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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF TURBOJET-ENGINE THRUST AUGMENTATION BY COMBINED COMPRESSOR COOLANT INJECTION AND TAIL-PIPE BURNING

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NATIONAL ADVISORY COMMITTEE
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EXPERIMENTAL INVESTIGATION OF TURBOJET-ENGINE THRUST AUGMENTATION BY COMBINED COMPRESSOR COOLANT INJECTION AND TAIL-PIPE BURNING

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SUMMARY

An investigation of combined compressor coolant injection and tail-pipe burning as a means of turbojet-engine thrust augmentation was conducted at sea-level, zero ram conditions on a 4000 pound thrust, axial-flow-type turbojet engine. Water - alcohol injection flows from 2 to 5 pounds per second were introduced into the compressor in conjunction with tail-pipe burner fuel-air ratios from 0.017 to stoichiometric.

The maximum augmented thrust ratio obtained during the investigation was 1.70, which resulted from a combination of nearly stoichiometric fuel-air ratio in the tail-pipe burner and 2.0 pounds per second compressor injection at the engine inlet. Achievement of greater augmentation by combination injection rates greater than 2 pounds per second with high fuel-air ratios in the tail-pipe burner was precluded by inefficient and unstable combustion in the tail-pipe burner. Tail-pipe burner combustion temperatures and efficiencies decreased with the addition of alcohol and water vapor from the compressor coolant injection. The unaugmented thrust loss due to the combined augmentation system components was approximately 1 to $1\frac{1}{2}$ percent of the thrust.

INTRODUCTION

The successful use of coolant injection into the compressor and tail-pipe burning as independent methods of augmenting the performance of the turbojet engine logically suggests the combined application of these methods to obtain even greater augmentation. The large amount of additional thrust that may be anticipated from the combined augmentation system would result in improvement of the take-off and climb characteristics of current airplanes and would be useful in increasing the acceleration of high-speed aircraft during transonic operation.

The analytical investigation presented in reference 1 considers the combined operation of compressor coolant injection and tail-pipe burning, and indicates that in combination the individual methods of augmentation augment each other; that is, the resultant increase in engine performance is approximately equal to the product of the augmented thrust ratios obtainable with each system. In order to determine experimentally the magnitude of the available augmentation and to study the practical limitations of the combined augmentation system, an investigation was conducted at the NACA Lewis laboratory during 1950 on a 4000-pound thrust, axial-flow-type turbojet engine operating at sea-level, zero ram conditions.

The introduction of the coolant at the engine inlet was used for moderate injected flow rates and compressor interstage injection of the coolant was added for high rates of coolant injection (in excess of 3 lbs/sec or a coolant-air ratio of 0.05). Independent tail-pipe burner performance was investigated for a range of fuel-air ratios from approximately 0.017 to stoichiometric. The investigation of the combined-augmentation system included a range of compressor injection flow rates from 2 to 5 pounds per second for each of several tail-pipe burner fuel-air ratios up to either stoichiometric or the combustion stability limit. The thrust augmentation and accompanying liquid-consumption results are presented in addition to the calculated tail-pipe burner gas temperatures and combustion efficiencies obtained during the investigation.

APPARATUS

Engine. - The investigation was conducted on an early production model axial-flow-type turbojet engine with a nominal military rating of 4000 pounds of thrust with a rotor speed of 7700 rpm, and a turbine discharge gas temperature of 1200° F at sea-level and zero ram conditions. The engine has an 11-stage axial-flow compressor, 8 cylindrical combustion chambers, and a single-stage turbine. Additional compressor balance air and bearing cooling air was provided from an outside source to augment the air bled from the compressor (detailed description in reference 2) to prevent contamination of the lubrication system by the injected water - alcohol mixture and to insure against failure of the bearings.

