	----	----	----	1782	1710
.804	.828	533	14.31	579	564	579	564	30.50	31.32	1451	1413
.891	.915	536	14.30	670	649	675	654	39.05	40.12	1535	1486
.927	.957	537	14.30	711	687	704	680	41.75	42.92	1585	1532
.964	.993	539	14.29	738	711	726	699	44.16	45.40	1635	1574
1.013	1.042	540	14.29	766	736	754	725	47.11	48.45	1707	1641
1.067	1.096	541	14.29	790	756	770	739	49.96	51.38	1790	1717
.911	.940	534	14.31	577	561	577	561	30.40	31.22	1442	1401
.947	.976	536	14.31	587	566	586	567	34.58	35.52	1470	1423
.997	1.031	538	14.30	622	600	632	610	39.20	40.27	1530	1476
1.034	1.068	538	14.30	675	651	674	650	41.90	43.07	1590	1534
1.067	1.110	541	14.29	715	686	709	680	44.60	45.85	1627	1581
1.118	1.151	542	14.29	746	714	735	704	47.35	48.70	1712	1639
1.173	1.210	545	14.28	772	735	762	726	50.45	51.90	1805	1719

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

TABLE I - PERFORMANCE OF CENTRIFUGAL-FLOW-TYPE TURBOJET ENGINE WITH INJECTION

Run	Barometric pressure (lb/sq in. absolute)	Exhaust-nozzle diameter (in.)	Water flow, W_w (lb/sec)		Alcohol flow, W_a (lb/sec)		Rotor speed, N (rpm)		Thrust, F (lb)		Air flow, W_a (lb/sec)	
			Read	Corrected	Read	Corrected	Read	Corrected	Read	Corrected	Read	Corrected
(a) Injection of water - Concluded												
C21	14.34	11.6	0.83	0.870			13,855	13,896	1048	1077	24.04	26.17
C22			.83	.865			14,497	14,269	1197	1230	22.42	26.22
C23			.83	.870			16,083	14,700	1348	1386	26.82	28.12
C24			.83	.870			15,496	15,129	1509	1552	28.11	29.66
C25			.83	.878			16,226	16,249	[illegible]	1827	29.22	31.59
C26			.83	.872			15,844	15,473	1620	1667	28.29	30.44
C27			1.335	1.400			14,988	14,894	1341	1572	26.22	27.50
C28			1.335	1.400			15,495	16,174	1521	1562	27.22	29.05
C29			1.335	1.405			16,097	16,750	1754	1805	29.52	30.83
C30			1.335	1.405			16,211	15,471	1639	1872	28.57	30.03
C31			1.92	2.015			15,777	15,488	1984	1870	27.72	29.11
C32			1.92	2.015			15,327	15,026	1453	1484	26.42	27.77
(b) Injection of water-alcohol mixtures												
D1	14.47	12.0	0	0	0	0	16,082	15,782	1284	1308	27.52	28.65
D2			0	0	0	0	15,926	15,365	1150	1172	26.30	27.35
D3			.2	.220	0	0	16,062	15,705	1427	1456	29.35	30.51
D4			.4	.419	.1	.104	16,047	15,742	1422	1450	29.52	30.22
D5			.3	.319	.2	.206	16,055	15,740	1422	1450	29.55	30.54
D6			.2	.208	.5	.513	16,040	15,898	1406	1433	29.10	30.34
D7			.1	.104	.4	.417	16,029	15,694	1391	1419	28.96	30.12
D8			0	0	.6	.622	16,026	15,646	1376	1402	28.70	29.92
E1	14.17	12.0	0	0	0	0	14,087	13,797	822	856	23.46	23.86
E2			0	0	0	0	15,069	14,740	995	1036	24.40	25.00
E3			0	0	0	0	16,032	15,652	1212	1262	26.50	25.37
E4			0	0	0	0	16,535	16,107	1349	1401	27.55	28.56
E5			1.42	1.527	0	0	16,492	16,132	1632	1701	30.08	31.04
E6			1.42	1.526	0	0	16,000	15,270	1466	1527	28.88	30.75
E7			1.42	1.520	.08	.085	16,499	16,112	1642	1712	30.19	30.81
E8			1.42	1.526	.08	.085	16,007	16,050	1465	1527	28.86	30.72
E9			1.42	1.520	.21	.224	16,550	16,147	1665	1735	30.26	30.26
E10			1.42	1.526	.21	.223	16,004	15,655	1470	1532	28.83	30.49
E11			1.42	1.520	.51	.551	16,504	16,119	1665	1735	30.29	31.32
E12			1.42	1.525	.51	.550	15,997	15,527	1474	1536	29.22	30.99
E13			1.42	1.523	.40	.428	16,503	16,089	1660	1730	30.92	31.34
E14			1.42	1.527	.40	.426	16,032	15,609	1497	1542	28.27	30.72
E15			1.42	1.521	.49	.523	16,503	16,105	1668	1738	30.95	31.51
E16			1.42	1.527	.49	.520	16,270	15,829	1470	1532	28.83	30.70
E17			1.42	1.520	.57	.606	16,506	16,101	1670	1742	30.29	31.52
E18			1.42	1.525	.57	.606	15,972	15,545	1480	1542	28.83	30.88

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

792

792

OF WATER AND WATER-ALCOHOL MIXTURES AT COMPRESSOR INLETS - Concluded

Fuel flow, W_f (lb/hr)		Total liquid consumption, W_t (lb/sec)		Cowl-inlet total temperature, T_0 (°R)	Cowl-inlet total pressure, P_0 (lb/sq in. absolute)	Compressor-outlet total temperature, T_2 (°R)				Compressor-outlet total pressure, P_2 (lb/sq in. absolute)		Tail-pipe indicated gas temperature, T_7 (°R)	
						Unshielded type		Stagnation type					
Read	Corrected	Read	Corrected	Read	Read	Read	Corrected	Read	Corrected	Read	Corrected	Read	Corrected
(a) Injection of water - Concluded													
1470	1482	1.238	1.282	539	14.30	596	573	598	576	39.15	40.22	1528	1471
1610	1629	1.277	1.316	536	14.30	660	639	612	593	42.14	43.32	1572	1522
1759	1770	1.319	1.362	542	14.29	635	608	647	620	45.19	46.46	1620	1551
1920	1932	1.363	1.407	542	14.29	660	651	694	665	48.09	49.46	1678	1607
2235	2246	1.451	1.499	544	14.28	730	696	736	702	52.56	54.18	1812	1729
2040	2050	1.397	1.444	544	14.28	720	687	714	681	50.05	51.50	1732	1652
1840	1855	1.846	1.915	540	14.29	606	583	606	583	45.04	46.31	1602	1540
2038	2053	1.901	1.970	541	14.29	612	587	616	591	48.38	49.76	1662	1595
2304	2320	1.975	2.049	542	14.28	619	593	628	602	52.41	53.92	1752	1678
2150	2164	1.932	2.006	542	14.29	620	594	625	599	50.30	51.73	1711	1639
2345	2362	2.571	2.671	541	14.29	620	595	616	591	50.15	51.58	1686	1618
2160	2177	2.520	2.620	540	14.29	640	615	610	587	47.06	48.38	1636	1573
(b) Injection of water-alcohol mixtures													
1700	1700	0.472	0.472	539	14.42	862	830	853	821	46.05	46.93	1797	1730
1560	1563	.433	.434	537	14.42	843	814	838	810	43.35	44.18	1750	1691
1615	1617	1.004	1.025	539	14.41	787	757	774	745	49.20	50.18	1691	1628
1690	1686	.969	.988	539	14.41	790	760	786	756	49.10	50.08	1680	1617
1570	1559	.936	.953	540	14.41	797	766	792	762	49.10	50.08	1680	1615
1425	1403	.896	.911	542	14.41	806	772	802	768	48.66	49.63	1695	1624
1320	1292	.867	.880	542	14.42	810	776	806	772	48.46	49.43	1705	1633
1175	1137	.826	.838	543	14.42	824	788	817	781	48.07	48.98	1716	1641
1214	1237	0.337	0.344	541	14.14	788	756	781	749	35.91	37.35	1578	1514
1384	1409	.384	.391	542	14.13	825	790	818	783	40.03	41.63	1635	1566
1526	1652	.452	.459	545	14.12	864	823	857	816	-----	-----	1745	1662
1780	1805	.494	.501	547	14.12	887	842	877	832	47.11	49.04	1615	1722
2190	2234	2.098	2.208	542	14.11	635	606	654	626	52.80	55.02	1675	1604
2000	2042	2.046	2.152	541	14.11	621	596	631	605	49.61	51.69	1602	1537
2090	2122	2.151	2.265	544	14.11	629	600	627	598	53.05	55.28	1671	1594
1895	1926	2.096	2.209	543	14.11	618	591	617	590	49.66	51.75	1595	1525
2000	2024	2.256	2.374	543	14.11	630	602	621	594	53.30	55.54	1668	1594
1792	1817	2.196	2.314	541	14.11	620	595	615	590	49.71	51.80	1585	1520
1888	1900	2.324	2.448	544	14.11	629	600	621	592	53.39	55.63	1650	1574
1700	1717	2.272	2.392	541	14.11	620	595	615	590	49.96	52.06	1573	1509
1780	1778	2.384	2.514	546	14.11	629	598	621	590	53.34	55.58	1644	1563
1625	1632	2.341	2.466	542	14.11	622	596	615	589	50.15	52.26	1574	1507
1695	1688	2.451	2.584	545	14.11	628	598	621	591	53.49	55.74	1650	1571
1525	1524	2.404	2.532	542	14.11	618	592	614	588	49.81	51.90	1565	1499
1625	1614	2.511	2.646	544	14.11	627	598	621	592	53.64	55.69	1650	1574
1460	1456	2.466	2.596	541	14.11	618	593	614	589	49.96	52.06	1567	1503

