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RESEARCH MEMORANDUM

INVESTIGATION OF THRUST AUGMENTATION USING WATER-ALCOHOL INJECTION ON A 5200-POUND-THRUST AXIAL-FLOW-TYPE TURBOJET ENGINE AT STATIC SEA-LEVEL CONDITIONS

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RESEARCH MEMORANDUM

INVESTIGATION OF THRUST AUGMENTATION USING WATER-ALCOHOL INJECTION ON A 5200-POUND-THRUST AXIAL-FLOW-TYPE TURBOJET ENGINE AT STATIC SEA-LEVEL CONDITIONS

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SUMMARY

An investigation to evaluate the thrust augmentation available with various types of water-alcohol injection system was conducted on a 5200-pound-thrust axial-flow-type turbojet engine at sea-level, zero-ram conditions. The engine was equipped with a variable-area exhaust nozzle which was used to maintain constant tail-pipe gas temperature during injection. During this investigation, runs were made with inlet injection, interstage injection, combustion-chamber injection, and a combination of interstage and combustion-chamber injection. All these runs were made over a range of coolant-flow rates at approximately rated engine speed and tail-pipe gas temperature and with an engine-inlet air temperature of 100° F.

A maximum thrust augmentation of 39.5 percent was obtained at a coolant-air ratio of 0.148 with the combination system, which consisted in injecting coolant in the compressor sixth stage up to a coolant-air ratio of about 0.023 and injecting the remainder of the coolant in the combustion chambers. Combustion-chamber injection alone provided about 24.5 percent thrust augmentation at a coolant-air ratio of 0.10. The unaugmented thrust loss with the combination system was about 1 percent and with interstage injection in the sixth and eighth stages of the compressor was about 2 percent. No measurable thrust loss was encountered with the inlet or combustion-chamber injection systems. The engine suffered no ill effects as a result of interstage or combustion-chamber coolant injection; however, an external source of turbine cooling air was used during these runs.

INTRODUCTION

The increasing range and pay load requirements for turbojet-powered aircraft have increased the take-off problem. The engines for these aircraft are usually designed primarily for good cruise economy in order to satisfy the long-range requirement; accordingly, the take-off thrust of these same engines may be marginal under normal conditions. In cases where take-off must be accomplished at a relatively high-altitude airfield or on a hot day, it is necessary to provide these engines with some form of thrust augmentation. This thrust augmentation can be accomplished in any one of several ways, namely, bleed-off, tail-pipe burning, water injection, or rocket assist. References 1 and 2 present analyses of these various augmentation systems.

The research reported herein, which was conducted at the NACA Lewis laboratory, is concerned with the use of water-alcohol or coolant injection as a means of thrust augmentation of an axial-flow turbojet engine. This coolant can, of course, be injected at any one of several places in the engine, that is, at the compressor inlet, midway through the compressor (interstage), or in the combustion chamber. Results of experimental investigations of thrust augmentation obtainable with inlet and interstage injection are presented in references 3 and 4. These results indicate that thrust augmentations of about 15 percent can be obtained with inlet injection at an inlet-air temperature of 88° F and that about 22 percent augmentation can be obtained with inlet and interstage injection at an inlet-air temperature of 80° F. In an investigation reported in reference 5, an 18 percent thrust augmentation was obtained with one type of axial-flow engine by combustion-chamber injection alone.

An examination of the results of references 3 to 5 indicated that possibly greater thrust augmentations could be obtained by combining combustion-chamber injection with inlet and interstage injection. As a means of evaluating such a system, an investigation was conducted on a 5200-pound-thrust axial-flow engine at sea-level, zero-ram conditions. During this investigation each of the injection systems was operated alone and one set of runs was made with a combination of interstage and combustion-chamber injection (hereinafter called the combination system). All these runs were made over a range of coolant-air ratios and at an inlet-air temperature of 100° F. The results are presented to show the effect of coolant injection on thrust, compressor performance, fuel flow, combustion efficiency, and turbine-discharge temperature.

APPARATUS

Engine. - The investigation was conducted on a production-model axial-flow-type turbojet engine with a nominal military rating of 5200 pounds of thrust with a rotor speed of 7950 rpm and with a tail-pipe gas temperature of 1275° F at sea-level, zero-ram conditions. The engine has a 12-stage axial-flow compressor, 8 cylindrical combustion chambers, and a single-stage turbine. The combustion chambers are equipped by the manufacturer for water-alcohol injection.

Engine installation. - The general arrangement of the engine installation is shown in figure 1. The engine was mounted on a swinging frame suspended from the ceiling of the test chamber. The engine tail pipe extended through a diaphragm-type seal in the rear wall so that the exhaust gas was discharged into a sound-muffling chamber at approximately atmospheric pressure. The engine thrust was balanced and measured by a null-type air-pressure diaphragm. The greater portion of the engine combustion air was ducted from the atmosphere into the airtight test chamber and measured by a 26-inch, long-radius A.S.M.E. nozzle. The remainder of the combustion air was supplied by the

laboratory high-pressure air system and entered the test chamber through a single can-type combustor that was used to maintain the desired engine inlet-air temperature. Heating of the inlet air was accomplished by mixing the exhaust gas from the combustor with the atmospheric air. The heater air flow was metered with an A.S.M.E. flat-plate orifice. The engine was equipped with a clamshell-type variable-area exhaust nozzle to permit the adjustment of tail-pipe temperature independent of the coolant-flow rate. The exhaust-nozzle area was determined by means of a remote-reading position indicator. In order to avoid corrosion of the parts around the turbine bearing, an outside source of air was used to cool the forward side of the turbine.

A rotor-blade-clearance indicator of NACA design was installed at the fifth, eighth, and twelfth stages of the compressor to detect any blade rubbing that might occur because of overcooling of the compressor casing by centrifugal separation of the injected coolant. The clearance between the indicators and the rotor-blade tips was adjusted to the minimum specified blade clearance for the respective stages as indicated in the following table:

Compressor stage	Clearance (in.)
5	0.034
8	.025
12	.015

Coolant-injection systems. - For this investigation the coolant-injection nozzles were located at the engine inlet, compressor sixth stage, compressor eighth stage, and combustion chamber. A list of these positions and the type, size, number, and capacity of the nozzles is given in table I.

The inlet-injection system consisted of 34 conventional atomizing nozzles installed in a ring at the engine-cowl inlet. The interstage-injection system consisted of either 18 solid-jet-type nozzles located in the sixth stage of the compressor or 36 solid-jet-type nozzles equally divided between the sixth and eighth stages of the compressor. The combustion-chamber injection system consisted of 4 conical spray nozzles per combustion chamber equally spaced around the periphery and located about 10 inches downstream of the fuel nozzle. Figure 2 shows the details of the interstage and combustion-chamber injection nozzles. The interstage-injection nozzles were designed to emit a solid stream of coolant that would penetrate the compressor air stream to within 0.25 inch of the rotor hub. The tips of the combustion-chamber injection nozzles were designed to inject the coolant inside the combustion-chamber liners. The combustion chambers of this engine were equipped with thimble-type liners (fig. 3) that were designed to promote better mixing of the coolant and air and thus decrease the flame length.

Fuel and coolant mixture. - Fuel conforming to specification MIL-F-5624A was burned in the engine combustors. The coolant consisted of a mixture of 30 percent MIL-A-6091 alcohol and 70 percent water by unmixed volume. The water was drawn from the domestic supply and chemically softened from 163 parts per million to 10 parts per million to decrease mineral deposits on the compressor blades. The engine fuel flow was measured with a calibrated flow meter. The coolant-flow rates were measured with calibrated thin-plate orifices.

Temperature and pressure instrumentation. - The locations for the instrumentation for temperature and pressure measurement are shown in figure 4. The temperatures recorded and the number, type, and location of the thermocouples were as follows:

(a) Total temperature at engine inlet: average of 20 individually recorded thermocouples, five in each of four rakes 90° apart at inlet-cowling entrance.

(b) Total temperature at compressor discharge: average of 24 thermocouples, six in each of four rakes located upstream of combustion chambers 2, 4, 6, and 8.

(c) Total temperature at turbine discharge: average of 28 thermocouples located 4 inches downstream of the trailing edge of the turbine, five in each of two rakes on the center lines of combustion chambers 2 and 6, five in each of two rakes midway between combustion chambers 4 and 5 and between 8 and 1, two in each of two rakes on the center lines of combustion chambers 4 and 8 and two in each of two rakes located midway between combustion chambers 2 and 3 and between 6 and 7.

(d) Total temperature in the tail pipe halfway down inner cone: average of 30 thermocouples, four in each of five rakes and 10 individual strut type.

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

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

(b) Static pressure at compressor inlet: average of three wall static taps located in the straight section of the inlet cowling.

(c) Interstage static pressures: average of two wall static taps located in the fourth, sixth, and eighth stages of the compressor.

(d) Total pressure at compressor discharge: average of 24 total pressure tubes, six in each of four rakes located upstream of combustion chambers 1, 3, 5, and 7.

(e) Static pressure at compressor discharge: average of four wall static taps located upstream of combustion chambers 1, 3, 5, and 7.

(f) Total pressure at turbine discharge: average of 12 total pressure tubes located 4 inches downstream of the trailing edge of the turbine, two rakes of three tubes each located on the center lines of combustion chambers 4 and 8, and two rakes of three tubes each located midway between combustion chambers 2 and 3 and between 6 and 7.

(g) Static pressure at turbine discharge: average of four wall static taps in the outer wall, 4 inches downstream of the trailing edge of the turbine and located on the vertical and horizontal center lines of the engine.

(h) Static pressure at exhaust-nozzle discharge: one static pressure tube installed in the sound-muffling chamber in the plane of the exhaust nozzle.

PROCEDURE

The performance data presented herein were obtained at sea-level, zero-ram conditions with an engine inlet-air temperature of 100° F, a constant engine speed of 7890 rpm, and a constant indicated tail-pipe gas temperature of 1275° F. (This value of engine speed is slightly below that for military rated thrust for this engine.) The tail-pipe gas temperature was maintained constant by means of the variable-area exhaust nozzle.

The range of coolant-flow rates covered was from zero to the value at which the compressor blades started to contact the blade-clearance-indicator probes or the value at which engine instability or unsafe operation occurred. Some of the interstage-injection runs were made with the coolant flow equally divided between the sixth- and eighth-stage injection nozzles. During the runs made with a combination of interstage and combustion-chamber injection, 2 pounds per second of coolant were injected in the sixth stage and the balance in the combustion chambers. The range of coolant-air ratios covered with each injection system is presented in the following table:

Injection station	Range of coolant-air ratios
Inlet	0-0.042
Sixth stage	0- .049
Sixth and eighth stage	0- .092
Combustion chamber	0- .100
Sixth stage and combustion chamber	0- .148

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Normal-performance runs were also conducted with each system in order to determine the unaugmented performance of the engine. The tail-pipe gas temperature was based on the average of 30 thermocouples located halfway down the inner cone; this position corresponds to that recommended by the engine manufacturer.