Engine installation. - A schematic diagram 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 slot in the rear wall into a sound muffling chamber, in which the pressure was approximately atmospheric. 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 air-tight test chamber and measured by a 26-inch diameter, long-radius ASME nozzle. The bearing cooling air was discharged from the engine into the test cell after fulfilling its function and was metered by an ASME flat-plate orifice.

Coolant injection systems. - The compressor coolant injection was accomplished by inlet and interstage injection of a water - alcohol mixture. The inlet-injection system consisted of 34 conventional atomizing nozzles installed in a ring at the engine inlet. The interstage-injection system used in this investigation was identical to the "single-stage" system described in reference 2, and consisted of twenty 0.045-inch diameter interstage nozzles installed in the sixth stage of the compressor used in conjunction with the inlet injection nozzles.

Tail-pipe burner. - The tail-pipe burner configuration used in this investigation was based on the design variables found to be desirable for optimum operation as reported in reference 3. A schematic diagram showing the general physical arrangement of the engine and tail-pipe burner is presented in figure 2. The standard 21-inch diameter tail pipe was replaced by a $25\frac{3}{4}$-inch diameter tail pipe that was approximately 72 inches long. The tail pipe was connected to the engine by means of a 36-inch long diffuser section of 1 to 1.4 area ratio, embodying a constant rate of area change with length. The downstream end of the diffuser inner cone terminated in a $6\frac{1}{2}$-inch diameter blunted section that served as a flame seat during operation of the tail-pipe burner. There were 12 fuel-spray bars capable of being immersed to various depths across the annulus installed 12 inches upstream of the diffuser discharge. The basic fuel-spray bar design designated as arrangement A is shown in figure 2. Arrangement B provided that the innermost pair of orifices be enlarged to 0.060 inches in diameter and that a 0.060-inch diameter hole be added to the spray-bar tip. The tail-pipe burner ignition system was of the hot streak type (reference 4), which utilized an additional fuel nozzle installed midway along one of the primary combustion chambers.

Two flame holders, designated flame holders A and B, were used during the investigation. Each flame holder was installed approximately 26 inches downstream of the fuel spray bars. Flame holder A (fig. 3(a)) was a two-ring, corrugated, V-gutter type that blocked 31 percent of the tail-pipe burner cross-sectional area. Flame holder B (fig. 3(b)) was a two-ring, plain V-gutter type that blocked 36 percent of the tail-pipe burner area.

A series of fixed-area conical exhaust nozzles ranging in exit diameter from 18.75 to 25.00 inches were used during most of the investigation. For the nonburning runs and for the combination runs during which the water - alcohol mixture was only injected at the engine inlet, a variable-area clamshell-type nozzle was used.

Fuels and coolant mixture. - Fuel conforming to specification MIL-F-5624 was burned in the engine primary combustor, and fuel conforming to specification MIL-F-5616 was burned in the tail-pipe burner. A water - alcohol mixture containing 30 percent by volume of alcohol was injected into the compressor. The alcohol was a blend of 50 percent ethyl and 50 percent methyl alcohol by volume. The water was obtained from the domestic supply.

Instrumentation. - The locations of the instrumentation for temperature and pressure measurement are given in figure 2. The temperatures recorded, and the number, type, and location of 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 the inlet cowling.

(b) Gas temperature at turbine discharge (station 5) T_5: average of 16 unshielded strut-type thermocouples equally spaced around one-half the circumference of the diffuser section and located approximately 4 inches downstream of the turbine discharge.

(c) Gas temperature at tail-pipe burner inlet (station 6) T_6: average of 8 unshielded strut-type thermocouples equally spaced around the circumference of the tail-pipe burner. These thermocouples were installed only during runs for which the tail-pipe burner was inoperative.

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

(a) Total and static pressure at the engine inlet (station 1) were assumed equal to test-cell static pressure that was measured as the average of two static tubes in a quiescent zone of the test cell.

(b) Static pressure at exhaust-nozzle discharge (station 7) p_7: two static-pressure probes manifolded and installed in the sound-muffling chamber in the plane of the exhaust nozzle.