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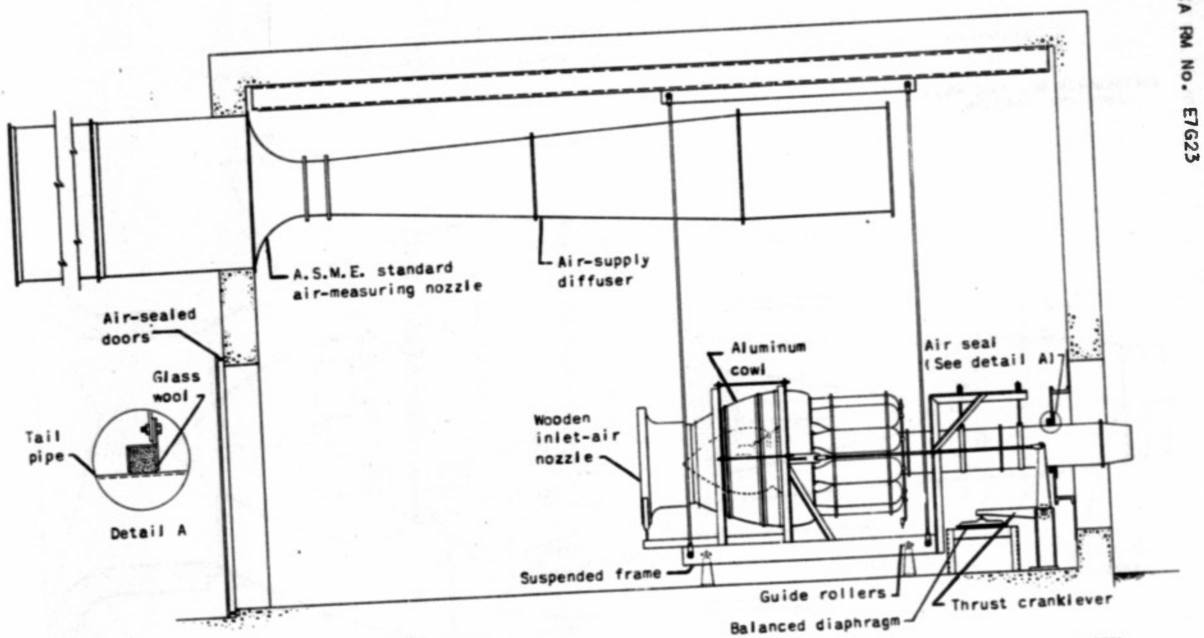

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Figure 1. - Diagram of setup for refrigerant-injection investigations on centrifugal-flow-type turbojet engine.

25

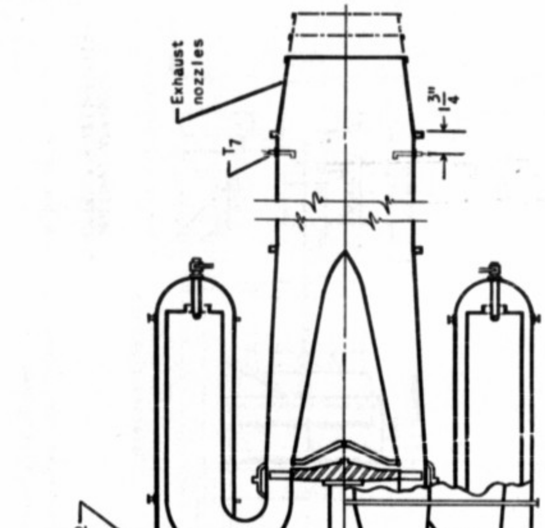


Figure 2. - Pressure and temperature instrumentation and regrigerant-injection equipment for a centrifugal-flow-type turbojet engine.

Figure 3. - Injection setup showing carbon dioxide injection apparatus in foreground.

27

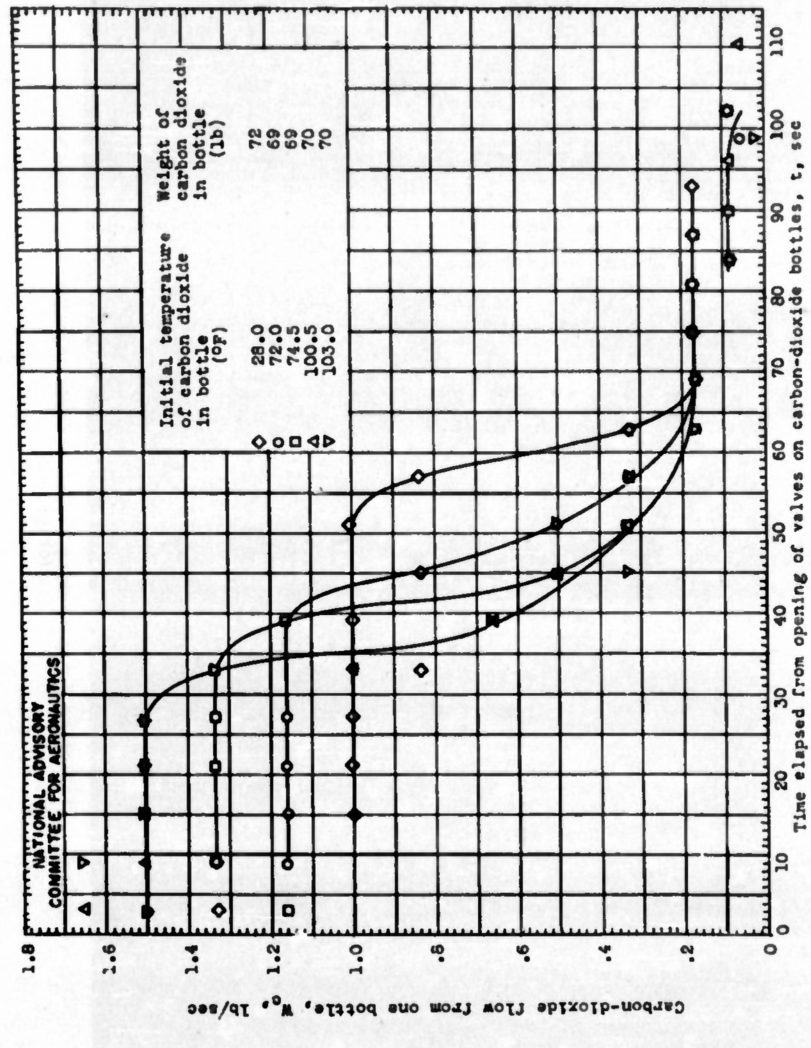
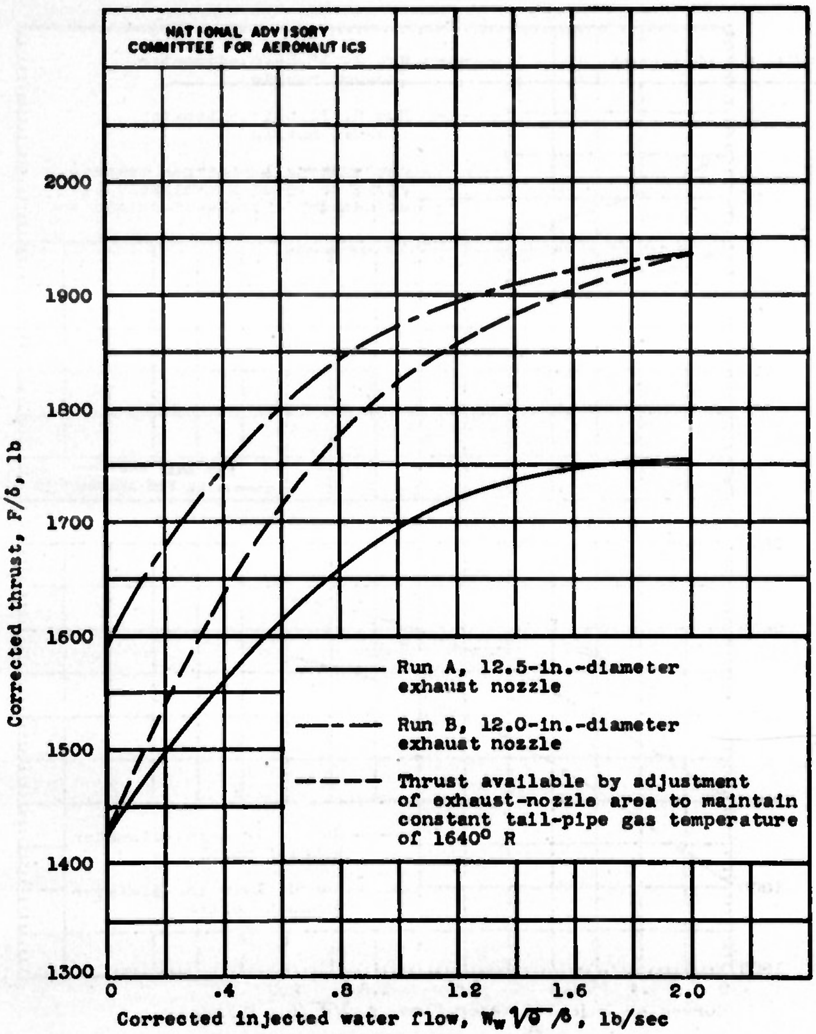


