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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF THRUST AUGMENTATION OF 4000-POUND-THRUST AXIAL-FLOW-TYPE TURBOJET ENGINE BY INTERSTAGE INJECTION OF WATER-ALCOHOL MIXTURES IN COMPRESSOR

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

An experimental investigation of thrust augmentation of a 4000-pound-thrust axial-flow-type turbojet engine by interstage injection of water-alcohol mixtures into the compressor was conducted at sea-level, zero-ram conditions. The interstage-injection systems consisted of interstage-injection nozzles extending through the compressor casing at the leading edge of the stator blades in various stages of the compressor and atomizing nozzles installed at the engine inlet. The number, the size, and the arrangement of the interstage nozzles were varied to produce a satisfactory augmentation system of minimum complication. The engine was equipped with a variable-area exhaust nozzle in order to control exhaust-gas temperature independently of injection rate. The augmented performance of the engine was determined over a range of injected flow at approximately rated engine speed and tail-pipe gas temperature for four water-alcohol mixtures and at various engine inlet-air temperatures. In addition, noninjection runs with each of the interstage-injection-nozzle arrangements installed on the engine compressor were made in order to determine the effects of the presence of these nozzles on the unaugmented performance of the engine.

An augmented thrust ratio of 1.22 was obtained with the injection of 6.5 pounds per second of water-alcohol mixture for a corrected engine inlet-air temperature of 80° F with an injection system utilizing 20 interstage nozzles. This system introduced no loss in normal thrust; it was therefore unnecessary to resort to more complicated injection methods such as using the stator blades as injectors in order to avoid normal performance loss.

INTRODUCTION

One method of augmenting the thrust of turbojet engines under investigation at the NACA Lewis laboratory consists of the injection of water and of water-alcohol mixtures into the compressor. Evaporation of the injected mixture both before and during compression results in cooling of the air with a consequent increase in compressor pressure ratio and mass flow and an attendant increase in thrust. The results of several investigations (references 1 to 3) show that for centrifugal-flow-type turbojet engines this method can be satisfactorily applied by simply injecting the mixture at the compressor inlet. The application of inlet injection to an axial-flow-type turbojet engine (reference 4), however, is limited to low injection rates and accompanying low values of thrust augmentation because of centrifugal separation of the air and injected mixture in the compressor. In addition, operation at high injection rates results in overcooling of the compressor casing relative to the rotor hub and blades with consequent damage to the engine because of blade rubbing.

In order to offset the effects of centrifugal separation and thus increase the thrust augmentation obtainable by water-alcohol injection as applied to an axial-flow engine, an investigation of compressor interstage injection was conducted at sea level, zero-ram conditions on a 4000-pound-thrust axial-flow-type turbojet engine. The interstage-injection system consisted of a number of interstage-injection nozzles extended through the compressor casing between the stator blades in various stages of the compressor together with atomizing nozzles similar to those used in reference 4 installed at the compressor inlet. The interstage nozzles directed a solid liquid jet of water and alcohol toward the rotor hub. The number, the size, and the arrangement of the interstage nozzles were varied in an effort to produce a satisfactory augmentation system of minimum complexity.

Both the augmented and the comparative noninjection runs with each of the interstage-nozzle arrangements installed on the engine compressor were conducted for approximately rated engine speed and tail-pipe gas temperature. A range of injected flow was investigated for four different mixtures of water and alcohol. Normal performance runs were also made for comparison with the noninjection runs to determine the effect of the presence of the injection nozzles on the performance of the engine. Temperature surveys were taken at several compressor interstage positions, at the compressor discharge, along the compressor casing, and at the turbine discharge.

APPARATUS

Engine. - The investigation was conducted on an early production model of a J35 turbojet engine, which 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 sea-level, zero-ram conditions.

Engine installation. - The general arrangement of the engine installation is shown in figure 1. The engine was mounted on a swinging framework suspended from the ceiling of the test chamber with the tail pipe extending through the rear wall into a sound-muffling chamber. The engine exhaust gases passed through this muffling chamber to the outside atmosphere. The engine thrust was balanced and measured with an air-pressure diaphragm. Most of the combustion air entered the nearly airtight test chamber through a 26-inch-throat-diameter A.S.M.E. nozzle, which was used to measure the air flow. The remainder of the combustion air was supplied and metered as subsequently described. The engine speed and fuel flow were measured with standard instrumentation. An inlet cowling (fig. 2) facilitated measurement of the inlet-air temperature and also provided support for the atomizing nozzles at the engine inlet. In order to provide control of the exhaust gas temperature independent of the injection rate, a spherical clamshell-type variable-area exhaust nozzle was installed at the end of the standard engine tail pipe.

In order to prevent the injected water-alcohol mixture from contaminating the oil system by draining into the accessory gear case and being picked up by the sump pump, the compressor balance air (balances end thrust of compressor-turbine combination), which is normally supplied by bleeding air from the eighth stage of the compressor, was supplied to the engine from an outside source. As a precaution against failure of the mid, damper, and aft bearings (all of which are cooled by air bled from the compressor), additional cooling air and oil were supplied to these bearings from outside sources. In addition, filters were installed in the air lines that run from the compressor to the various bearing seals and to the upstream face of the turbine-wheel disk.

The compressor balance air and bearing cooling air that were supplied by the outside source were metered by an A.S.M.E. flat-plate orifice. After fulfilling the intended functions, this air was discharged from the engine into the test cell so that the total combustion-air flow to the engine was thus equal to the sum of this air flow and the air flow through the 26-inch nozzle.

A rotor-blade-clearance indicator of NACA design was installed at the sixth and the tenth stages of the compressor to detect any blade rubbing that might occur because of overcooling of the compressor casing resulting from centrifugal separation of the injected mixture and the air. The clearance between the indicator and the rotor-blade tips was adjusted to the minimum specified blade clearance of 0.050 inch. The actual measured clearances between the rotor-blade tips and the casing for the engine used in the investigation were as follows:

Compressor stages	Measured clearance (in.)
1-3	0.055
4-6	.060
7-11	.063

Interstage-injection nozzles. - In order to offset the centrifugal effects of the rotating compressor blades, it was considered desirable to place a maximum amount of the injected liquid in the region of the rotor-blade roots by introducing the injected mixture through the compressor casing in the form of a solid liquid jet, which would impinge upon the rotor hub. The nozzles selected for this function were a simple convergent type with the converging portion consisting of a 60° cone and the throat consisting of a cylinder with a length-diameter ratio of 0.5 (inset, fig. 3). These nozzles were installed on the ends of 1/8-inch-diameter stainless-steel tubes, which extended approximately halfway across the compressor annular passage and which were positioned near the leading edge of the stator blades. This installation was selected on the basis of results of preliminary bench tests, which indicated that for practical ranges of injection pressure and nozzle size, location of the nozzles approximately halfway across the compressor annular passage was necessary in order to secure the desired injected liquid distribution. Nozzles with throat diameters of 0.025, 0.036, and 0.045 inch were used in various combinations in order to include the desired ranges of injected flow and pressure.

Interstage-injection systems. - Three different interstage-injection systems were used. The first system, which is designated the three-stage system, utilized 60 interstage nozzles that were equally distributed among the third, sixth, and ninth stages of the compressor (fig. 3). The second system, which is designated the reduced three-stage system, utilized 30 interstage nozzles equally distributed among the three aforementioned stages of the compressor; and the third system, which is designated the single-stage system, utilized 20 interstage nozzles installed in the sixth stage of the compressor. For each of the three systems, a group of 34 conventional atomizing nozzles having approximately the same pressure-drop flow characteristics as the corresponding group of interstage nozzles was installed in a ring at the engine inlet (fig. 2). For each system, the interstage nozzles installed on each stage of the compressor were connected to a manifold ring for that stage, as were the atomizing nozzles installed at the engine inlet. (These groups of nozzles will henceforth be called injection stages.) A photograph showing the extension tubes of the single-stage system installed in the compressor casing and connected to the injection manifold for the stage is presented in figure 4.

For all three systems investigated, the injection-stage manifolds were connected by stage supply lines to a common header in which a supply pump was installed. The header was connected to a supply tank in which the desired water-alcohol mixtures were blended. The flow of the mixtures to each of the injection stages was controlled by individual hand-throttling valves and was measured by individual venturis installed in the stage supply lines.

Fuel and injected mixtures. - Fuel conforming to specification AN-F-32 (Amendment-3) was used. Water-alcohol mixtures of 0, 15, 30, and 45 percent by volume of alcohol were used in the investigation. The alcohol was a blend of 50 percent by volume ethyl and 50 percent by volume methyl alcohol. The water was drawn from the domestic supply.

Temperature and pressure instrumentation. - The locations of the instrumentation for temperature and pressure measurement are shown in figure 5. The temperatures recorded and the number, the type, and the location of the thermocouples were as follows:

(a) Total temperature at engine inlet (station 1) T_1: average of 20 individually recorded thermocouples, 5 in each of 4 rakes 90° apart at inlet-cowling entrance

(b) Compressor-casing temperature: one thermocouple embedded in outside wall of compressor casing at first, fifth, and eleventh stages of compressor

(c) Compressor interstage air temperatures: two probes placed approximately 45° on each side of bottom center in each of the third, sixth, and ninth stages of compressor. Each probe has three equally spaced thermocouples radially distributed across compressor annular passage.

(d) Total temperature at compressor discharge (station 3) T_3: four radial rakes with five equally spaced thermocouples installed alternately with four radial rakes containing two thermocouples in compressor-discharge section, each rake in line with center line of one of the combustion chambers. The average T_3 was taken as the average of all 28 thermocouples.

(e) Gas temperature at turbine discharge (station 5) T_5: 16 probes equally spaced around the circumference and located approximately 4 inches downstream of the turbine discharge with half of the probes in line with the center lines of the combustion chambers and the other half midway between the combustion chambers. Twelve probes were single strut-type thermocouples and four were radial survey rakes, each containing four equally spaced thermocouples. Two of the rakes (designated rakes B and C) were in line with the center lines of combustion chambers 1 and 4, respectively (fig. 5), and two of the rakes (designated rakes A and D) were in line with a position midway between combustion chambers 1 and 8 and between combustion chambers 4 and 5, respectively.

(f) Indicated gas temperature at tail-pipe inlet (station 6) T_6: average of eight strut-type thermocouples equally spaced circumferentially and extending 4 inches through tail-pipe wall

The pressures measured and the number, the type, and the location of pressure tubes were as follows:

(a) Total pressure at engine inlet (station 1) P_1 (assumed equal to cell static pressure): two static tubes in quiescent zone of test chamber

(b) Compressor static pressure: two static wall taps connected to a common manifold in third, sixth, and ninth stator stages of compressor

(c) Total pressure at compressor discharge (station 3) P_3: four total-head rakes of three pressure tubes each installed in the compressor-discharge section in line with combustion chambers 1, 3, 5, and 7, respectively (fig. 5). Corresponding tubes of each rake were connected to a common manifold. The average P_3 was taken as the average of the three readings obtained.

(d) Tail-pipe static pressure (station 7) P_7: two static pressure taps in a manifold and installed near the variable-area exhaust nozzle on tail pipe

(e) Muffler static pressures: two static pressure tubes installed in muffler near engine tail pipe

PROCEDURE

The augmented performance of the 4000-pound-thrust axial-flow-type turbojet engine by compressor interstage injection of water and alcohol was determined under sea-level, zero-ram conditions for a constant engine speed of 7610 ±10 rpm and a constant indicated tail-pipe gas temperature of $1200^{\circ} \pm 10^{\circ}$F. (These values of engine speed and tail-pipe gas temperature are slightly under rated conditions for the engine.) The tail-pipe gas temperature was maintained constant by means of the variable-area exhaust nozzle.

The range of conditions covered and the number and the size of the interstage-injection nozzles used during the augmentation runs are presented in the following table:

Injected mixture (percent by volume)		Number of nozzles			Injection stages	Corrected injected flow range (lb/sec)	Pressure-drop range across interstage-injection nozzles (lb/sq in.)
		Diameter (in.)					
Water	Alcohol	0.025	0.036	0.045			
100	0		60		Inlet, 3,6,9	3.17	68
100	0	30	30			3.38	164
85	15		60			5.06-6.46	162-267
85	15	30	30			3.58-5.08	160-322
70	30		60			4.68-6.59	168-338
70	30	30	30			3.30-5.13	136-341
55	45		60			5.19-6.64	205-330
55	45	30	30			3.62-5.21	164-345
70	30			30	Inlet, 3,6,9	5.56-6.55	234-333
70	30		15	15		4.10-6.08	204-445
55	45		30			3.12-4.17	273-505
70	30			20	Inlet, 6	3.47-6.54	92-329
70	30				Inlet	0.78-1.76	-----------

The highest injected flow obtained with interstage injection was limited by the capacity of the supply pump to about 6.6 pounds per second. The lowest injected flow obtained with interstage injection was arbitrarily set at about 3.0 pounds per second because flows below this value were believed to be out of the range of interest inasmuch as inlet injection can be satisfactorily used for injected flows up to about 3.0 pounds per second (reference 4). In order to provide adequate penetration of the injected liquid over the ranges of injected flow indicated in the preceding table, two sets of interstage-injection nozzles were used for the runs utilizing the three-stage system and three sets were used for the runs utilizing the reduced three-stage system. The different size nozzles of each set were in every case evenly distributed among the three injection stages and were installed in alternate positions in each stage. Only one set was used for the runs with the single-stage system. For all the runs, the injected flow was evenly divided among the injection stages indicated in the third column of the preceding table.

Runs were made with inlet injection alone in order to obtain comparative performance data. With each interstage-injection system, a series of noninjection runs, on which the thrust augmentation was based, was taken either immediately before or immediately after each series of interstage-injection runs listed in the table. In addition, a series of normal performance runs was made so that a comparison of the performance of the normal engine and the engine with the injection systems installed could be made.

Inasmuch as no control of the air temperature was provided in the setup, the engine inlet-air temperature was dependent upon the prevailing atmospheric conditions at the time of the runs and varied from about 59° to 110° F throughout the course of the investigation.