These and all symbols used in this report are given in appendix A.

PROCEDURE

The augmented performance presented herein was determined at sea-level, zero ram conditions with an average engine-inlet temperature of 80° F, a constant engine speed of 7610 rpm, and a constant indicated turbine-discharge gas temperature of 1200° F. The range of test conditions covered, the exhaust-nozzle diameter, the fuel-spray-bar design and immersion depth across the $5\frac{1}{2}$-inch diffuser annulus (designated as the distance from the wall of the diffuser inner cone to the tip of the spray bar), and the particular flame-holder design used during the augmentation runs are presented in the following table:

Range of tail-pipe burner fuel-air ratios	Range of compressor injection flow rates (lb/sec)	Exhaust-nozzle diameter (in.)	Fuel-spray-bar design immersion depth from cone, (in.)		Flame-holder design
0.017 - 0.020	0, 2.96 - 4.97	18.75	A	1/2	B
.019 - .024	0, 2.95 - 5.04	19.50	A	1/2	B
.024 - .036	0, 2.99 - 5.11	20.25	B	3/4	B
.039 - .059	0, 2.93	21.00	B	1	A
.038 - .067	0, 2.92 - 4.01	21.00	B	3/4	B
.058	0	21.75	B	1	B
.065	0	22.00	B	1 1/4	B
.067	0	22.50	B	1 3/8	B
.035 - .064	2.0	variable	B	3/4	B

The tail-pipe burner fuel-air distribution was varied by adjustment of the immersion depth of the fuel-spray bars across the diffuser annulus and by using one of the two spray-bar designs. Maintenance of the proper fuel-air distribution was critical in attaining stable combustion in the tail-pipe burner. The problems encountered due to this instability will be discussed in a later section of this report.

For all combination runs a premixed coolant of water and alcohol was injected into the compressor. For the runs during which water - alcohol mixture was injected at both the inlet and the sixth stage of the compressor, the flow was evenly divided between the stations. All the combination runs except those with inlet injection alone were conducted with the series of fixed-area exhaust nozzles. For each exhaust-nozzle size the injected flow was set at values within the range given in the table and at each injected flow, the tail-pipe burner fuel flow was set at a value giving a turbine-discharge-gas temperature of 1200° F. The combination runs with inlet injection were conducted with a variable-area exhaust nozzle and at a constant injected flow of 2 pounds per second. The use of the variable-area exhaust nozzle for the complete test program would have been desirable because it would have expedited the testing, but unfortunately it was not made available until the later phase of the program. For the runs during which the variable-area exhaust nozzle was used, several tail-pipe burner fuel flows were established; and at each fuel flow, the variable-area nozzle was closed until the limiting turbine-discharge temperature of 1200° F was reached.

A series of normal performance runs was made to provide a basis of comparison of the augmented engine with the unaugmented. For these runs the standard 21-inch diameter tail pipe was used. The thrust losses due to the tail-pipe burner flame holder and fuel-spray bars during unaugmented operation with the $25\frac{3}{4}$-inch diameter tail pipe were determined with a continuously variable-area exhaust nozzle.

For the type of engine investigated it is good practice to measure the indicated turbine-discharge gas temperature at a station in the tail pipe where the gas has become well mixed and the temperature gradients are small. When operating without tail-pipe burning, station 6 adequately fulfilled this requirement and was used. During operation with tail-pipe burning, station 5 was selected for the turbine-discharge temperature measurements since no station downstream of the fuel-spray bars could be used because of the danger of either raw fuel impinging or flame seating on the thermocouples. Inasmuch as station 5 is located in a region of steep and shifting temperature gradients it was necessary to determine a temperature calibration of station 5 against the temperatures at station 6 for both compressor coolant injection and noninjection runs. This calibration was then used during the combination runs in setting the desired turbine-discharge-gas temperature.