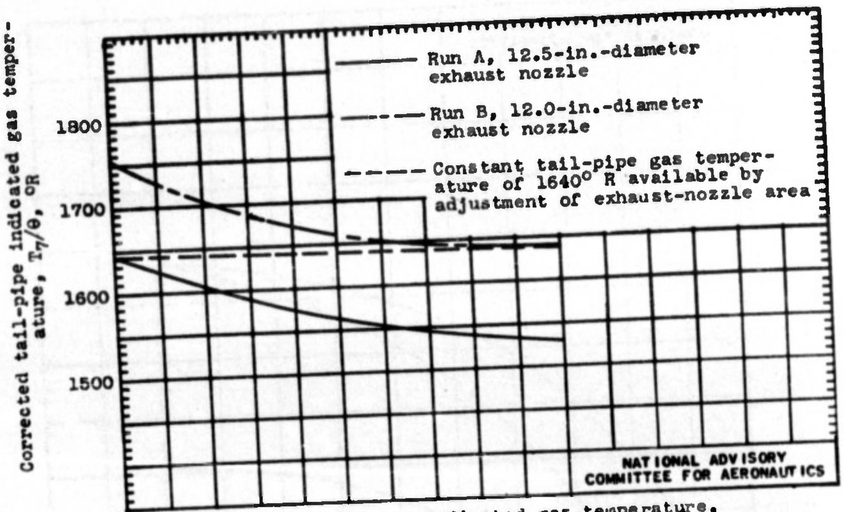
Figure 4. - Instantaneous carbon-dioxide flow for several 75-pound-capacity carbon-dioxide bottles at different initial temperatures.

742

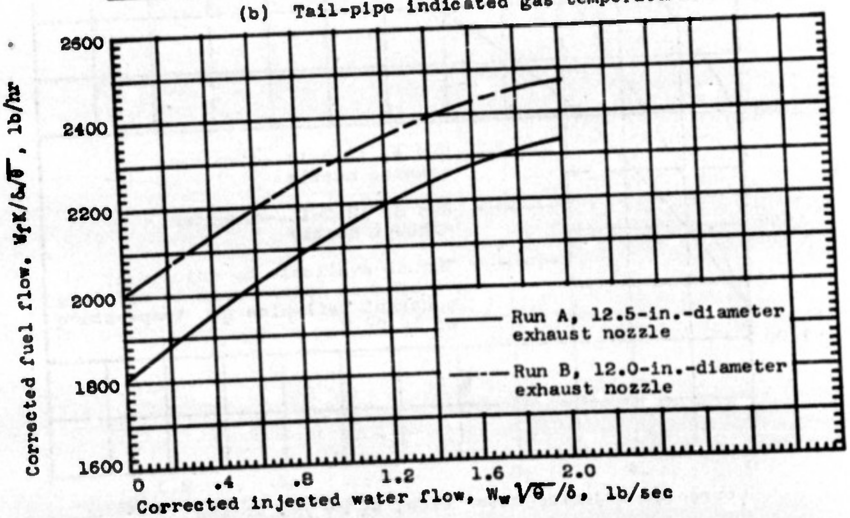


(a) Thrust.

Figure 5. - Engine performance for various injected water flows for runs A and B. Corrected rotor speed, 16,500 rpm; cowl-inlet air temperature, 534° to 540° R.

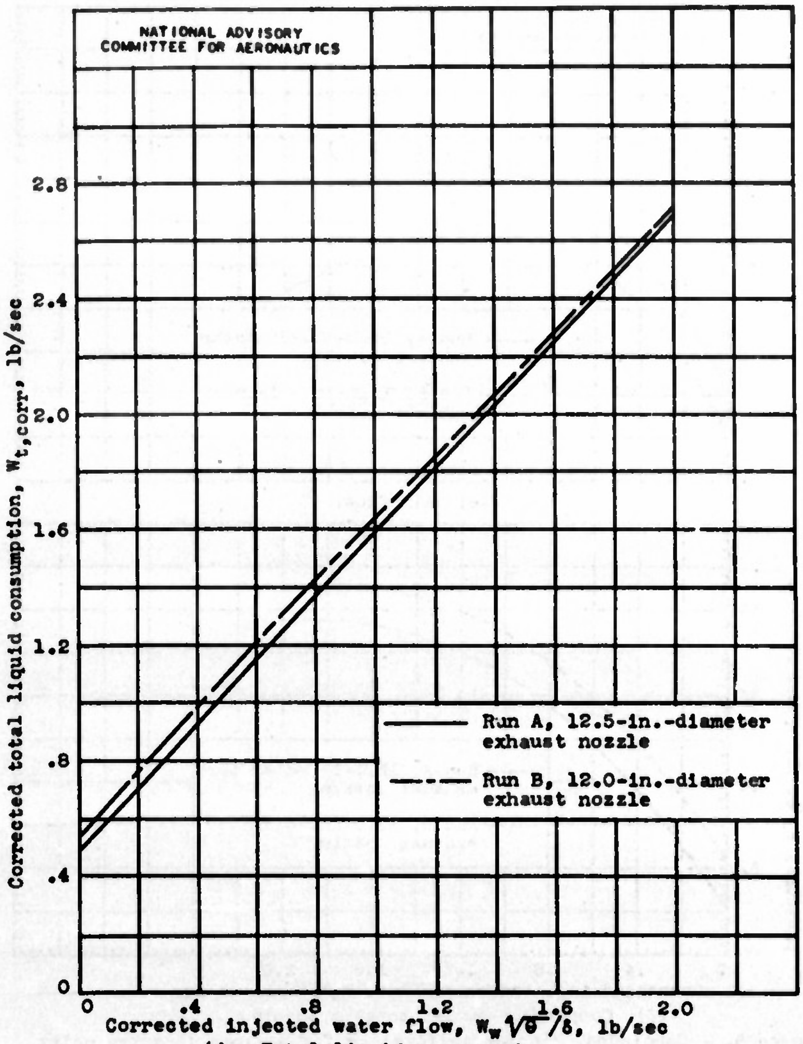


(b) Tail-pipe indicated gas temperature.



(c) Fuel flow.

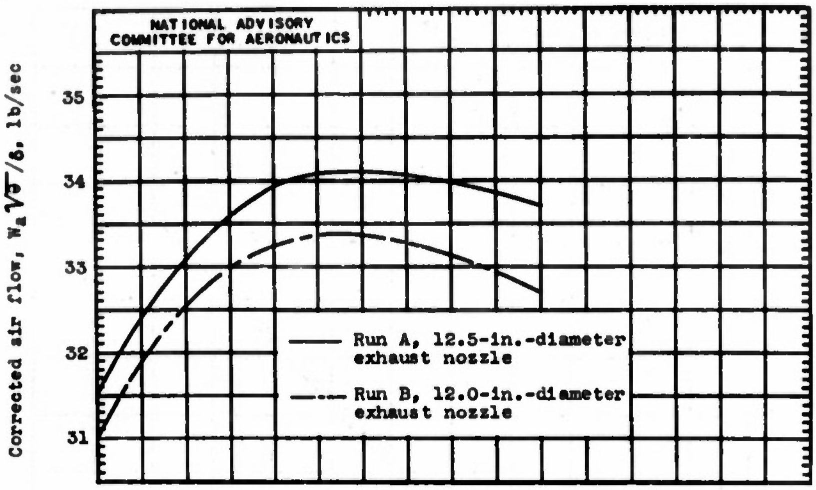
Figure 5. - Continued. Engine performance for various injected water flows for runs A and B. Corrected rotor speed, 16,500 rpm; cowl-inlet air temperature, 534° to 540° R.



