NACA

RESEARCH MEMORANDUM

ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF THRUST

AUGMENTATION OF AXIAL- AND CENTRIFUGAL-COMPRESSOR

TURBOJET ENGINES BY INJECTION OF WATER AND ALCOHOL

IN COMBUSTION CHAMBERS

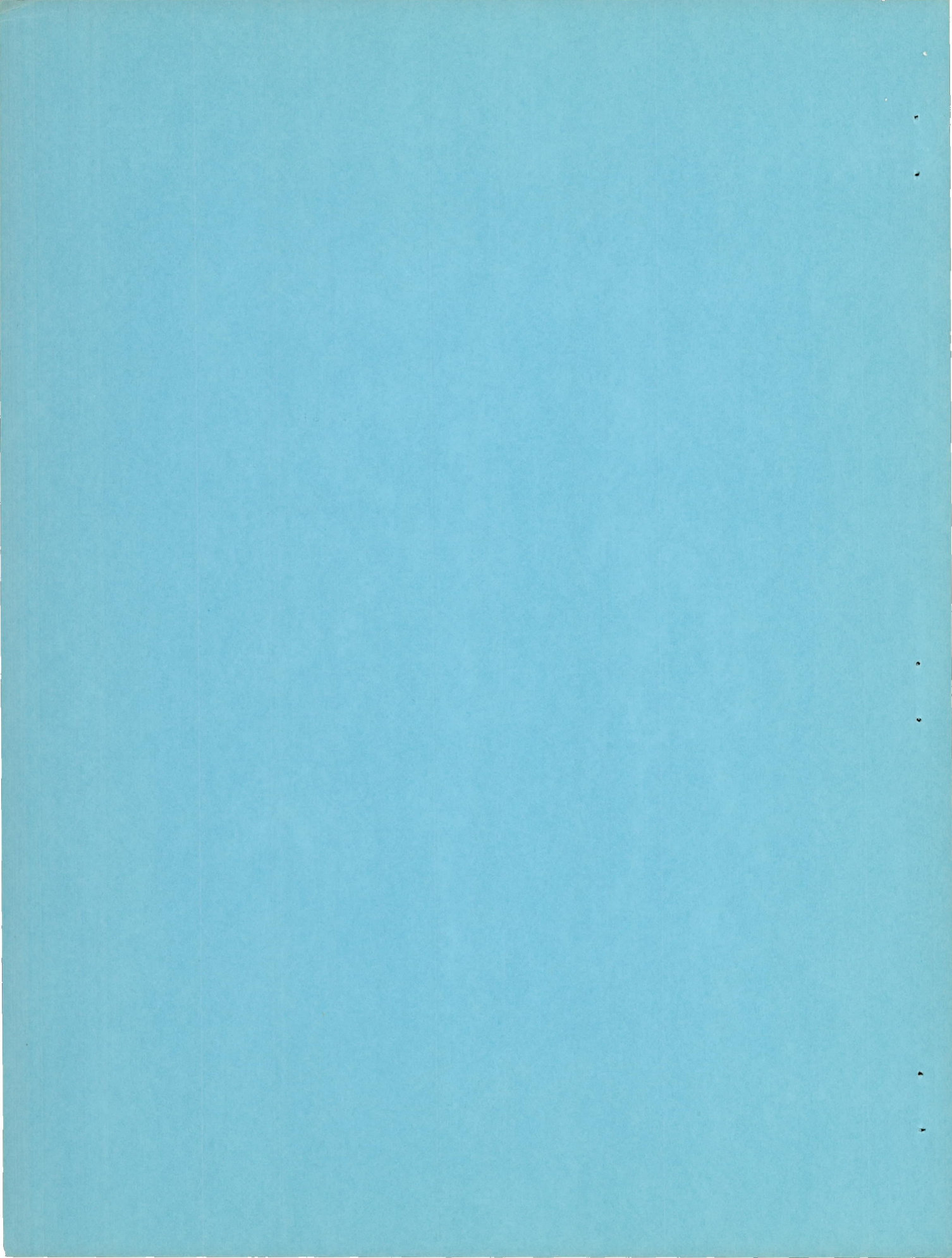By David S. Gabriel, Harry W. Dowman
and William L. Jones

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF THRUST AUGMENTATION OF

AXIAL- AND CENTRIFUGAL-COMPRESSOR TURBOJET ENGINES BY

INJECTION OF WATER AND ALCOHOL IN COMBUSTION CHAMBERS

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SUMMARY

An investigation of thrust augmentation by injection of water
and water-alcohol mixtures in the combustion chambers has been con-
ducted at sea-level zero-ram flight conditions on 4000-pound-thrust
axial-flow and centrifugal-flow turbojet engines. The engines
were equipped with variable-area exhaust nozzles that were used to
maintain constant turbine-outlet temperatures during injection.
The thrust augmentation, compressor characteristics, fuel flow,
and turbine-outlet-temperature distributions are presented for
various injection rates and water-alcohol mixtures. The thrust
augmentation obtained by combustion-chamber injection is compared
with results of both inlet injection and interstage injection
from other investigations for the axial-flow-type engine. A method
of computing the thrust augmentation by injection into the combus-
tion chambers is also presented and is compared with the results of
the experimental investigation of the axial-flow engine.

A maximum ratio of augmented to normal thrust of 1.18 was
obtained for the axial-flow-compressor engine by the injection of
0.78 pound per second of alcohol and 4.6 pounds per second of water
into the combustion chamber. The computed augmented-thrust ratios
were within 1 percent of the experimental results. No appreciable
thrust augmentation was obtained with the centrifugal-flow-type
engine by injection of water into the combustion chamber. This
result is explained by the shape of the compressor-characteristic
curves for this engine.

INTRODUCTION

As a part of a general research program of thrust augmentation of turbojet engines, several investigations of injection of water and water-alcohol mixtures have been conducted at the NACA Lewis laboratory. Results of investigations of injection of water and alcohol into the compressor inlets of both axial- and centrifugal-flow engines are presented in references 1 to 3. Interstage injection into the compressor of an axial-flow engine was also investigated (reference 4).

An investigation of water and water-alcohol injection into the combustion chambers of 4000-pound-thrust axial- and centrifugal-flow engines at sea-level, zero-ram conditions is reported herein. Similar injection systems were used on both the axial- and centrifugal-flow engines; four different arrangements of injection nozzles were investigated on the axial-flow engine. Both engines were equipped with variable-area exhaust nozzles to provide control of the exhaust-gas temperature independent of injection rate and engine speed. The investigation with the axial-flow engine was conducted at limiting conditions of speed and exhaust-gas temperature and covered a range of injection rates from 0 to 4.6 pounds per second of water with 0.8 pound per second of alcohol and a somewhat smaller range of injection rates with water alone. The investigation with the centrifugal-flow engine was conducted over a range of engine speeds and was confined to the injection of 1 and 2 pounds per second of water alone.

The thrust-augmentation and fuel-flow data, compressor characteristics, and turbine-outlet temperature distributions are given for the various injection-nozzle arrangements used in the axial-flow engine. For the centrifugal-flow engine, thrust data and compressor characteristics are presented. The thrust augmentation of the axial-flow engine is compared to that obtained with inlet injection and interstage injection. A method of computing the thrust augmentation by combustion-chamber injection is also presented and is compared with the experimental results for the axial-flow engine.

APPARATUS

Engines. - The investigation was conducted on J35 and J33 engines. The J35 engine has an 11-stage axial-flow compressor, eight cylindrical combustion chambers, and a single-stage turbine. The nominal military rating of the engine is 4000-pounds thrust at a rotor speed of 7700 rpm and zero-ram, sea-level conditions.

The J33 engine has a double-entry centrifugal-flow compressor, 14 cylindrical combustion chambers, and a single-stage turbine. The nominal military rating of the engine is 4000-pounds thrust at 11,500 rpm and zero-ram, sea-level conditions.

Engine installation and component parts. - The general arrangement of the installation of the J35 engine in the test chamber is shown in figure 1. The J33 setup was similar in most details. The engine was mounted on a swinging framework suspended from the ceiling of the test chamber; the engine thrust was balanced and measured with an air-pressure diaphragm. Engine air entered the nearly air-tight chamber through two 18-inch-diameter A.S.M.E. nozzles that were used to measure the air flow. The engine speed and the fuel flow were measured with standard instrumentation.

A spherical clamshell-type variable-area exhaust nozzle was installed at the end of a tail pipe 30 inches in length, which provided for discharge of the exhaust gas outside the test chamber. A cowling was installed at the engine inlet to facilitate measurement of the engine inlet-air temperature.

Liquids. - For this investigation AN-F-32 (Amendment-3) fuel was used. The alcohol used was a mixture of 50-percent methyl and 50-percent ethyl alcohol by volume. The water was obtained from Cleveland city mains.

Water-alcohol injection systems. - For the investigation in the J35 engine four modifications of the water- and alcohol-injection nozzles, designated nozzle arrangements A, B, C, and D, were used. The locations and the details of installation of the nozzles are shown in figure 2. The number, size, type, and location of injection nozzles used are listed in the following table:

Nozzle arrangement	Type spray	Nozzles per chamber	Throat diameter (in.)	Distance from upstream flange of chamber, (in.)
Water nozzles				
A	Hollow cone	2	0.182	$15\frac{1}{2}$
B	Hollow cone	3	.149	$15\frac{1}{2}$
C	Hollow cone	3	.073	$15\frac{1}{2}$
D	Solid jet	3	.073	$15\frac{1}{2}$
Alcohol nozzles				
A	Hollow cone	2	0.089	$17\frac{1}{2}$
B	Hollow cone	3	.073	$17\frac{1}{2}$
C	Hollow cone	3	.055	$17\frac{1}{2}$
D	Solid jet	3	.055	$17\frac{1}{2}$

On the basis of preliminary investigations conducted on a single combustion chamber (reference 5), the liquids were introduced at approximately the midpoint of the combustion chamber into the primary combustion zone near the liner walls. The injected liquids entered the nozzles tangentially; the swirl thereby induced a fine hollow cone spray for all of the injection systems except D. System D utilized nozzles with straight through flow to obtain a solid jet. In all configurations the water was introduced upstream of the alcohol.

Only one injection system was used on the J33 engine. One solid jet and three hollow-cone water-injection nozzles (similar to those used on the J35 engine) were attached to each burner at

the locations shown in figure 3. The nozzles were located as near
as possible to the midpoint of each combustion chamber. The number,
size, type, and location of nozzles used in the J33 engine are
summarized in the following table:

Type spray	Nozzles per chamber	Throat diameter (in.)	Distance from upstream flange of chamber, (in.)
Hollow cone	3	3/16	12
Solid jet	1	3/16	12

The single solid-jet-type nozzle (used in each combustion
chamber) was installed on the outer periphery of the engine in an
effort to eliminate a high-temperature region at the root of the
turbine blades.

Temperature and pressure instrumentation. - The locations of
temperature and pressure instruments on both engines are shown in
figure 1. The number, type, and location of thermocouples in the
J35 engine were as follows:

(a) Total temperature at engine inlet (station 0) T_0: Average
of 20 thermocouples, five in each of four rakes 90° apart,
at entrance to inlet cowling

(b) Total temperature at compressor outlet (station 2) T_2:
Average of 20 thermocouples, five in each of four rakes
located upstream of combustion chambers 2, 4, 6, and 8

(c) Turbine-outlet-temperature survey downstream of the com-
bustion chambers (station 5) T_5: four rakes of four
thermocouples each located at four radii downstream of
center lines of combustion chambers 2, 4, 6, and 8.
The four thermocouple readings at each radius were aver-
aged to obtain an average radial temperature distribution.

(d) Turbine-outlet-temperature survey between combustion
    chambers (station 5) T_5': four rakes of four thermo-
    couples located at four radii downstream of midpoints
    between burners 2 and 3, 4 and 5, 6 and 7, and 8 and 1.
    The four thermocouple readings at each radius were aver-
    aged to obtain an average radial temperature distribution.

(e) Temperature at tail-pipe inlet (station 7) T_7: Average
    of eight strut-type thermocouples equally spaced circum-
    ferentially and 4 inches from tail-pipe wall

The number, type, and location of pressure tubes in the J35
engine were as follows:

(a) Total pressure at engine inlet (station 0) P_0: one open-
    end tube in quiescent zone of test chamber

(b) Total pressure at compressor outlet (station 2) P_2:
    Average of 12 total-pressure tubes, three in each of
    four rakes upstream of combustion chambers 1, 3, 5,
    and 7

Similar instrumentation was used for the J33 engine.

PROCEDURE

The investigation of engine performance with water and alco-
hol injection in the combustion chambers of the J35 engine was con-
ducted for the following injection flows:

Nozzle arrange-ment	Water flow (lb/sec)	Alcohol flow (lb/sec)
A,B,C,D	0	0
A,B,C,D	0.8	0,0.8
A,B,C,D	1.6	0,0.8
A,B,C,D	2.4	0,0.8
A,B,C,D	3.2	0.8
A,B,D	3.2	0
C,D	4.0	0.8
C	4.25	0.8
D	4.6	0.8

All runs were made at an indicated engine speed of 7700 rpm with
an indicated tail-pipe temperature of 1660° R (maintained by exhaust-
nozzle adjustment). The runs with zero water and alcohol injection
were conducted periodically during the course of the investigation
in order to provide normal performance data upon which to base the
thrust augmentation.

Injection into the combustion chambers of the J33 engine was
investigated over an engine-speed range from 10,500 to 11,500 rpm.
Two series of runs were conducted, one with an exhaust-nozzle size
providing an indicated tail-pipe temperature of 1685° R at 11,500
rpm and the other with an exhaust-nozzle size providing an indicated
tail-pipe temperature of 1660° R at 11,500 rpm (both maintained by
exhaust-nozzle adjustment) with water-injection flows of 1.0 and
2.0 pounds per second, respectively. The reason for operating at
two tail-pipe temperatures will be subsequently discussed. Normal
performance data were also obtained over a range of engine speeds
with the exhaust-nozzle size providing an indicated tail-pipe tem-
perature of 1685° R at 11,500 rpm upon which to base the augmentation.