RESULTS AND DISCUSSION

Engine Performance

In the following discussion a comparison is made of the augmentation of turbojet-engine performance by compressor coolant injection, tail-pipe burning, and by their combined application. Primary consideration has been given to the attainment of maximum thrust augmentation, although the liquid requirements necessary to achieve the augmentation are presented. In the course of the investigation several fundamental combustion problems were encountered and are discussed in detail.

Augmented engine performance. - The experimentally determined performance of an axial-flow-type turbojet engine utilizing the compressor-injection system, the tail-pipe burning system, and the combined-augmentation system is presented in figure 4. Augmented thrust ratio (ratio of augmented thrust to normal-performance thrust) is presented as a function of augmented liquid ratio (augmented total liquid consumption to normal fuel flow). The normal performance data used in determining the augmented performance were obtained from the standard engine configuration exclusive of the tail-pipe burner or compressor-injection components.

The augmented performance produced by use of the compressor-injection system shown in figure 4 is based on the data presented in reference 2.

The absence of a variable-area exhaust nozzle during the initial phase of this investigation precluded independent investigation of the compressor-injection system, but the data compared here were obtained on a similar model engine equipped with an identical compressor-injection configuration. The compressor-injection system operating with an engine-inlet air temperature of 80° F produced an augmented thrust ratio of 1.22 with an augmented liquid ratio of approximately 7. The nature of this curve is such that additional thrust augmentation is attainable only at the expense of greatly increased injected flow.

The performance of the tail-pipe burner system shown was obtained with a series of fixed-area exhaust nozzles, each making operation possible at limiting turbine-discharge temperature with a different tail-pipe burner fuel-air ratio. A maximum augmented thrust ratio of 1.51 was obtained at stoichiometric fuel-air ratio and an augmented liquid ratio of 3.96. This performance favorably approaches the ideal performance predicted in reference 1; that is, an augmented thrust ratio of 1.55 is theoretically predicted for an augmented liquid ratio of 4.00 and stoichiometric combustion.

The augmented performance obtained by the use of the combined-augmentation system is shown for coolant-injection rates of 2, 3, 4, and 5 pounds per second. The curves obtained have been extrapolated to the augmentation obtainable with compressor coolant injection independent of tail-pipe burning, so that each curve represents a range of tail-pipe burner fuel-air ratios from zero to the maximum obtainable with the combination. The maximum augmented thrust ratio obtained during this investigation was 1.70 with a fuel-air ratio of 0.064 in the tail-pipe burner and a compressor-injection rate of 2 pounds per second giving a combined augmented liquid ratio of 5.6. The maximum augmentation obtainable with compressor coolant injection decreased with an increase of injection rate because of the greater susceptibility to unstable and inefficient combustion with increased concentration of water and alcohol in the tail pipe. Combustion instability increased with injection flow rate thereby limiting operation of the combination-augmentation system to slightly lower fuel-air ratios as the compressor injection flow rate was increased. A discussion of the probable causes and effects of combustion instability is included in a later section.

For small requirements of thrust augmentation the compressor-injection system would be desirable due to its simplicity as opposed to the more complex tail-pipe burning system. For applications requiring moderate amounts of thrust augmentation, augmented thrust ratios up to approximately 1.5, the greatest economy of liquid consumption for a given amount of augmentation is attainable with the tail-pipe burning system. In order to obtain augmented thrust ratios in excess of 1.5 it is necessary to resort to the combined-augmentation system. Although the maximum augmentation obtained during this investigation was limited to 70 percent, this system appears to have potentialities of reaching still higher amounts of augmentation provided combustion inefficiency and instability can be overcome at high injected flow rates.