DATA CORRECTION AND ANALYSIS

It was determined from unpublished tests, that the conventional method for correcting normal performance data by the correction factor θ (where $\theta = \frac{\text{engine inlet-air total temperature}}{\text{NACA standard sea-level temperature}}$) does not apply for water-alcohol injection data. Experimentally determined relations were therefore used in order to reduce the interstage-injection data to a common engine inlet-air temperature. These relations were determined from cross plots of data obtained at several reference operating conditions from time to time during the investigation. The conditions represented by these data include various values of injected flow for a range of about 4.0 to 6.0 pounds per second for each of three injected water-alcohol mixtures containing 15-, 30-, and 45-percent alcohol. Curves showing the variations of augmented thrust ratio (ratio of augmented thrust to thrust without injection), compressor pressure ratio, fuel flow, and air flow resulting from changes in engine inlet-air temperature are presented in figure 6. The symbols shown do not represent actual data points but rather intersections of the curves from which the cross plots were made. The variations shown are applicable only to the type of engine and injection system investigated and to the range of inlet-air temperature covered in this investigation (59° to 110° F). Inasmuch as it was possible to fit a straight-line curve to the data in each plot, the corrections for inlet-air temperature for the range of injected flows and mixtures investigated may be specified by constants, which are determined from the slopes of these straight lines. Thus, the correction to augmented thrust ratio amounts to an increase of about 0.017 for an increase of 10° F in engine inlet-air temperature.

The standard engine inlet-air temperature to which the injection data were reduced was 80° F because it was a representative average value for these data and thus kept the temperature correction to a minimum.

Data were corrected to NACA standard sea-level pressure by the correction factor δ (where $\delta = \frac{\text{engine inlet-air total pressure}}{\text{NACA standard sea-level pressure}}$), which was applied in a manner similar to the conventional method of correcting normal performance data. Because the range of adjustment in this investigation was very small, any error involved in this method of correction is believed to be negligible. The corrected parameters for the injected flow data are thus similar to those conventionally used for normal performance data except for the omission of the correction factor θ, which was replaced by the experimentally determined relations. In order to keep the ratios of injected liquid to air and of total liquid flow to air unchanged by the pressure correction, the injection flow W_i was corrected in the same manner as the air and fuel flows by simply dividing by the factor δ so that the corrected injected flow parameter was W_i/δ. No temperature correction was applied to injected flow, which was the independent variable for these runs. No correction was made for the variations in the humidity of the inlet air inasmuch as the effect on augmented performance was considered to be negligible.

RESULTS AND DISCUSSION

The uncorrected data obtained during the investigation of the augmented performance of the 4000-pound-thrust axial-flow-type turbojet engine by compressor interstage injection of water and alcohol mixtures are presented in table I.

Unaugmented Performance with and without Interstage-Injection Nozzles

The results of runs that were made without injection in order to determine the effect of the various interstage-injection-nozzle systems on the normal performance of the engine indicated that at rated engine speed the loss in the normal thrust of the engine varied from 0 percent for the single-stage system to about $1\frac{1}{2}$ percent for the three-stage system.

An attempt was made to eliminate the loss in normal performance associated with the three-stage injection system by moving the nozzles flush with the compressor casing; this arrangement, however, proved unsatisfactory and was eliminated from further consideration because of blade rubbing during injection caused by inadequate penetration of the injection liquid and associated uneven radial temperature distribution in the compressor, which is illustrated later.

Augmented Performance with Three-Stage System

Plots showing the augmented performance of the engine obtained with the three-stage system corrected to an engine inlet-air temperature of 80° F and NACA standard sea-level pressure are presented in figures 7 and 8.

Compressor pressure ratio. - In figure 7(a) the compressor pressure ratio P_3/P_1 is plotted against corrected injected flow W_i/δ for the various water-alcohol mixtures investigated. The dashed portion of the curve for injected flows below 3.0 pounds per second in this and succeeding figures presenting augmented performance represents an extrapolation to zero injected flow or the normal performance condition. The data for the various mixtures fall on a single curve and a linear increase in compressor pressure ratio with injected flow is indicated for flows up to about 5.0 pounds per second. For higher flows, the curve shows a tendency to level off. At a corrected injected flow of 6.5 pounds per second, the pressure ratio is 4.21 as compared with a value of 3.79 for no injection, representing an increase of about 11 percent.

Engine fuel flow. - The variation of the corrected engine fuel flow W_f/δ with corrected injected flow W_i/δ is presented in figure 7(b) for the various water-alcohol mixtures. Because of the extra fuel required to vaporize the injected water, the corrected engine fuel flow necessary to maintain the desired engine conditions increases with injection rate for the mixtures containing 0- and 15-percent alcohol. Inasmuch as the alcohol burns in the combustion chambers and thus also acts as a fuel, an increase in the alcohol concentration results in a decrease in the engine fuel requirement so that for the 45-percent alcohol mixture the engine fuel flow decreases with injected flow and for the 30-percent alcohol mixture there is practically no change in engine fuel flow with injected flow. The 30-percent alcohol mixture may thus be injected at any flow rate within the range investigated without appreciable adjustment of the engine fuel throttle.

The engine fuel system pumping limit is represented in figure 7(b) by a horizontal broken line at a corrected engine fuel flow of approximately 1.48 pounds per second. The water-alcohol mixtures containing 0- and 15-percent alcohol could not be injected at rates higher than about 3.5 and 5.9 pounds per second, respectively, because of this limit.

Air and total gas flows. - In figure 7(c) is presented a plot of corrected air W_a/δ and total gas W_g/δ flows against corrected injected flow W_i/δ where the total gas flow is the sum of the air, fuel, alcohol, and water flows. For injected flows up to about 5.0 pounds per second, the increase in total gas flow with injected flow is approximately linear; for higher injected flows, there is a slight falling off of the gas-flow curve. A comparison of this curve with the one of compressor pressure ratio in figure 7(a) reveals that for the range of injected flow covered in this investigation the total gas flow through the engine is very nearly proportional to the compressor pressure ratio. The increase in total gas flow over that for no injection amounted to about 10 percent at an injected flow of 6.5 pounds per second.

The air flow remained practically constant at a value slightly higher than that for no injection with change in injected flow up to about 5.0 pounds per second. For higher injected flows, there is a slight falling off in the air-flow curve in the same range of injected flow in which a falling off of the total gas flow occurred.

Augmented thrust ratio. - The thrust augmentation obtained is presented in figure 7(d) as a plot of the augmented thrust ratio against corrected injected flow W_i/δ where the augmented thrust ratio is defined as the ratio of the augmented thrust F_a to the thrust without injection F_n. With the exception of the data points representing insufficient injection pressure, which are discussed later, all the data for the various water-alcohol mixtures may be represented by a single curve, thus indicating that the thrust augmentation obtained at a given injection rate is essentially independent of the alcohol content of the injected mixture. For the range of injected flows covered, the augmented thrust ratio varied from about 1.15 at 3.2 pounds per second to about 1.23 at 6.5 pounds per second. About half of the thrust augmentation for the injected flow of 6.5 pounds per second is a result of the increase in total gas flow previously noted and the remainder is attributed to the increase in the exhaust jet velocity provided by the higher compressor pressure ratio. The curve tends to level off at the higher injected flows indicating that additional thrust augmentation is to be obtained only at the expense of greatly increased injected flow.

As previously discussed, two different sets of interstage-injection nozzles for the three-stage injection system were necessary in order to provide adequate penetration of the injected liquid over the range of injected flow covered in the investigation. Satisfactory penetration, as indicated by temperature profiles in the compressor, was obtained with the set of nozzles used for the low part of the flow range (tailed data symbols, fig. 7(d)) over the entire range of flow for which they were used and also with the set of nozzles used for the upper part of the flow range (plain data symbols, fig. 7(d)) at flows above 5.5 pounds per second. At flows below 5.5 pounds per second, the set of nozzles used for the upper flow range gave poor penetration (data symbols with horizontal lines, fig. 7(d)), which resulted in losses in augmented thrust ratio of as much as 0.05. The augmented performance of the engine is therefore dependent upon the penetration of the injected liquid and the use of the proper nozzle size for the desired flow range.

A plot of the variation of augmented thrust ratio F_a/F_n against corrected total liquid flow W_t/δ is given in figure 8, where the total liquid flow is equal to the sum of the fuel, water, and alcohol flows. The data trends in this plot are similar to those of figure 7(d) with the exception of slight separation with alcohol concentration, the higher alcohol concentration requiring a lower total liquid flow for a given value of augmented thrust ratio. For example, if an augmented thrust ratio of 1.2 is desired, an increase in the alcohol concentration from 15 to 45 percent will result in a decrease in total liquid flow from 6.4 to 5.4 pounds per second. The corresponding decrease in total specific liquid consumption is from 5.4 to 4.5 pounds per hour per pound of thrust. This effect is primarily the result of the partial replacement of the engine fuel by the injected alcohol, as noted in the discussion of figure 7(b).

Augmented Performance with Other Injection Systems

Data points showing the thrust augmentation obtained with the reduced three-stage and single-stage injection systems are presented in figure 9 as a plot of the augmented thrust ratio F_a/F_n against corrected injected flow W_i/δ. Included for comparison is the curve representing the results obtained with the three-stage system (fig. 7(d)), and also data for inlet injection alone. The extrapolated portion of the curve for inlet injection alone was drawn using the data of reference 4 as a guide. For the range of injected flow investigated, the augmented thrust ratio with both the reduced three-stage and single-stage systems appears to be slightly less than that for the three-stage system. At an injected flow of 6.5 pounds per second, the data indicate a value of augmented thrust ratio of about 1.22 for the two simplified systems, whereas a value of 1.23 is indicated by the curve for the three-stage system. The values of augmented thrust ratio for each system investigated, however, are based on the noninjection performance of the engine with the particular system installed, so that the slightly lower noninjection performance of the engine with the three-stage system results in a slightly higher calculated value of augmented thrust ratio. If the values of augmented thrust ratio were based on the standard normal performance (no nozzles installed) of the engine, the results would be essentially the same for all three systems, and the recalculated value of augmented thrust ratio for the three-stage system at an injected flow of 6.5 pounds per second would be about 1.22 instead of 1.23. Thus, the single-stage injection system produces thrust augmentation equal to that of the other injection systems with greater simplicity of installation and with no loss in normal performance due to the presence of the injection nozzles. The single-stage system is therefore considered to be suitable without having to resort to more complicated injection methods such as the use of the stator blades as injectors to eliminate normal performance losses.

A comparison of the curves for interstage and inlet injection for injected flows higher than about 2.5 pounds per second indicates that the augmented thrust ratio attainable by interstage injection is greater than that by inlet injection alone, the difference increasing with injected flow. The performance indicated for inlet injection alone at low injected flows may be obtained with any of the interstage systems investigated by merely shutting off the flow to the interstage-injection nozzles and injecting only at the inlet.

Temperature Surveys

Typical temperature surveys at various positions in the compressor are presented in figure 10 for the three interstage-injection systems investigated. Included are curves giving the temperature distributions for no injection, for inlet injection alone, for the three-stage system with insufficient penetration, and for the three-stage system with the interstage-injection nozzles flush with the casing wall. The variation of the temperature at the compressor discharge (as determined from the average of the temperatures measured by corresponding thermocouples of the eight radial rakes) with radial distance across the compressor-discharge annulus is illustrated in figure 10(a). The temperature distributions obtained for the three satisfactory interstage-injection systems are noted to be uniform and about 220° F lower than that for no injection. This uniformity of temperature distribution indicates that there is good radial distribution of the injected liquid for all three of these systems. Conversely, when the injection pressure was insufficient to provide adequate penetration, the temperatures in the region of the blade roots remained fairly high, whereas the temperatures near the blade tips became relatively low resulting in an uneven temperature distribution and decreased cooling of the air. Similar temperature profiles were obtained for all the previously noted augmentation data points for which the loss in augmentation was attributed to lack of penetration of the injected liquid. The arrangement with the interstage nozzles flush with the compressor casing produced the steepest temperature gradient measured, with the temperature ranging from the uncooled normal value at the roots to the fully cooled value at the tips of the rotor blades. The temperature distribution obtained for inlet injection alone is likewise noted to be steep, although not quite as severe as for the configuration with the flush interstage nozzles.

In figure 10(b) are presented typical curves showing the radial distribution of temperature across the compressor annular passage (as determined for each stage from the average of the temperatures measured by corresponding thermocouples of the two radial rakes) in the stator row of the third, sixth, and ninth stages of the compressor. The temperature profiles in the third stage are similar for the various interstage-injection configurations presented. This result is to be expected inasmuch as the only injected liquid influencing the temperature pattern in the third stage is that injected at the inlet. (The inlet nozzle arrangement was the same for all configurations presented.) For all these configurations, the temperature of the air measured near the rotor hub of the third stage is about 25° F higher than that at the other radial positions, thus indicating some centrifugal separation of the air and the injected liquid even at this early stage. Consideration of the flat temperature profiles at the sixth and ninth stages of the compressor as well as those at the compressor discharge indicates that when operating each of the three satisfactory interstage-injection systems with sufficient injection pressure the centrifugal effects of the rotating blades are offset. The centrifugal effects became progressively worse, however, for the other cases presented, as evidenced by the progressively steeper temperature profiles when passing from the sixth to the ninth stage of the compressor.

The longitudinal temperature distribution of the air and of the casing along the compressor are presented in figure 10(c). The solid curves represent the temperature distribution of the air (average of all measured radial temperatures at each stage) and the dashed curves the temperature distribution of the compressor casing. For all runs with injection, the casing temperature increases with distance along the compressor at about a constant rate, which is less than that for no injection. For the runs with the three satisfactory interstage-injection systems and for the run with no injection, the air-temperature curves practically coincide with the corresponding compressor-casing-temperature curves, whereas for the other systems the air temperature is higher than the corresponding casing temperature with the difference increasing as the air proceeds through the compressor. This difference between the air and the compressor-casing temperature is a further indication of centrifugal separation of the injected liquid and the air for these unsatisfactory configurations.

Typical circumferential and radial temperature surveys at the turbine discharge (as determined from a single thermocouple on each rake) are presented in figures 11(a) and 11(b), respectively, for the various configurations investigated. Inspection of these curves indicates that none of the configurations investigated distinctly affects the turbine-temperature profiles. The average temperature indicated by these curves is higher than the average temperature of 1200° F measured by the more reliable thermocouples installed in the tail pipe, probably because they were installed in a high-temperature portion of a region of large temperature gradients.

Engine Operation

Engine operation with the three interstage-injection systems was satisfactory at all times, and no evidence of compressor-blade rubbing existed except when the interstage-injection nozzles of the three-stage system were moved flush with the compressor-casing inner wall. In this case, about 0.010 inch was rubbed off the compressor-casing wall in the last two stages of the compressor. Inspection of the engine oil system during and at the conclusion of the investigation revealed that no water or alcohol contaminated the lubricating oil at any time. Two engine-bearing failures occurred during the course of the runs. The first failure could not be directly attributed to water-alcohol injection because the engine had been previously run for a considerable length of time in another investigation. The second failure occurred approximately 25 engine operating hours after the engine had been overhauled subsequent to the time of the first failure. Approximately 13 of these 25 hours were accumulated with interstage injection.