CORRECTION AND ADJUSTMENT OF DATA

All performance data presented were corrected to standard sea-
level conditions by use of the conventional generalization parameters
in order to adjust for small variations in inlet conditions that
occurred during the investigation. These factors, although unveri-
fied by experiment for application to combustion-chamber injection
data, are believed accurate for the small ranges of inlet conditions
encountered in this investigation; they should not be used, however,
to extrapolate the present data to altitude conditions without
further experimental verification.

The corrected engine-performance parameters are:

F/δ thrust

$N/\sqrt{\theta}$ engine speed

P/δ pressure

T/θ temperature

$\dfrac{W_a\sqrt{\theta}}{\delta}$ air flow

$$\frac{W_w \sqrt{\theta}}{\delta} \quad \text{injected-water flow}$$

$$\frac{W_{al} \sqrt{\theta}}{\delta} \quad \text{injected-alcohol flow}$$

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

where

$\delta \qquad \dfrac{\text{compressor-inlet total pressure}}{\text{NACA standard sea-level pressure}}$

$\theta \qquad \dfrac{\text{compressor-inlet total temperature}}{\text{NACA standard sea-level temperature}}$

All the symbols used in this report are defined in appendix A.

The correction factors applied to the injected-water and -alcohol flows are the same as those applied to the air flow in order to maintain the same water-air and alcohol-air ratios before and after data correction. The factor K included in the correction to engine-fuel flow serves to maintain a heat balance from uncorrected to corrected conditions. The factor K is defined as follows:

$$K = 1 + \left(\frac{1200}{\eta_f h_f} \frac{W_w}{W_f} - 0.35 \frac{W_{al}}{W_f} \right) (\theta - 1)$$

where h_f is the heating value of the fuel and η_f is the combustion efficiency. The value of 0.35 in the equation is the effective ratio of the net heating value of the alcohol to the net heating value of the fuel and was obtained from analysis of the data reported herein. The value of 1200 accounts for the enthalpy rise of the water during vaporization.

Because the investigation of the axial-flow engine was conducted at various ambient conditions, the data were not obtained at exactly the same corrected engine speeds and tail-pipe temperatures. Additional adjustment of the data was therefore made to reduce the results to a constant corrected engine speed of 7550 rpm

and a tail-pipe temperature of 1580° R. These adjustments were made by using the slopes of curves of the corrected engine-performance parameters plotted against engine speed for nonaugmented operation. Although this procedure may not be exact, the resultant error for the small range of engine speeds involved (7400 to 7700 rpm) is believed to be negligible.

ANALYSIS

The effect on engine operation of injection of liquids into the combustion chamber may be illustrated by reference to the compressor-characteristics curves of figure 4, which were obtained on the axial-flow engine. Because the flow through the turbine-nozzle throat is sonic and the area is fixed, the ratio of total gas flow to turbine-inlet (or compressor-outlet) pressure is constant for a given turbine-inlet temperature if the change in physical properties of the working fluid with injection of water is neglected. The injection of water and alcohol therefore tends to produce a decrease in compressor air flow. This air-flow decrease, however, is accompanied by a simultaneous increase in compressor-pressure ratio, as shown by the compressor-characteristic curves for a given engine speed. A new equilibrium operating point of the engine, having a lower compressor air flow, a higher compressor-pressure ratio, and hence a higher total gas flow through the turbine, is thus obtained. The thrust augmentation produced therefore depends on the operating characteristics of the compressor and is a result of both the increased mass flow and the higher jet velocity provided by the increased pressure ratio. In addition to these effects, the increased gas constant and specific heat of the water-alcohol-air mixture contribute, to a smaller degree, to an increase in the turbine-outlet pressure and consequently in the jet velocity.

The foregoing discussion of the fundamental effects of combustion-chamber injection on the engine cycle indicates that the thrust augmentation may be calculated from a knowledge of the compressor characteristics. Calculation of augmented-thrust ratios (ratio of augmented to normal thrust) was therefore made based on the experimental compressor-characteristic curve (fig. 4) for the engine. For this analysis, the new equilibrium running point between the compressor and the turbine was determined for various injection rates by graphically superimposing the compressor- and turbine-flow characteristics. (See appendix B.) Using the compressor-pressure ratio and air flow thus determined, the performance of the complete cycle was computed from values of

compressor efficiency computed from unaugmented test data, an
assumed value of turbine efficiency, and conventional thermodynamic
methods of analysis. The analysis was made for a range of water-
injection rates from 1 to 5 pounds per second and for alcohol-
injection rates of 0 and 0.78 pound per second. Calculations of
thrust augmentation were made using values of thermodynamic proper-
ties of the working fluid (γ and R) taking into account the changes
in these properties caused by the injected water and alcohol, and
additional calculations were made neglecting these changes in gas
properties. Further details of the method of analysis and the
equations used are given in appendix B.

RESULTS AND DISCUSSION

The results of the investigations with the axial- and
centrifugal-flow engines are presented separately and a comparison
of combustion-chamber injection with other injection methods is
given for the axial-flow engine.

Performance of Axial-Flow Engine

Compressor operating characteristics. - The shift in the engine
operating point with combustion-chamber injection (previously dis-
cussed) is illustrated in figures 5 and 6. The air flow and
compressor-pressure ratio for nozzle-arrangement C are plotted
against the total liquid flow for constant corrected engine speed
and tail-pipe gas temperature. Figure 5 shows that the air flow
decreases slightly with increased liquid-injection rates. Although
the scatter in the data is relatively large, the trend was con-
firmed by data from other nozzle arrangements. The small change
in air flow is accompanied by a relatively large change in
compressor-pressure ratio, as shown by the data in figure 6. The
curve of pressure ratio predicted from the measured air flow and
the compressor-characteristic curves of figure 4 is shown by the
dashed line in figure 6. The departure of the dashed curve from
the experimental points is attributed to discrepancies in the air-
flow data.

Experimental thrust augmentation. - The augmented-thrust ratios
experimentally obtained for the four injection-nozzle arrangements
are plotted in figure 7 as a function of corrected total liquid flow
for 0 and 0.78 pound per second of corrected injected-alcohol flows
and for a corrected engine speed of 7550 rpm and a corrected tail-
pipe temperature of 1580° R. All the data correlate, indi-
cating that within the accuracy of the data the amount

of augmentation available for a given total liquid flow was inde-
pendent of both the nozzle arrangement and the mixture of water and
alcohol injected. The maximum injection rate of water alone was
limited by the capacity of the engine fuel system to a flow of 3.2
pounds per second. For this condition, the augmented-thrust ratio
was 1.12 with a total liquid flow of 4.6 pounds per second. For
the water-alcohol mixture, the maximum injected flow rate was 4.6
pounds per second of water plus 0.78 pound per second of alcohol
as limited by hot streaks and overheating of the engine tail pipe.
The maximum augmented-thrust ratio obtained at this point was 1.18
with a total liquid flow of 6.63 pounds per second. The augmented-
thrust ratio showed no tendency to drop off with increased injected
flow rate. This result indicates that higher augmentations might
have been obtained with an improved injection system that would per-
mit operation with higher flows. Operation of the engine became
increasingly impaired, however, as the injected flows were increased,
as will be subsequently discussed.

Fuel flow. - The corrected fuel flow obtained with nozzle-
arrangement C is plotted against corrected injected-water flow for
0 and 0.78 pound per second of injected-alcohol flow in figure 8.
The fuel flow increases rapidly as the injected-water flow increases
and decreases with injected-alcohol flow. With an alcohol flow of
0.78 pound per second and a water flow of 2.67 pounds per second,
the fuel flow is equal to the fuel flow without injection. The mix-
ture of water and alcohol for constant engine fuel flow is therefore
23-percent alcohol by weight. The data are insufficient to deter-
mine whether the engine could be operated at this constant fuel flow
for other injected flows with this mixture.

An increase in the injected-alcohol flow from 0 to 0.78 pound
per second decreased the fuel flow required by approximately 0.27
pound per second.   Calculations based on these flow rates and on
heating values of 18,700 and 10,900 Btu per pound for fuel and alco-
hol, respectively, and for a fuel combustion efficiency of 95 percent
indicate that 56 percent of the heating value of the alcohol is
released in the combustion chambers.

Turbine-outlet temperature surveys. - Temperature surveys at
the turbine outlet for various rates of water and alcohol injection
with nozzle-arrangement D are shown in figure 9. The temperature
distributions for nozzle-arrangements A, B, and C were similar to
those for arrangement D, and no significant differences were obtained
by the changes made in the nozzle arrangement. Curves are shown
for the average radial distribution between burners and directly
downstream of the burners. (See section entitled "Temperature and
Pressure Instrumentation" for location of thermocouple rakes.)

All the data are for the same over-all average tail-pipe gas temperature (1660° R). The radial temperature gradient is about the same for all injection rates; increasing the injected-water and -alcohol flow decreased the temperatures between the combustion chambers (fig. 9(a)) by about the same amount as it increased the temperatures directly downstream of the burner (fig. 9(b)). The change in temperature was approximately 300° R for an injection of 4.6 pounds per second of water and 0.78 pound per second of alcohol. Inasmuch as the gas temperature for unaugmented operation was higher directly downstream of the combustion chambers, injection had the effect of increasing the highest temperatures and decreasing the lowest temperatures.

Operating characteristics. - Visual observations of the engine during this investigation showed that water-injection rates above 3 pounds per second caused hot streaks to appear on the tail cone. In general, the hot streaks became brighter with increases in injected-water flow. The addition of alcohol to the injected mixture also caused the streaks to become more pronounced, possibly due to afterburning of the alcohol through the turbine. No significant difference was observed for any of the nozzle arrangements investigated, and because of these hot streaks the maximum injected flow was limited to 5.4 pounds per second.

Immediately after operation with injection of 4.6 pounds per second of water and 0.80 pound per second of alcohol during the investigation of nozzle-arrangement D, a turbine blade was found to be broken off at a point about one-third of the blade length from the tip. The warped condition of a number of the blades in the turbine-nozzle diaphragm after this failure is shown in figure 10.

The exact cause of these failures was not determined, but it is probable that the failures were caused by prolonged operation at maximum turbine-inlet temperature and engine speed with frequent changes in temperature distribution caused by variable rates of injection encountered while setting test conditions.

Comparison with other injection methods. - A comparison of thrust augmentation by water injection at the compressor inlet and by interstage injection with that obtained by combustion-chamber injection is shown in figure 11. The data for inlet injection (reference 2) and for interstage injection (reference 4) are compared with combustion-chamber-injection results on an uncorrected basis because of the uncertainty of the correction methods for inlet injection in an axial-flow-compressor engine. The comparison shows that injection at the compressor inlet

produces greater thrust augmentation than combustion-chamber
injection throughout almost the entire range of flows investigated.
The use of compressor-inlet injection at total liquid flows above
3.5 or 4.0 pounds per second, however, has been found to result in
sufficient centrifugal separation of the liquid and air and atten-
dant uneven temperature distributions in the compressor to produce
rubbing of the compressor blades on the casing (reference 2). In
view of this limitation to the applicability of compressor-inlet
injection, it appears that for augmented-thrust ratios above about
1.14 the combustion-chamber injection system is superior to that
of inlet injection. Interstage injection produces a greater thrust
augmentation over the entire range of liquid flows than combustion-
chamber injection. The maximum difference is about 5 percent of
the normal thrust at a total liquid flow of 5.5 pounds per second.

  Calculated augmented-thrust ratio. - The augmented-thrust ratio
calculated by the method discussed in the section entitled "Analysis"
and outlined in appendix B is shown in figure 12 and is compared
with the curve of experimental augmented-thrust ratio taken from
figure 7. Calculated curves are shown for two cases: (1) neglecting
and (2) accounting for the effect of the presence of water and
alcohol on the gas properties (γ and R). As previously discussed,
the analysis was made for a range of injected-water flows from 1 to
5 pounds per second and for injected-alcohol flows of 0 and 0.78
pound per second; for simplicity, it was assumed that all the
injected alcohol and fuel burned. On this basis, the augmented-
thrust ratio as a function of total liquid flow was independent of
the water-alcohol mixture for the range investigated and therefore
the results for the various water-alcohol mixtures are not dis-
tinguished in figure 12. If a 50-percent combustion efficiency
for the alcohol had been assumed (as indicated by the experimental
results), an increase in total liquid flow of about 3 percent at
the same augmented-thrust ratios would have been obtained for the
conditions with alcohol injection. The curve of augmented-thrust
ratio calculated by accounting for changes in gas properties with
injection is about 1 percent higher than the experimental curve.
The curve for calculated augmentation neglecting the changes in
gas properties is considerably lower than the experimental curve,
particularly at the higher total liquid flows. Results of the
analysis further show that about one-fourth of the augmentation
produced is due to changes in thermodynamic properties of the work-
ing fluid and of the remaining three-fourths, half is due to increased
mass flow and half to increased jet velocity resulting from the
higher compressor-pressure ratio. The thrust augmentation obtained
by combustion-chamber injection may thus be calculated with good
accuracy if the changes in gas properties are considered.

Performance of Centrifugal-Compressor Engine

The results of the investigations conducted with the
centrifugal-flow engine are summarized in figure 13, in which the
corrected thrust is plotted against the corrected engine speed for
two tail-pipe-temperature settings at maximum engine speed. The
maximum injected-water flow with the variable-area nozzle set for
a tail-pipe temperature of 1685° R was limited to a flow between
1.5 and 2.0 pounds per second by compressor surge. Inasmuch as
the thrust increase shown by the line for an injection rate of 1.0
pound per second was small, very little further increase could be
expected up to surge. As an alternative method of operation, the
tail-pipe gas temperature was reduced to 1660° R at maximum speed
by increasing the exhaust-nozzle area to permit a higher total mass
flow and an attendant higher injection rate, which was accompanied
by a favorable change in gas properties before surge was encountered.
The injected-water flow at this tail-pipe-temperature setting was
limited to a flow between 2.0 and 2.5 pounds per second by compressor
surge. The augmented thrust for a tail-pipe temperature of 1660° R
and an injected-water rate of 2.0 pounds per second was, however,
about the same as the normal thrust at a tail-pipe temperature of
1685° R. Thus for both conditions investigated, the thrust augmenta-
tion was very small.