RESULTS AND DISCUSSION

The manner in which thrust augmentation is obtained with various types of coolant-injection systems is discussed in reference 1. In order to facilitate the interpretation of the data presented in the present paper, a brief summary of the principles involved in thrust augmentation with several coolant-injection systems is presented in the following paragraphs.

To augment the thrust of a turbojet engine it is necessary to increase the exhaust-gas velocity or increase the mass flow. Coolant injection serves to increase both of these quantities. The mechanism by which these quantities are increased is illustrated with the aid of the schematic axial-flow-compressor characteristic curve shown in figure 5. With inlet coolant injection the inlet-air temperature is reduced. This increases the corrected engine speed and causes the compressor operating point to move from point 1 to point 2 on the operating line. This shift of the operating point results in a higher compressor pressure ratio and a higher mass flow. The increase in pressure ratio provides a higher tail-pipe pressure and thus a higher pressure ratio across the exhaust nozzle which in turn provides an increase in exhaust-gas velocity. With interstage coolant injection, augmentation is accomplished in the same manner as with inlet coolant injection; however, in this case the shift in operating point is not so clearly defined because only the latter part of the compression process is being cooled.

With combustion-chamber injection, as with the other injection methods there is an increase in mass flow through the turbine when coolant is injected. In order to pass this increased mass flow through the turbine, a higher compressor-discharge pressure is required. The effect on the compressor is much the same as throttling down the flow at the discharge; the operating point on figure 5 thus moves from point 1 to point 3 along a constant-speed line. This shift of the operating point results in an increase in pressure ratio with a slight decrease in air flow. The increase in pressure ratio along with the net increase in mass flow (air plus coolant) provides the increase in thrust. Further examination of the compressor curve indicates that the amount of coolant that can be injected may be limited by compressor surge.

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Engine Performance

Engine thrust. - The effect of the coolant-air ratio on the ratio of augmented to normal thrust for the various injection systems is presented in figure 6. With inlet injection, a thrust increase of about 19 percent was realized at a coolant-air ratio of 0.042. Subsequent runs with inlet injection indicated, however, that compressor-blade rub had been encountered at a coolant-air ratio of 0.010. An examination of the compressor casing indicated that about 0.012 inch of metal had been rubbed off the casing at the eighth stage during the earlier runs. This operation with blade rub inadvertently occurred because of malfunctioning of the blade-clearance indicators. Although in a similar investigation reported in reference 4 no blade rub was encountered below a coolant-air ratio of 0.025 with inlet injection, the engine used during that investigation had higher specified minimum blade clearances. For all the remaining runs during this investigation a new engine was used.

With interstage injection, equal augmentation was obtained with sixth-stage or sixth- and eighth-stage injection. Below a coolant-air ratio of 0.025, the interstage-injection nozzle pressure drop was quite small and thus good penetration of the coolant into the compressor air stream was prevented. This poor penetration of the coolant diminishes the cooling effectiveness which probably accounts for the inflection in the curve at the lower injected flow rates. System flow limitations prevented operation with coolant-air ratios above 0.05 with sixth-stage injection alone. With the sixth- and eighth-stage system an augmentation ratio of 1.200 was realized at a coolant-air ratio of 0.092. This system was flow limited at this coolant-air ratio by limiting manifold pressure.

The augmentation ratio varied almost linearly with the coolant-air ratio for combustion-chamber injection. An augmentation ratio of 1.245 was obtained at a coolant-air ratio of about 0.100. This flow was obtained at the manufacturer's limiting combustion-chamber-coolant manifold pressure. The augmentation available with combustion-chamber injection can be predicted by means of an equation from reference 5. A curve based on the values of thrust augmentation obtained from this equation is presented in figure 7 along with a reproduction of the combustion-chamber injection curve of figure 6. A comparison of these curves indicated very good agreement in that the predicted augmentation ratio was only about 1.6 percent higher than the value obtained experimentally at a coolant-air ratio of 0.100. Although these data extend only to a coolant-air ratio of 0.100, a coolant-air ratio of approximately 0.125 was reached in the combustion chamber during the combination-system runs. The calculated augmentation ratio for a coolant-air ratio of 0.125 is 1.330, which indicates that an augmentation ratio of about 1.310 may be obtained by extending the combustion-chamber injection curve. The calculated augmentation ratio is based on experimentally determined normal-performance data along with a manufacturer's compressor-performance curve. Assumptions of constant turbine efficiency, constant engine fuel flow, and choked turbine nozzles were made.

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The combination system consisted in injecting coolant in the sixth stage of the compressor up to a coolant-air ratio of about 0.023 and then injecting the remainder of the coolant in the combustion chambers. The curve as shown in figure 6 becomes linear above a coolant-air ratio of 0.023. An augmentation ratio of 1.395 was obtained at a coolant-air ratio of 0.148.

Of the various systems investigated, inlet injection provided the most augmentation per pound of coolant at the low coolant-flow rates. Interstage injection gave more augmentation per pound of coolant than combustion-chamber injection up to a coolant-air ratio of 0.077. The combination system provided more augmentation per pound of coolant than either the interstage or combustion-chamber injection systems alone over the entire range of coolant-flow rates.

It is not intended that these data be interpreted as applying to all engines. The augmentation available with any particular engine is a function of the compressor characteristics and compressor surge limit. For example, with combustion-chamber injection in the present engine, an augmented thrust ratio of 1.245 was obtained; however, in order to obtain this thrust increase it was necessary that the compressor pressure ratio be increased by about 9 percent (fig. 8). In other words, in order to obtain this much augmentation it is essential that the compressor be able to provide the necessary pressure ratio without reaching the surge limit as shown in figure 5.

Compressor pressure ratio. - The effect of the coolant-air ratio on the ratio of augmented compressor pressure ratio to the normal compressor pressure ratio for the various injection systems is presented in figure 8. In all cases the compressor pressure ratio increased as the coolant-flow rate increased. Combustion-chamber injection provided a 9-percent increase in pressure ratio at the highest coolant-air ratio

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of 0.100. The maximum increase in pressure ratio of 15 percent was obtained with the combination system at a coolant-air ratio of 0.148. At any coolant-air ratio the combination and interstage-injection systems provided the same pressure-ratio increase as the inlet-injection system even though the inlet-injection system provided more thrust per pound of coolant at the lower flow rates. Similarly, the pressure-ratio increase with combustion-chamber injection was lower than the interstage system over the entire range of flow rates, although the former provided a greater thrust increase above a coolant-air ratio of 0.077 and a lesser thrust increase below this coolant-flow rate. As will be explained in the following paragraphs, the reason for these higher thrusts at lower pressure ratios manifests itself in the way in which the various injection systems affect the compressor air flow and efficiency characteristics.

Air flow, total mass flow, and turbine pressure ratio. - Figures 9 to 11, which show the effect of the coolant-air ratio on the ratio of augmented to normal air flow, augmented to normal total mass flow, and augmented to normal turbine pressure ratio, respectively, can be used to explain why some of the injection systems provided more thrust at lower compressor pressure ratios than other systems.

The air flow followed the trends discussed earlier, that is, with inlet and interstage injection there was a slight increase in air flow due to the increase in corrected engine speed, and with combustion-chamber injection there was a slight decrease in air flow due to the increase in compressor pressure ratio at a constant corrected compressor speed. The total mass flow increased in all cases because of the presence of the coolant.

Because in any turbojet engine the turbine work must be approximately equal to the compressor work, the turbine-pressure-ratio variation along with the variation in total mass flow for a given discharge temperature would indicate the manner in which the compressor work varied. An examination of figures 10 and 11 indicates that inlet injection required the least compressor work at the lower coolant-flow rates. This fact is in agreement with the analysis of reference 6. At the higher coolant-flow rates the interstage system required considerably more compressor work than any of the other systems. Therefore, the differences in the relation of augmented thrust ratio to compressor pressure ratio for the various injection systems are resolved. Although the compressor pressure ratio was lower with combustion-chamber injection than with interstage injection, the compressor work was much greater in the latter case at the higher coolant-flow rates. This greater quantity of compressor work which caused the turbine pressure ratio to be higher with interstage injection caused the exhaust-nozzle pressure ratio to be less with combustion-chamber injection and therefore the thrust augmentation was not so great. This same argument holds true for the case of inlet and interstage injection.

Compressor static pressure. - The fact that compressor performance is greatly influenced by coolant injection is illustrated in figure 12, which shows the effect of coolant-air ratio on compressor static pressure at various stages in the compressor. With inlet injection a drop in static pressure was obtained at the fourth, sixth, and eighth stages of the compressor. With interstage injection a drop in compressor static pressure occurred at these same stages up to a coolant-air ratio of about 0.035. Above this coolant-air ratio the compressor static pressure increased at all stages. With combustion-chamber injection an increase in compressor static pressure with increasing coolant-flow rate was obtained at all stages. 2624

The reason for the decreases in compressor static pressure at the earlier compressor stages with inlet or interstage injection probably lies in the fact that when a coolant is injected in the compressor, the stage matching is upset. Because most of the coolant evaporation probably takes place in the later stages of the compressor, it is likely that the Mach number of these stages is increased more than in the earlier stages. As these later stages are cooled, their pressure ratio is increased; if all the stages increased proportionately, the over-all pressure ratio would probably be far in excess of that required for an equilibrium engine operating condition. Therefore, some of the earlier stages of the compressor are probably unloaded or are forced to operate at a lower pressure ratio in order that the over-all compressor pressure ratio meet equilibrium requirements.

Fuel flow. - Figure 13 shows the effect of the coolant-air ratio on the ratio of augmented to normal fuel flow for the various injection systems. With inlet and interstage injection, the fuel flow remained almost constant up to a coolant-air ratio of 0.035. Above this value the fuel flow decreased. With combustion-chamber injection it was necessary to decrease the fuel flow about 22 percent as the coolant-air ratio was increased to 0.060. As the coolant-flow rate was further increased the fuel flow had to be increased. With the combination system the fuel flow remained constant up to a coolant-air ratio of about 0.023; it was then decreased about 19 percent at a coolant-air ratio of about 0.098. As the coolant-flow rate continued to increase, the fuel flow increased until at a coolant-air ratio of 0.148 the fuel-flow rate was about 8 percent higher than normal. The dashed line in figure 12 indicates how the fuel flow would vary if all the alcohol and fuel were burned.

Combustion efficiency. - The variation of combustion efficiency with coolant-air ratio for the various injection systems is presented in figure 14. This efficiency is based on the ratio of the enthalpy rise across the engine to the input enthalpy which includes the heat of combustion of the fuel and alcohol. The reason that the combustion efficiency with inlet injection at zero coolant flow was lower than

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for all other injection systems is attributed to the fact that these data were obtained on a different engine. With inlet and interstage injection the efficiency decreased as the coolant flow was started and continued to decrease as the coolant flow rate was increased. With combustion-chamber injection, the efficiency remained unchanged up to a coolant-air ratio of about 0.040; it then decreased with increasing coolant-flow rate. With the combination system, the efficiency decreased as the coolant flow was started in the sixth stage but remained constant at about 0.900 as the coolant flow was started in the combustion chamber. When the coolant-air ratio exceeded about 0.060 the combustion efficiency again decreased when the coolant-air ratio was increased.