A summary of the augmented performance obtained with each of the three systems of augmentation is presented in figure 5. The locus of the experimental limits obtained by combining various compressor injected flows with tail-pipe burning is shown for the combined-augmentation system. The locus of the points of maximum augmented thrust ratio predicted by a theoretical analysis is shown in order to indicate the level of augmentation that may be anticipated from this system. The theoretical maximums curve was determined by considering the tail-pipe burning system as operating in series with the compressor-injection system for several compressor-injection flow rates. It is noted that the combustion stability limit curve, which represents the greatest augmentation obtained with approximately stoichiometric fuel-air ratio and with each compressor-injection flow rate, is less than that indicated by the theoretical maximums except for the condition of 2 pounds per second of compressor injection. This condition included the minimum amount of water - alcohol injection investigated and nearly stoichiometric fuel-air ratio in the tail-pipe burner. With increased injected flow rates and therefore increased augmented liquid ratios the experimental maximums curve deviates more markedly from the theoretically predicted performance because of decreasing combustion efficiency and poorer stability with increasing injected flow. From these considerations the current applications of the combined-augmentation system to turbojet engines and tail-pipe burners of this design should apparently be limited to low compressor-injection rates until the combustion problems have been overcome.

Tail-pipe burner combustion performance. - The tail-pipe burner combustion efficiencies and temperatures encountered during independent operation and in combination with compressor coolant injection are presented in figure 6. The tail-pipe burner combustion temperature and efficiency were calculated from measured values of thrust, mass flow, and exhaust-nozzle exit area with the unburned alcohol present in the tail-pipe burner considered as an equivalent fuel. The tail-pipe burner fuel-air ratio was based on the unburned air, that is, the air that was available for combustion in the tail-pipe burner. The combustion efficiency was computed as a ratio of the actual enthalpy rise across the combustor to the heat input of the fuel and was based on the calculated combustion temperature. The alcohol that remained unburned after the primary combustion process was considered to burn in the tail-pipe burner and was reduced to an equivalent fuel for the purposes of the calculation. If the alcohol input to the tail-pipe burner was considered negligible in the combustion calculations, combustion efficiency values approximately 25 percent greater than those shown would have been obtained. A detailed explanation of the method of calculation is included in appendix B.

Considering the effect of fuel-air ratio on the tail-pipe burner temperature (fig. 6(a)), it will be noted that for independent operation of the tail-pipe burner the combustion temperature increased linearly with fuel-air ratio to a value of 0.04 above which the rate of increase of combustion temperature with fuel-air ratio became less. A maximum combustion temperature of about 3800° R was obtained at stoichiometric fuel-air ratio. When the lowest compressor-injection flow rate (2 lb/sec) was used in combination with the tail-pipe burner, a combustion temperature of approximately 3640° R was obtained with a fuel-air ratio of 0.059.

The combustion-temperature data shown do not include data for all the fuel-air ratios investigated in combination with the compressor-injection rate of 2 pounds per second. The run during which maximum augmentation was achieved included a tail-pipe burner fuel-air ratio of 0.064. Sufficient data were not obtained to compute the combustion temperature and efficiency for this condition. When increased quantities of water - alcohol mixture (3 to 5 lb/sec) were used in combination with tail-pipe burning, the maximum combustion temperature obtainable was considerably less. The maximum temperature obtainable with the combination of 5 pounds per second injection and tail-pipe burning was approximately 670° less than that achieved with independent operation of the tail-pipe burner at the same fuel-air ratio. The salient decrease in combustion temperature with injection flow rates greater than 2 pounds per second resulted from significant changes in the composition and properties of the products of combustion and also from a reduction of the combustion efficiency with the presence of large quantities of alcohol and water vapor.

For independent operation of the tail-pipe burner the combustion efficiency reached a maximum value at a fuel-air ratio of approximately 0.04 as may be seen in figure 6(b). The peak combustion efficiency is shown to exceed ideal efficiency and may be attributed to the assumptions made in the method of calculation. Although the magnitudes are questionable, the relative values of efficiency are significant for comparative purposes.