The small increase in thrust with water injection is explained
by the compressor-characteristic curves for a similar centrifugal-
flow-type engine, which are replotted from an unavailable publi-
cation in figure 14. Also shown in this figure are the operating
points for two rates of water injection. It is apparent that the
shift in the compressor operating point with increased injection
rate produces very little increase in compressor-pressure ratio
due to the very flat compressor characteristic and, consequently,
the compressor-outlet pressure is nearly constant for all injection
rates from normal operation to surge. Because the compressor-outlet
pressure is nearly constant (fig. 14), the mass flow through the
engine was also nearly constant; hence the thrust produced is
approximately constant.

SUMMARY OF RESULTS

The following results were obtained in the sea-level, zero-
ram investigation of thrust augmentation of 4000-pound-thrust
axial- and centrifugal-compressor turbojet engines by injection
of water and water-alcohol mixtures in the combustion chambers:

1. The injection of liquids into the combustion chamber caused a shift in the equilibrium running point of the engine to a lower air flow, a higher pressure ratio, and a higher total mass flow rate. This shift in running conditions of the engine was a result of the flow limitations imposed by the turbine nozzles and depended in magnitude upon the compressor characteristics of the engine. From a knowledge of the compressor characteristics, the thrust augmentation produced could be calculated with a good degree of accuracy provided that changes in thermodynamic properties of the working fluid were properly accounted for. In a sample calculation, the computed augmented-thrust ratio was within 1 percent of the experimental results.

2. A maximum augmented-thrust ratio of 1.18 was obtained for the axial-flow-compressor engine for a maximum injection rate of 0.78 pound per second of alcohol and 4.6 pounds per second of water; the total liquid flow including fuel at this condition was 6.63 pounds per second.

3. Within the range of conditions investigated, the thrust augmentation of the axial-flow engine for a given total liquid flow was unaffected by the injection-nozzle arrangement used or by the mixture of water and alcohol injected.

4. For the four nozzle arrangements used on the axial-flow engine, the intensity of hot streaks in the tail pipe during operation with high total liquid flows was considered sufficiently severe to limit the amount of injected flow to values less than

about $5\frac{1}{2}$ pounds per second.

5. The increase in compressor-pressure ratio with injection rate for the centrifugal-flow engine was small due to the flat compressor characteristic at the operating point. As a result, the total mass flow through the engine was nearly constant and the thrust increase was small. The injected-water flow for this engine was limited to small quantities by compressor surge.

6. Because combustion-chamber injection permitted operation at higher liquid flows than the operational limit with compressor-inlet injection, it is considered superior to inlet injection for the axial-flow engine for total liquid flows above 3.5 to 4.0 pounds per second. Compressor-interstage injection produced higher thrust augmentation than combustion-chamber injection over the entire range of liquid flows investigated.

7. Injection into the axial-flow engine had little effect on the radial turbine-outlet-temperature profile. The normally present circumferential temperature gradients, however, became more severe with increased injection rate, with the temperatures directly downstream of the combustion chambers increasing as much as 300° F and the temperatures between combustion chambers decreasing as much as 300° F as the injection rate was increased up to 5.4 pounds per second. Inasmuch as the temperature without injection was higher downstream of the combustion chamber, injection had the effect of increasing the highest temperatures and decreasing the lowest temperatures. Changes in the injection-nozzle arrangement had little effect on the temperature distributions.

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APPENDIX A

SYMBOLS

A_t effective turbine-nozzle-throat area, sq ft

C constant

C_v exhaust-nozzle velocity coefficient

c_p specific heat at constant pressure, Btu/(lb)($^\circ$R)

F normal jet thrust (without injection), lb

F_A augmented jet thrust (with injection), lb

g mass conversion factor, ft/sec^2

h_f lower heating value of fuel, Btu/lb

J mechanical equivalent of heat, ft-lb/Btu

N engine speed, rpm

P total pressure, lb/sq in. abs.

p static pressure, lb/sq in. abs.

R gas constant, ft-lb/(lb)($^\circ$R)

T total temperature, $^\circ$R

V velocity, ft/sec

W_a air flow, lb/sec

W_{al} injected-alcohol flow, lb/sec

W_f engine fuel flow, lb/sec

W_m flow of gas mixture passing through turbine, lb/sec

W_w injected-water flow, lb/sec

β function of properties of water-air mixture

γ ratio of specific heat

δ $\dfrac{\text{compressor-inlet total pressure}}{\text{NACA standard sea-level pressure}}$

η_c compressor adiabatic efficiency

η_f combustion efficiency

η_t turbine adiabatic efficiency

θ $\dfrac{\text{compressor-inlet total temperature}}{\text{NACA standard sea-level temperature}}$

Subscripts:

A   augmented

A'   augmented neglecting changes in gas properties

A''   augmented accounting for changes in gas properties

a   air

g   gas

j   jet

m   mixture passing through turbine

S   standard

w   water

0   cowling or compressor inlet

2   compressor outlet

4   turbine inlet

5   turbine outlet

APPENDIX B

METHOD OF CALCULATING AUGMENTED-THRUST RATIO FOR

COMBUSTION-CHAMBER INJECTION OF WATER AND ALCOHOL

The following values were assumed constant throughout the calculation:

$c_{p,a}$ 0.24 Btu/(lb)($^{\circ}$R)

$(c_{p,m})_S$ 0.273 Btu/(lb)($^{\circ}$R)

R_w 85.8 ft-lb/(lb)($^{\circ}$R)

η_t 0.81

γ_a 1.4

$\gamma_{m,S}$ 1.336

For the engine speed considered, calculations of compressor efficiency η_c from the unaugmented test data (the data from which the compressor-characteristic curve was determined) showed that the efficiency was nearly constant at a value of 0.84. This value was accordingly used in the analysis.

The equilibrium running point of the engine for various rates of injection into the combustion chamber is determined by superimposing the compressor and turbine operating characteristics.

For supercritical-pressure ratio across the turbine nozzles, the mass flow of mixture through the turbine is given by

$$W_m = A_t \ P_4 \sqrt{\frac{\gamma_m \ g}{R_m T_4}\left(\frac{2}{\gamma_m+1}\right)^{\frac{\gamma_m+1}{\gamma_m-1}}} \tag{1}$$

From zero-ram sea-level conditions

$$P_0 = 2116 \text{ lb/sq ft} \tag{2}$$

When pressure losses in the combustion chamber are neglected,

$$P_2 = P_4 \tag{3}$$

By use of equations (2) and (3), equation (1) may be written

$$W_m = 2116 \; A_t \; \frac{P_2}{P_0} \sqrt{\frac{\gamma_m \; g}{R_m T_4}\left(\frac{2}{\gamma_m + 1}\right)^{\frac{\gamma_m + 1}{\gamma_m - 1}}} \tag{4}$$

A factor β is defined as

$$\beta = \sqrt{\frac{\gamma_m}{R_m}\left(\frac{2}{\gamma_m + 1}\right)^{\frac{\gamma_m + 1}{\gamma_m - 1}}} \tag{5}$$

For these computations, the fuel flow and the injected-alcohol flow are neglected in evaluating β. For a constant gas temperature, β is therefore a function of only the water-air mixture passing through the turbine.

For simplicity, the turbine-inlet temperature T_4 is considered constant for that part of the analysis concerned with establishing the operating point of the engine. For the rest of the analysis, the turbine-outlet temperature is assumed to be constant, and the turbine-inlet temperature variable. Check calculations reveal that this simplifying assumption produces negligible error.

Because T_4 is considered constant, a constant C may be defined as

$$C = 2116 \; A_t \sqrt{\frac{g}{T_4}} \tag{6}$$

where A_t is evaluated from analysis of normal engine performance data.

By substituting equations (5) and (6) into equation (4)

$$W_m = C\beta \frac{P_2}{P_0} \tag{7}$$

From conservation of mass for standard conditions

$$(W_m)_S = (W_a)_S + (W_f)_S \tag{8}$$

and for augmented conditions

$$(W_m)_A = (W_a)_A + (W_f)_A + W_w + W_{al} \tag{9}$$

For augmented conditions, substitution of equation (9) in equation (7) therefore gives

$$(W_a)_A + (W_f)_A + W_{al} + W_w = C\beta \frac{P_2}{P_0} \tag{10}$$

Rearrangement of equation (10) gives

$$(W_a)_A = C\beta \frac{P_2}{P_0} - \left[(W_f)_A + W_w + W_{al}\right] \tag{11}$$

This equation expresses the turbine-flow characteristics in terms of conventional compressor characteristics, that is, W_a and P_2/P_0.

Assumed values of W_a and W_w permit determination of corresponding values of β. Assuming the temperature rise in the combustion chamber to be constant for all operating conditions and a combustion efficiency of 100 percent serves as a basis for evaluating the fuel flow W_f from the charts of reference 6, which includes the heating value of the alcohol. With all factors of equation (11) except P_2/P_0 thus determined or assumed, P_2/P_0 is calculated for several values of W_a, and the points thus obtained are plotted on the same coordinates as the compressor-characteristic curve; the intersection of the two curves thus establishes the equilibrium running point of the engine. The final operating curves are shown in figure 15, where the compressor-characteristic curve for a corrected engine speed of 7550 rpm and the turbine-flow characteristics for a range of water- and alcohol-injection rates are illustrated.

When the running points of the engine for various injection rates and mixtures have been established by the foregoing procedure, the augmented-thrust ratios may be calculated by means of the following equations.

The temperature rise through the compressor is determined from the pressure ratio established by this procedure from

$$T_2 - T_0 = \frac{T_0}{\eta_c}\left[\left(\frac{P_2}{P_0}\right)^{\frac{\gamma_a-1}{\gamma_a}} - 1\right] \tag{12}$$

Because the compressor and turbine work are equal

$$W_a\, c_{p,a}\,(T_2 - T_0) = W_m\, c_{p,m}\,(T_4 - T_5)$$

Solving for the turbine-temperature ratio gives

$$\frac{T_4}{T_5} = 1 + \frac{W_a\, c_{p,a}\,(T_2 - T_0)}{W_m\, c_{p,m}\, T_5} \tag{13}$$

Expressing the turbine pressure ratio in terms of the temperature ratio and substituting from equation (3) gives

$$\frac{P_4}{P_5} = \frac{P_2}{P_5} = \left[1 + \frac{1}{\eta_t}\left(\frac{T_4}{T_5} - 1\right)\right]^{\frac{\gamma_m}{\gamma_m-1}} \tag{14}$$

The exhaust-nozzle pressure ratio may be determined from the compressor and turbine pressure ratios as follows:

$$\frac{p_0}{P_5} = \left(\frac{P_0}{P_2}\right)\left(\frac{P_2}{P_5}\right)\left(\frac{p_0}{P_0}\right) \tag{15}$$

Inasmuch as $p_0 = P_0$ at zero-ram sea-level conditions, equation (15) reduces to

$$\frac{p_0}{P_5} = \left(\frac{P_0}{P_2}\right)\left(\frac{P_2}{P_5}\right) \tag{15a}$$

The expression for the jet thrust for zero-ram sea-level conditions is

$$F = \frac{W_m}{g} V_j \tag{16}$$

Where

$$V_j = C_v \sqrt{\frac{2\gamma_m}{\gamma_m - 1} \, g \, R_m \, T_5 \left[1 - \left(\frac{p_0}{P_5} \right)^{\frac{\gamma_m - 1}{\gamma_m}} \right]} \tag{17}$$

Expressing the engine performance in terms of the augmented thrust ratio and canceling like terms gives

$$\frac{F_{A''}}{F_S} = \frac{W_{m,A''}}{W_{m,S}} \sqrt{ \frac{ \left(\dfrac{\gamma_m}{\gamma_m - 1} \right)_A R_{m,A} \left[1 - \left(\dfrac{p_0}{P_5} \right)_{A''}^{\left(\frac{\gamma_m - 1}{\gamma_m} \right)_A} \right] }{ \left(\dfrac{\gamma_m}{\gamma_m - 1} \right)_S R_{m,S} \left[1 - \left(\dfrac{p_0}{P_5} \right)_S^{\left(\frac{\gamma_m - 1}{\gamma_m} \right)_S} \right] } } \tag{18}$$

For the case where the change in thermodynamic properties due to injection are neglected, equation (18) reduces to

$$\frac{F_{A'}}{F_S} = \frac{W_{m,A'}}{W_{m,S}} \sqrt{ \frac{ \left[1 - \left(\dfrac{p_0}{P_5} \right)_{A'}^{\left(\frac{\gamma_m - 1}{\gamma_m} \right)_S} \right] }{ \left[1 - \left(\dfrac{p_0}{P_5} \right)_S^{\left(\frac{\gamma_m - 1}{\gamma_m} \right)_S} \right] } } \tag{19}$$