The decrease in combustion efficiency at low coolant-flow rates with inlet and interstage injection is due to the fact that alcohol, mixed with diluent air, passed through the turbine without being burned. At the higher coolant-flow rates, the presence of water vapor causes the decrease in efficiency. With combustion-chamber injection all the coolant was injected into the combustion chamber in a region where the gas temperature was quite high; therefore, at the lower coolant flow rates all the alcohol was burned and the combustion efficiency remained high. At the higher coolant-flow rates the increased amount of water vapor present caused a decrease in combustion efficiency.

Exhaust-nozzle area. - Figure 15 shows the effect of the coolant-air ratio on the variation of the ratio of augmented to normal exhaust-nozzle area for constant tail-pipe temperature operation. Inlet injection required a reduction in exhaust-nozzle area of about 14 percent at a coolant-air ratio of 0.042. With interstage injection the exhaust-nozzle area was about the same as the normal value at a coolant-air ratio of 0.091 although it was necessary to vary the nozzle area considerably between normal performance and this flow rate. Combustion-chamber injection required a reduction of about 10 percent in exhaust-nozzle area at a coolant-air ratio of 0.100. The combination system required a reduction of about 11 percent in exhaust-nozzle area at a coolant-air ratio of 0.148. Since these data were obtained at a constant tail-pipe temperature any changes in turbine pressure ratio would directly affect the required exhaust-nozzle area. This fact can be readily seen by a comparison of figures 10 and 14.

The data in figure 15 would indicate that in order to realize maximum gains from coolant injection, it would be necessary to provide the engine with some form of adjustable nozzle.

Turbine-discharge temperature. - The effect of coolant injection on the turbine-discharge temperature distribution for the various injection systems is presented in figure 16. With an average tail-pipe temperature of 1275° F for normal performance, the turbine-discharge gas temperature was 1217° F at the blade tip, 1299° F at the blade mean, and 1254° F at the blade root. Inlet injection had no effect on temperature profile shape, but the maximum temperature was increased about 40° F. With interstage injection in the sixth stage, the turbine-discharge temperature at the inner wall increased about 140° F at a coolant-air ratio of 0.023. The outer-wall temperature at this coolant-air ratio was about 85° F cooler than normal. At a coolant-air ratio of 0.049 the temperature at the inner wall increased about 105° F. The reason for the greater increase at the lower coolant flow rate was that the fluid penetration in the compressor was not large enough at the lower injection pressure; the resultant throwing out of fluid against the compressor case thus provided a compressor-discharge temperature profile which was cool at the outer wall. This profile persisted through the turbine; therefore, to obtain the desired tail-pipe average temperature, the inner-wall turbine-discharge temperature was quite high. With interstage injection at the sixth and eighth stages, the turbine-discharge temperatures followed almost the same trend as with sixth-stage injection. However, in this case the maximum increase in blade-root gas temperature was 90° F at a coolant-air ratio of 0.092. Combustion-chamber injection had practically no effect on the turbine discharge temperature profile shape. At a coolant-air ratio of about 0.100 the blade-root gas temperature was decreased about 45° F. A possible reason for this cooling is that some water vaporization might still be taking place downstream of the turbine. With the combination system the blade-root gas temperature increased about 200° F at a coolant-air ratio of 0.148. The blade-tip gas temperature at this same coolant-flow rate was decreased about 105° F. The coolant injected in the sixth stage was apparently the main contributor to this variation.

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Operational Characteristics

Immediately following the runs made with the inlet-injection system, a scraping noise was heard in the rear portion of the engine. Upon disassembly of the engine it was found that some corrosion had taken place in the vicinity of the turbine bearing and that compressor blade rub had occurred. In order to avoid this bearing corrosion, the replacement engine, which was used for the remainder of the investigation, was equipped with an outside source of cooling air for the upstream side of the turbine. An inspection of the second engine after the completion of this investigation indicated that the engine had suffered no ill effects due to coolant injection. The total running time with coolant injection on this engine was about 8 hours, during which time about 120,000 pounds of coolant were consumed.

The various coolant-injection systems were subject to the following limitations:

1. Inlet injection was limited by blade rub.

2. Interstage injection was limited by manifold pressure to 500 pounds per square inch gage, although this limitation could be raised by redesign of the injection nozzles.

3. Combustion-chamber injection was also limited by manifold pressure (250 lb/sq in. gage). This limitation also could have been removed by redesign of the injection manifold.

4. Combination-system injection was limited by the flow capacity of the test stand. However, at a coolant-air ratio of 0.148 a red glow was observed in the tail pipe and some engine-speed instability was evident. This flow rate was therefore assumed to be about the maximum for safe engine operation.

The various coolant-injection systems caused the following unaugmented thrust losses:

1. The inlet spray ring had no measurable effect on thrust.

2. The injection nozzles in the sixth stage of the compressor caused a 1-percent loss in thrust.

3. The injection nozzles in both the sixth and eighth stages of the compressor caused about a 2-percent thrust loss.

4. Because the combustion-chamber injection nozzles were standard equipment on this engine, no measurement of their normal-performance loss was made. However, because of the location of these nozzles it is assumed that they cause no measurable loss.

CONCLUDING REMARKS

The thrust augmentations obtained during this investigation are by no means general. Those obtained with any other engine would depend entirely upon the operational characteristics and the compressor surge limit for that particular engine. The engine used, however, is considered typical of current, single-spool, axial-flow engines.

The results of this investigation indicate, in general, that the use of water-alcohol injection for engine thrust augmentation offers considerable promise as a method of decreasing the distance required for take-off of turbojet-powered aircraft. A maximum thrust augmentation of 39.5 percent was obtained at a coolant-air ratio of 0.148 with a combination of sixth-stage and combustion-chamber injection. With combustion-chamber injection alone, an augmentation of about 24.5 percent was realized at a coolant-air ratio of 0.100. Inlet injection provided the most augmentation per pound of coolant at the lower coolant-flow rates but compressor blade rub occurred at a coolant-air ratio of 0.010 with this system. These data were obtained at sea-level, zero-ram conditions, with the engine inlet temperature maintained at 100° F.

The unaugmented thrust loss with the combination system was about 1 percent and was about 2 percent with interstage injection in the sixth and eighth stages of the compressor. No measurable thrust loss was encountered with the inlet or combustion-chamber injection systems. In order to realize the maximum gains from coolant injection, it would be necessary to provide the engine with some form of adjustable nozzle to maintain limiting-tail-pipe temperature. The engine suffered no ill effects as a result of interstage or combustion-chamber coolant injection; however, an external source of turbine cooling air was used during these runs.

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TABLE I - NOZZLES USED FOR VARIOUS INJECTION SYSTEMS

Injection station	Type of spray	Spray angle (deg)	Number of nozzles	Nozzle diameter (in.)	Rated capacity (gal/min)	Distance from nozzle tip to compressor rotor, (in.)
Inlet	Hollow cone	80	34	-----	0.4[a]	-----
Sixth stage	Solid jet	--	18	0.055	1.85[b]	1.125
Eighth stage	Solid jet	--	18	.055	1.85[b]	1.00
Combustion chamber	Solid cone	95	32	-----	1.90[a]	-----

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[a]Pressure, 100 lb/sq in. gage.

[b]Pressure, 500 lb/sq in. gage.

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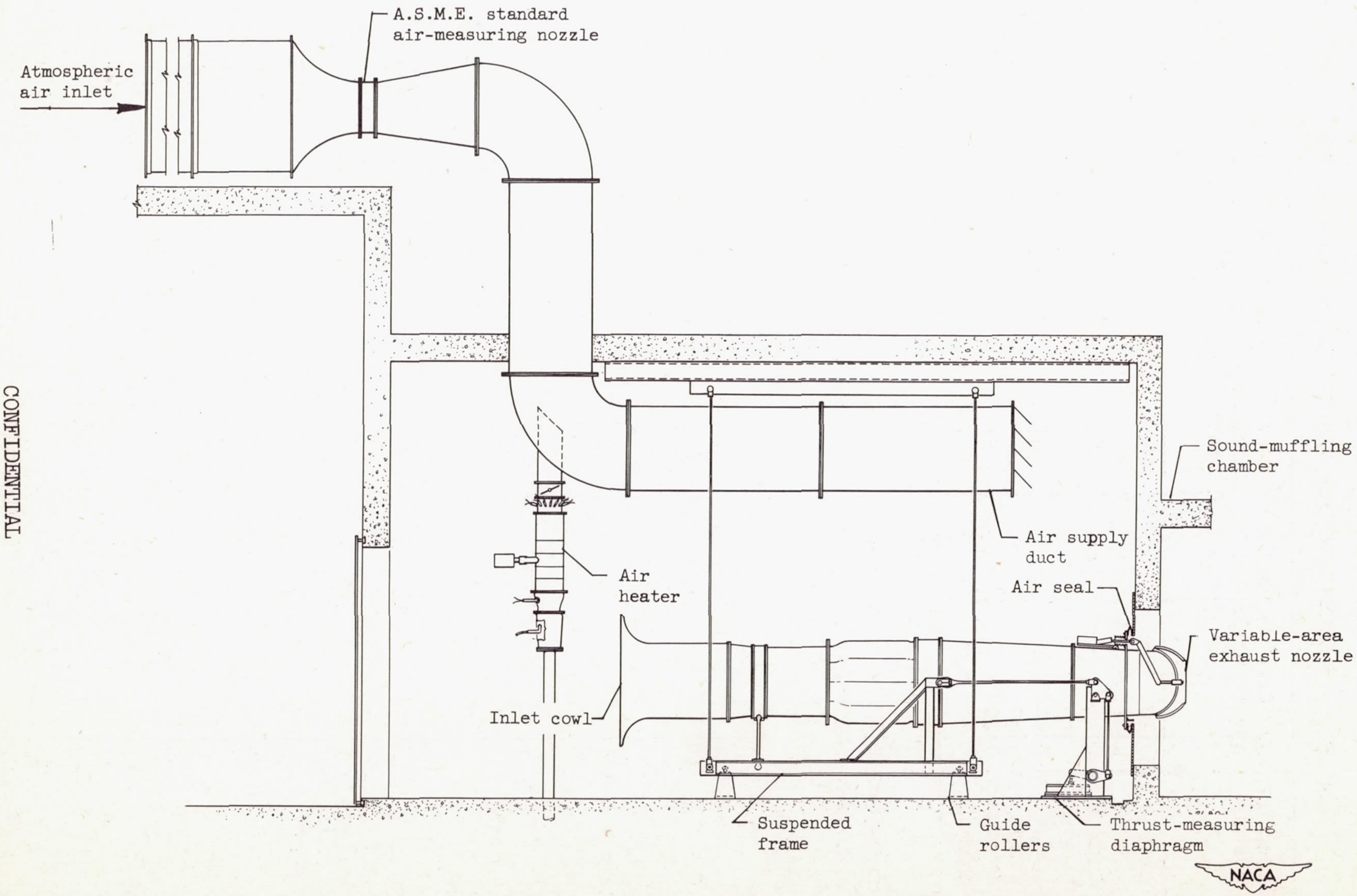

Figure 1. - Schematic diagram of engine installation.