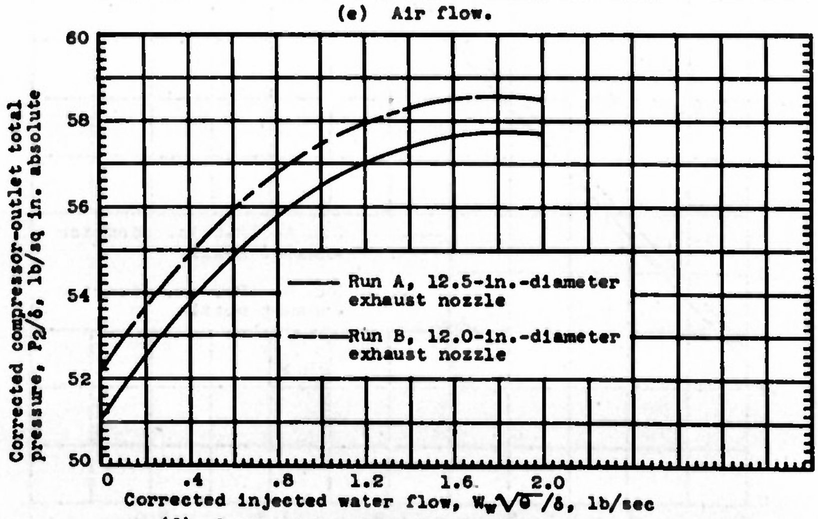
(d) Total liquid consumption.

Figure 5. - Continued. Engine performance for various injected water flows for runs A and B. Corrected rotor speed, 16,500 rpm; cowl-inlet air temperature, 534° to 540° R.

21



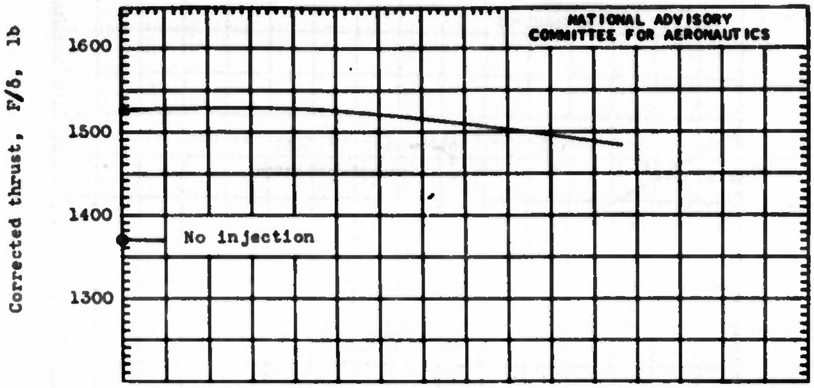
(e) Air flow.



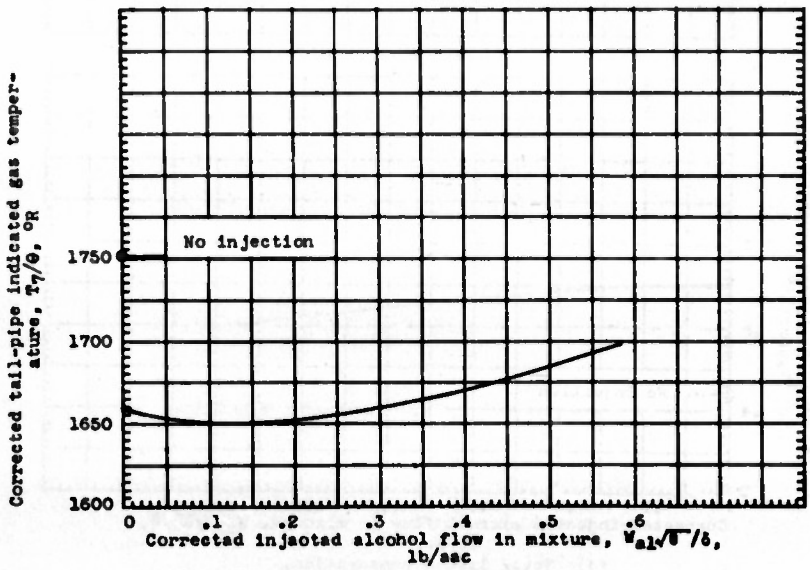
(f) Compressor-outlet total pressure.

Figure 5. - Concluded. Engine performance for various injected water flows for runs A and B. Corrected rotor speed, 16,500 rpm; cowl-inlet air temperature, 534° to 540° R.

32



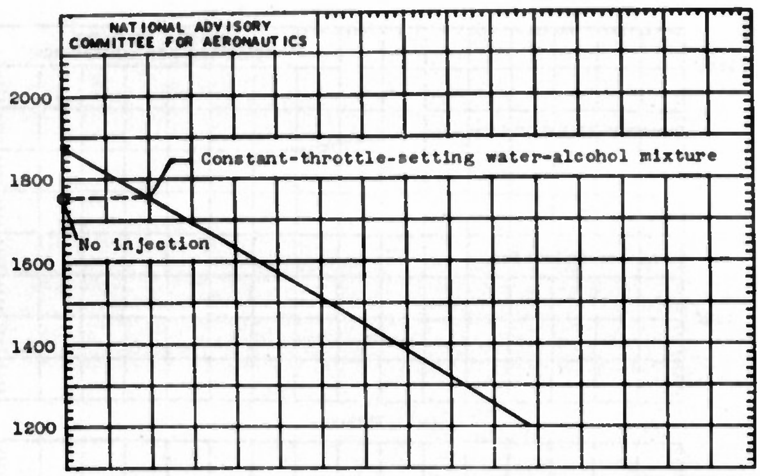
(a) Thrust.



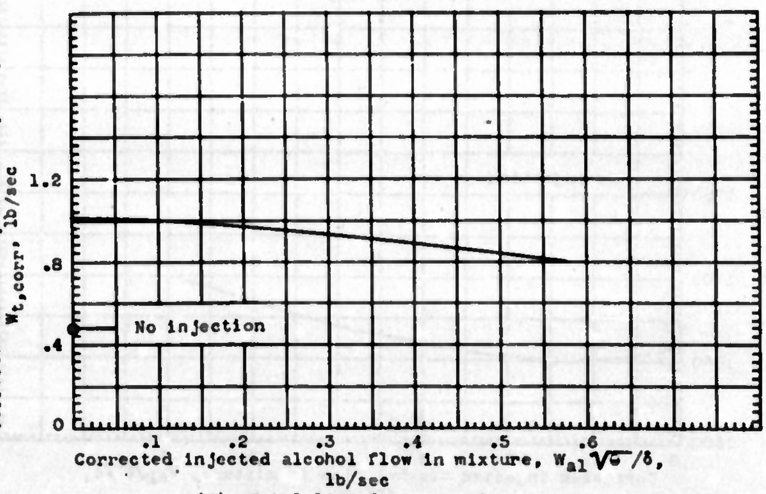
(b) Tail-pipe indicated gas temperature.

Figure 6. - Engine performance for various water-alcohol mixtures injected during run D. Corrected total mixture flow, approximately 0.52 pound per second; corrected rotor speed, 16,000 rpm; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 537° to 543° R.