The specific heat of the air, water, fuel, and alcohol mix-
ture is determined from the law of mixtures, as follows:

$$c_{p,m} = c_{p,g}\left(\frac{W_m - W_w}{W_m}\right) + c_{p,w}\frac{W_w}{W_m} \qquad (20)$$

where $c_{p,g}$, as well as R_g to be used later, are determined from
curves of specific heat of gases for various fuel-air ratios and
temperatures prepared from the data of reference 7. The injected
alcohol was considered as fuel in the fuel-air ratio used in these
charts. The specific heat of the water vapor $c_{p,w}$ is obtained
from the following empirical equation of reference 8:

$$c_{p,w} = 19.86 - \frac{597}{\sqrt{T}} + \frac{7500}{T} \qquad (21)$$

Similarly, the value of the gas constant R_m is determined
from

$$R_m = R_g\left(\frac{W_m - W_w}{W_m}\right) + R_w\frac{W_w}{W_m} \qquad (22)$$

The value of the specific heat function is determined from

$$\frac{\gamma_m}{\gamma_m - 1} = \frac{J\,c_{p,m}}{R_m}$$

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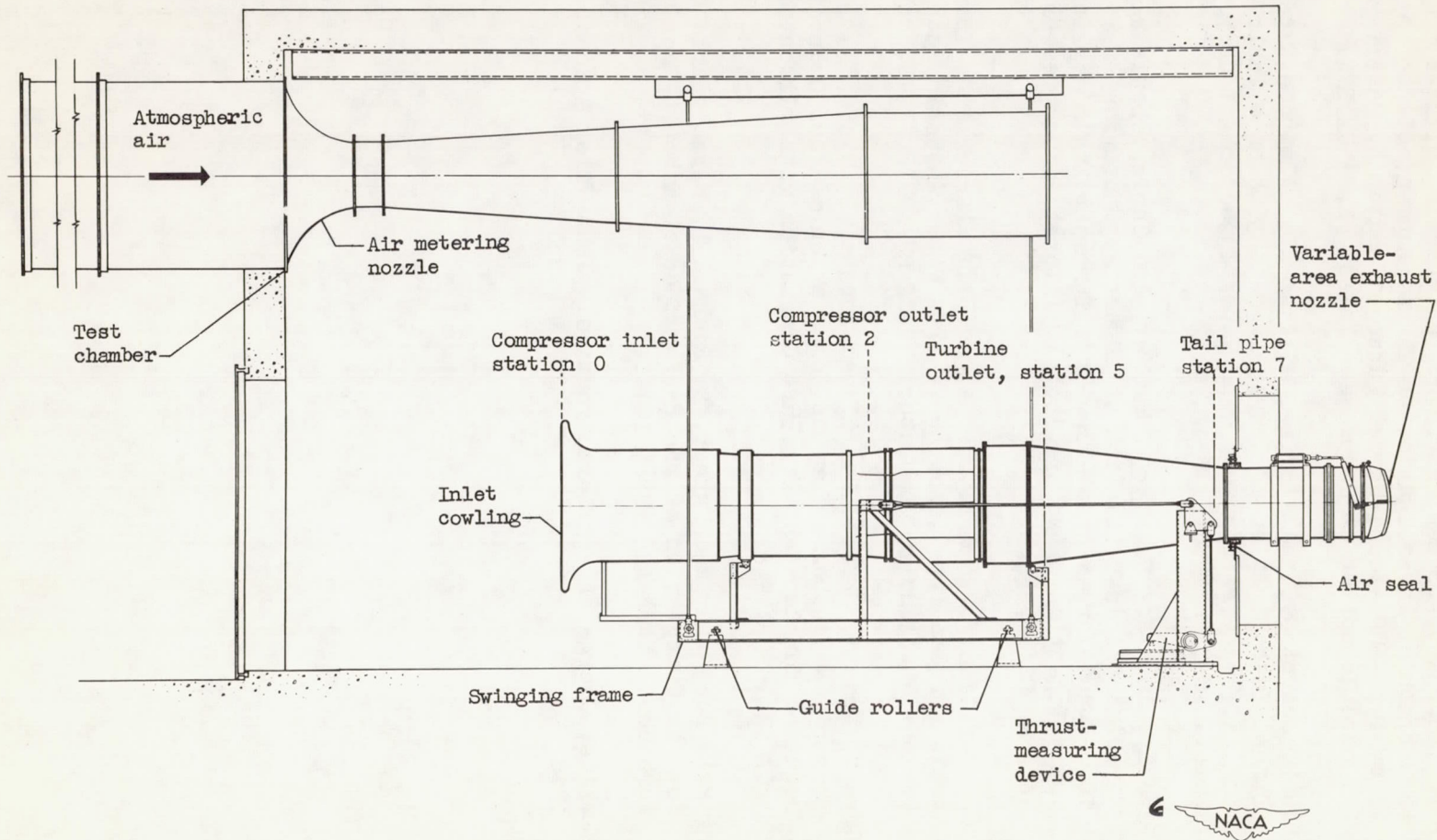
Figure 1. - Typical installation of turbojet engine.
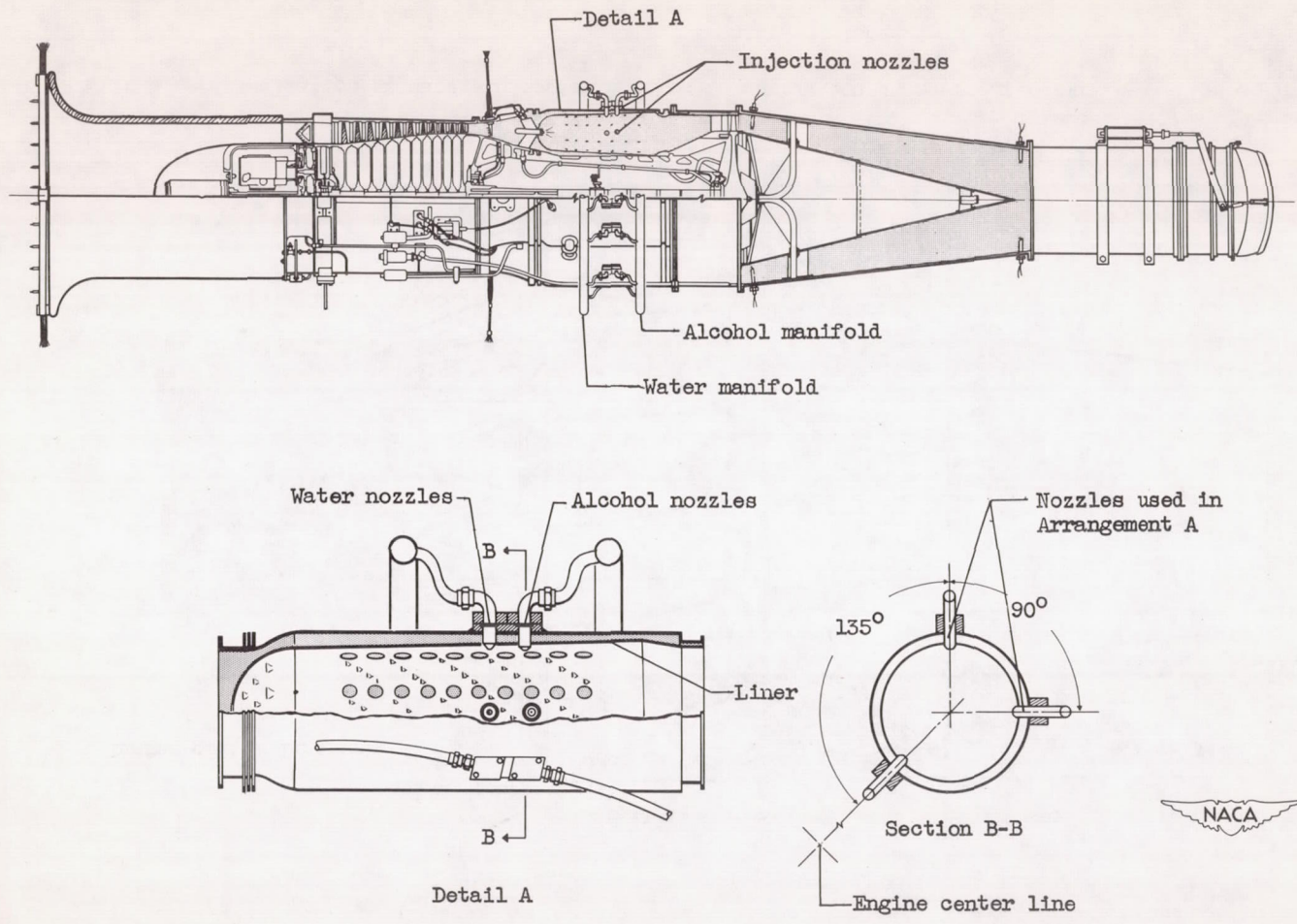
Figure 2. - Installation of water-alcohol injection nozzles in combustion chambers of axial-flow engine.
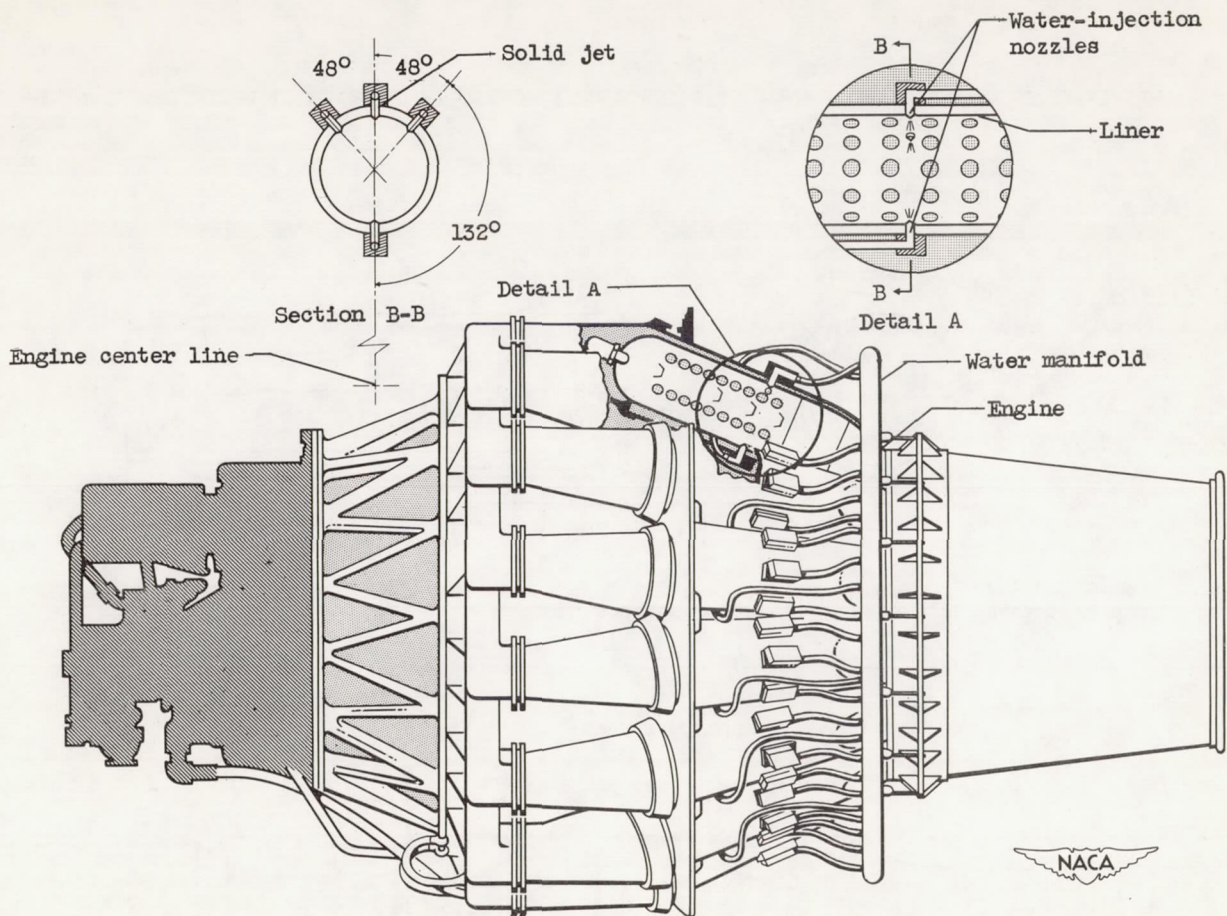
Figure 3. - Installation of water-injection nozzles in combustion chambers of centrifugal-flow engine.