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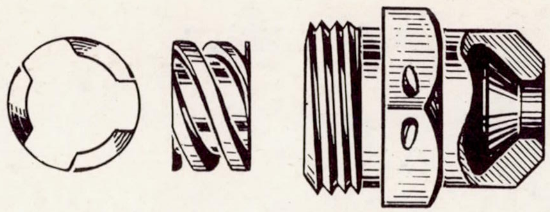
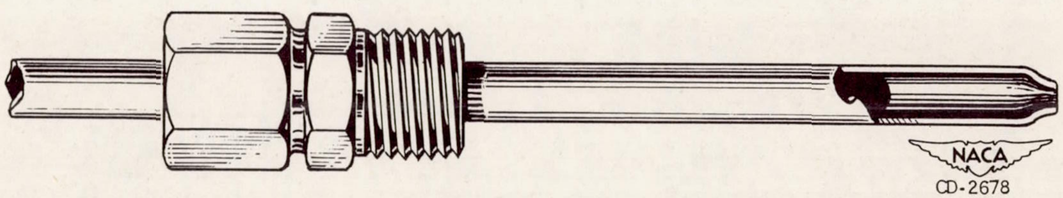


(a) Combustion-chamber injection nozzle.



(b) Interstage injection nozzle.

Figure 2. - Water-alcohol injection nozzles.

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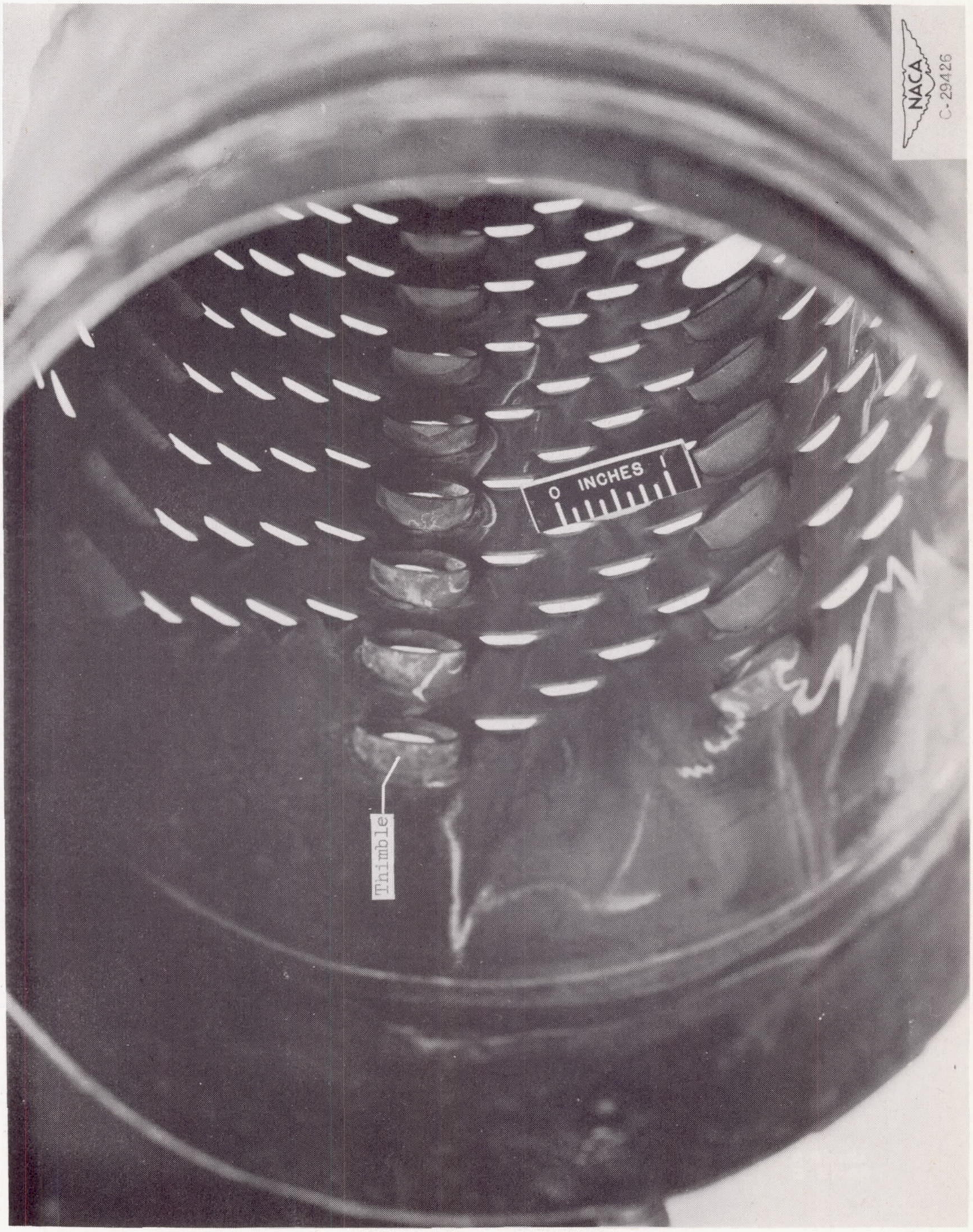

Figure 3. - Photograph of combustion-chamber liner showing thimbles.

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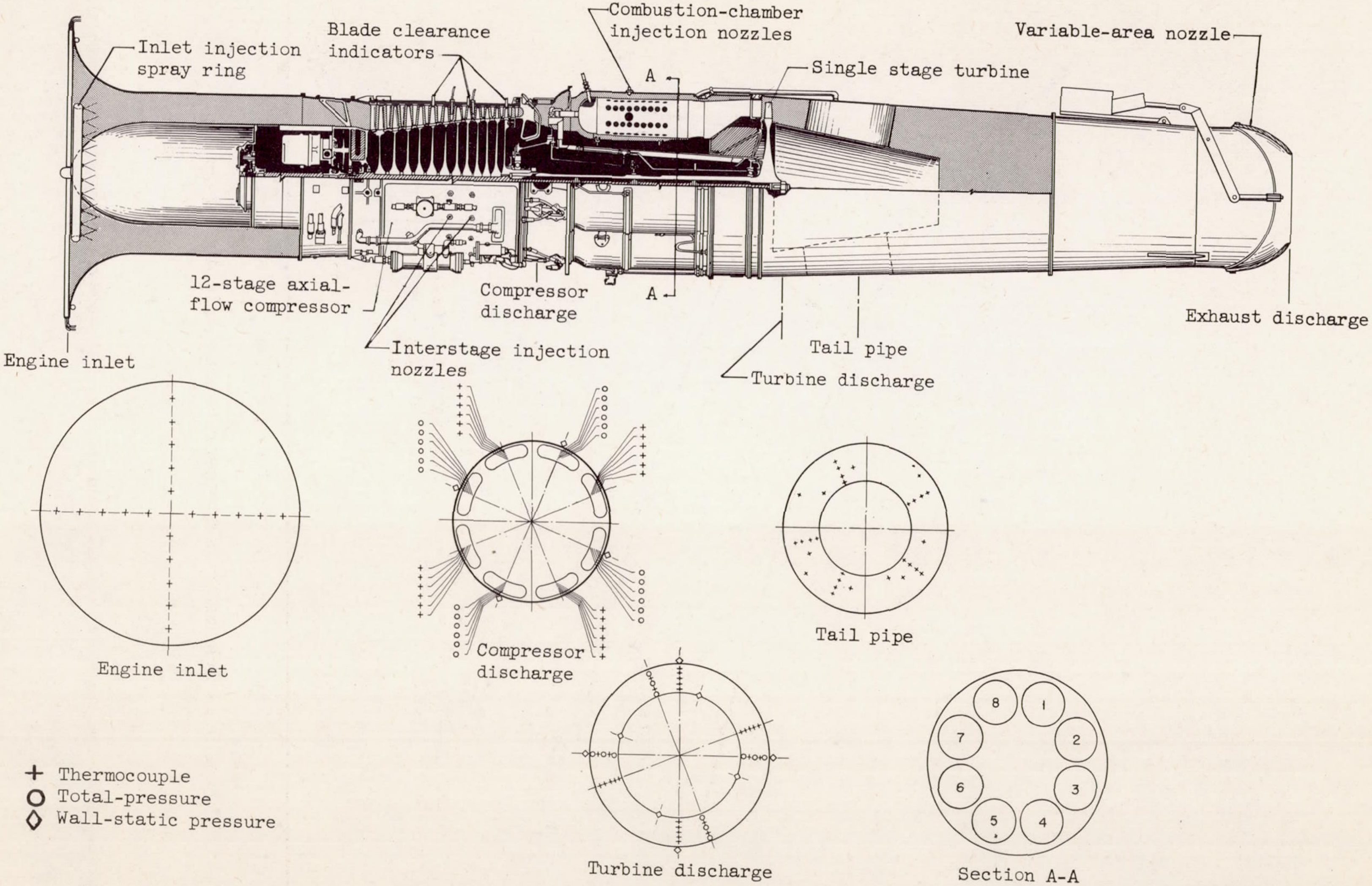

Figure 4. - Engine instrumentation.