The experience gained during this investigation is insufficient to draw any definite conclusions regarding the effect of interstage injection on the life of the engine bearings, but in all probability the bearing life of the engine investigated was shortened. Although the conditions of this investigation were probably more severe with regard to engine life than would occur in service operation because of the large percentage of total operating time at augmented conditions, the practical application of liquid injection may require bearing-cooling systems that do not utilize cooling air bled from the compressor.

SUMMARY OF RESULTS

The thrust-augmentation investigation of a 4000-pound-thrust axial-flow-type turbojet engine at sea-level, zero-ram conditions by compressor interstage injection of water-alcohol mixtures produced the following results:

1. An augmented thrust ratio of 1.22 was obtained with the injection of 6.5 pounds per second of water-alcohol mixture for a corrected engine inlet-air temperature of 80° F when using a

simple injection system composed of 20 interstage nozzles at one of the compressor stages and atomizing nozzles at the compressor inlet. This system introduced no loss in normal thrust; it was therefore unnecessary to resort to more complicated injection methods such as using the stator blades as injectors in order to avoid normal performance loss.

2. For the water-alcohol mixtures investigated, an increase in the alcohol concentration resulted in a decrease in the total liquid flow for a given value of augmented thrust ratio.

3. The magnitude of thrust augmentation obtained for a given injection rate was dependent on the inlet-air temperature. For a range of inlet-air temperature from 59° to 110° F, an increase in engine inlet-air temperature of 10° F resulted in an increase in the augmented thrust ratio of 0.017.

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

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2. Jones, William L., and Engelman, Helmuth W.: Experimental Investigation of Thrust Augmentation of 4000-Pound-Thrust Centrifugal-Flow-Type Turbojet Engine by Injection of Water and Alcohol at Compressor Inlets. NACA RM E7J19, 1947.

3. Ellisman, Carl: Flight Investigation of Thrust Augmentation of a Turbojet Engine by Water-Alcohol Injection. NACA RM E7G29, 1947.

4. Baron, Burnett, Dowman, Harry W., and Dackis, William C.: Experimental Investigation of Thrust Augmentation of Axial-Flow-Type 4000-Pound-Thrust Turbojet Engine by Water and Alcohol Injection at Compressor Inlet. NACA RM E7K14, 1948.

TABLE I -

Run	Injected mixture (percent by volume)		Number of inter-stage-injection nozzles	Inter-stage-injection-nozzle diameter (in.)	Injection stage	Engine inlet-air tempera-ture (°F)	Inlet-air relative humidity (percent)	Pressure correction factor, δ	Ambient-tempera-ture correction factor, θ
	Water	Alcohol							
127	(a)							0.982	1.046
132	100	0	60	0.036	Inlet,3,6,9	79	48	.982	
161	(a)							0.964	1.031
163	100	0	30	0.025	Inlet,3,6,9	74	57	.964	
			30	.036					
118	(a)					108	41	0.965	1.094
119	85	15	60	0.036	Inlet,3,6,9	109	40	.964	
120	85	15				110	40	.964	
121	85	15				110	40	.964	
127	(a)							0.982	1.046
125	85	15	60	0.036	Inlet,3,6,9	80	48	.982	
126	85	15				80	48	.982	
156	(a)					77	62	0.967	1.034
157	85	15	30	0.025	Inlet,3,6,9	74	62	.967	
			30	.036					
158	85	15				73	62	.967	
159	85	15				74	62	.967	
160	85	15				72	62	.967	
113	(a)					99	75	0.966	1.093
114	70	30	60	0.036	Inlet,3,6,9	99	67	.965	
115	(a)					107	46	0.966	1.093
116	70	30	60	0.036	Inlet,3,6,9	104	46	.966	
117	70	30				110	46	.966	
144	(a)					84	33	0.976	1.049
146	70	30	60	0.036	Inlet,3,6,9	86	33	.976	
147	70	30				86	33	.976	
148	70	30				86	33	.976	
149	70	30				84	33	.976	
174	(a)					60	70	0.975	1.001
175	70	30	60	0.036	Inlet,3,6,9	56	70	.974	
176	(a)					62	50	0.973	1.006
177	70	30	60	0.036	Inlet,3,6,9	58	50	.973	
178	70	30				60	50	.973	
179	(a)					66	70	0.978	1.014
180	70	30	60	0.036	Inlet,3,6,9	62	70	.978	
181	70	30				61	70	.978	
182	(a)					75	76	0.975	1.030
184	70	30	60	0.036	Inlet,3,6,9	71	76	.975	
185	70	30				71	76	.975	
186	70	30				70	76	.975	
150	(a)					74	100	0.970	1.029
152	70	30	30	0.025	Inlet,3,6,9	71	100	.970	
			30	.036					
153	70	30				69	100	.970	
154	70	30				69	100	.970	
155	70	30				71	100	.970	
137	(a)					85	100	0.969	1.051
140	55	45	60	0.036	Inlet,3,6,9	84	100	.968	
141	55	45				85	100	.968	
142	55	45				85	100	.968	
143	55	45				87	100	.968	

[a]Noninjection run used as basis for calculation of augmented thrust ratio for succeeding runs.

UNCORRECTED DATA

Measured engine speed, N (rpm)	Measured tail-pipe temperature, T_7 (°F)	Total injected flow, W_i (lb/sec)	Measured engine fuel flow, W_f (lb/sec)	Measured engine air flow, W_a (lb/sec)	Measured thrust, F (lb)	Compressor pressure ratio, P_3/P_1	Augmented thrust ratio, F_a/F_n	Average pressure drop across inter-stage-injection nozzle (lb/sq in.)
7616	1192		1.086	65.25	3636	3.728		
7612	1188	3.11	1.396	65.66	4049	3.958	1.114	68
7617	1185		1.083	65.51	3481	3.794		
7615	1190	3.25	1.431	66.39	4003	4.056	1.150	164
7613	1196		1.006	60.55	3188	3.676		
7608	1199	4.88	1.289	62.15	3970	4.078	1.246	162
7598	1209	5.39	1.339	61.75	4020	4.132	1.261	197
7590	1186	6.23	1.381	61.60	3991	4.165	1.252	267
7616	1192		1.086	65.25	3636	3.728		
7597	1195	5.75	1.423	66.15	4393	4.189	1.208	253
7608	1209	5.35	1.414	65.99	4296	4.166	1.181	219
7628	1197		1.086	66.32	3527	3.788		
7610	1208	3.46	1.283	66.99	4063	4.052	1.152	160
7613	1218	3.94	1.333	66.99	4103	4.092	1.164	210
7616	1217	4.43	1.356	66.91	4168	4.141	1.182	266
7612	1218	4.91	1.389	67.01	4211	4.179	1.194	322
7613	1204		1.022	60.85	3200	3.669		
7616	1220	4.52	1.042	63.10	3860	4.010	1.206	169
7615	1207		1.025	61.25	3273	3.707		
7609	1205	4.87	1.044	62.95	4029	4.150	1.231	168
7543	1228	6.35	1.050	62.08	4185	4.267	1.279	286
7536	1196		1.061	64.96	3403	3.735		
7611	1197	5.03	1.106	66.11	4123	4.105	1.212	198
7617	1192	5.49	1.088	66.11	4147	4.140	1.219	235
7618	1206	6.00	1.105	65.61	4217	4.178	1.239	278
7609	1198	6.44	1.097	65.61	4207	4.201	1.236	328
7615	1198		1.161	66.92	3802	2.955		
7615	1206	5.17	1.319	69.31	4490	3.333	1.181	205
7615	1210		1.161	67.93	3761	2.940		
7609	1197	5.70	1.329	69.12	4409	3.399	1.172	245
7613	1197	6.30	1.347	68.96	4443	3.437	1.181	301
7622	1198		1.139	67.92	3830	2.925		
7623	1196	4.97	1.306	69.27	4464	3.304	1.166	186
7612	1208	5.69	1.336	68.92	4557	3.377	1.190	243
7616	1206		1.117	66.17	3588	3.881		
7608	1204	4.99	1.297	67.72	4167	4.248	1.161	232
7613	1214	5.54	1.328	67.32	4233	4.334	1.180	286
7613	1218	6.00	1.356	67.27	4363	4.405	1.216	338
7617	1196		1.097	66.21	3583	3.806		
7618	1206	3.20	1.133	67.20	4064	4.029	1.134	136
7609	1199	3.80	1.146	67.65	4170	4.085	1.164	199
7617	1206	4.38	1.146	67.67	4219	4.123	1.178	263
7618	1202	4.98	1.146	67.66	4258	4.171	1.188	341
7621	1186		1.069	64.39	3395	3.722		
7618	1203	5.02	.854	65.40	3944	4.090	1.162	205
7599	1200	5.49	.825	65.35	4107	4.113	1.210	241
7602	1206	5.99	.784	65.35	4193	4.141	1.235	286
7611	1208	6.43	.758	65.06	4193	4.186	1.235	330

TABLE I - UNCORRECTED

Run	Injected mixture (percent by volume)		Number of inter-stage-injection nozzles	Inter-stage-injection-nozzle diameter (in.)	Injection stage	Engine inlet-air temperature (°F)	Inlet-air relative humidity (percent)	Pressure correction factor, δ	Ambient-temperature correction factor, θ
	Water	Alcohol							
161A	(a)					70	88	0.962	1.021
163A	55	45	30	0.025	Inlet,3,6,9	68	88	.962	
			30	.036					
164	55	45				67	88	.962	
165	55	45				67	88	.962	
166	55	45				66	86	.962	
206	(a)					89	80	0.956	1.058
207	70	30	30	0.045	Inlet,3,6,9	88	80	.958	
208	70	30				87	80	.956	
209	70	30				86	80	.956	
197	(a)					80	84	0.968	1.041
199	70	30	15	0.036	Inlet,3,6,9	79	84	.968	
			15	.045					
200	70	30				79	84	.968	
201	70	30				79	84	.968	
202	70	30				79	84	.968	
203	70	30				78	84	.968	
204	70	30				78	84	.968	
205	70	30				78	84	.968	
167	(a)					73	100	0.965	1.027
170	55	45	30	0.036	Inlet,3,6,9	70	100	.965	
171	55	45				70	100	.965	
174	(a)					60	70	0.975	1.001
173	55	45	30	0.036	Inlet,3,6,9	71	70	.965	
210	(a)					68	80	0.965	
212	70	30	20	0.045	Inlet, 6	65	80	.964	
215	(a)					68	86	0.968	1.017
217	70	30	20	0.045	Inlet, 6	64	86	.968	
218	70	30				65	86	.968	
219	70	30				65	86	.968	
220	70	30				65	86	.968	
192	(a)					70	80	0.974	1.030
194	70	30			Inlet	79	80	.973	
195	70	30				79	80	.973	
196	70	30				80	80	.974	
108	(b)		0			114	94	0.976	1.106
109						112	94	.977	1.102
110						110	94	.978	1.098
111						109	94	.979	1.096
112						111	94	.979	1.100
127			60		Inlet,3,6,9	83	48	.982	1.046
128						82	48	.983	1.044
129						80	48	.984	1.041
130						81	48	.985	1.042
131						80	48	.985	1.040
197			30		Inlet,3,6,9	80	84	.968	1.041
198						81	84	.970	1.042
167			30		Inlet,3,6,9	73	100	.965	1.027
168						73	100	.966	1.027
169						72	100	.967	1.025
236			20		Inlet, 6	62	100	.960	1.006
237						63	100	.961	1.008
238						61	100	.962	1.004
239						62	100	.963	1.006
240						60	100	.964	1.002
241						62	100	.961	1.006

[a]Noninjection run used as basis for calculation of augmented thrust ratio for succeeding runs.
[b]Normal performance runs to evaluate effect of presence of nozzles.

DATA - Concluded

Measured engine speed, N (rpm)	Measured tail-pipe temperature, T_7 (^{o}F)	Total injected flow, W_i (lb/sec)	Measured engine fuel flow, W_f (lb/sec)	Measured engine air flow, W_a (lb/sec)	Measured thrust, F (lb)	Compressor pressure ratio, P_3/P_1	Augmented thrust ratio, F_a/F_n	Average pressure drop across interstage-injection nozzle (lb/sq in.)
7617	1202		1.092	66.52	3578	3.836		
7611	1209	3.48	.967	67.60	4117	4.091	1.151	164
7603	1198	4.01	.944	67.65	4175	4.125	1.167	220
7613	1219	4.48	.931	67.65	4249	4.160	1.188	269
7626	1206	5.01	.889	67.66	4296	4.206	1.201	345
7616	1213		1.079	63.62	3391	3.970		
7617	1202	5.31	1.079	64.68	4074	4.369	1.201	234
7621	1208	5.84	1.079	64.65	4157	4.428	1.226	287
7616	1223	6.26	1.104	64.53	4257	4.474	1.256	333
7614	1202		1.083	65.11	3496	3.888		
7064	1259	3.97	1.200	66.49	4243	4.208	1.214	204
7614	1198	3.98	1.111	66.50	4101	4.171	1.173	204
7614	1209	4.52	1.125	66.50	4165	4.225	1.191	292
7613	1217	5.00	1.147	66.22	4248	4.370	1.215	314
7616	1203	4.99	1.117	66.22	4184	4.362	1.197	320
7617	1198	5.38	1.104	66.22	4223	4.398	1.208	386
7616	1197	5.89	1.114	66.23	4243	4.467	1.214	445
7624	1200		1.111	66.06	3621	3.851		
7614	1199	3.01	.997	67.80	4107	4.075	1.134	273
7609	1200	3.51	.978	67.60	4132	4.088	1.141	372
7615	1198		1.161	66.92	3802	2.955		
7615	1193	4.03	.942	67.54	4152	4.151	1.147	505
7610	1224		1.144	66.72	3690	4.122		
7605	1208	3.35	1.147	68.30	4214	4.341	1.142	92
7616	1209		1.128	66.77	3646	4.114		
7606	1211	4.81	1.147	67.61	4254	4.460	1.167	182
7613	1224	5.29	1.156	67.17	4318	4.503	1.184	228
7609	1220	5.80	1.153	67.12	4356	4.546	1.195	273
7613	1211	6.33	1.142	66.74	4356	4.597	1.195	329
7619	1193		1.103	66.32	3526	3.928		
7613	1209	0.76	1.125	66.51	3780	4.009	1.072	
7613	1204	1.25	1.117	66.71	3845	4.044	1.090	
7613	1198	1.71	1.119	66.41	3906	4.065	1.108	
7613	1200		1.011	61.40	3185			
7247	1133		.875	57.80	2788			
6886	1082		.769	53.80	2401			
6527	1041		.672	49.60	2029			
6158	1028		.606	45.50	1721			
7616	1192		1.086	65.25	3636			
7249	1119		.944	61.61	3164			
6890	1052		.819	57.46	2715			
6525	1004		.715	53.10	2311			
6344	988		.674	51.15	2132			
7614	1202		1.083	65.11	3496			
7070	1124		.886	59.04	2840			
7624	1200		1.111	66.06	3621			
7250	1113		.953	62.40	3135			
6892	1046		.825	58.26	2683			
7605	1198		1.119	67.09	3630			
7252	1134		.983	63.19	3195			
7065	1095		.911	61.12	2999			
6697	1023		.786	57.13	2547			
6340	979		.694	52.51	2177			
7432	1164		1.061	65.14	3453			