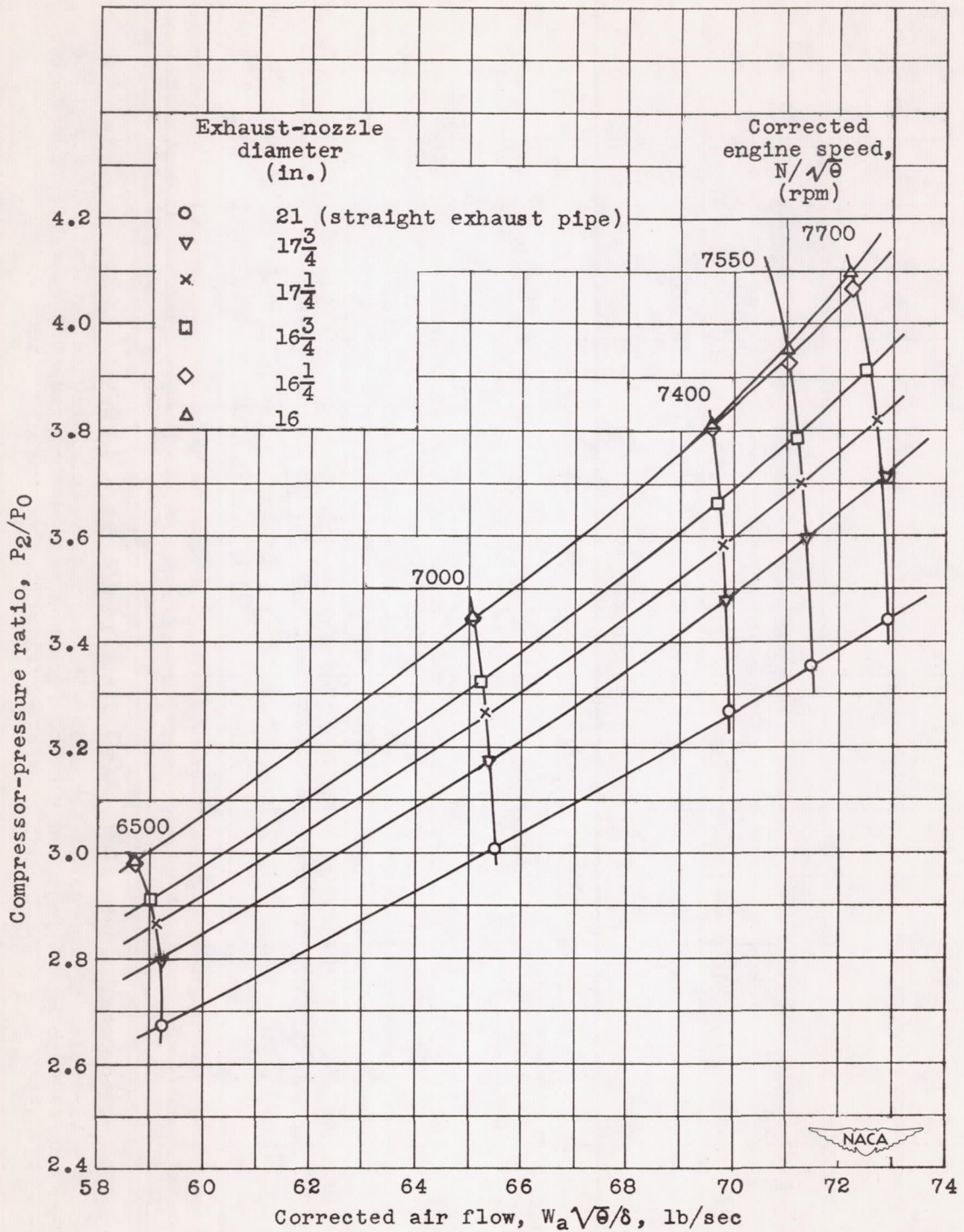
Figure 4. - Compressor-characteristic curves for various exhaust-nozzle sizes on axial-flow engine.
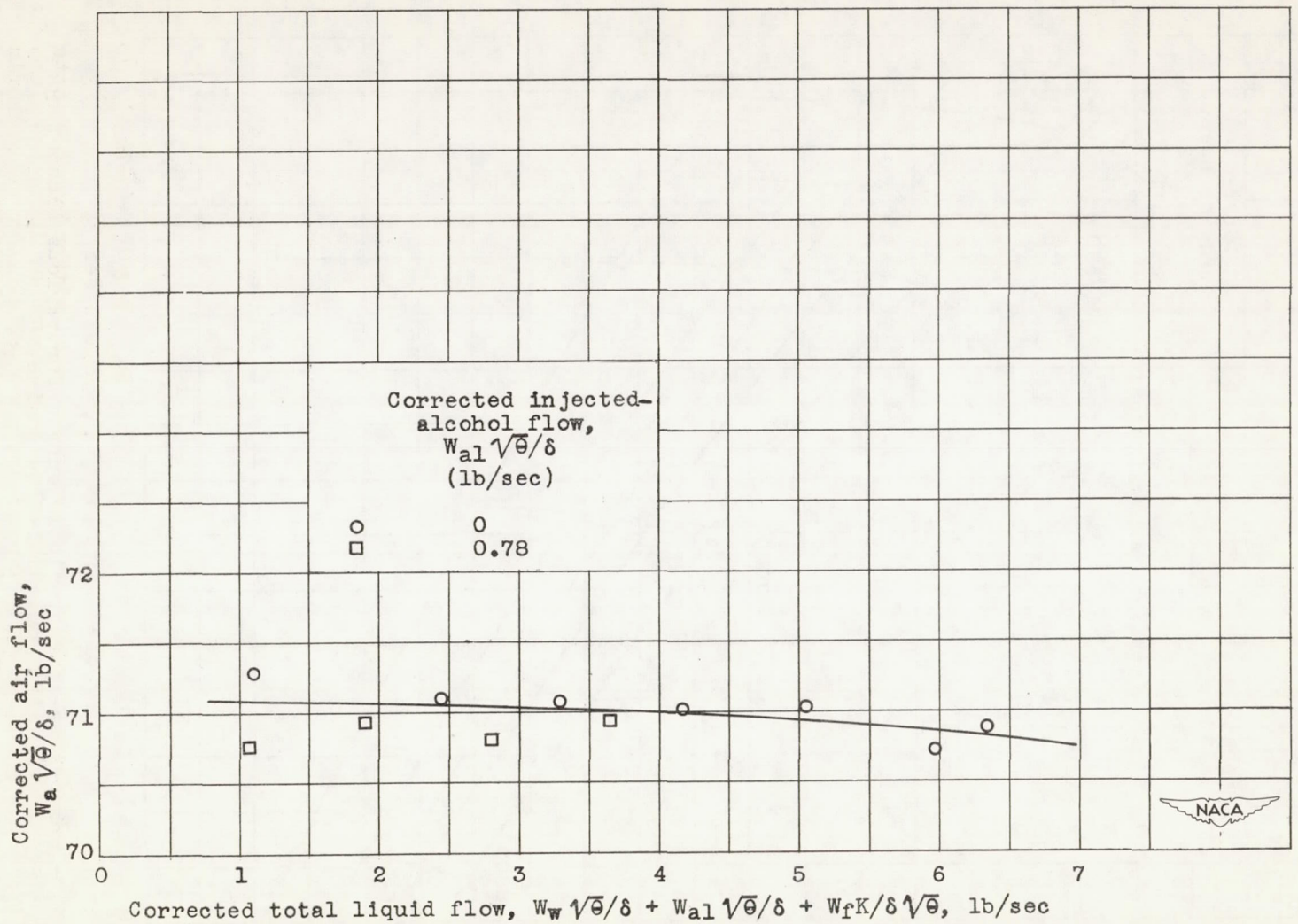
Figure 5. - Variation of corrected air flow with corrected total liquid consumption for 0 and
0.78 pound per second of injected alcohol flow for nozzle-arrangement C on axial-flow engine.
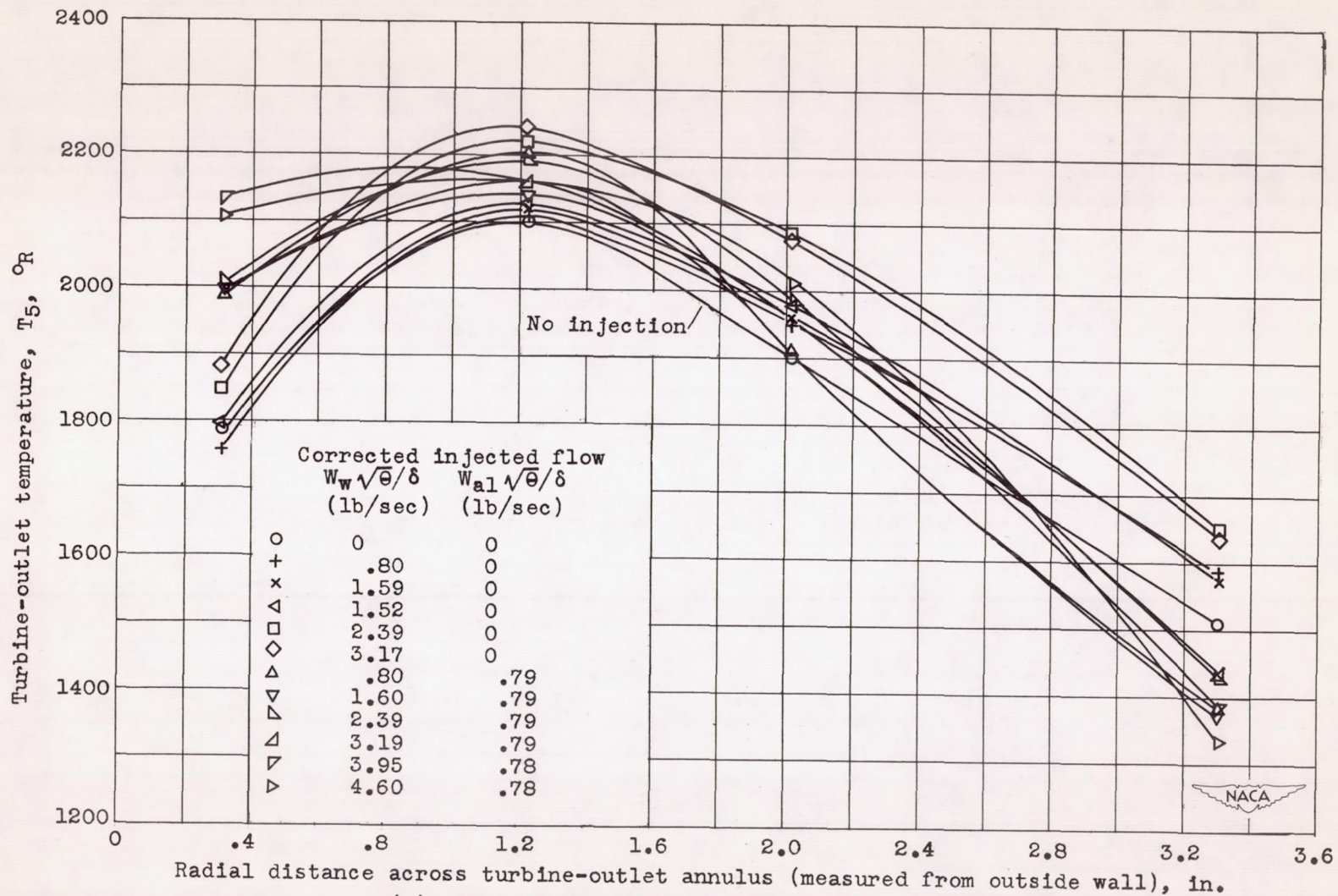Corrected engine speed, 7550 rpm; corrected tail-pipe temperature, 1580° R.
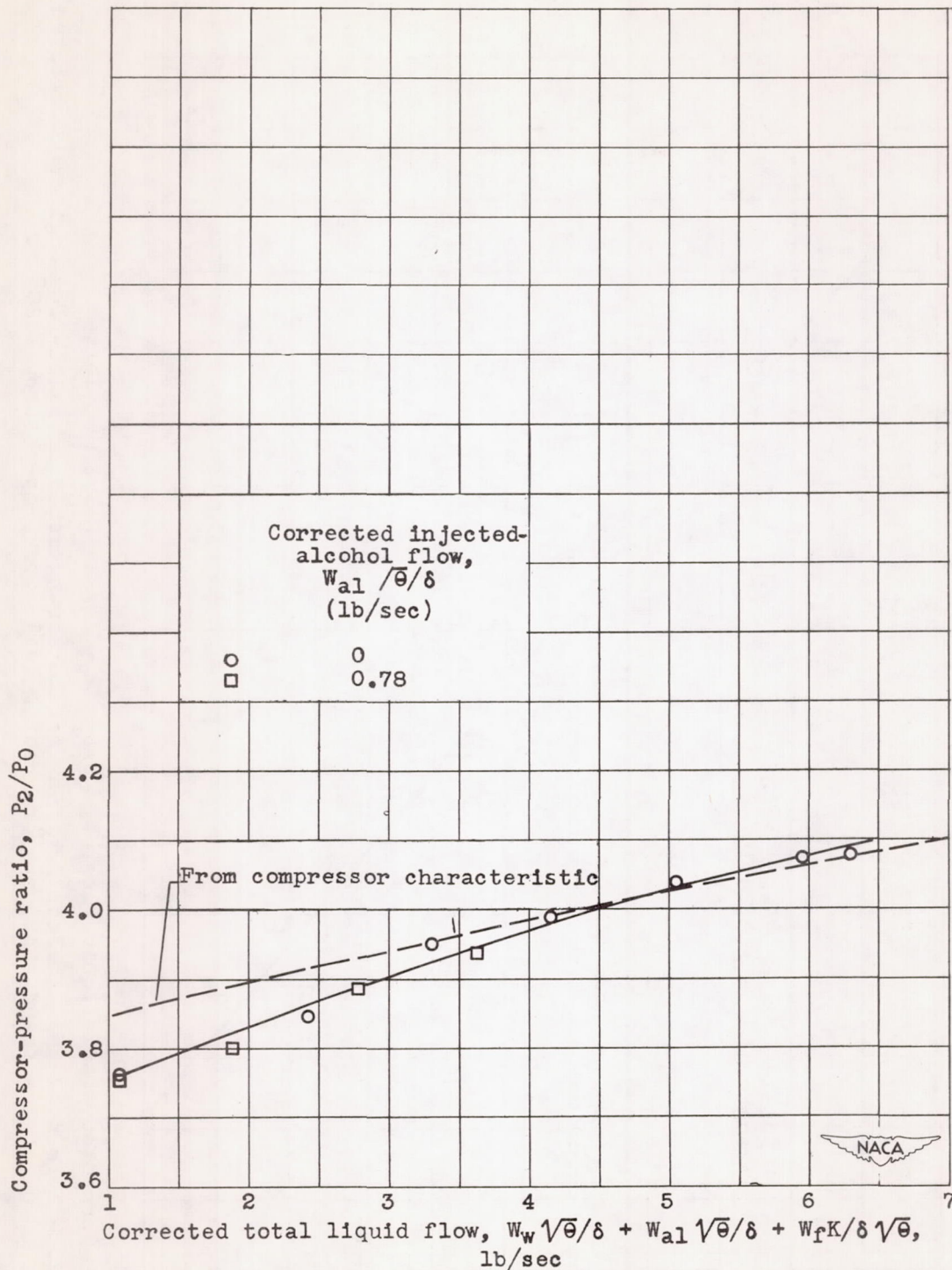
Figure 6. - Variation of compressor-pressure ratio with corrected total liquid consumption for 0 and 0.78 pound per second of injected alcohol flow for nozzle-arrangement C on axial-flow engine. Corrected engine speed, 7550 rpm; corrected tail-pipe temperature, 1580° R.
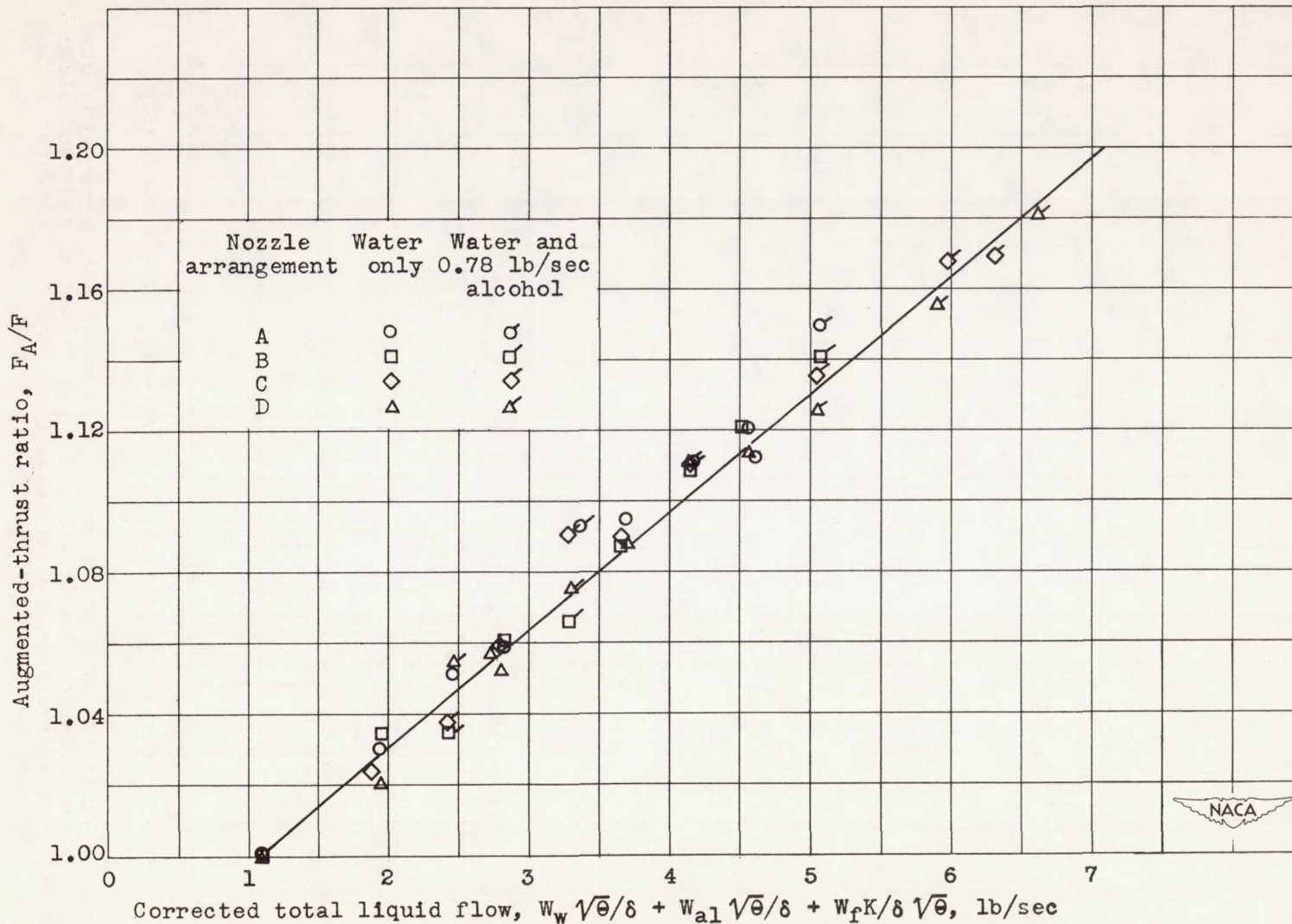
Figure 7. - Augmented-thrust ratio for four ñozzle arrangements on axial-flow engine. Corrected engine speed, 7550 rpm; corrected tail-pipe temperature, 1580° R.
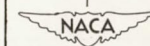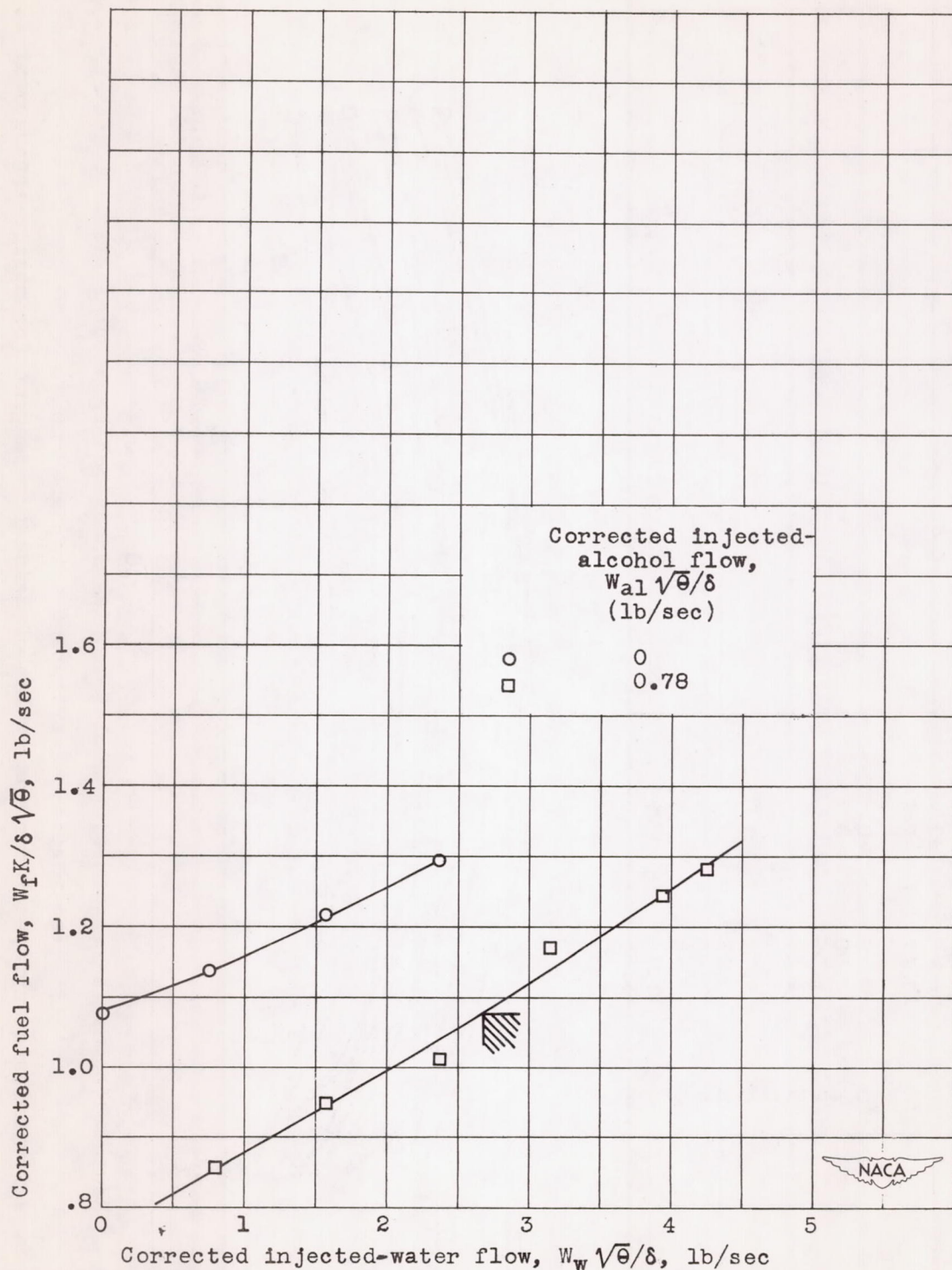
Figure 8. - Variation of corrected fuel flow with corrected injected-water flow for nozzle-arrangement C on axial-flow engine. Corrected engine speed, 7550 rpm; corrected tail-pipe temperature, 1580° R.