The combustion efficiencies calculated for operation of the combined-augmentation system decrease with an increase of compressor-injection rate and are as much as 35 percent lower (5 lbs/sec compressor injection) than those calculated for independent operation of the tail-pipe burner. The decrease of combustion efficiency probably results from the influence of the water vapor on the combustion process. It has been found that the velocity of flame propagation in a fuel-air mixture is substantially reduced by the addition of water vapor. Although the exact nature of this retarding action is not known, an hypothesis has been advanced that it is the result of dissipation of the high energy of OH radicals and newly formed water molecules through collision with the normal water molecules. In this manner, the concentration of the active energy carriers is reduced and consequently, the chemical reaction and propagation of the flame is slowed down. This phenomenon becomes increasingly important with greater concentration of water molecules. A detailed explanation of the process may be found in reference 5. Generalizing, it has been found that increasing the compressor-coolant-injection rate decreases both the combustion efficiency and the combustion temperature of the process.

Thrust losses. - The loss in normal performance due to the compressor-interstage-injection system was demonstrated in reference 2 to be negligible for the "single-stage" compressor-injection system used in this investigation. The decrease in thrust attributable to the tail-pipe burner flame holder and fuel-spray bars is shown in figure 7(a) where corrected thrust is presented as a function of corrected engine speed. The performance shown in figure 7(a) was determined with the tail-pipe-burner tail pipe that was larger in diameter than the standard engine tail pipe. The data for each curve were obtained with a constant exhaust-nozzle area that was set for each series to give rated tail-pipe-gas temperature at rated engine speed. The loss during unaugmented operation due to the presence of the 36 percent blocked-area flame holder, the larger of the two flame holders used, and the fuel-spray components was approximately 1 to $1\frac{1}{2}$ percent of the thrust. A plot of the corrected tail-pipe gas temperature obtained during the thrust-loss determination is shown in figure 7(b) to substantiate the constancy of the turbine-discharge-gas temperature throughout this phase of the investigation.

Operational Characteristics

Operation of both the tail-pipe burner system and the combined-augmentation system in the region of stoichiometric fuel-air ratio was characterized by combustion instability that took the form of high-frequency vibration. This vibration usually resulted in destruction of the flame holder or other components of the tail-pipe burner and necessitated increasing the strength of the various parts of the burner so much that the resultant component weights became impractical for aircraft application. Areas where welding had concentrated stresses were particularly vulnerable.

Measurements of the frequency of the sonic vibrations in the engine muffler revealed that a range of frequencies from 3500 to 5000 cycles per second were encountered with occasional peaks at 6000 cycles per second. The vibrations experienced probably are a composite of the vibrations of various integral parts and assemblies surrounding the tail-pipe burner and those caused by oscillatory combustion. The combustion vibrations could result from oscillations created by instability of the combustion between localized regions of over-rich and combustible fuel-air mixtures. Because these regions are dynamic and therefore are alternately capable and incapable of supporting combustion, a form of oscillation is established. This hypothesis is supported by the fact that the combustion instability is critical at high fuel-air ratios where proper mixing of the fuel and air becomes increasingly important. Further substantiation is offered by the fact that the high-frequency vibration was eliminated during independent operation of the tail-pipe burner and was eliminated under some conditions with the combined-augmentation system when the fuel-air distribution to the burner was varied. This variation was accomplished in two ways: (1) by moving the fuel-spray bars in and out radially across the diffuser, and (2) by changing from one design of spray bar to another. With an increase in the tail-pipe burner fuel-air ratio it was found that combustion stability was improved by moving the spray bars outward, thus concentrating more fuel where the gas stream velocity and available combustion air was a maximum. To provide fuel in the air stream near the diffuser inner cone, the type-B spray bar, with provision for increased fuel flow from the end of the spray bar, was used.