33

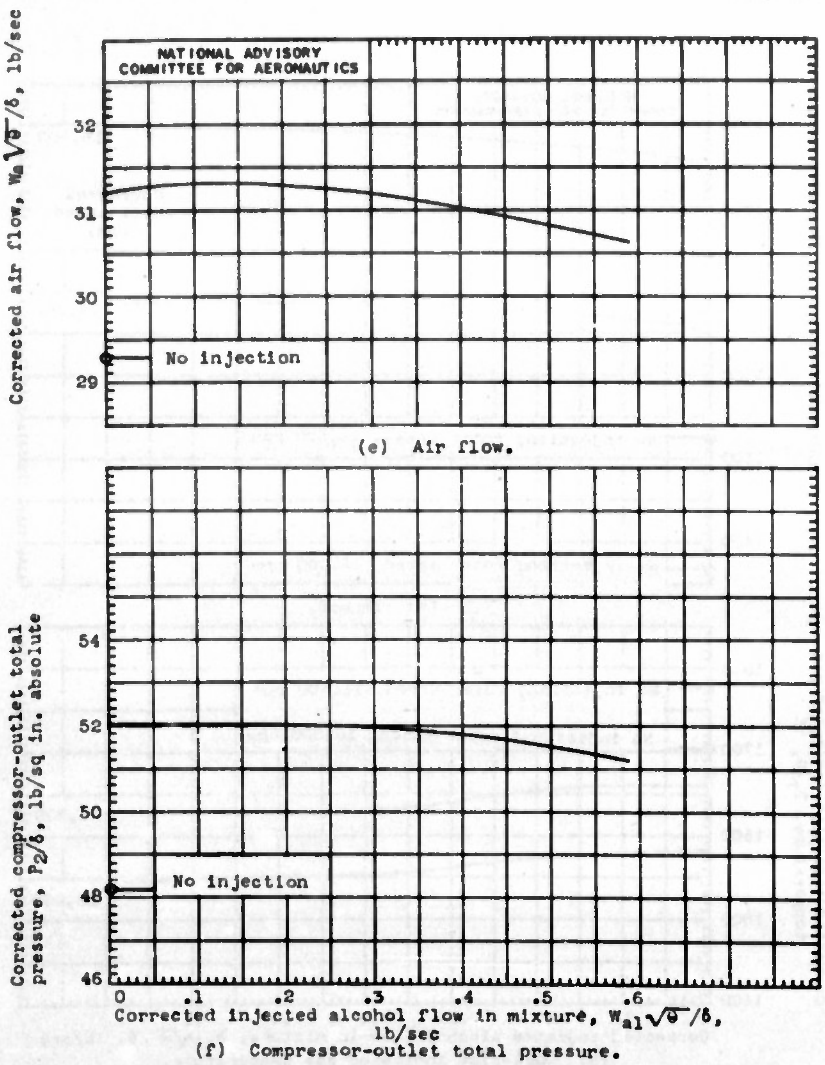


(c) Fuel flow.



(d) Total liquid consumption.

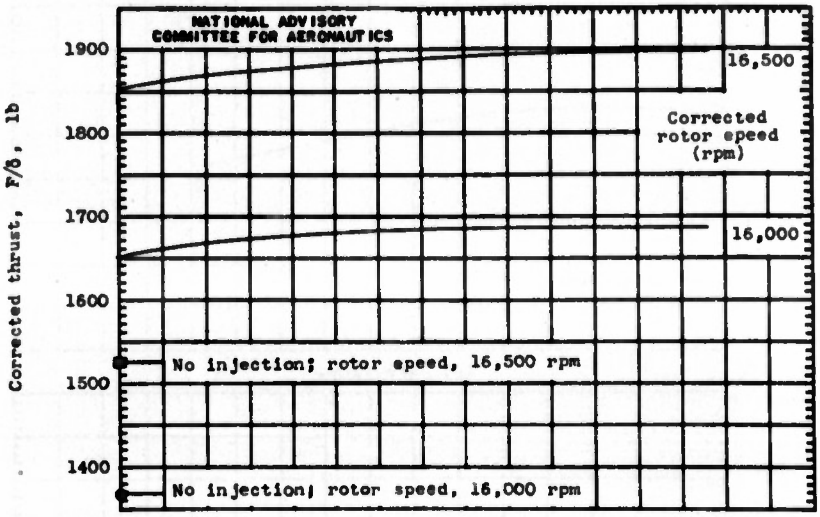
Figure 6. - Continued. Engine performance for various water-alcohol mixtures injected during run D. Corrected total mixture flow, approximately 0.52 pound per second; corrected rotor speed, 16,000 rpm; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 537° to 543° R.



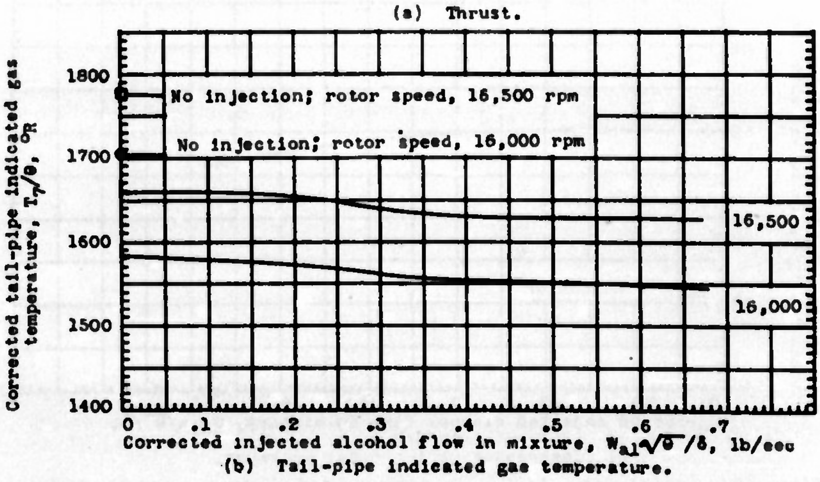
(f) Compressor-outlet total pressure.

Figure 6. - Concluded. Engine performance for various water-alcohol mixtures injected during run D. Corrected total mixture flow, approximately 0.52 pound per second; corrected rotor speed, 16,000 rpm; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 537° to 543° R.

35



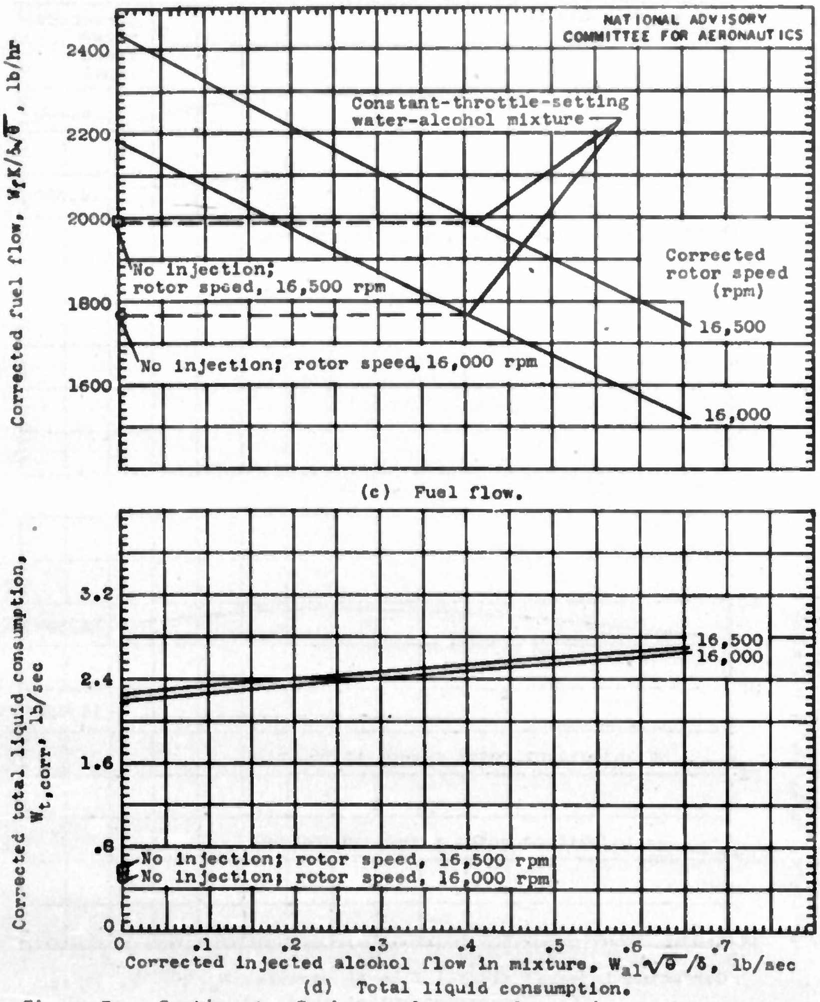
(a) Thrust.



(b) Tail-pipe indicated gas temperature.

Figure 7. - Engine performance for various water-alcohol mixtures injected during run E. Corrected water flow nearly constant at 1.6 pounds per second; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 541° to 546° R.