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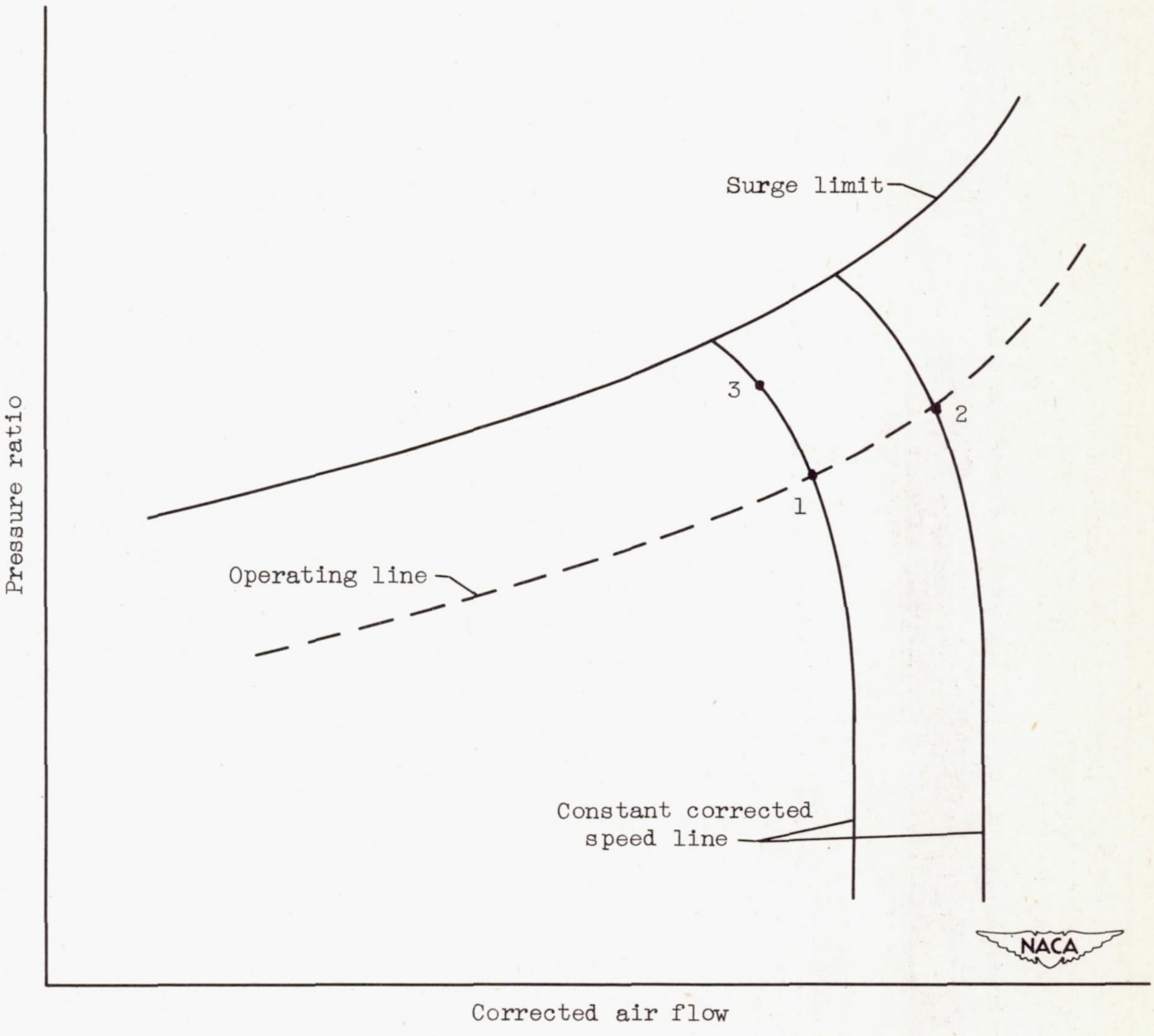

Figure 5. - Schematic compressor characteristic curve.

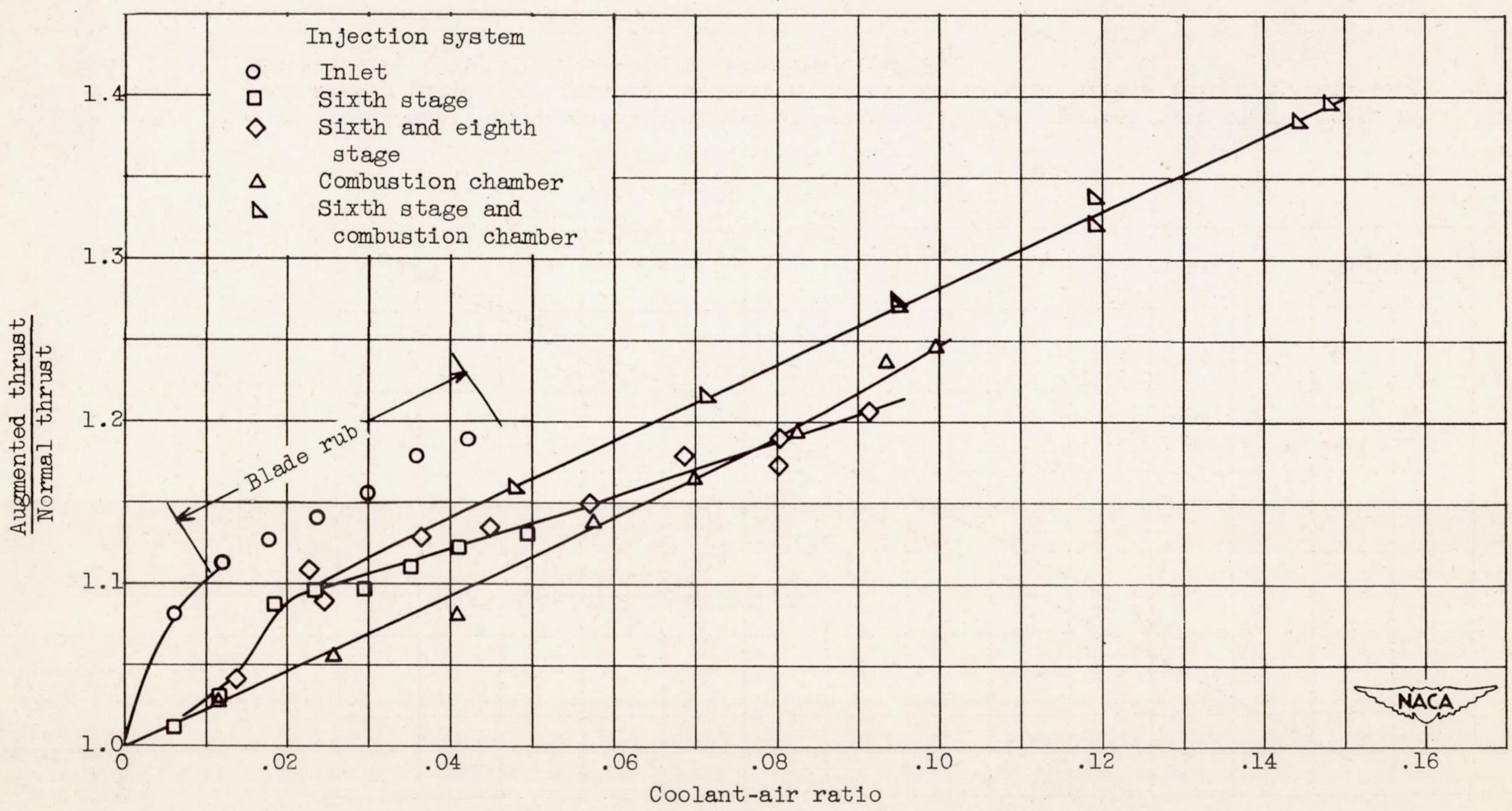

Figure 6. - Variation of ratio of augmented to normal thrust with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

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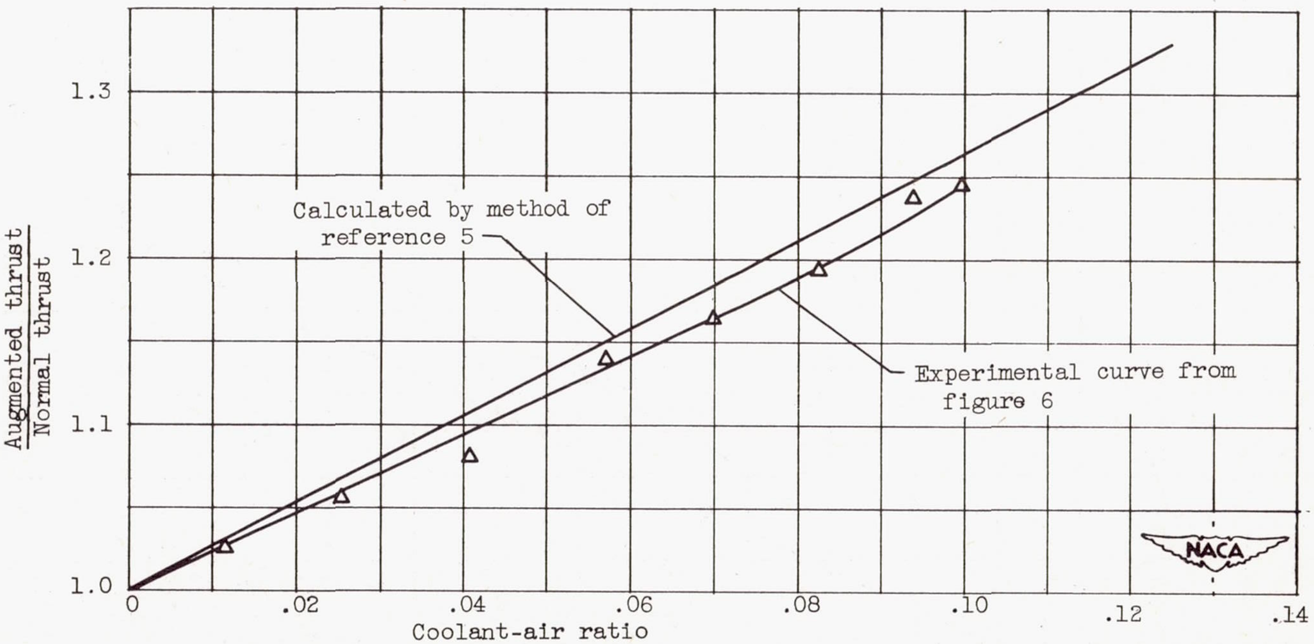

Figure 7. - Comparison of calculated and experimental thrust augmentation over a range of coolant-air ratios for combustion-chamber injection. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

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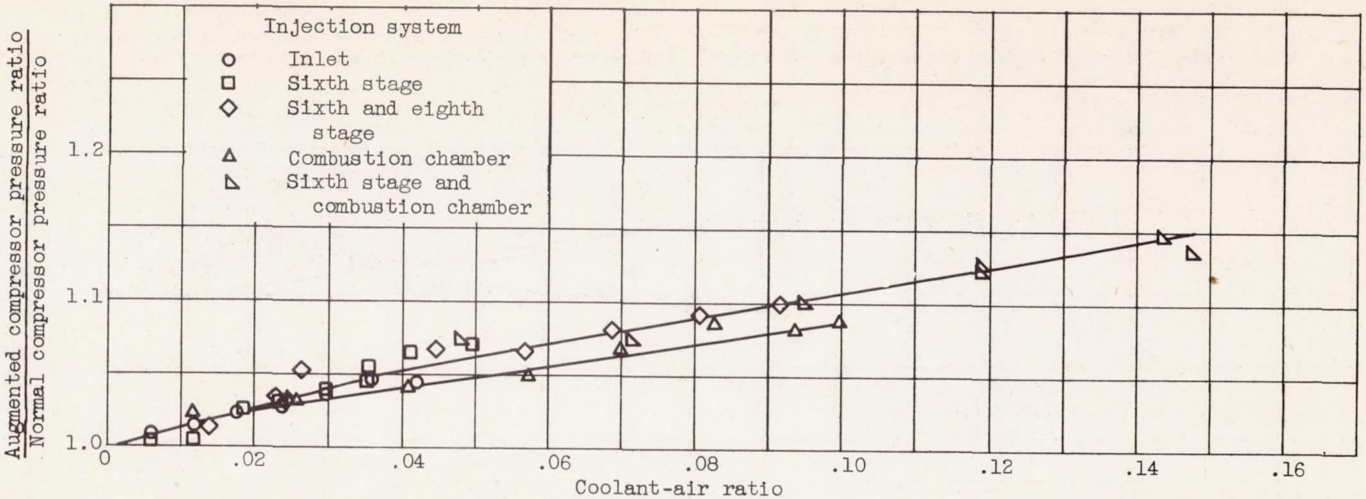