Although it was possible to eliminate the combustion instability during independent operation of the tail-pipe burner, this elimination was not always possible with the use of the combined-augmentation system at high tail-pipe burner fuel-air ratios. The presence of the unburned alcohol from the compressor coolant injection caused a poorer distribution of the combustible material and air than was present during tail-pipe burning alone. In addition, the reduction of the velocity of flame propagation due to the influence of the water vapor caused the poor distribution to be even more critical, and it was possible to eliminate the instability only at the lowest rate of water - alcohol injection.

Although the current investigation of the combined-augmentation system was limited by combustion instability, the range of operation of future applications might be extended by providing optimum distribution of the combustible material in the tail-pipe burner and available combustion air through proper design of the tail-pipe burner components.

A comparison of the flame holder designs used during the investigation indicated, in general, that more stable combustion at stoichiometric conditions was experienced with larger blocked-area flame holders. Although the tail-pipe burner alone was operable with an 18 percent blocked-area flame holder, a 30 percent or greater blocked-area flame holder was required when the combined-augmentation system was used.

CONCLUDING REMARKS

The maximum augmented thrust ratio obtained during the investigation of the use of combined compressor coolant injection and tail-pipe burning was 1.70, which resulted from a combination of a fuel-air ratio of 0.064 in the tail-pipe burner and 2.0 pounds per second compressor coolant injection at the engine inlet. Achievement of greater augmentation by combination of compressor coolant injection rates in excess of 2 pounds per second with high fuel-air ratios in the tail-pipe burner was precluded by inefficient and unstable combustion in the tail-pipe burner. The loss in unaugmented thrust due to the compressor-interstage injection system, and the tail-pipe-burner fuel-spray bars and flame holder was approximately 1 to $1\frac{1}{2}$ percent of the thrust.

The combustion instability encountered was characterized by high-frequency vibrations that usually resulted in destruction of the components of the tail-pipe burner. Combustion instability increased with injection flow rate limiting operation of the combined-augmentation system to slightly lower fuel-air ratios with higher compressor coolant injection flow rates. In addition, the tail-pipe burner combustion temperature and efficiencies decreased with addition of alcohol and water vapor in the compressor. The influence of the water vapor became increasingly important with the greater concentrations of water vapor accompanying increased injection flow rates. Even though the magnitude of the augmentation achieved during this investigation by the combined-augmentation system was considerable, it appears logical that even greater amounts of augmentation can be made available by improvement of combustion in the presence of compressor coolant injection.

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APPENDIX A

SYMBOLS

A	$(H_{H_2O} - 1/2\ H_{O_2})/2.016$
A_7	exhaust-nozzle exit area, ft^2
B	$(H_{CO_2} - H_{O_2})/12.01$
c_p	specific heat at constant pressure, Btu/(lb)(°F)
F	measured thrust, lb
f/a	fuel-air ratio
g	acceleration of gravity, ft/sec^2
H	molal enthalpy, Btu/(lb-mole)
h_a	enthalpy of air, Btu/lb
$h_{c,alc}$	heating value of alcohol, Btu/lb
$h_{c,f}$	heating value of primary fuel, Btu/lb
h_w	enthalpy of water, Btu/lb
J	Joules constant, 778 ft-lb/Btu
m	hydrogen-carbon ratio of fuel by weight
P	total pressure, lb/ft^2
p	static pressure, lb/ft^2
R	gas constant, ft/°R
T	total temperature, °R
V_j	jet velocity, ft/sec
W_a	weight of air flow, lb/sec
W_{alc}	weight of alcohol flow, lb/sec

W_b	tail-pipe burner fuel flow, lb/sec
W_f	engine fuel flow, lb/sec
W_g	total gas flow $(W_i + W_a + W_b + W_f)$, lb/sec
W_i	injected flow to compressor, $W_w + W_{alc}$, lb/sec
W_w	weight of water flow, lb/sec
γ	ratio of specific heats
δ	$P_1/2116$, $\dfrac{\text{compressor inlet absolute total pressure}}{\text{absolute static pressure of NACA standard atmosphere at sea level}}$
θ	$T_1/518.4$, $\dfrac{\text{compressor inlet absolute total temperature}}{\text{absolute static temperature of NACA standard atmosphere at sea level}}$
η_{alc}	alcohol combustion effectiveness
η_b	combustion efficiency of tail-pipe burner