	Corrected injected flow	
	$W_w \sqrt{\theta}/\delta$ (lb/sec)	$W_{al}\sqrt{\theta}/\delta$ (lb/sec)
○	0	0
+	.80	0
×	1.59	0
◁	1.52	0
□	2.39	0
◇	3.17	0
△	.80	.79
▽	1.60	.79
◁	2.39	.79
◁	3.19	.79
▽	3.95	.78
▷	4.60	.78
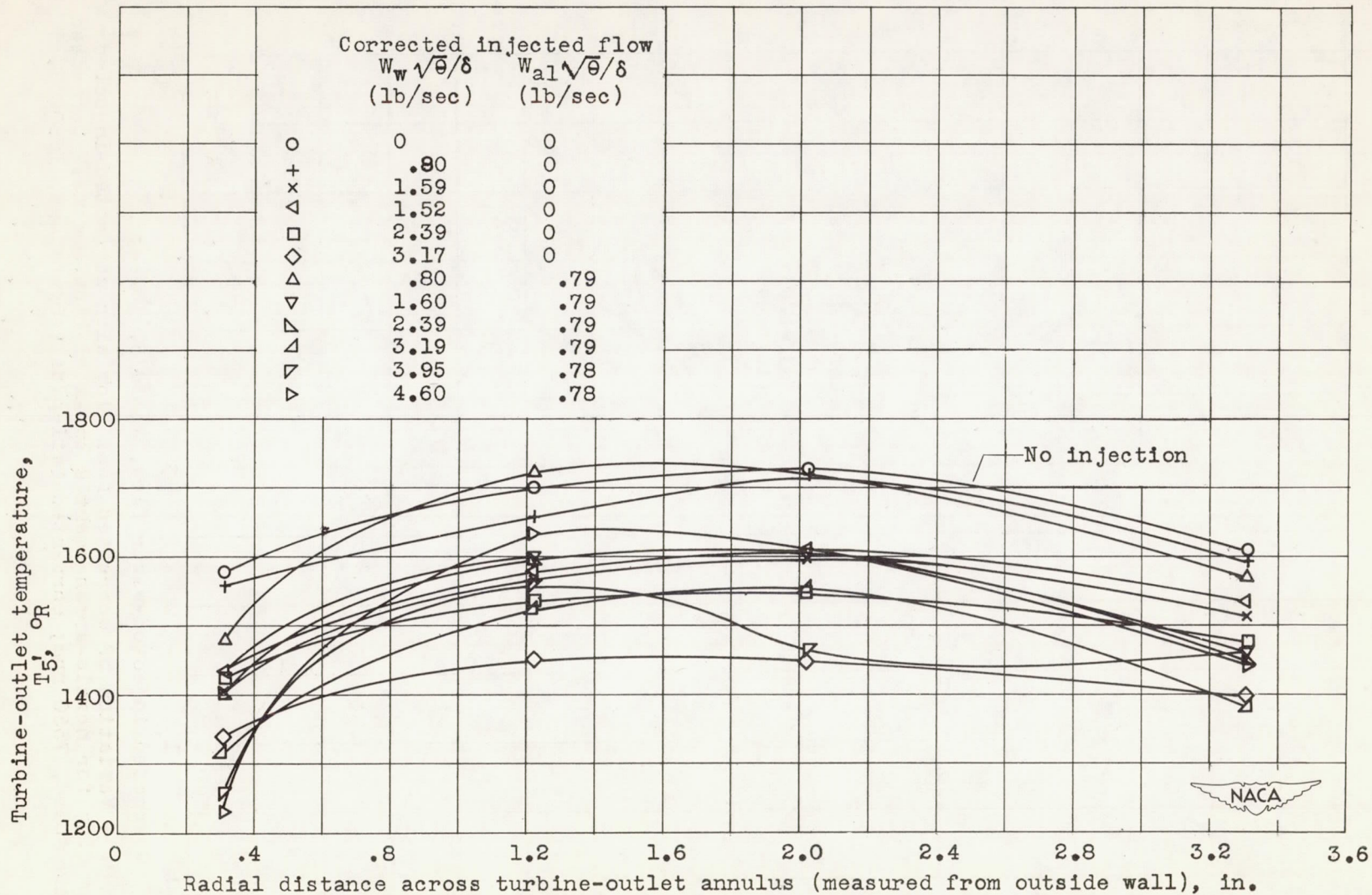
(a) Radial distribution between burners.

Figure 9. - Temperature surveys at turbine outlet of axial-flow engine for nozzle-arrangement D.

No injection

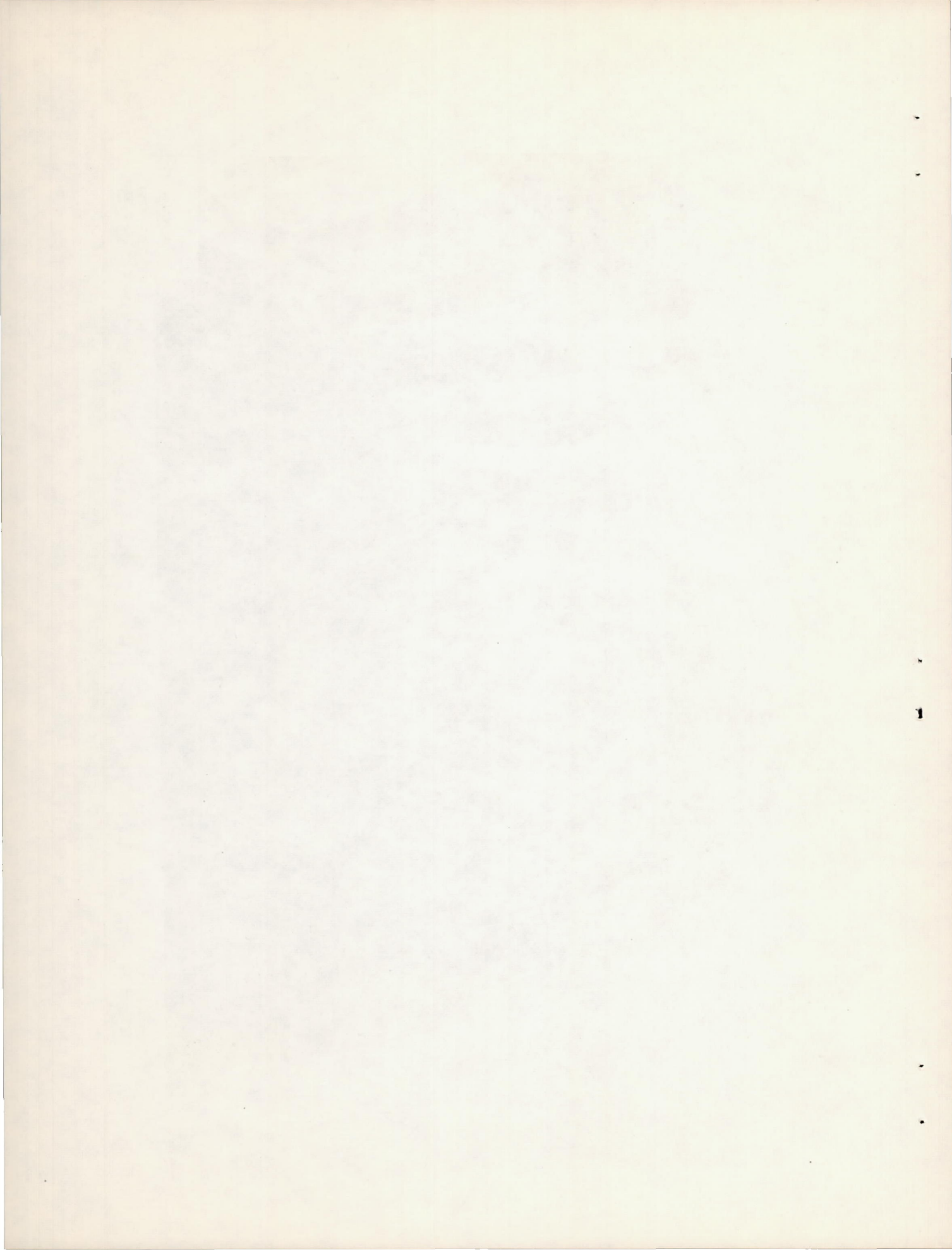|	Corrected injected flow	
	$W_w \sqrt{\theta}/\delta$	$W_{al} \sqrt{\theta}/\delta$
	(lb/sec)	(lb/sec)
○	0	0
+	.80	0
×	1.59	0
◁	1.52	0
□	2.39	0
◇	3.17	0
△	.80	.79
▽	1.60	.79
◸	2.39	.79
◿	3.19	.79
▽	3.95	.78
▷	4.60	.78

Radial distance across turbine-outlet annulus (measured from outside wall), in.