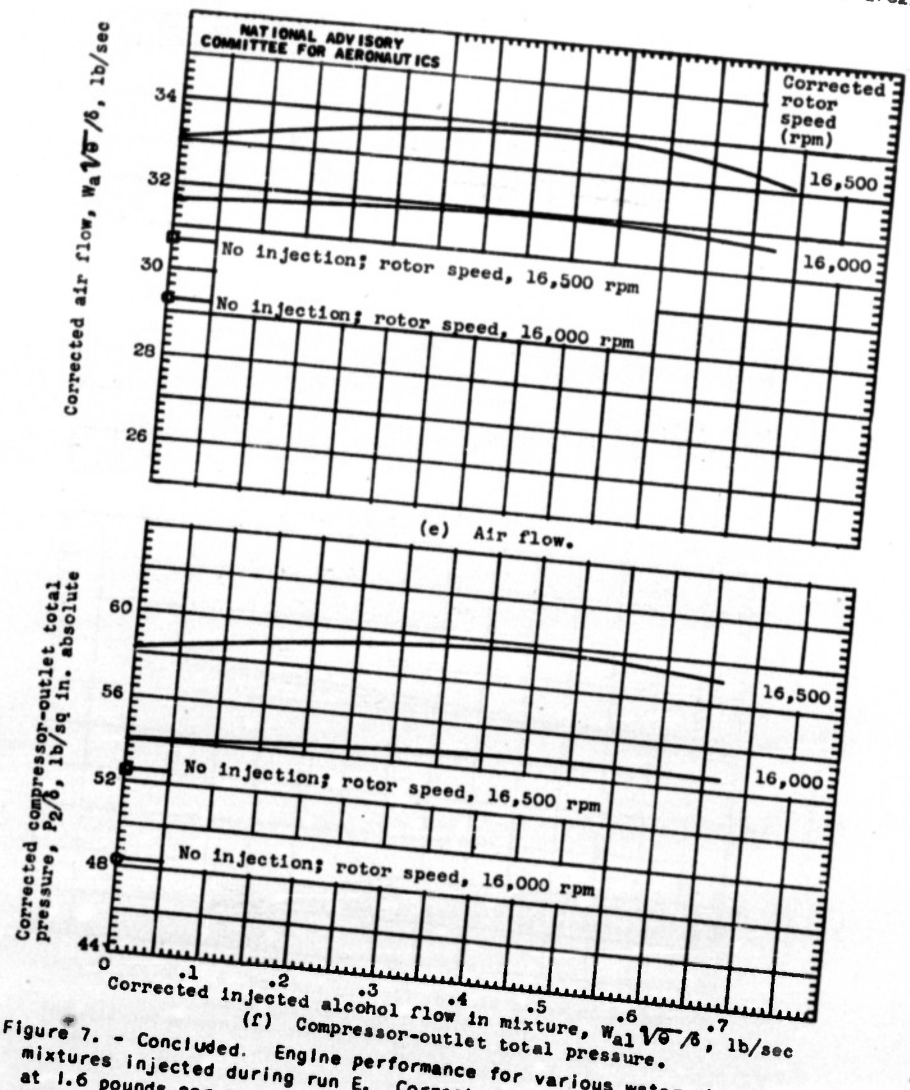
36



(d) Total liquid consumption.

Figure 7. - Continued. Engine performance for various water-alcohol mixtures injected during run E. Corrected water flow nearly constant at 1.6 pounds per second; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 541° to 546° R.

37



(e) Air flow.

(f) Compressor-outlet total pressure.

Figure 7. - Concluded. Engine performance for various water-alcohol mixtures injected during run E. Corrected water flow nearly constant at 1.6 pounds per second; exhaust-nozzle diameter, 12.0 inches; cowl-inlet air temperature, 541° to 546° R.

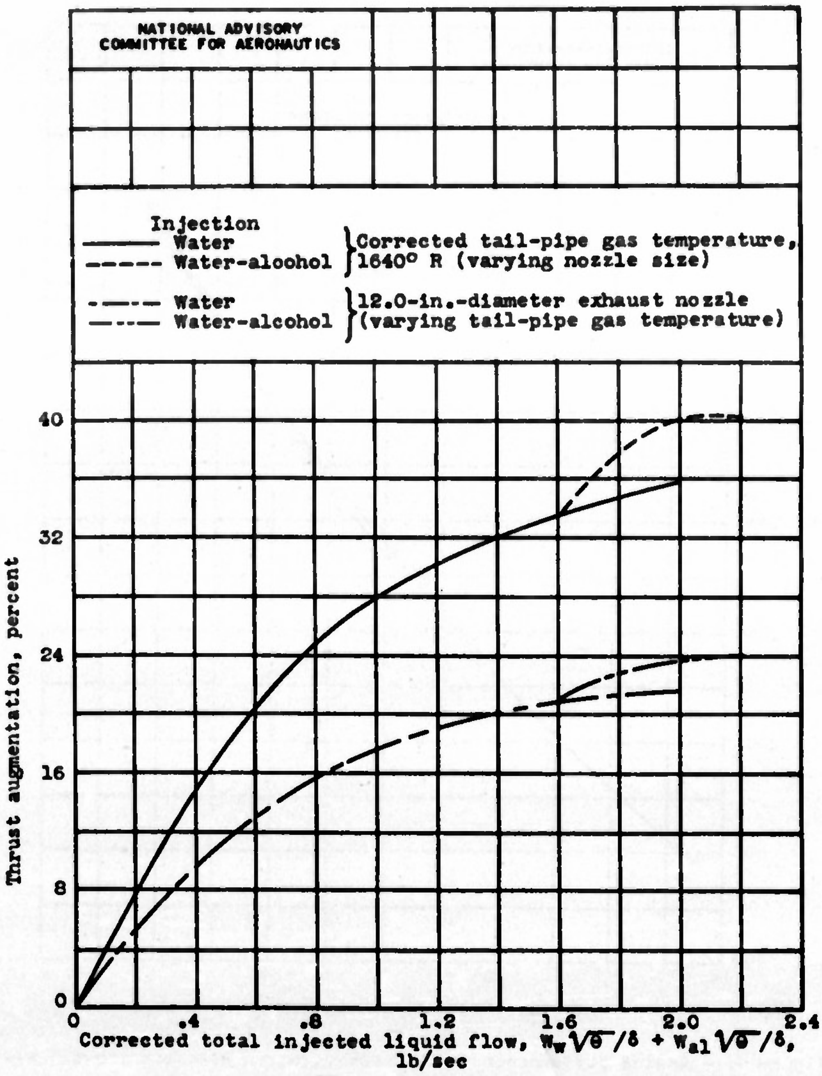
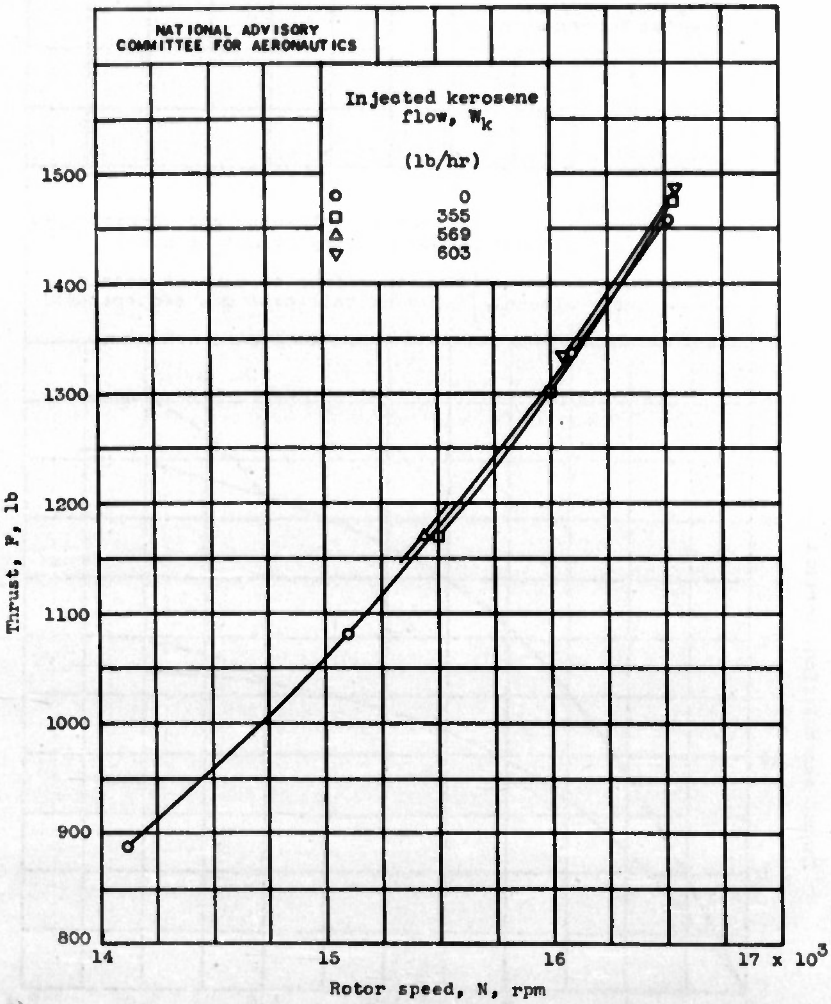