Figure 8. - Variation of ratio of augmented to normal compressor pressure ratio with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

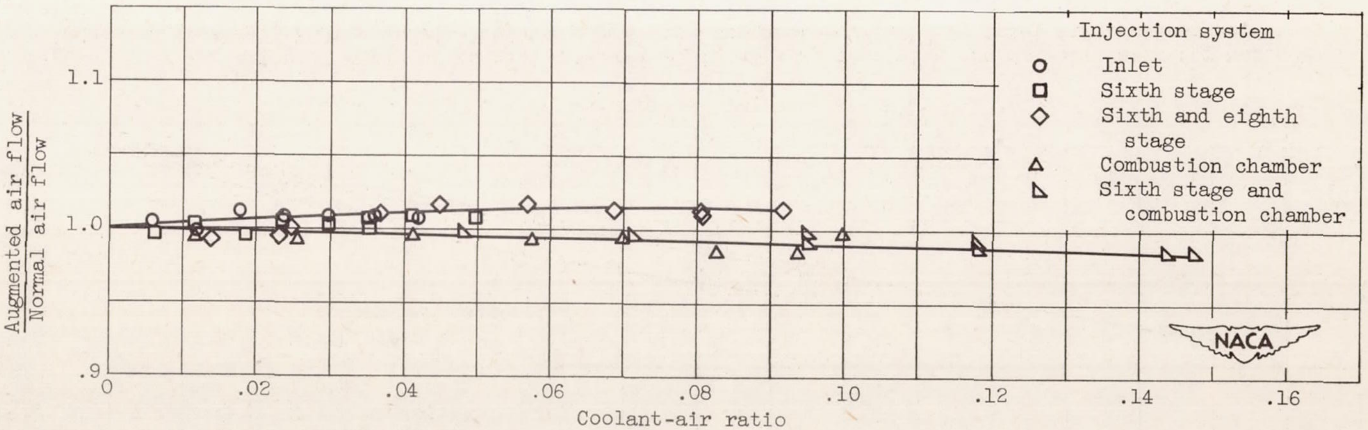

Figure 9. - Variation of ratio of augmented to normal air flow with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

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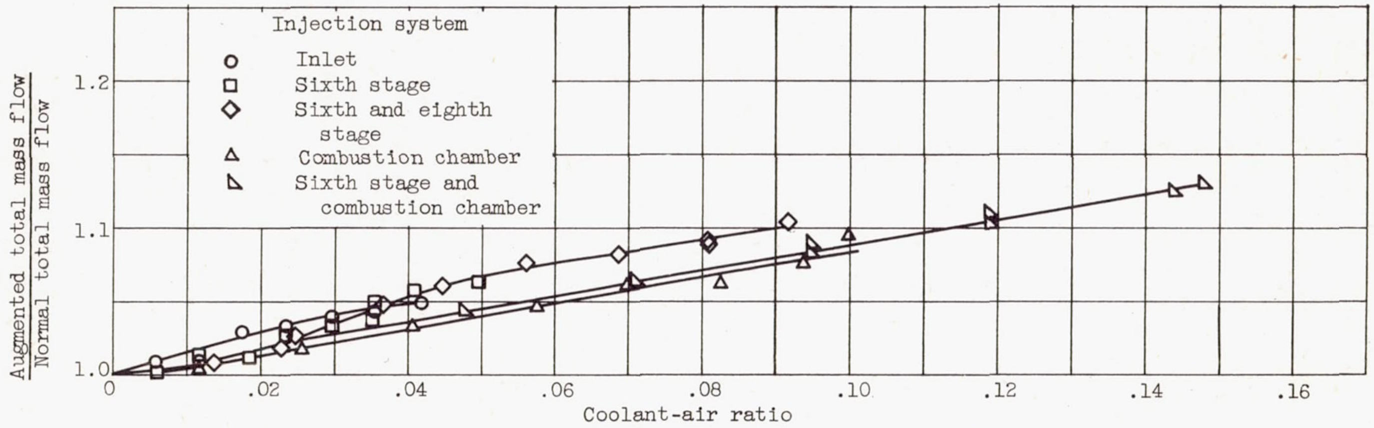

Figure 10. - Variation of ratio of augmented to normal total mass flow with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

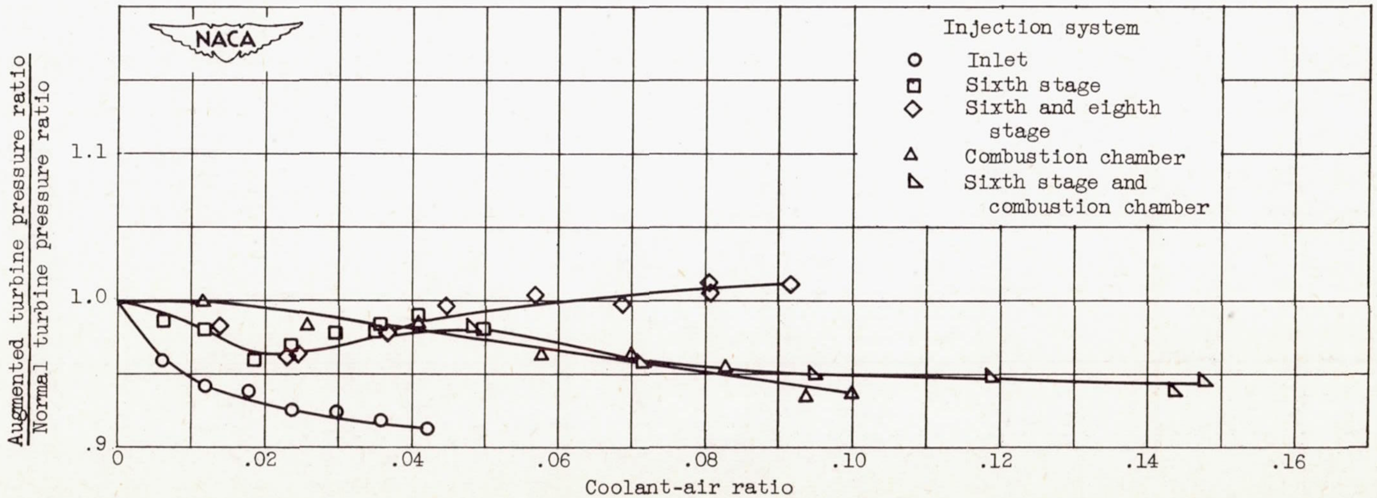

Figure 11. - Variation of ratio of augmented to normal turbine pressure ratio with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

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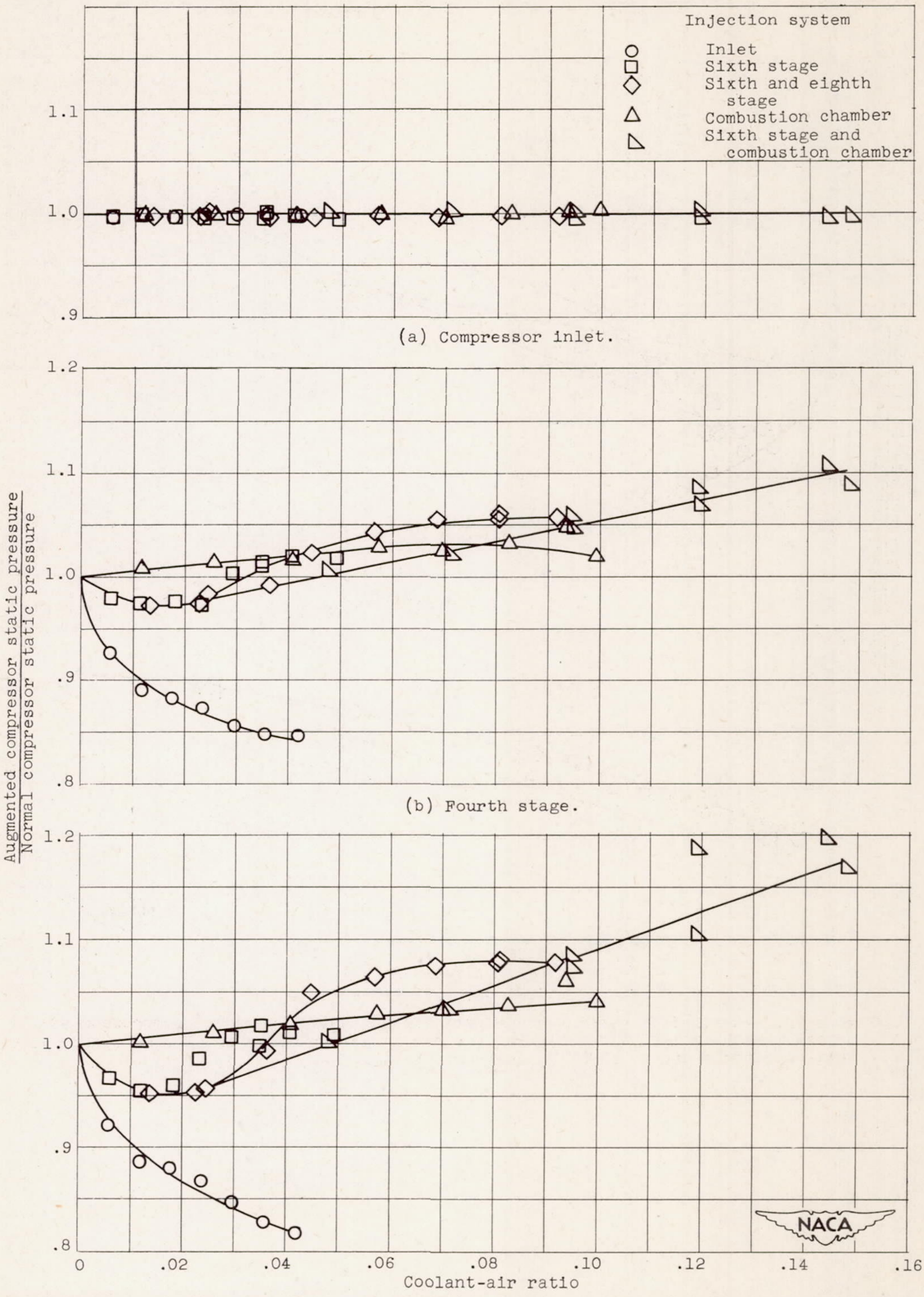

(c) Sixth stage.