(b)   Radial distribution downstream of burner.

Figure 9. - Concluded.   Temperature surveys at turbine outlet of axial-flow engine for nozzle - arrangement D.
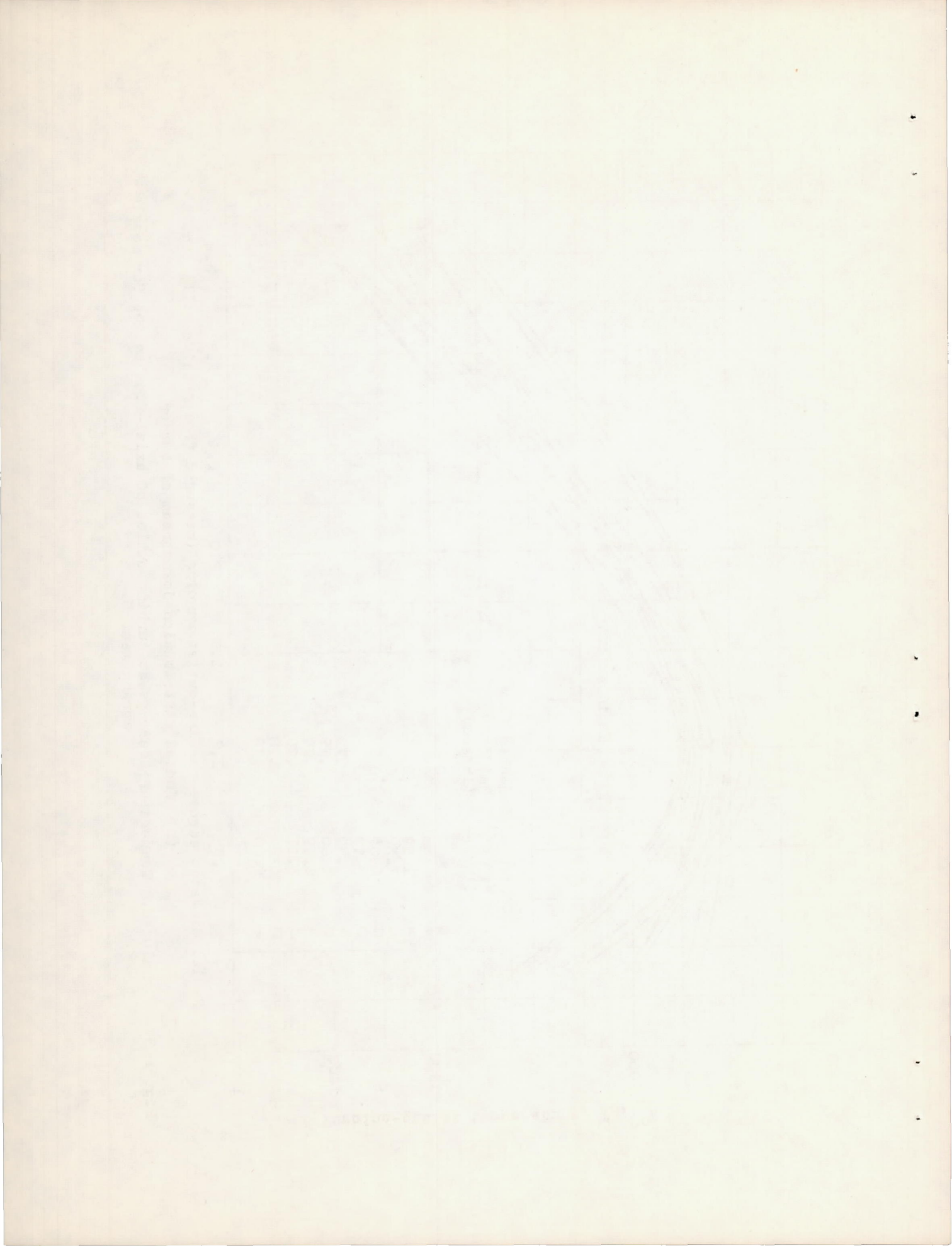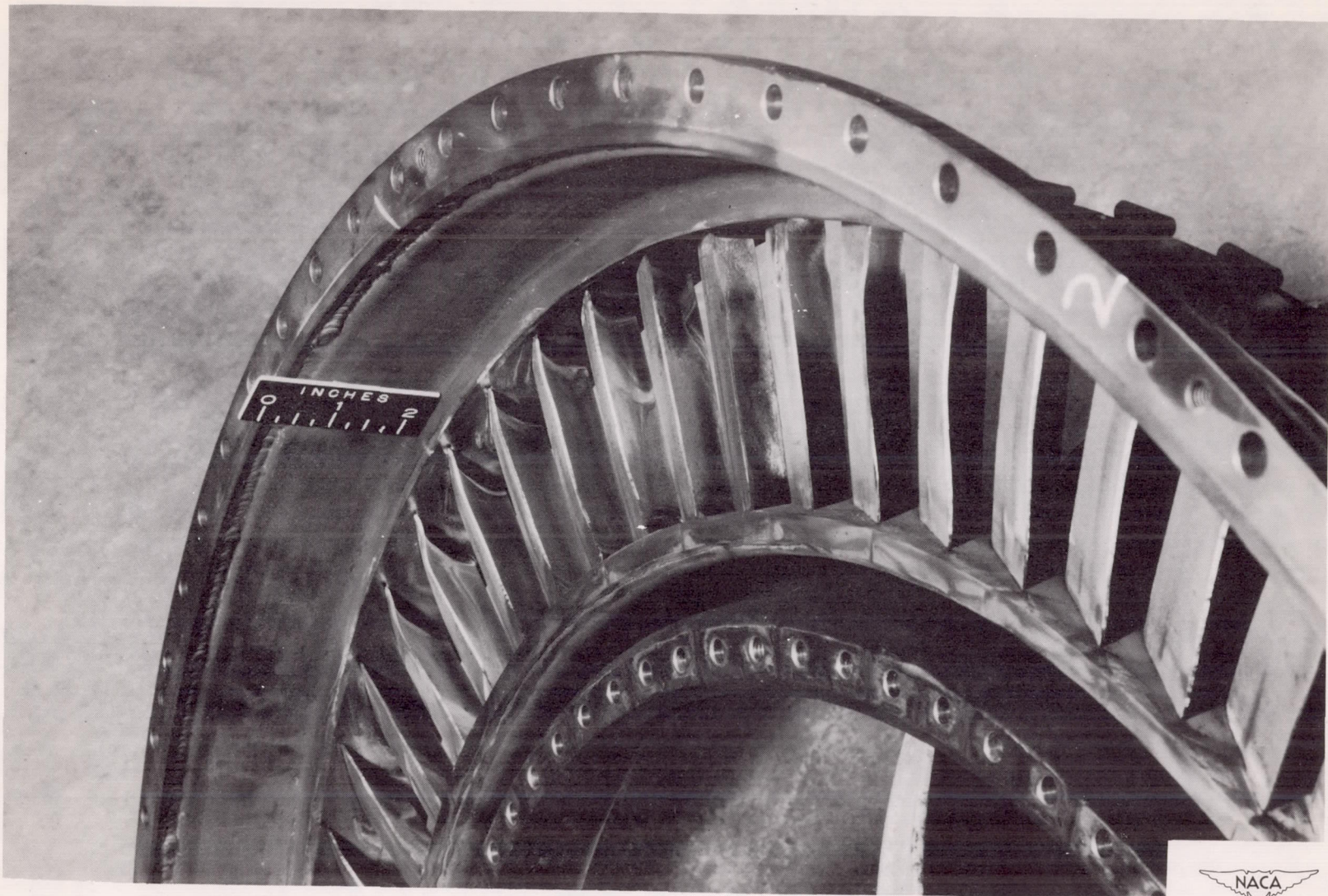
Figure 10. - Turbine-nozzle diaphragm for axial-flow engine after turbine-blade failure.
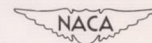
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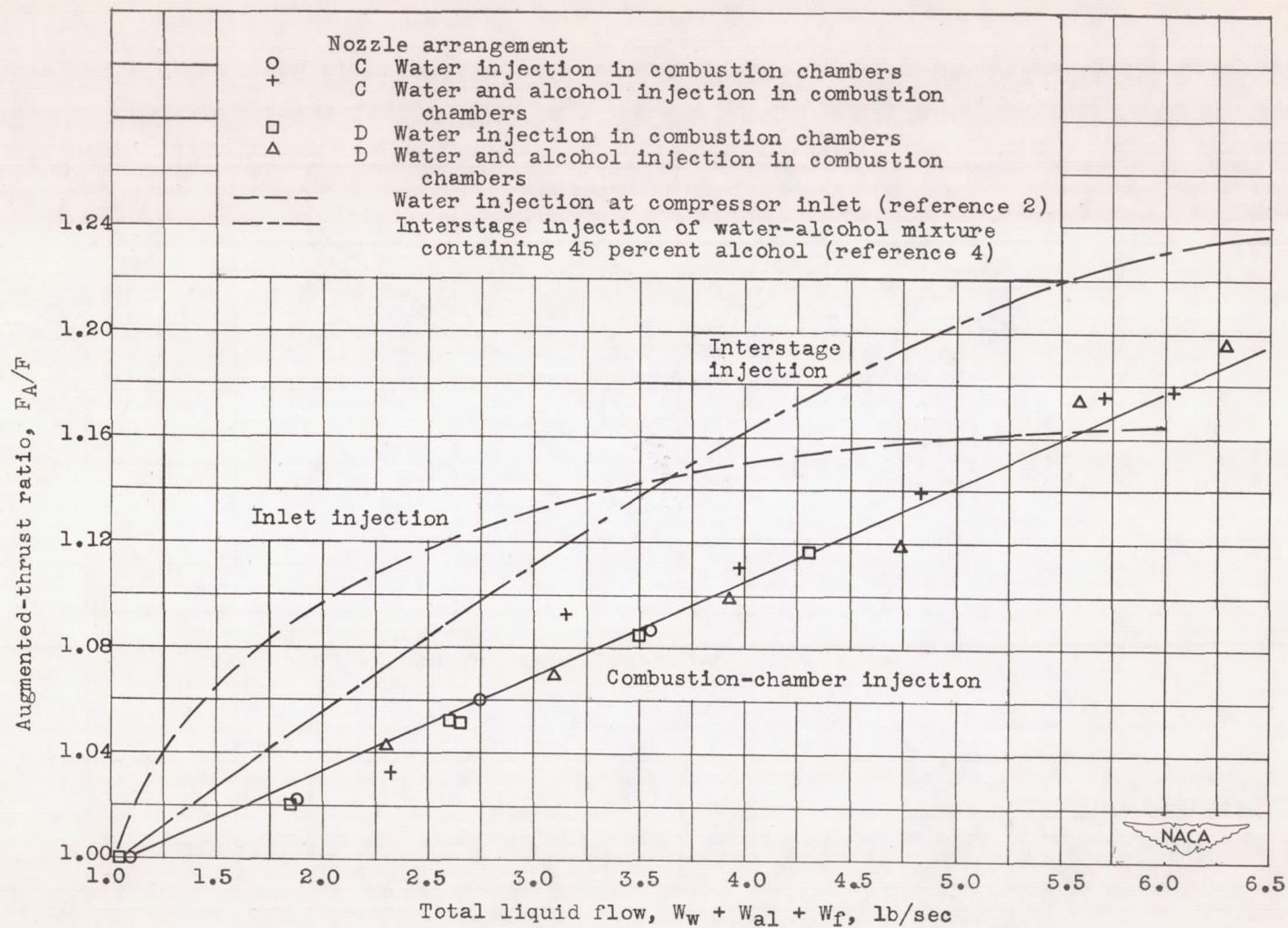
Figure 11. - Comparison of augmented-thrust ratio for water-alcohol injection in the combustion chamber with that for water injection at the compressor inlet and for water-alcohol injection interstage on axial-flow engine. Uncorrected engine speed, 7635 rpm; uncorrected tail-pipe temperature, 1665° R; engine-inlet temperature, 548° R.
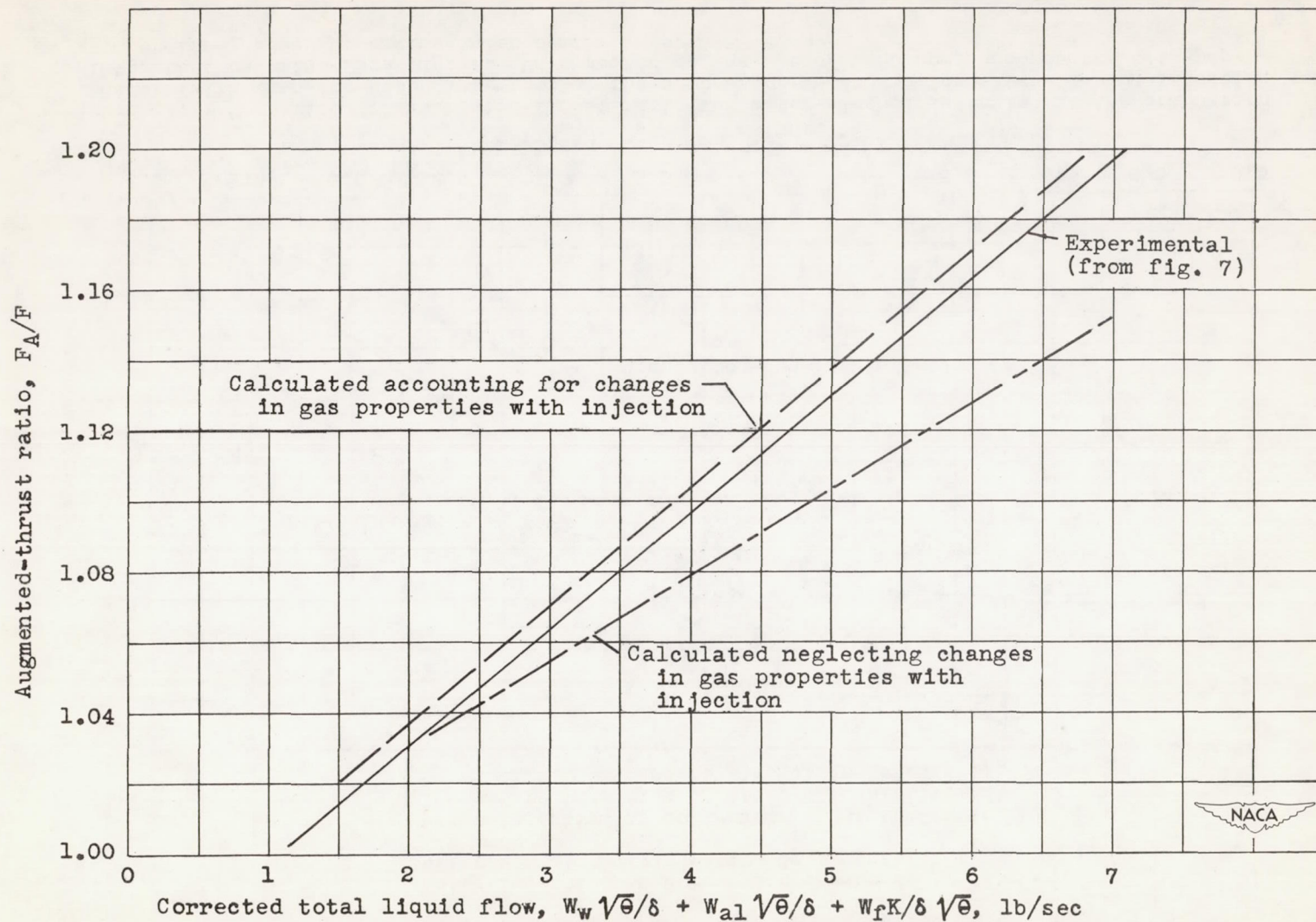
Figure 12. - Comparison of calculated and experimental augmented-thrust ratio for axial-flow engine.
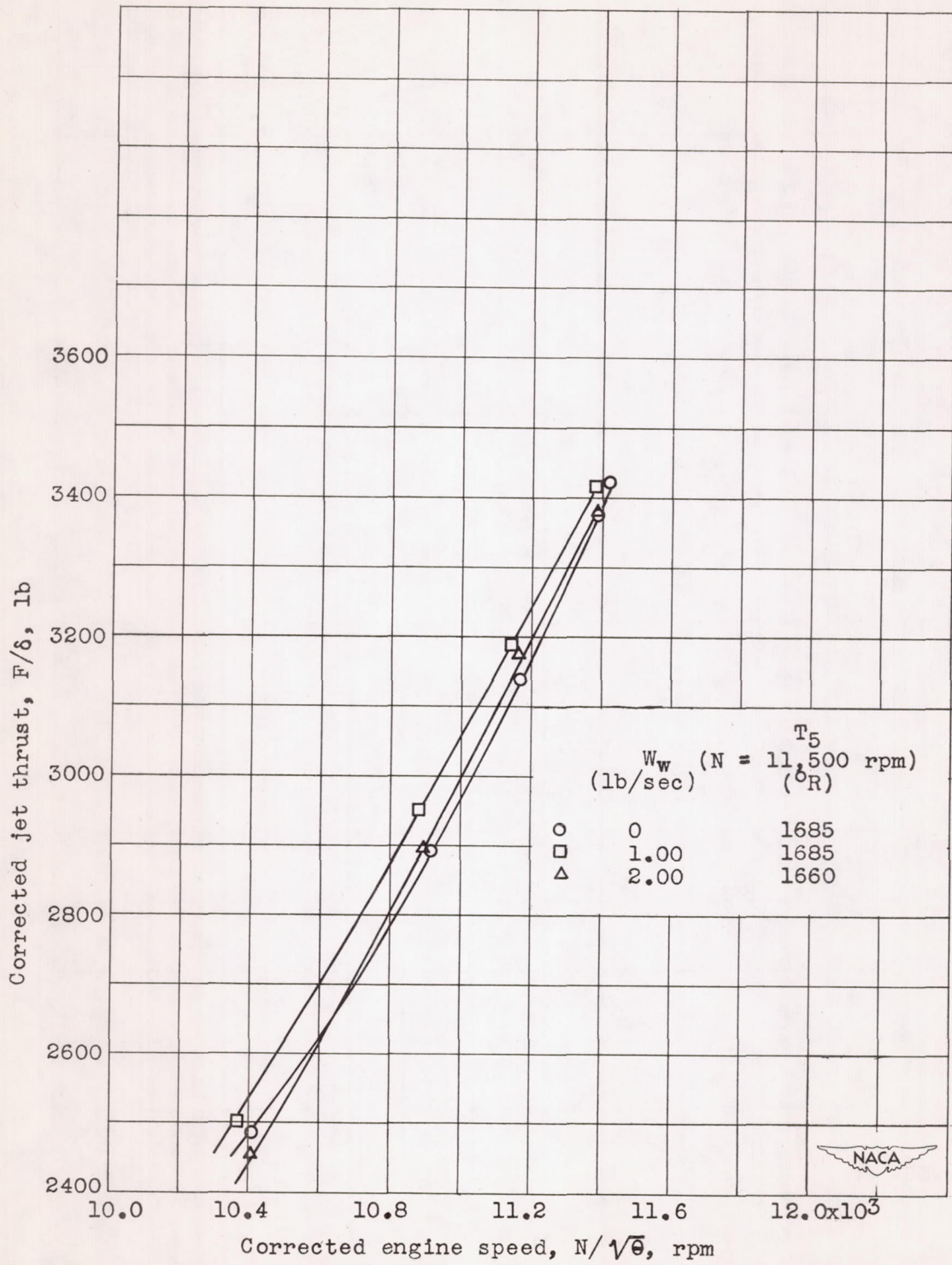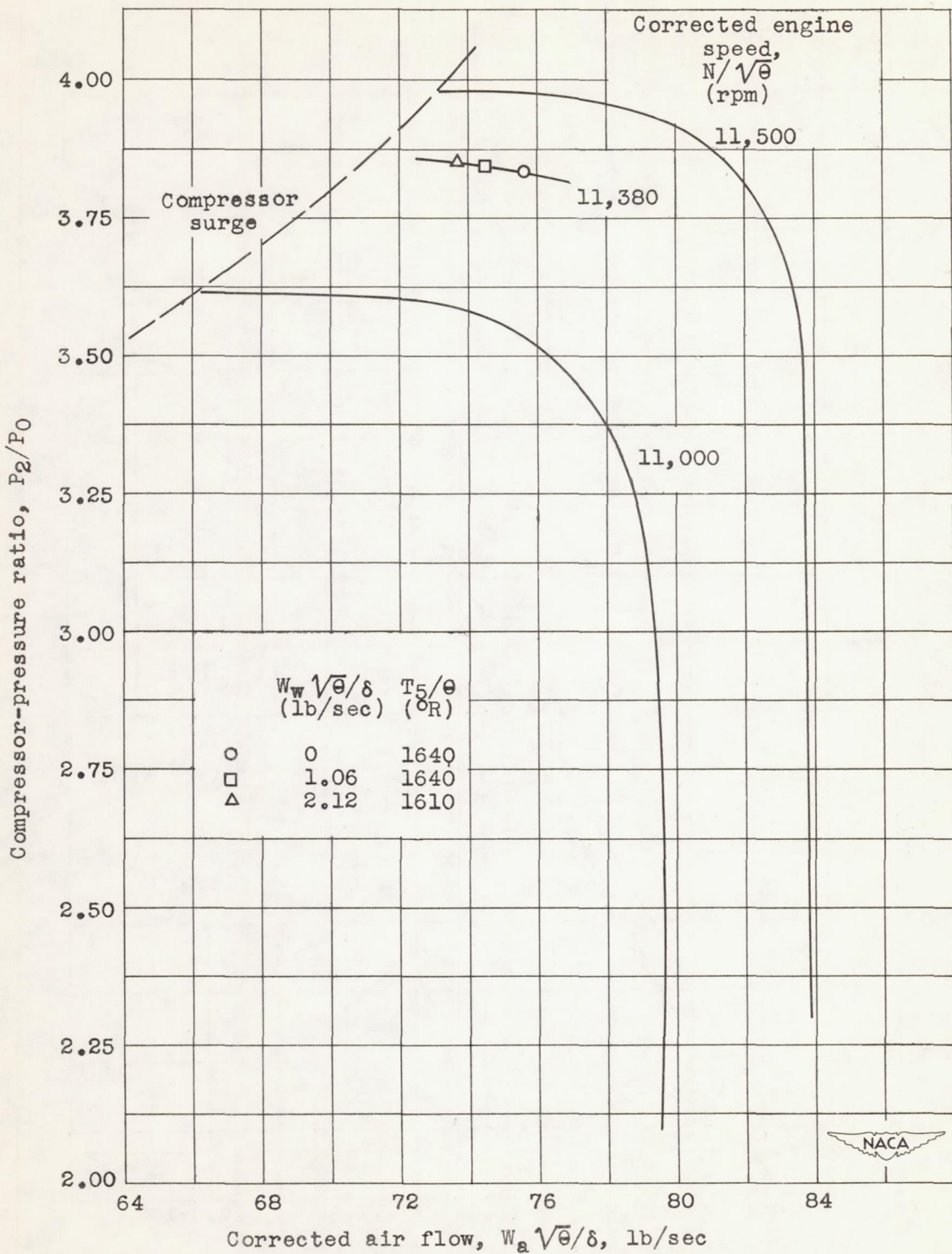
Figure 13. - Variation of corrected thrust for centrifugal-flow engine with corrected engine speed with and without injection.