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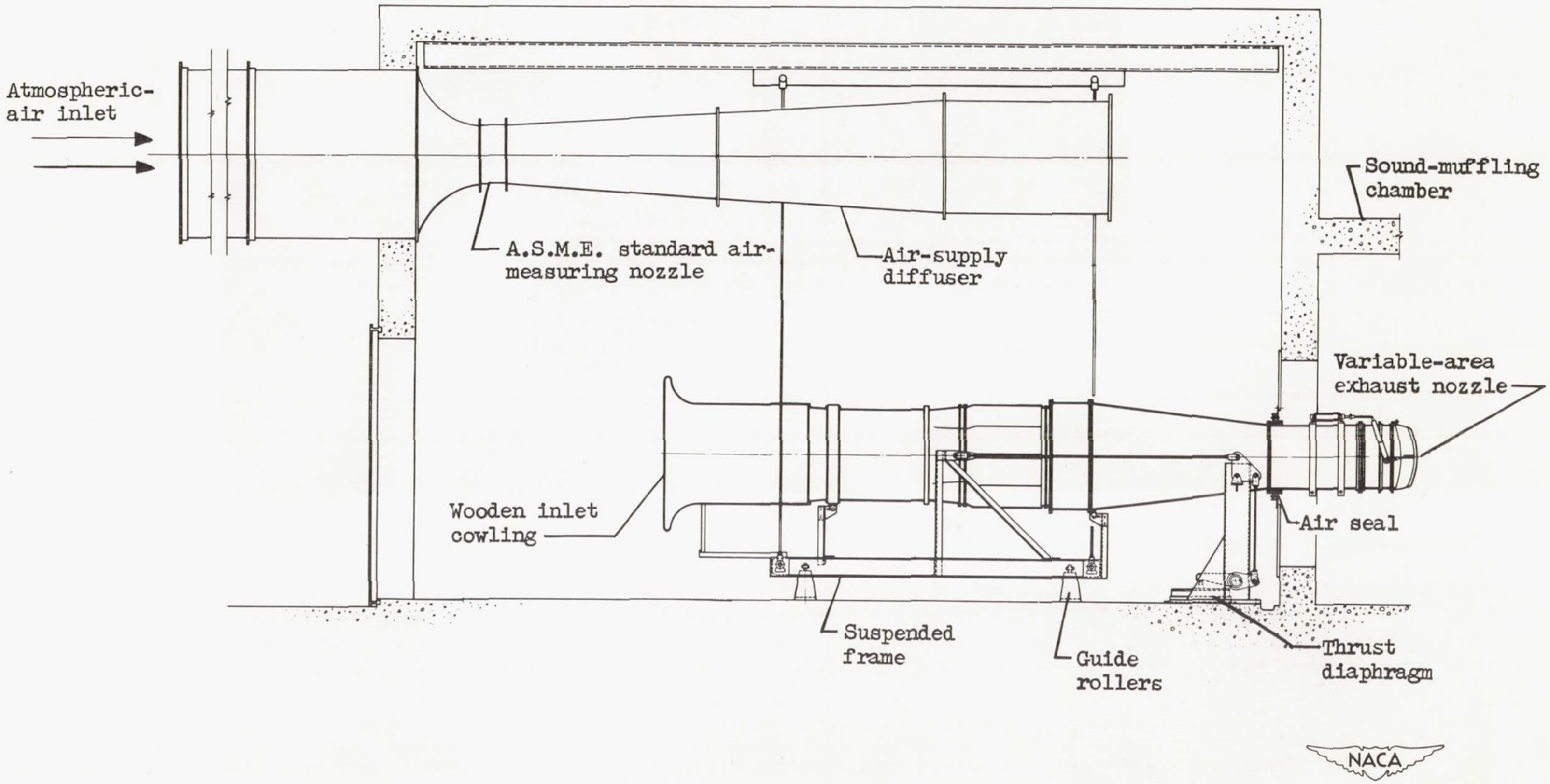


Figure 1. - Schematic diagram of engine installation.

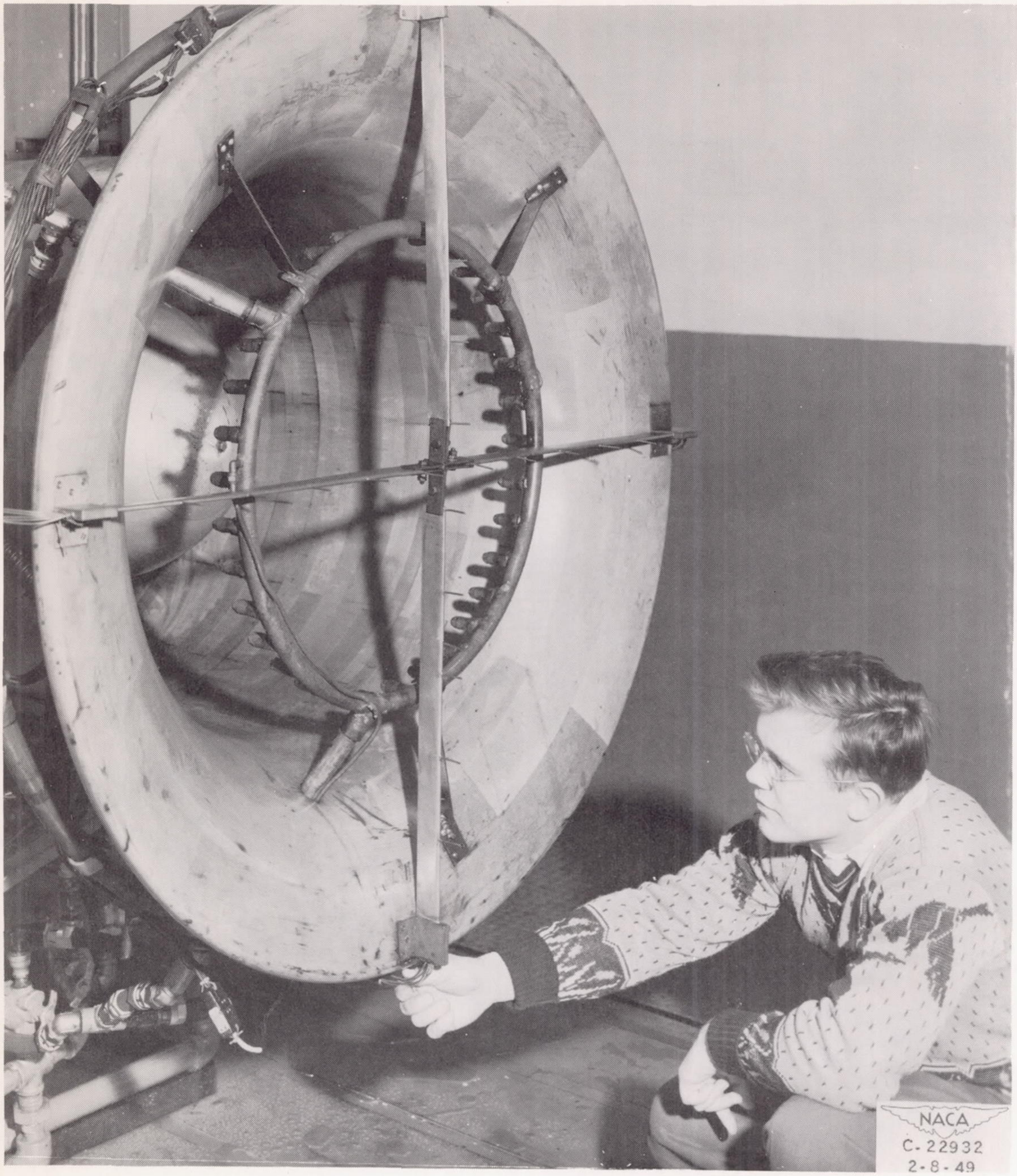


Figure 2. - Engine inlet cowling showing installation of atomizing nozzles.

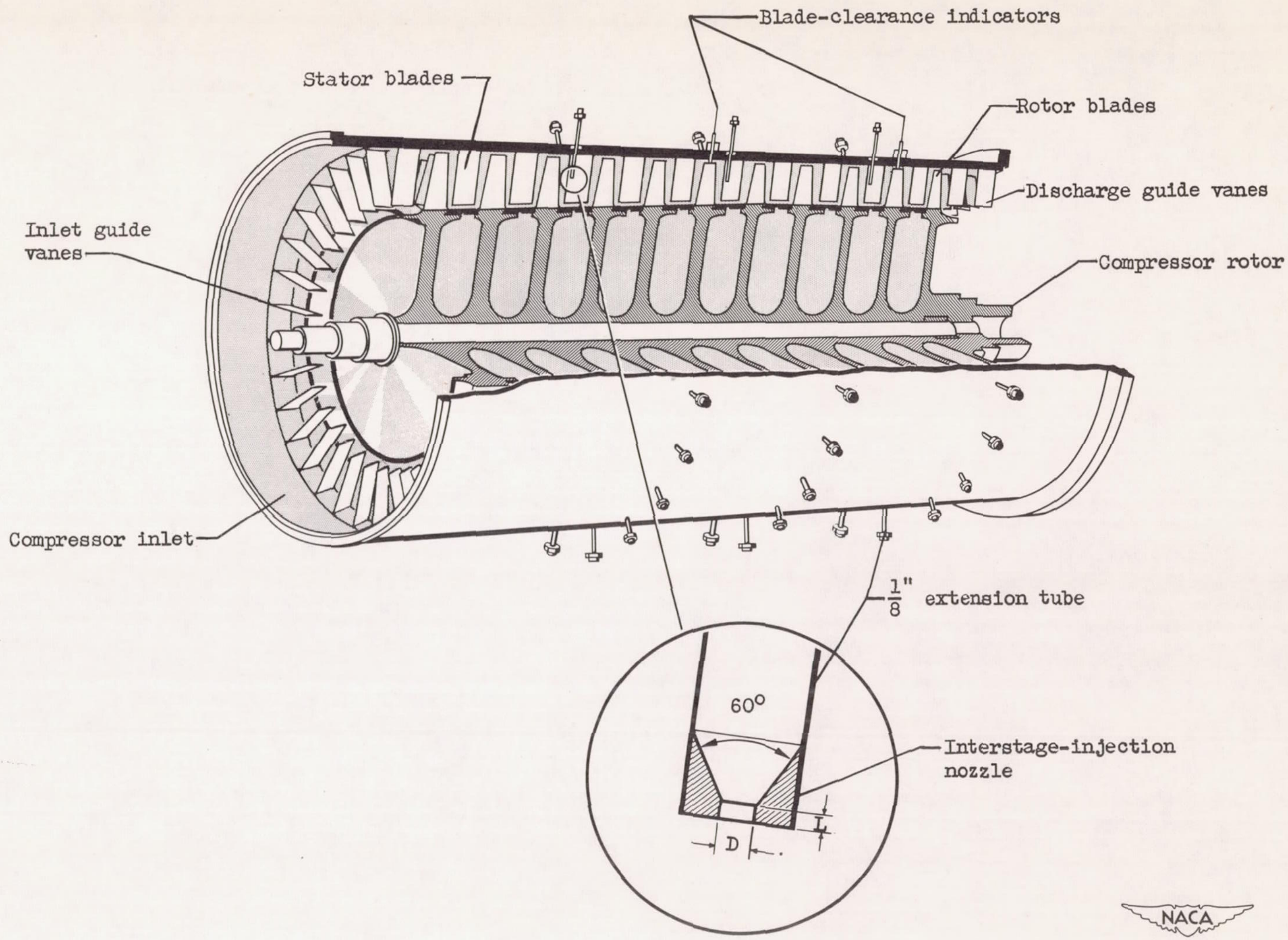


Figure 3. - Diagrammatic sketch of installation of interstage-injection nozzles in axial-flow compressor.

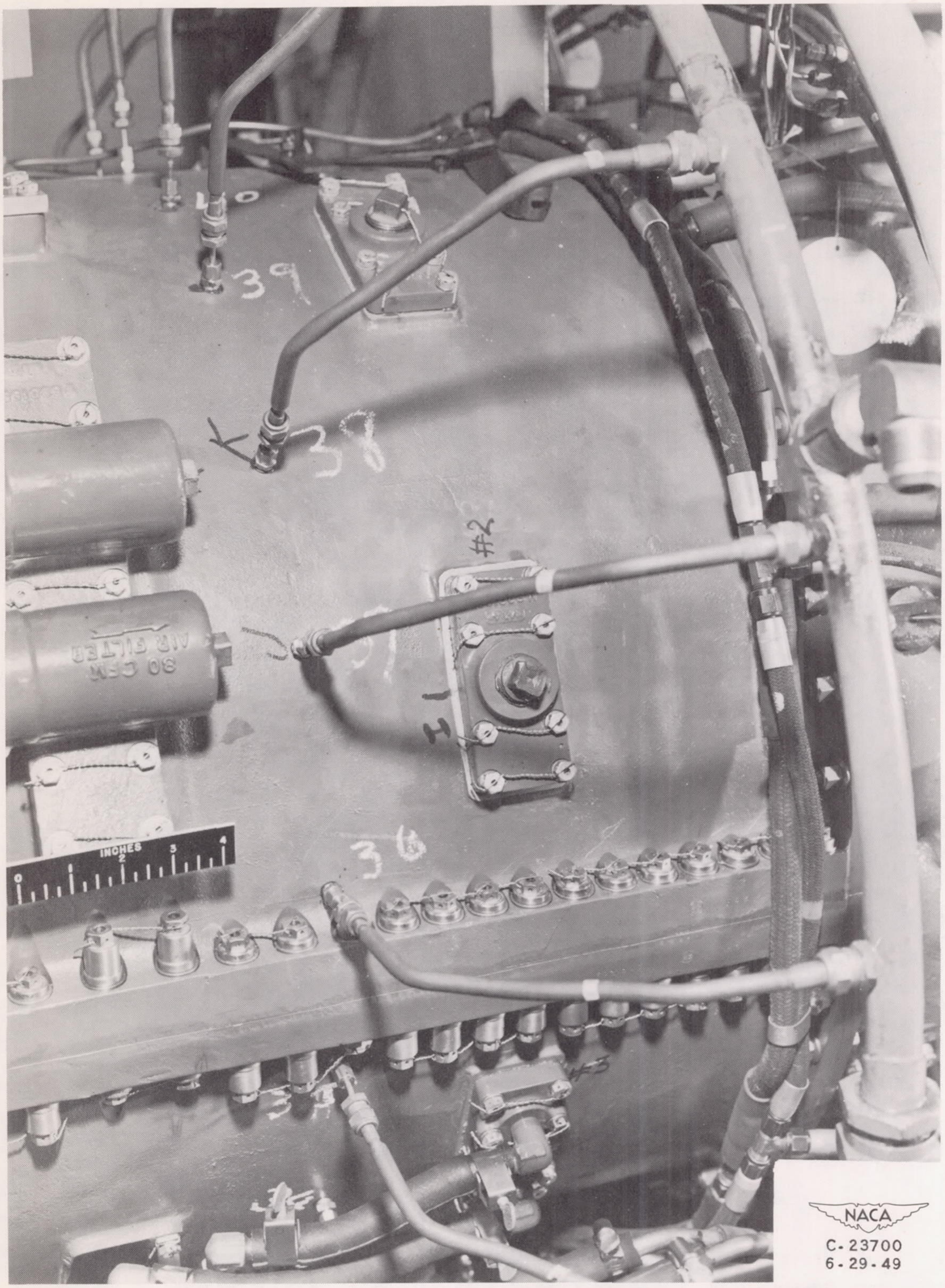


Figure 4. - Interstage-nozzle extension tubes of single-stage system installed in sixth stage of compressor. Extension tubes are shown connected to injection manifold.