Figure 12. - Variation of ratio of augmented to normal compressor static pressure with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

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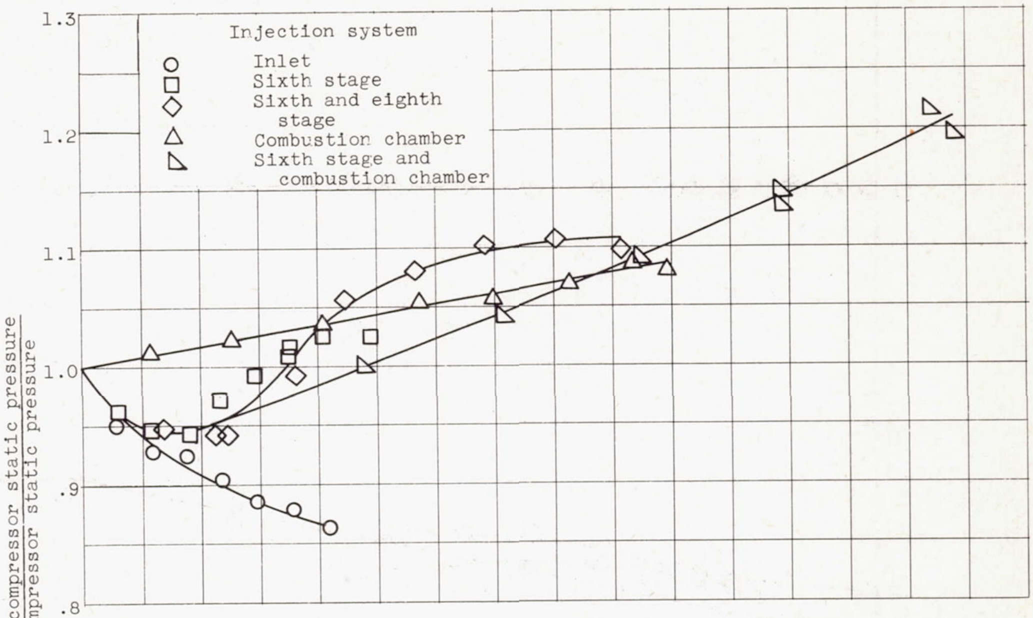
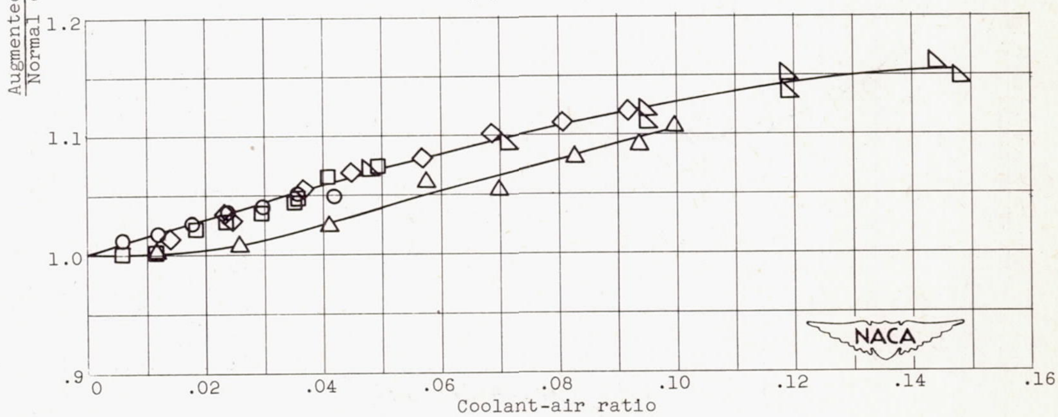


(d) Eighth stage.



(e) Compressor discharge.

Figure 12. - Concluded. Variation of ratio of augmented to normal compressor static pressure with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

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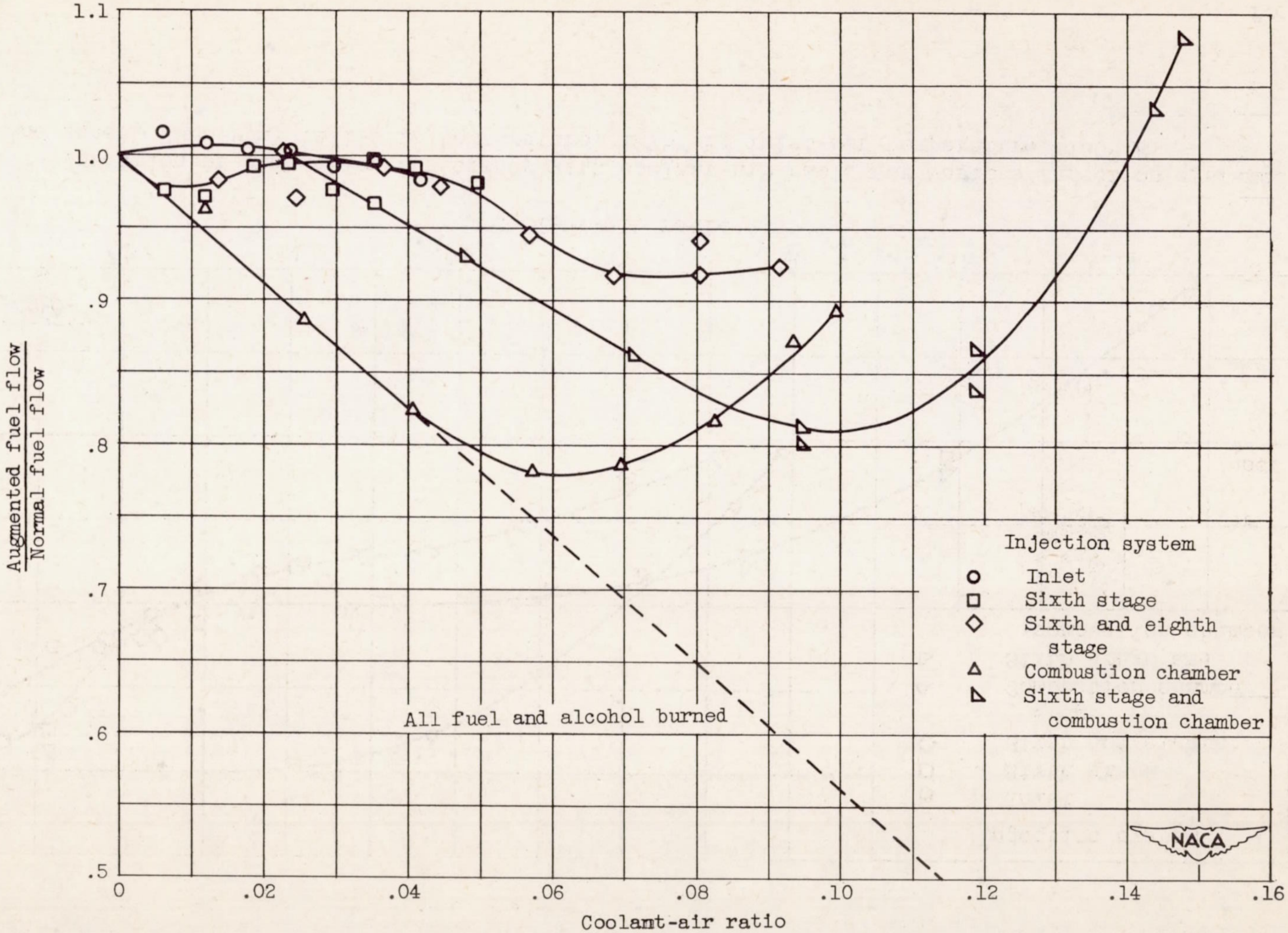

Figure 13. - Variation of ratio of augmented to normal engine fuel flow with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

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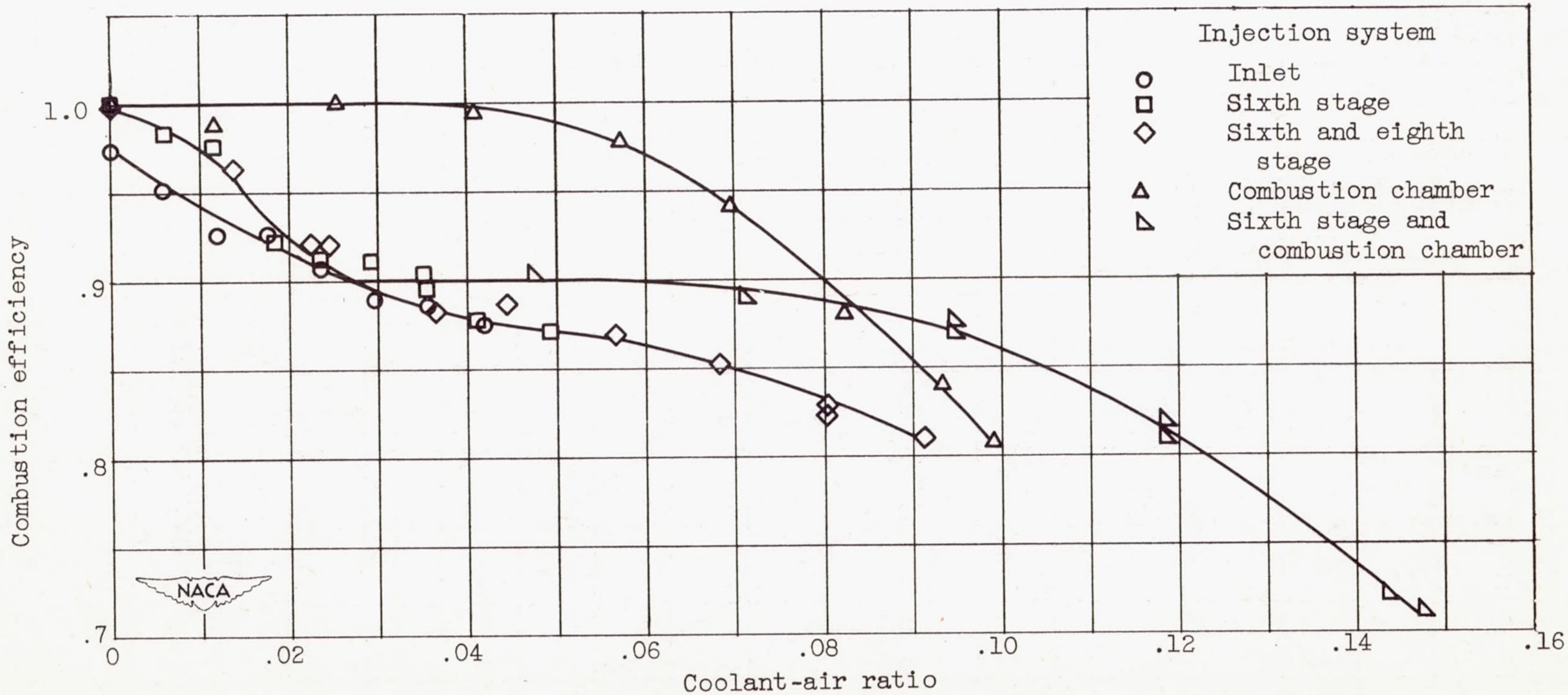