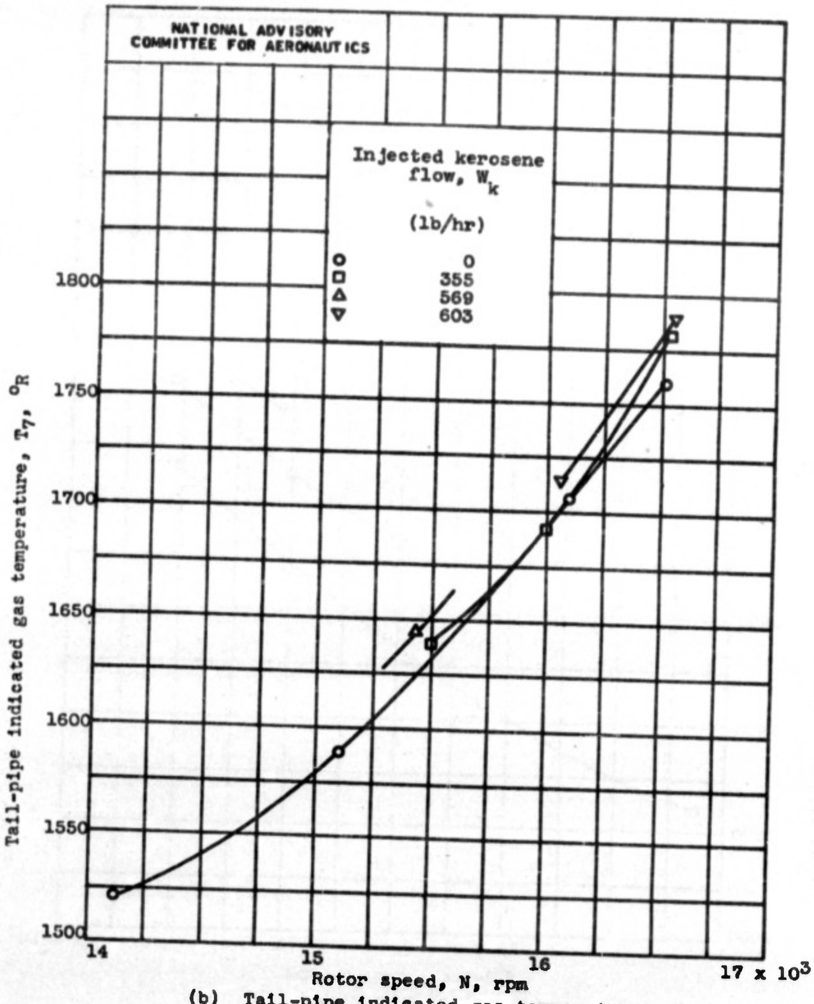
Figure 8. - Thrust augmentation of centrifugal-flow-type turbojet engine by water and water-alcohol injection at a corrected rotor speed of 16,500 rpm; cowl-inlet air temperature, 534° to 543° R.

39



(a) Thrust.

Figure 9. - Engine performance for various injected kerosene flows. Average ambient cell temperature, 535° R; 12.5-inch-diameter exhaust nozzle.

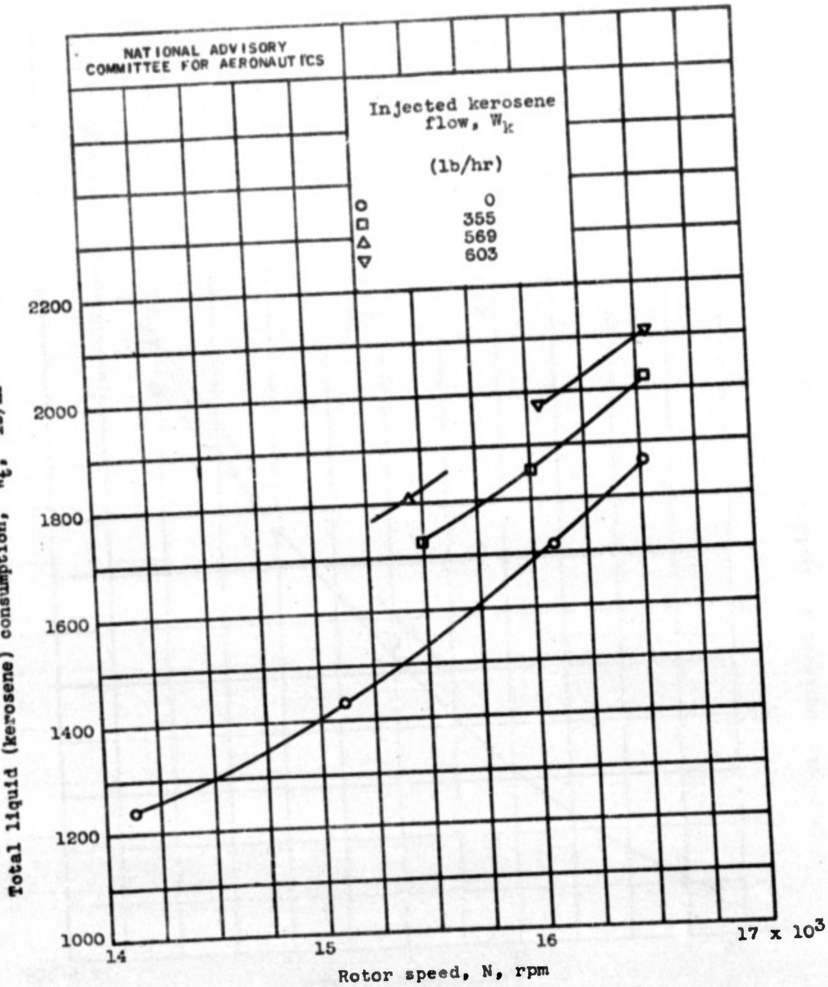


(b) Tail-pipe indicated gas temperature.

Figure 9. - Continued. Engine performance for various injected kerosene flows. Average ambient cell temperature, 535° R; 12.5-inch-diameter exhaust nozzle.

41

792

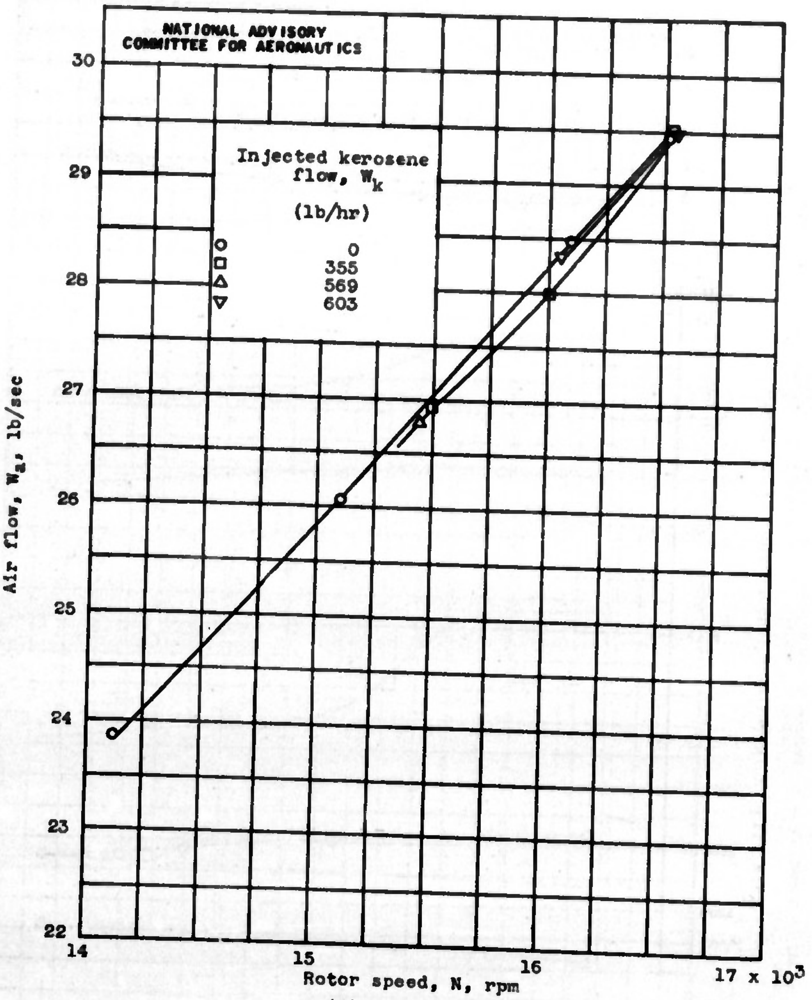


(c) Fuel flow.

Figure 9. - Continued. Engine performance for various injected kerosene flows. Average ambient cell temperature, 535° R; 12.5-inch-diameter exhaust nozzle.

42

742



(d) Air flow.

Figure 9. - Concluded. Engine performance for various injected kerosene flows. Average ambient cell temperature, 535° R; 12.5-inch-diameter exhaust nozzle.