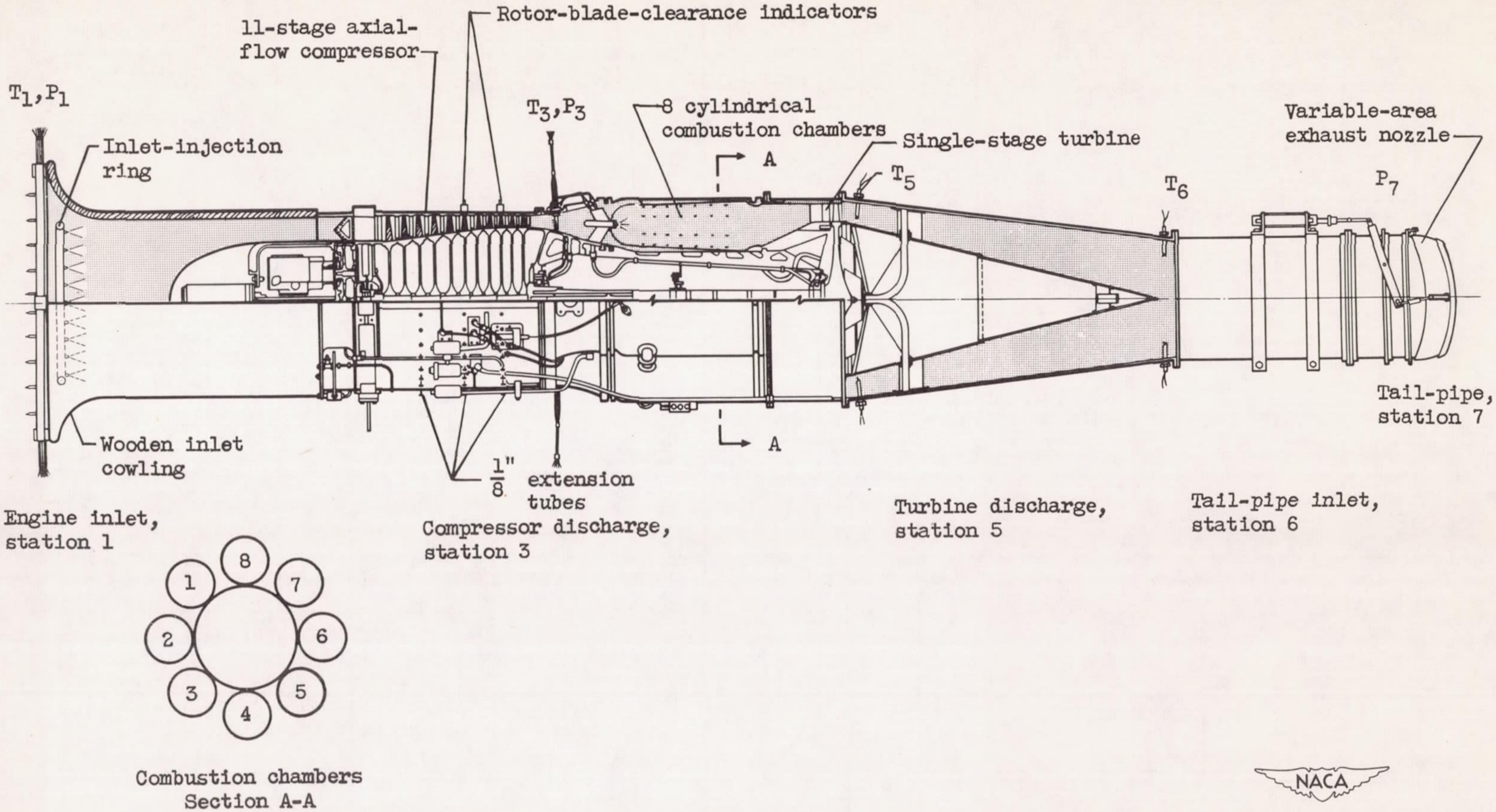


Figure 5. - Engine instrumentation.

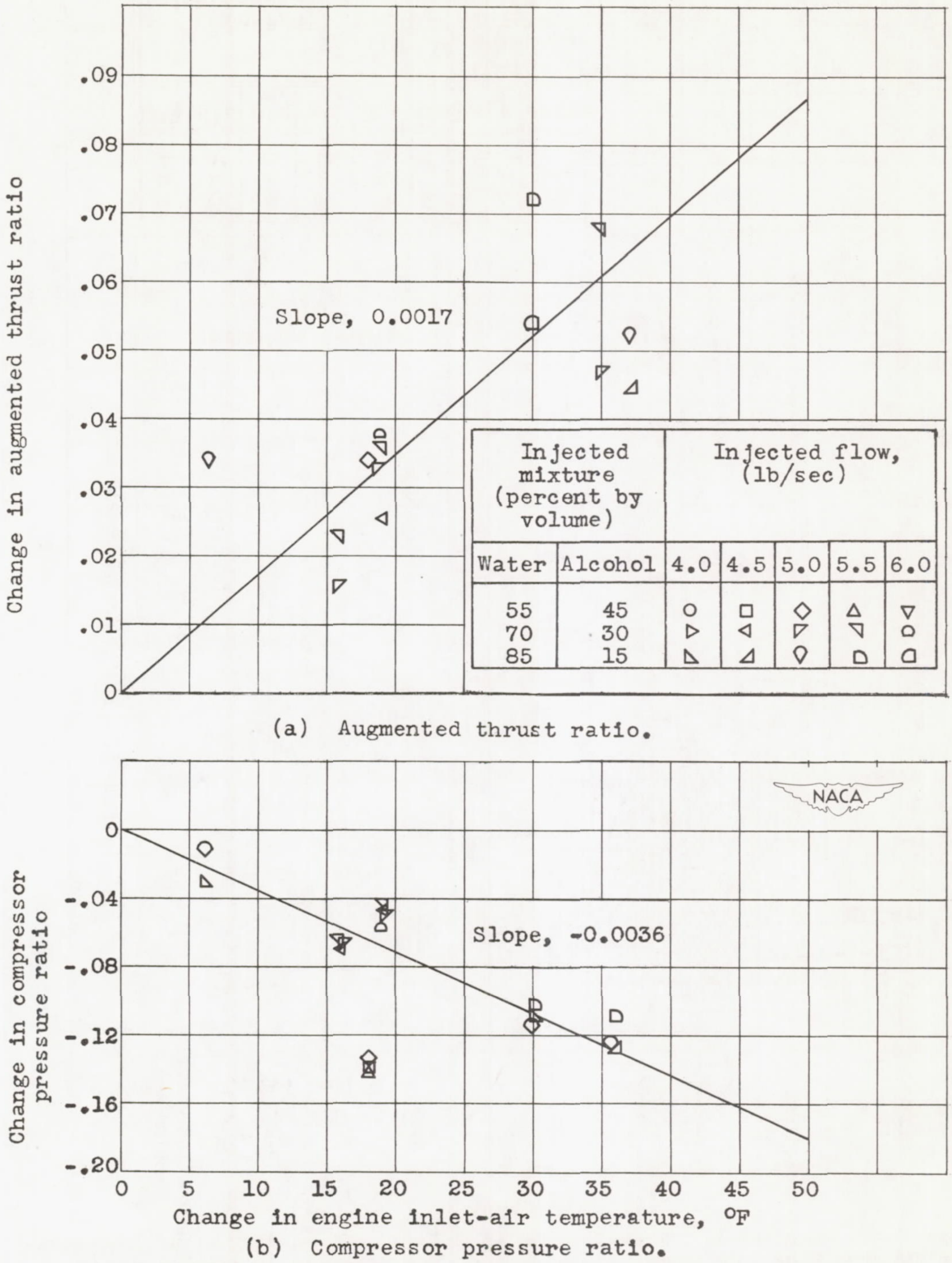
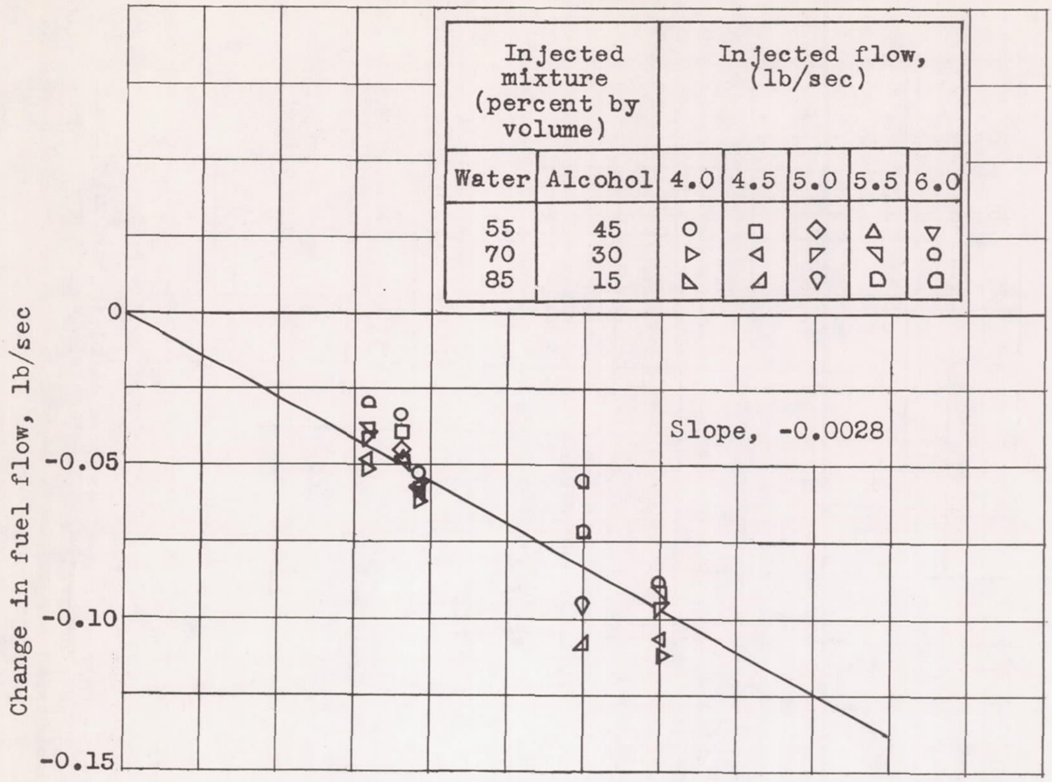
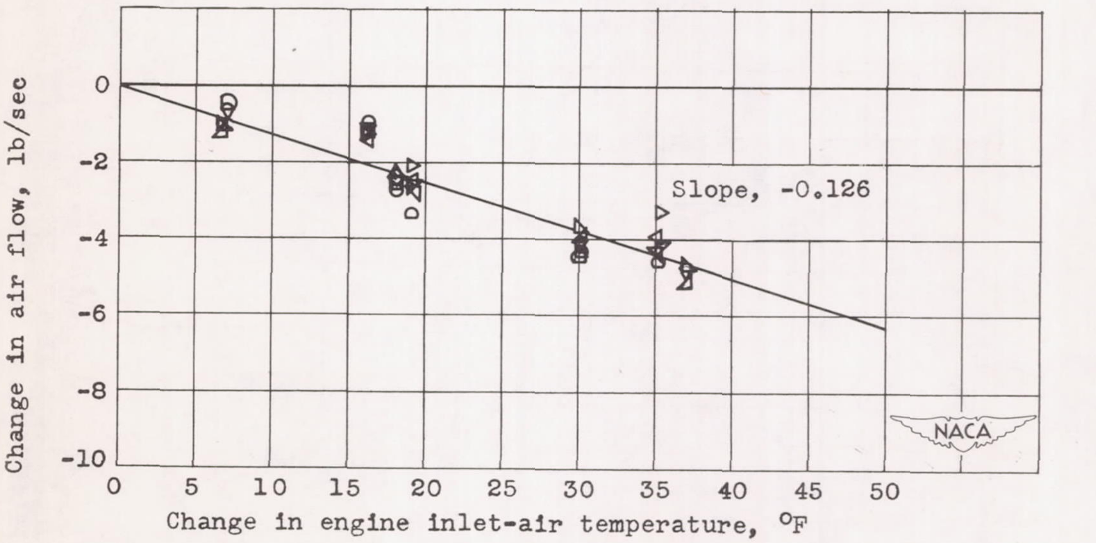


Figure 6. - Experimentally determined variation of augmented turbojet-engine performance resulting from changes in engine inlet-air temperature.