Figure 14. - Variation of combustion efficiency with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

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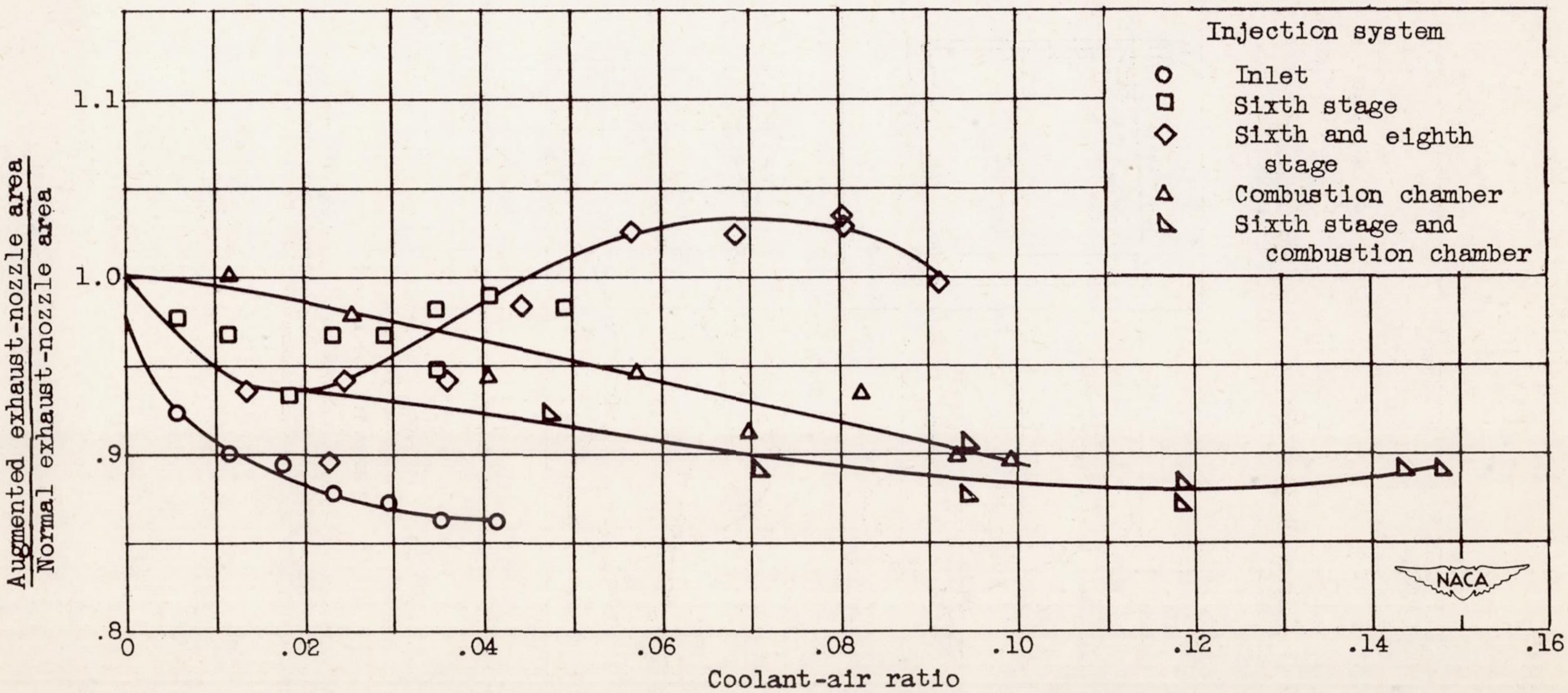

Figure 15. - Variation of ratio of augmented to normal exhaust-nozzle area with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

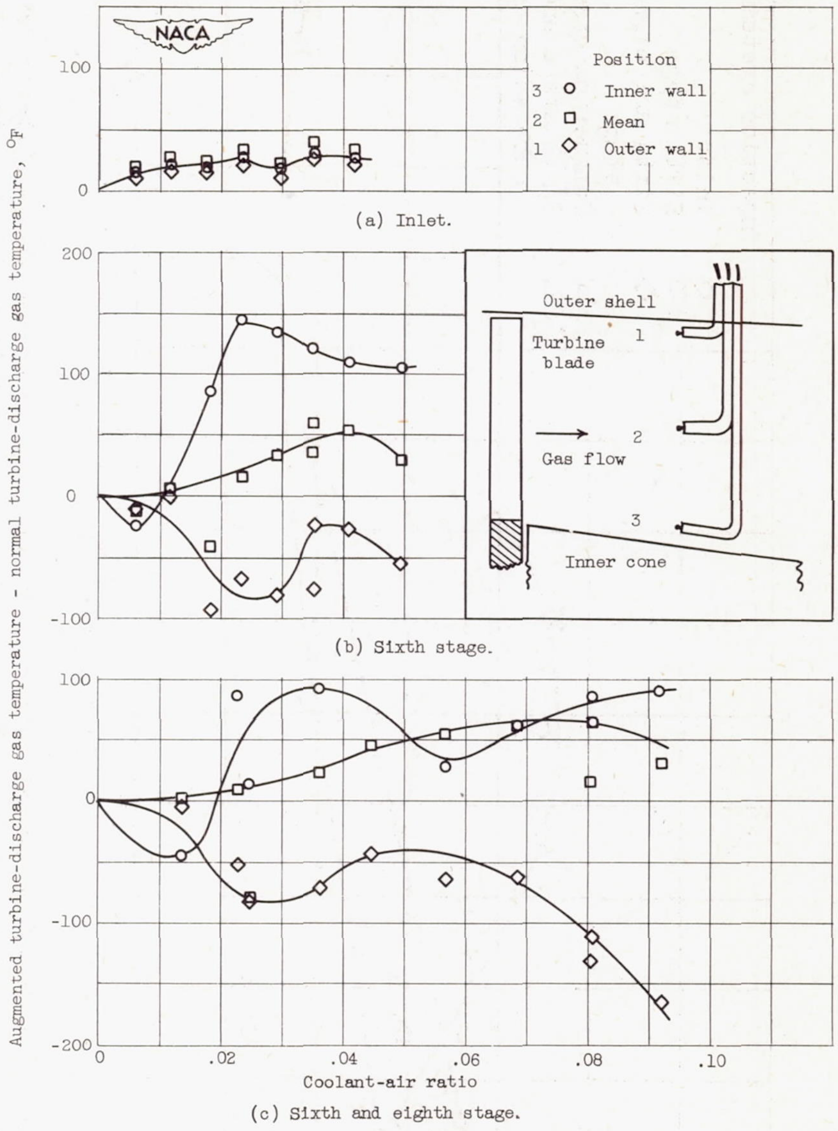

Figure 16. - Variation of turbine-discharge gas temperature with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.

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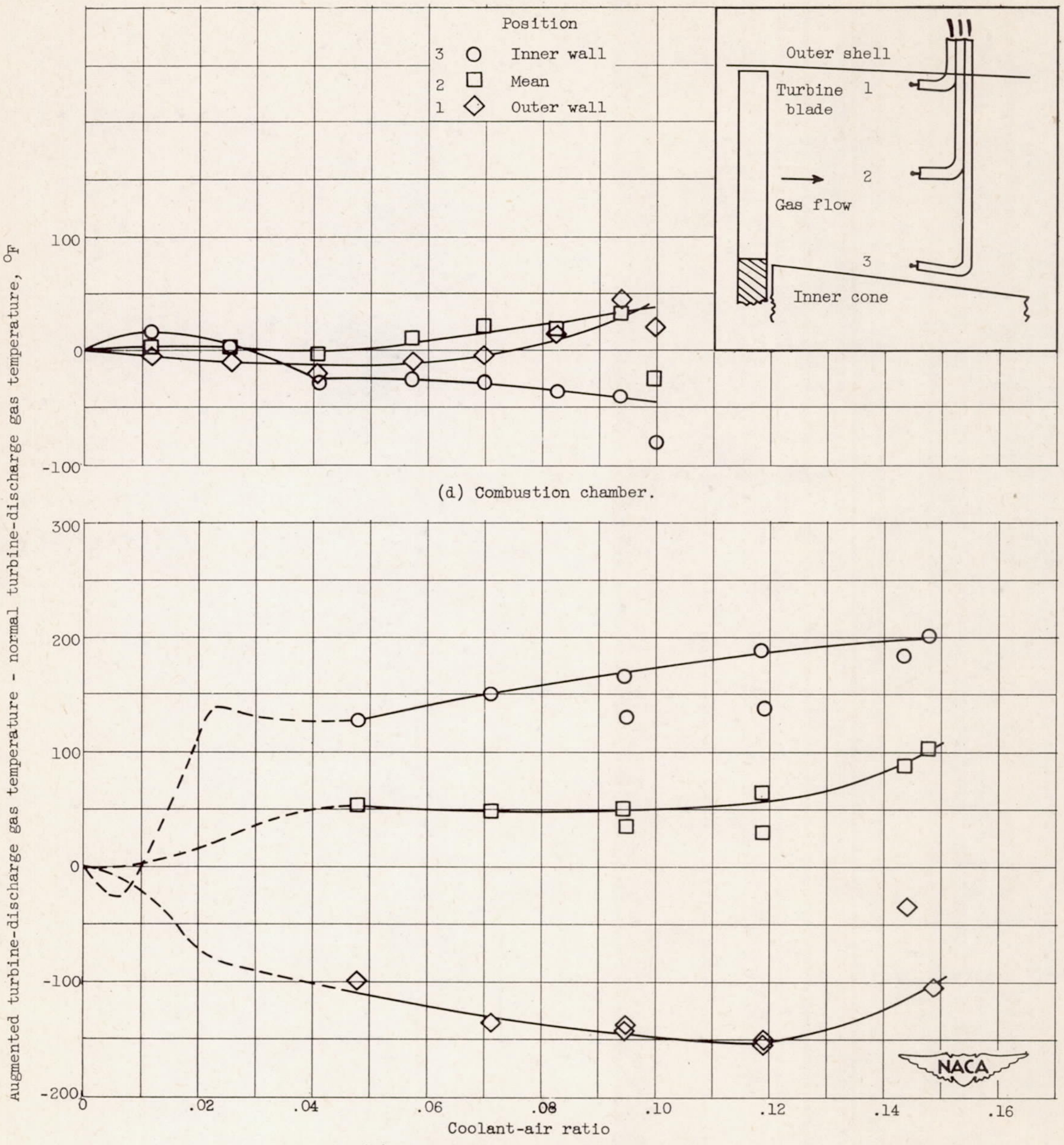

(d) Combustion chamber.

(e) Sixth stage and combustion chamber.

Figure 16. - Concluded. Variation of turbine-discharge gas temperature with coolant-air ratio for various injection systems. Engine speed, 7890 rpm; tail-pipe temperature, 1275° F; inlet-air temperature, 100° F.