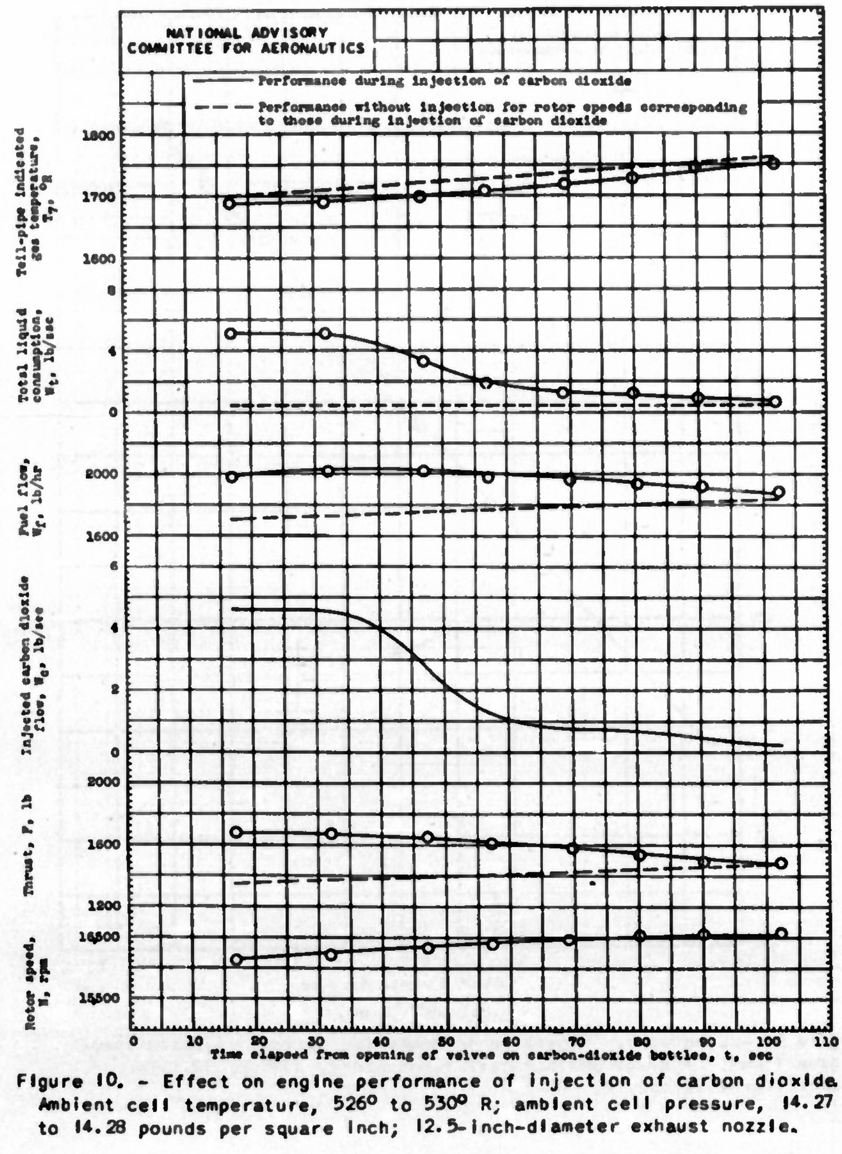


Figure 10. - Effect on engine performance of injection of carbon dioxide. Ambient cell temperature, 526° to 530° R; ambient cell pressure, 14.27 to 14.28 pounds per square inch; 12.5-inch-diameter exhaust nozzle.

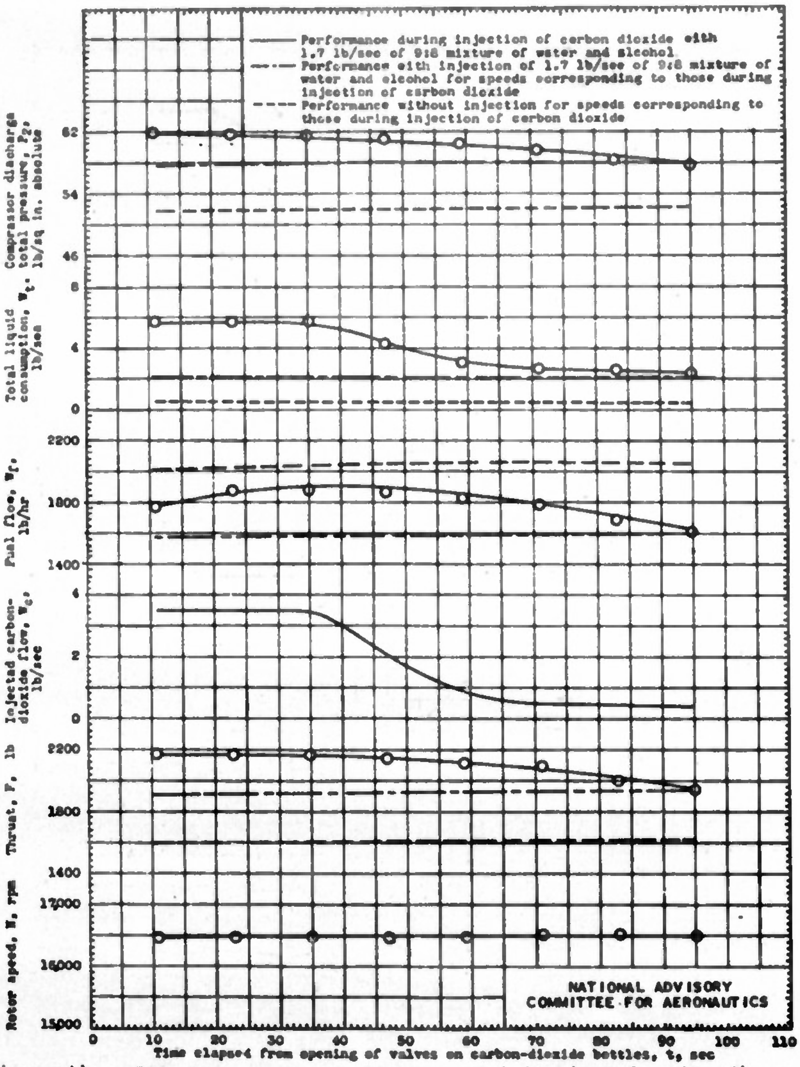


Figure 11. - Effect on engine performance of injection of carbon dioxide with 1.7 pounds per second of 9:8 mixture by weight of water and alcohol (alcohol consisting of 50-percent ethyl alcohol and 50-percent pure synthetic methyl alcohol). Ambient cell temperature, 507° to 514° R; ambient cell pressure, 14.50 to 14.51 pounds per square inch; 12.5-inch-diameter exhaust nozzle.

REEL – C

347

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10151

TSDIN FORM 69 A (13 MAR 47)

RESTRICTED

AUTHOR(S)		ATI- 10151
Jones, William L. Dowman, Herry W.	DIVISION: Power Plenta, Jet and Turbine (5) SECTION: Parformance (16) CROSS REFERENCES: Thruat augmentation (94090); Enginee, Jet propulsion - Turbo-jet (33750); Combustion - Mixture effects (23630)	ORIG. AGENCY NUMBER RM-E7G23 REVISION

AMER. TITLE: Investigation of thrust augmentation of e 1600-pound thrust centrifugal-flow-type turbojet engine by injection of refrigerants et compressor inlets

FORG'N. TITLE:

ORIGINATING AGENCY: National Advisory Committee for Aeronautics, Weshington, D. C.

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N.CLASS	U. S.CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Restr.	Aug'47	44	23	tables, diagrs, graphs

ABSTRACT

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NOTE: Requeste for copies of this report muet be addressad to: N.A.C.A., Washington, D. C.

TSDIN FORM 69 A (13 MAR 47)

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ATI- 10151

ORIG. AGENCY NUMBER

RM-E7G23

REVISION

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AUTHOR(S)

Jones, William L.
Dowman, Harry W.

DIVISION: Power Plants, Jet and Turbine (5)
SECTION: Performance (16)
CROSS REFERENCES: Thrust augmentation (94090); Engines, Jet propulsion - Turbo-jet (33750); Combustion - Mixture effects (23630)

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FORG'N. TITLE:

ORIGINATING AGENCY: National Advisory Committee for Aeronautics, Washington, D. C.

TRANSLATION:

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U.S.	Eng.		[redacted]	Aug'47	44	23	tables, diagrs, graphs

ABSTRACT

Investigations were conducted to determine effectiveness of refrigerants in increasing thrust of turbojet engines. Mixtures of water and alcohol were injected for a range of total flows up to 2.2 lb/sec. Kerosene was injected into inlets covering a range of injected flows up to approximately 30% of normal engine fuel flow. Injection of 2.0 lb/sec of water alone produced an increase in thrust of 35.8% of rated engine conditions and kerosene produced a negligible increase in thrust. Carbon dioxide increased thrust 23.5%.

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