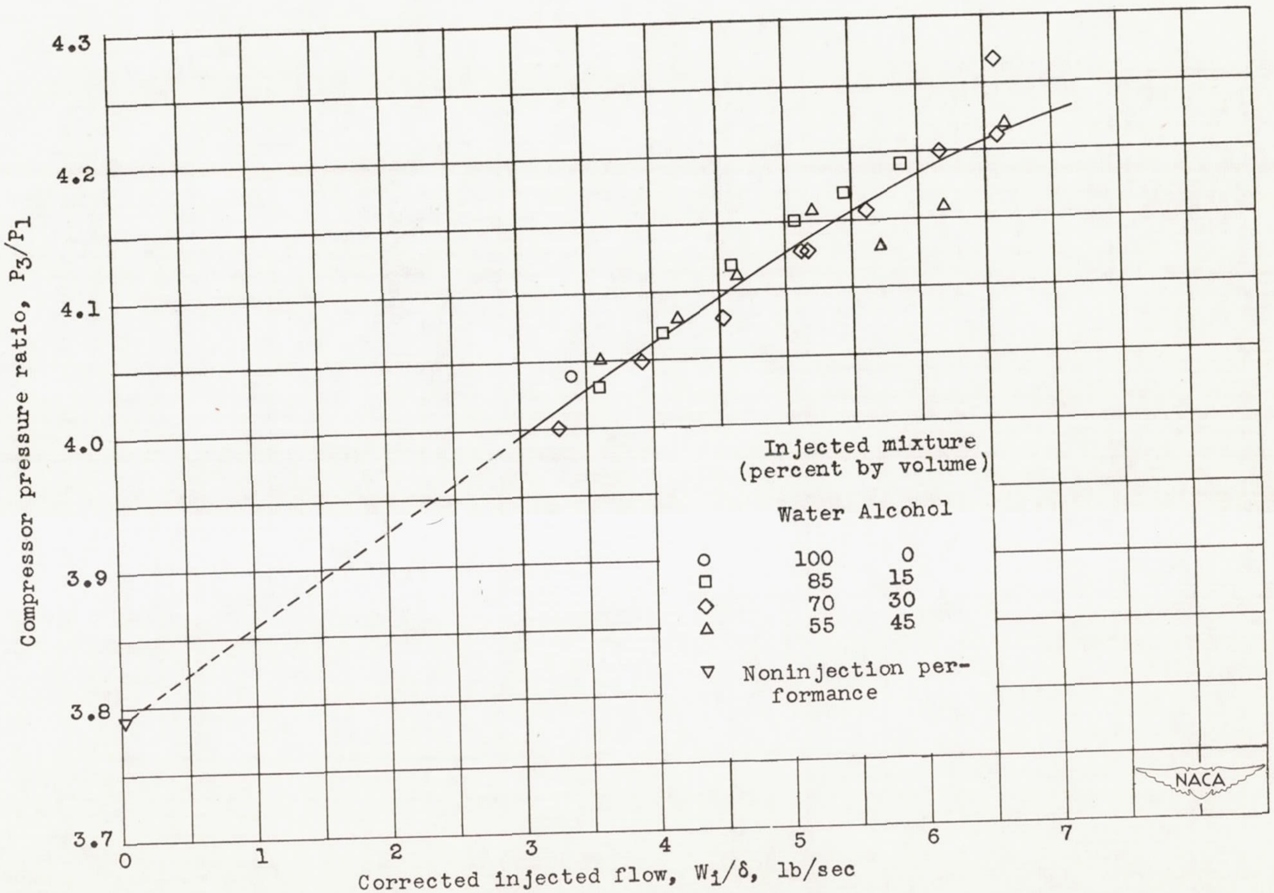


(c) Fuel flow.



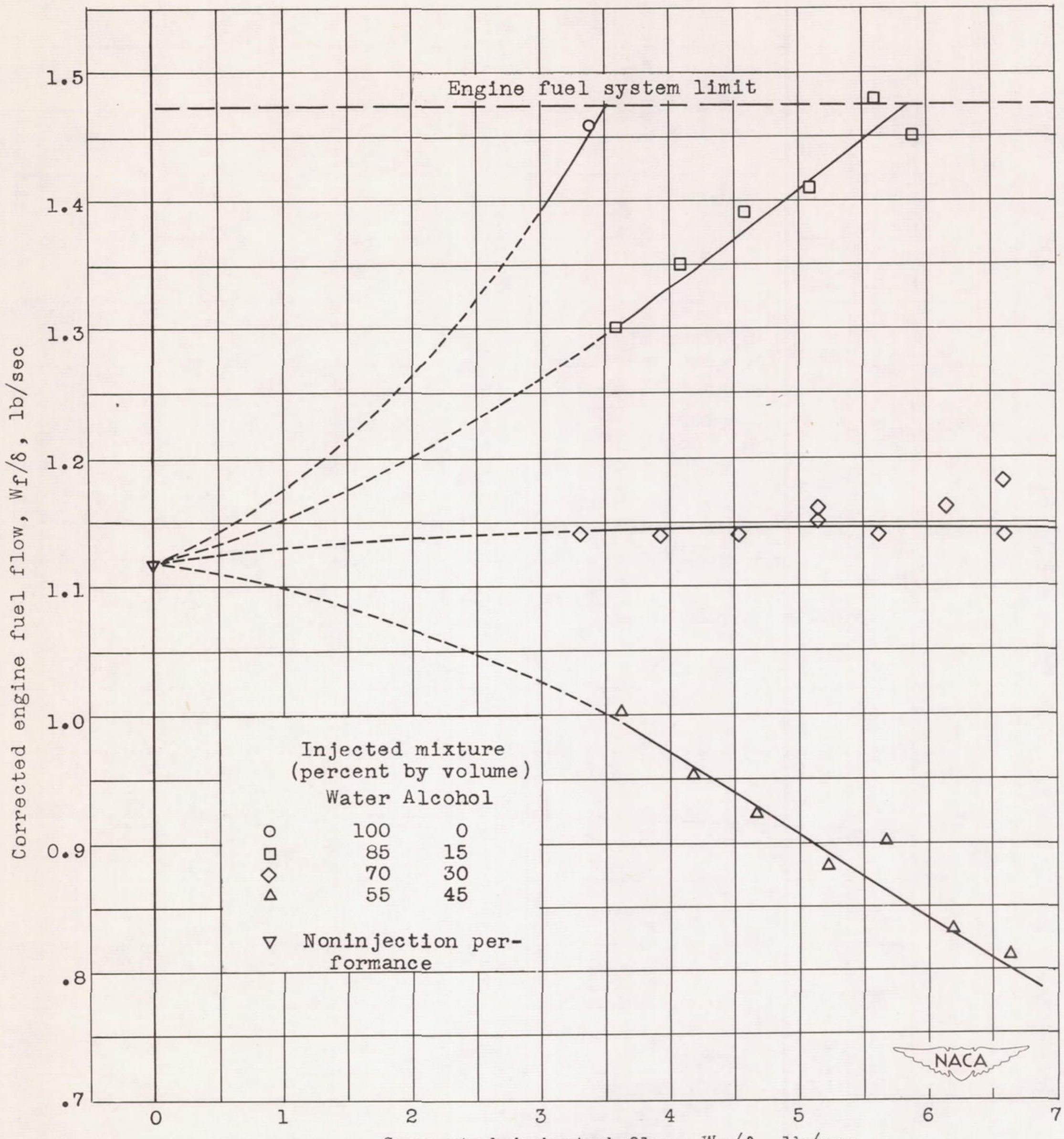
(d) Air flow.

Figure 6. - Concluded. Experimentally determined variation of augmented turbojet-engine performance resulting from changes in engine inlet-air temperature.



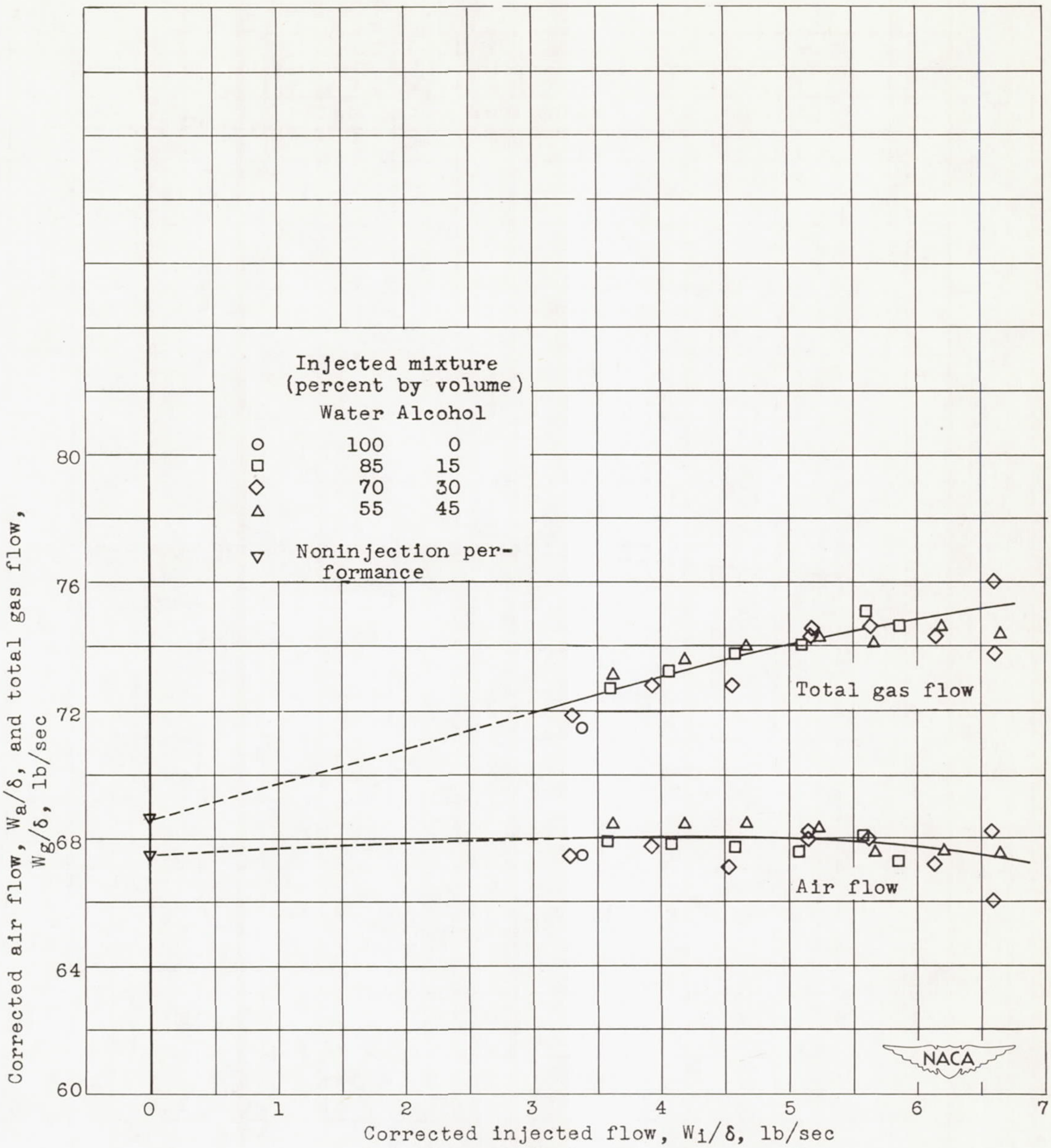
(a) Compressor pressure ratio.

Figure 7. - Turbojet-engine performance with three-stage system of water-alcohol injection investigated at sea-level, zero-ram conditions. Data corrected to engine inlet-air temperature of 80° F; engine speed, 7610 rpm; exhaust-gas temperature, 1200° F.



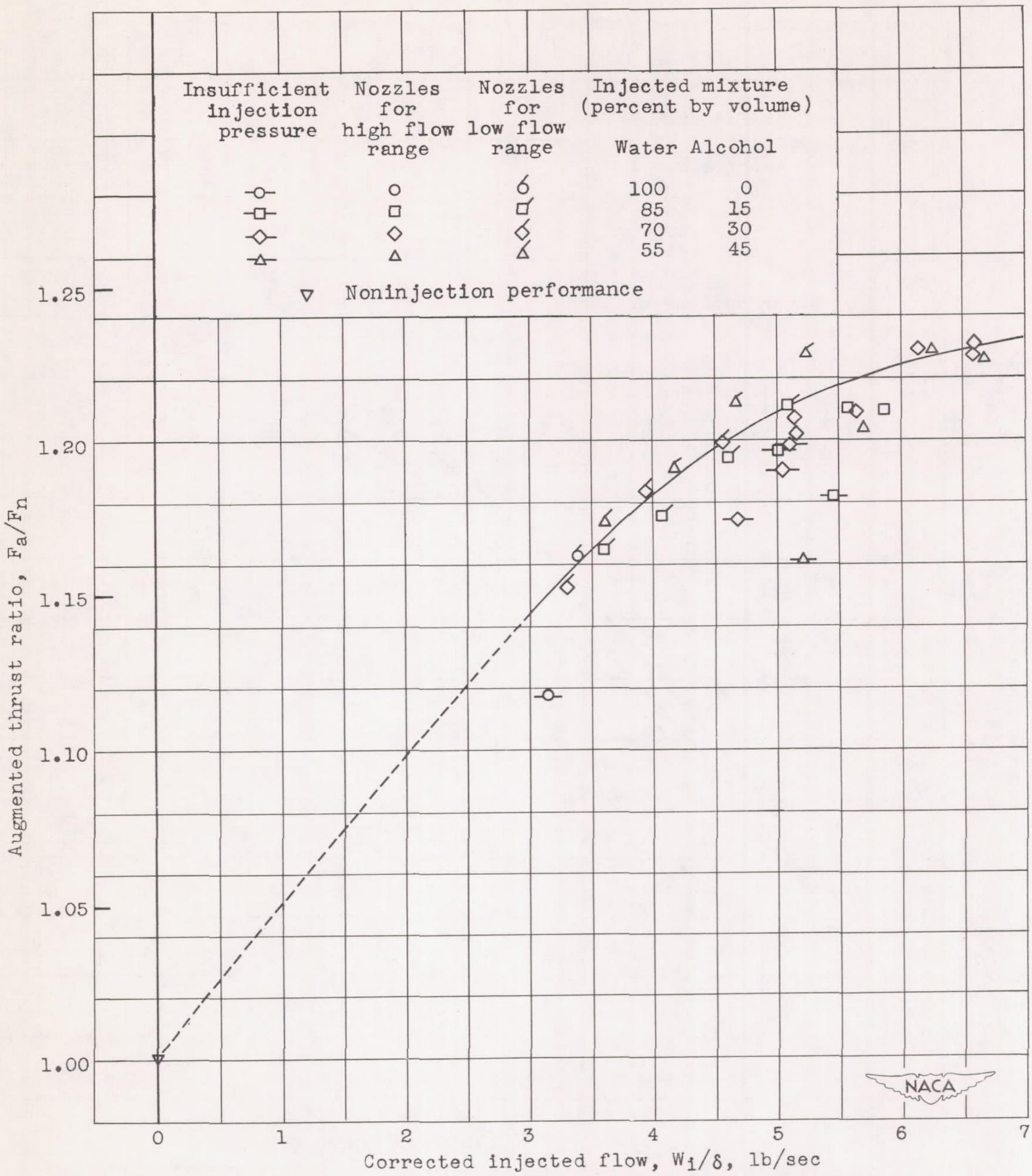
(b) Corrected engine fuel flow.