Figure 14. - Runs with and without injection superimposed on compressor-characteristic curves for similar centrifugal-flow engine.
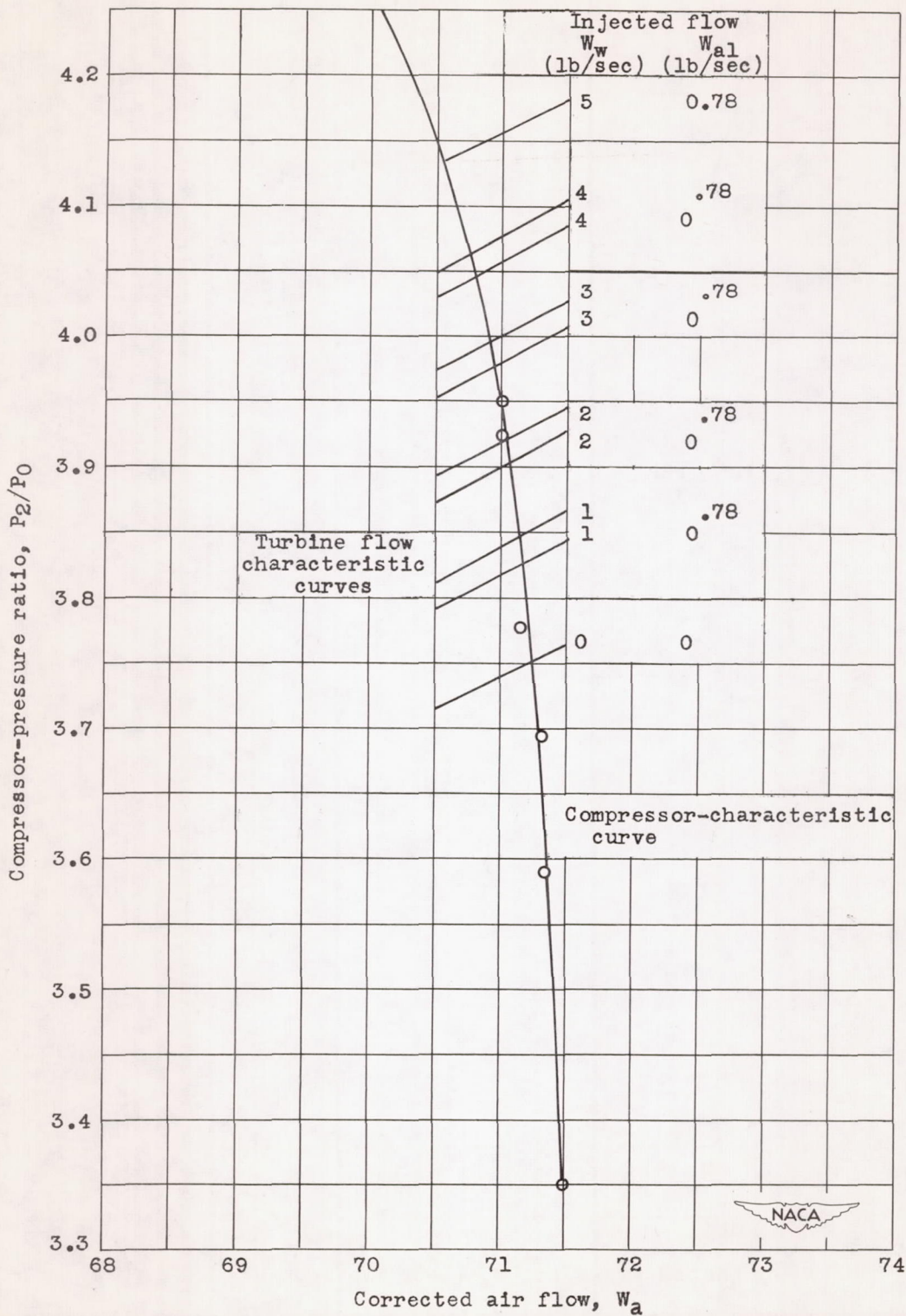
Figure 15. - Axial-flow-compressor characteristic curve for corrected engine speed of 7550 rpm showing operating points for several injection rates at zero-ram sea-level conditions.