Figure 7. - Continued. Turbojet-engine performance with three-stage system of water-alcohol injection investigated at sea-level, zero-ram conditions. Data corrected to engine inlet-air temperature of 80° F; engine speed, 7610 rpm; exhaust-gas temperature, 1200° F.



(c) Corrected air and total gas flow.

Figure 7. - Continued. Turbojet-engine performance with three-stage system of water-alcohol injection investigated at sea-level, zero-ram conditions. Data corrected to engine inlet-air temperature of 80° F; engine speed, 7610 rpm; exhaust-gas temperature, 1200° F.



(d) Augmented thrust ratio.

Figure 7. - Concluded. Turbojet-engine performance with three-stage system of water-alcohol injection investigated at sea-level, zero-ram conditions. Data corrected to engine inlet-air temperature of 80° F; engine speed, 7610 rpm; exhaust-gas temperature, 1200° F.

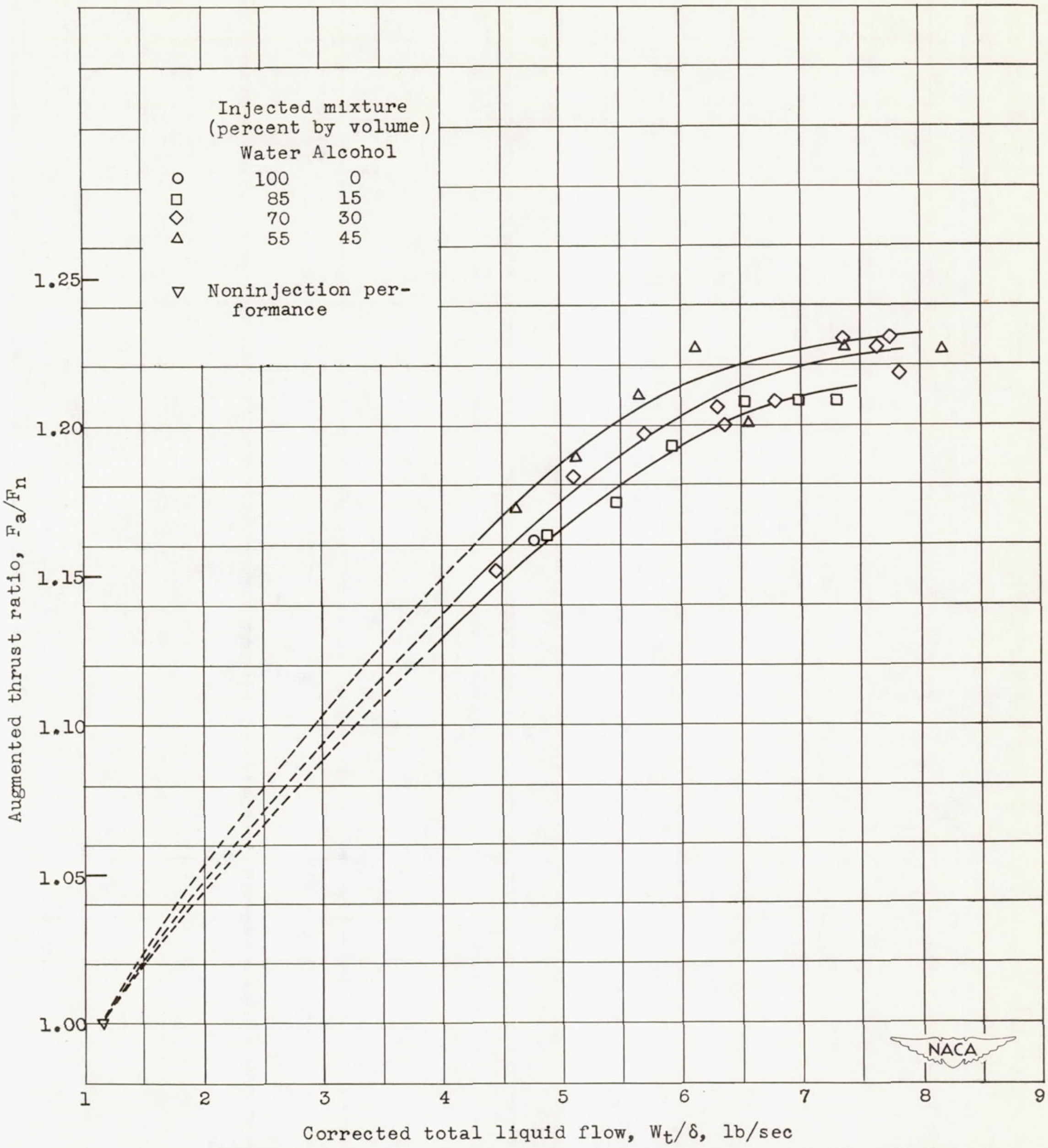


Figure 8. - Variation of augmented thrust ratio with corrected total liquid flow for three-stage system of water-alcohol injection investigated at sea-level, zero-ram conditions. Data corrected to an engine inlet-air temperature of 80° F; engine speed, 7610 rpm; exhaust gas temperature, 1200° F.

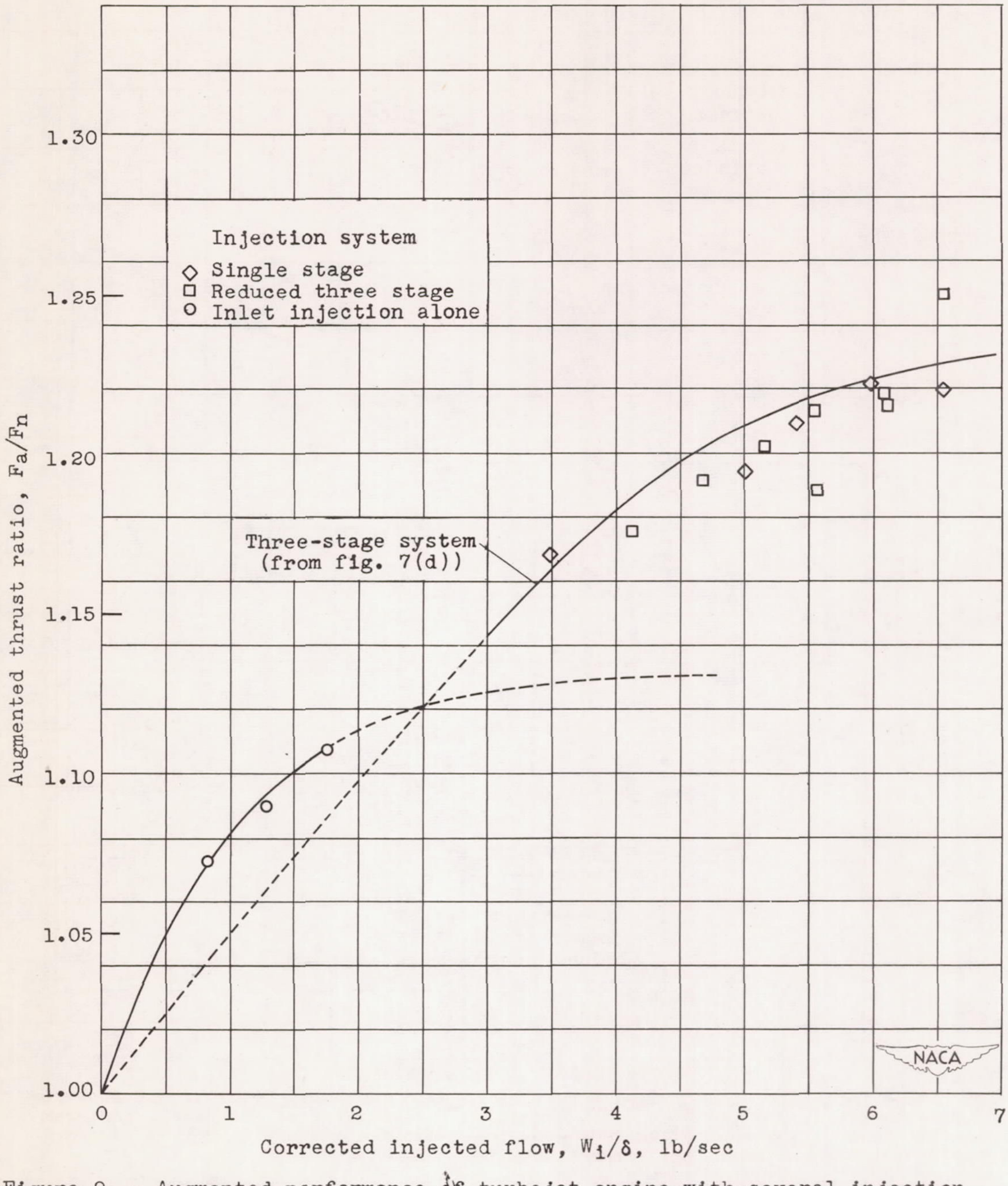
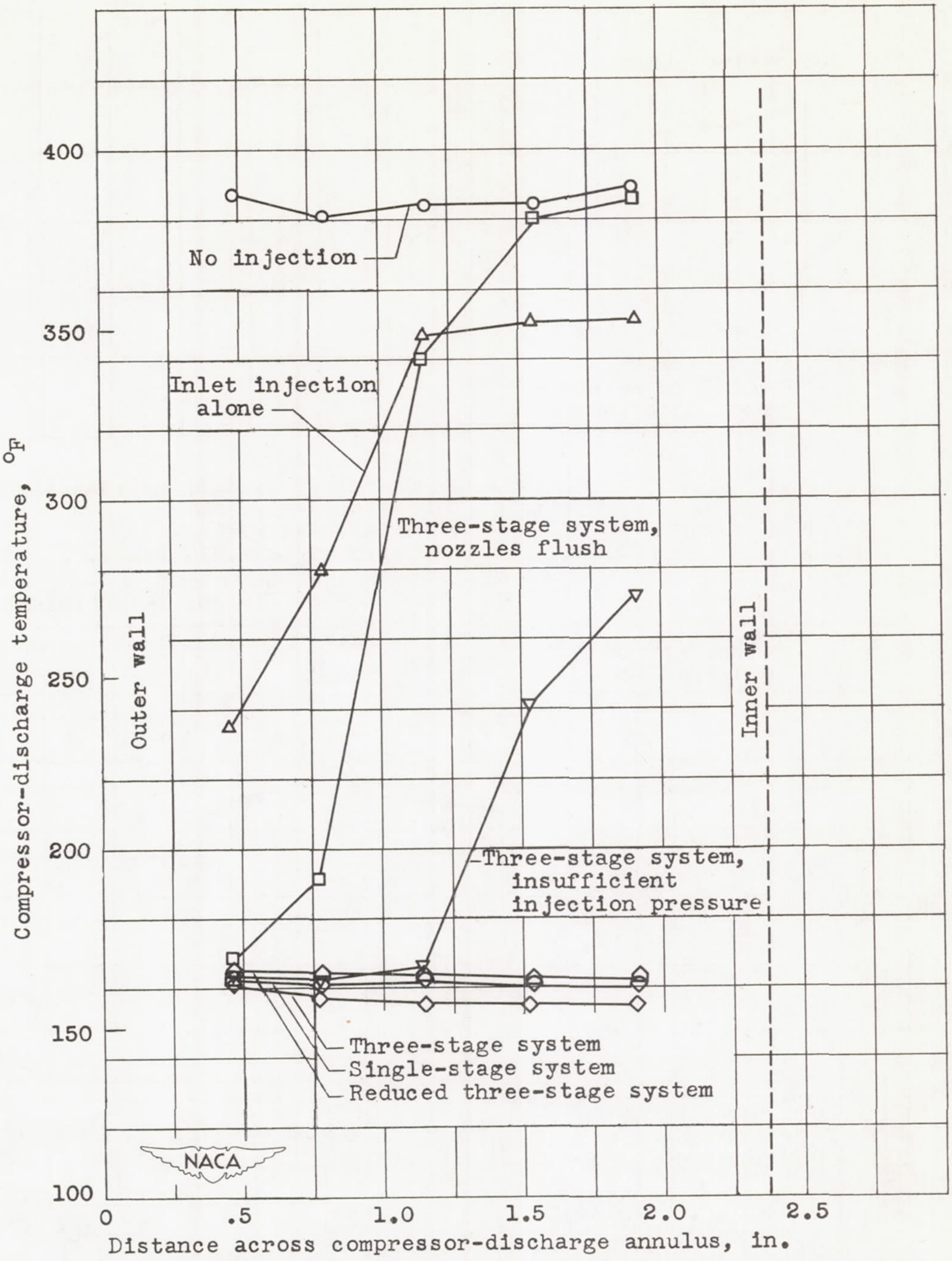
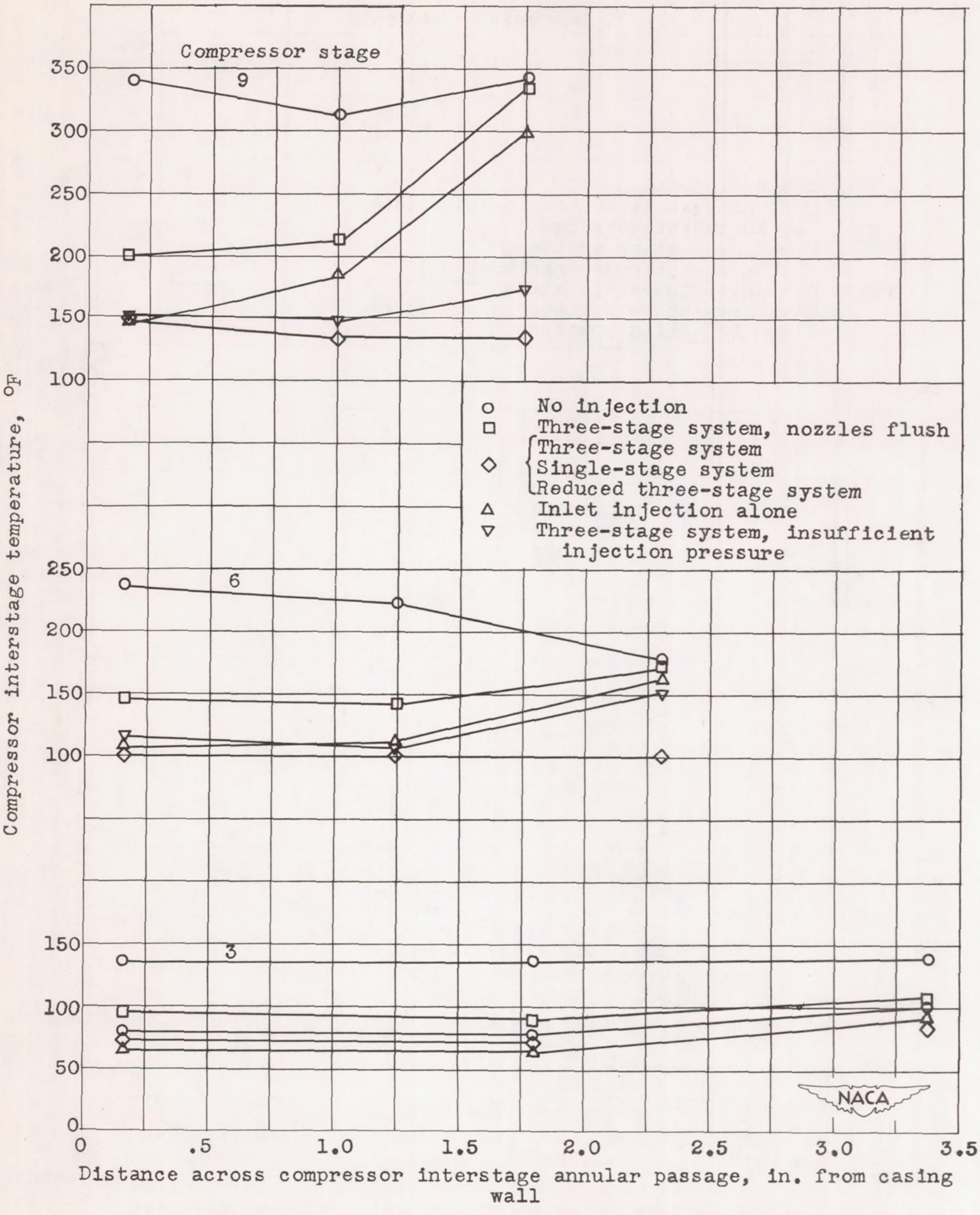


Figure 9. - Augmented performance of turbojet engine with several injection systems investigated at sea-level, zero-ram conditions. Data corrected to engine inlet-air temperature, 80° F; engine speed, 7610 rpm; exhaust-gas temperature, 1200° F.



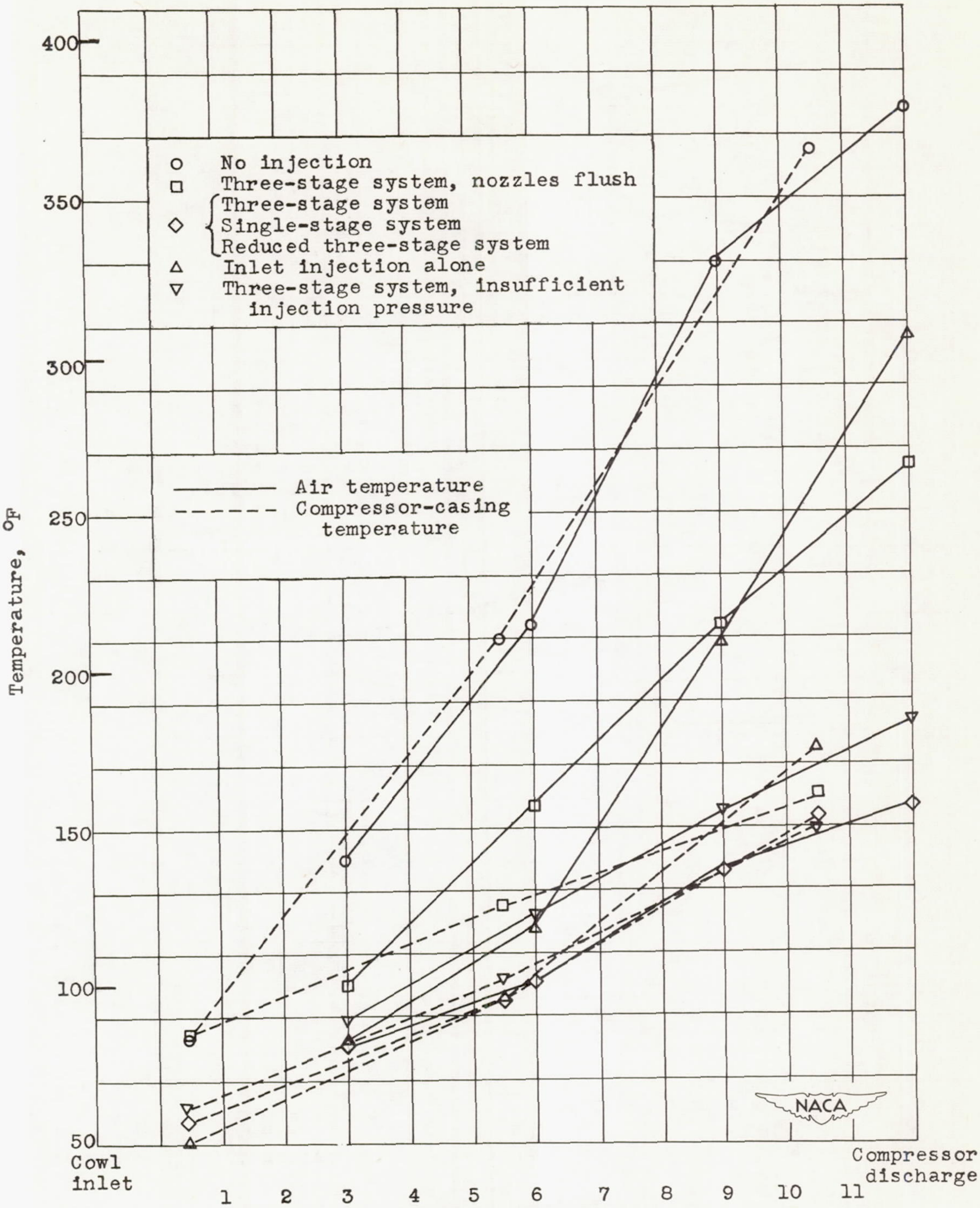
(a) Radial temperature distribution across compressor-discharge annulus.

Figure 10. - Compressor-temperature surveys of turbojet engine with various systems for injection of water-alcohol mixtures in compressor.



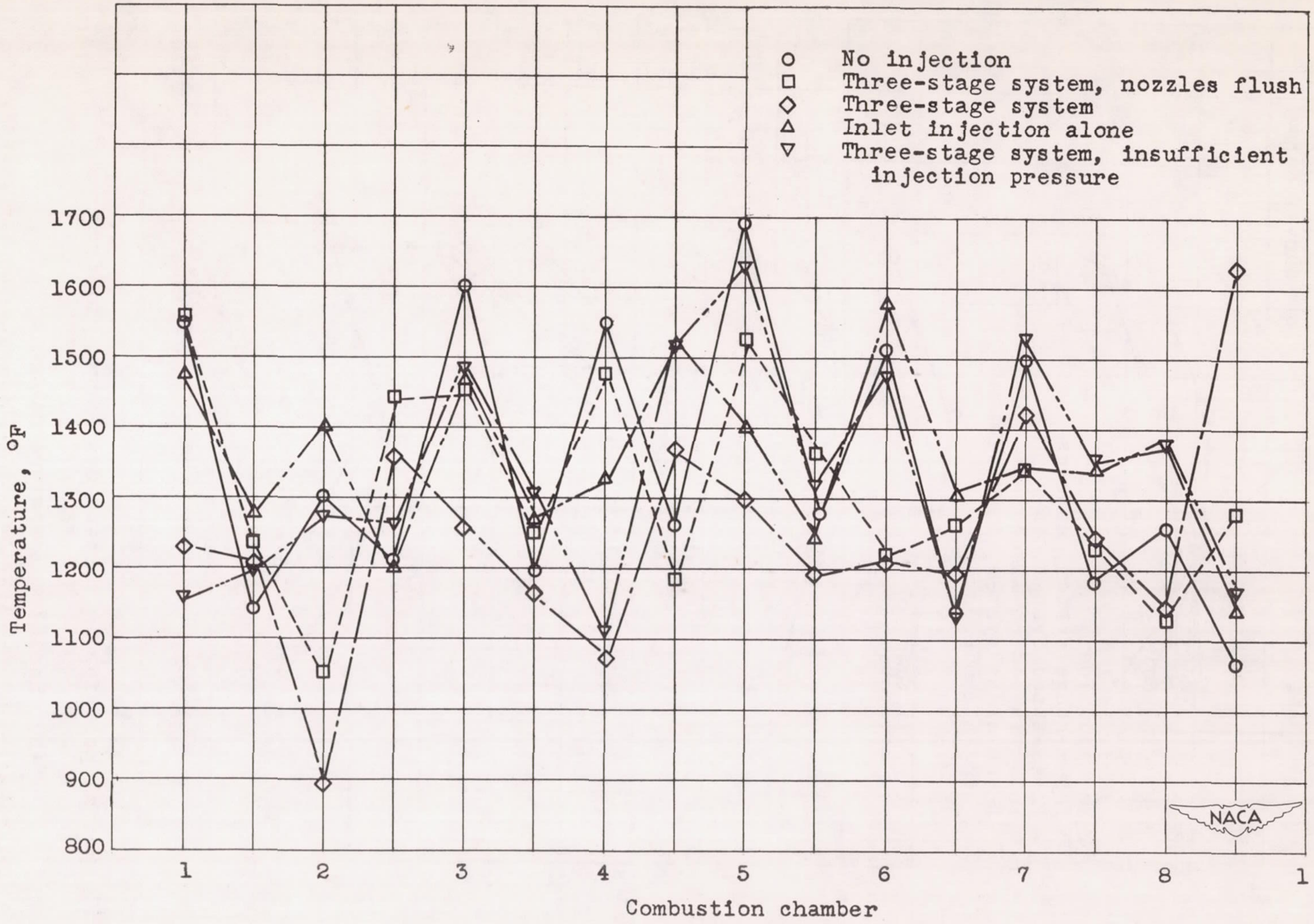
(b) Radial temperature distribution across compressor interstage annular passage.

Figure 10. - Continued. Compressor-temperature surveys of turbojet engine with various systems for injection of water-alcohol mixtures in compressor.



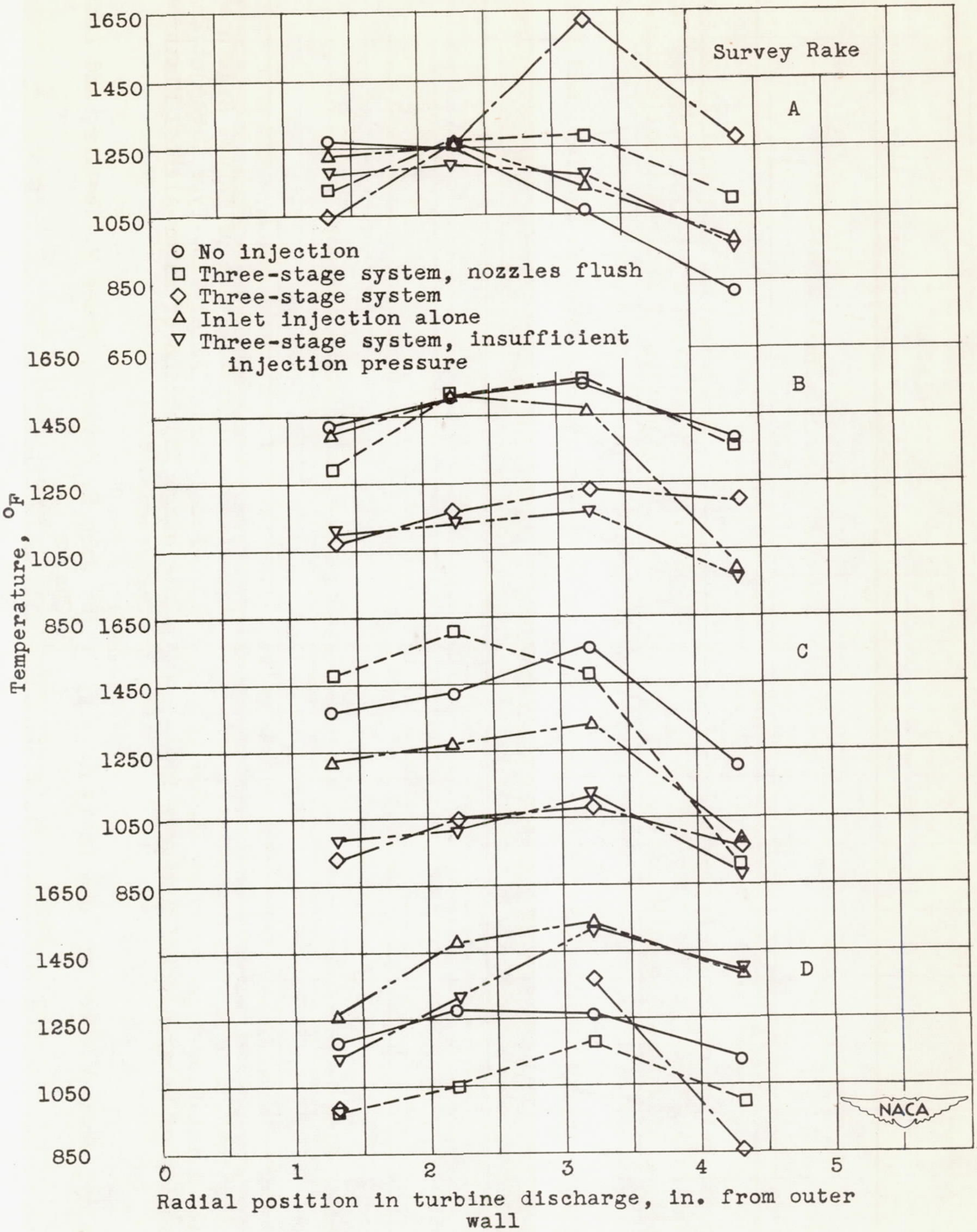
(c) Longitudinal temperature distribution along compressor.

Figure 10. - Concluded. Compressor-temperature surveys of turbojet engine with various systems for injection of water-alcohol mixtures in compressor.



(a) Circumferential temperature distribution.

Figure 11. - Turbine-discharge temperature surveys of turbojet engine with various systems for injection of water-alcohol mixtures in compressor.



(b) Radial temperature distribution.

Figure 11. - Concluded. Turbine-discharge temperature surveys of turbojet engine with various systems for injection of water-alcohol mixtures in compressor.