Subscripts:

1	engine inlet
3	compressor discharge
5	turbine discharge
6	tail-pipe burner inlet
7	exhaust discharge

APPENDIX B

METHOD OF CALCULATION

Tail-pipe burner combustion temperature. - The tail-pipe burner combustion temperature was computed as a function of measured thrust, the total mass flow through the engine and tail-pipe burner, and a calculated ratio of static to total pressure at the tail-pipe burner outlet. The calculated combustion temperature equation has been derived from the thrust equation

$$F = \frac{W_g}{g} V_j \tag{B1}$$

Assuming complete expansion of the exhaust jet and considering the fact that only subsonic flow was encountered at the exhaust-nozzle exit during this investigation, the combustion-temperature equation is of the following form

$$T_7 = \frac{(\gamma-1)\ F^2\ g}{(2\gamma)\ W_g{}^2\ R\left[1 - \left(\frac{p_7}{P_7}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{B2}$$

For the calculations when tail-pipe burning alone was used, the values of γ and c_p for the products of combustion were determined at the estimated combustion temperature and precombustion mixture fuel-air ratio. The gas constant R was determined from the following relationship

$$R = J\ c_p \left(1 - \frac{1}{\gamma}\right) \tag{B3}$$

The calculation of the combustion temperatures for the combined-augmentation system performance necessitated including the influence of the water vapor from the compressor coolant injection on the values of γ and R used in the computations. The value of R for water vapor is only slightly influenced by temperature and has been assumed constant at a value of 85.7. The values of γ for the water vapor were determined from the empirical equation (reference 6),

$$\gamma = 19.86 + \frac{7500}{T_7} - \sqrt{\frac{597}{T_7}} \tag{B4}$$

The values of γ and R for the gas mixture were assumed to be proportional to the weight of the water vapor and combustion gases present in the process. A negligible error results in the determination of the properties of the combustion gases when the alcohol is assumed as an equivalent fuel.

The total pressure at the tail-pipe burner outlet P_7 was not measurable so that the ratio of total to static pressure at the exhaust discharge (station 7) was calculated from

$$\frac{P_7}{p_7} = \left[1 + \frac{(\gamma-1)\ F}{2\gamma\ p_7\ A_7}\right]^{\frac{\gamma}{\gamma-1}} \tag{B5}$$

which assumes that the static pressure at the exhaust-nozzle discharge (station 7) is equal to the static pressure in the exhaust muffler. The exhaust-nozzle velocity and discharge coefficients were not determined in this investigation and have been assumed as ideal for purposes of calculation.

Tail-pipe burner combustion efficiency. - The tail-pipe burner combustion efficiency was computed as a ratio of the actual enthalpy rise across the combustor (based on the calculated combustion temperature) to the heat input of the fuel consumed. Ideal combustion of the engine fuel was assumed to take place in the primary combustor. To provide an estimate of the alcohol that burned in the primary combustor an alcohol-combustion-effectiveness factor was developed and is presented in figure 8 as a function of the corrected water - alcohol mixture flow rate for the 70 - 30 percent water - alcohol mixture. The alcohol-combustion effectiveness was derived from the consideration of a heat balance across the primary engine combustor and included the following assumptions: (a) The enthalpy rise through the primary combustion chamber is a constant for each injection flow rate, and (b) The combustion efficiency of the primary fuel remained unchanged. The values of the alcohol-combustion-effectiveness factor have been reduced from experimental data and are limited to the particular engine-combustion-chamber configuration investigated. The combustion efficiencies of the tail-pipe burner were determined by use of the following equation of the enthalpy rise across the combustor divided by the heat inputs of the fuels and was based on the discussion of combustion efficiency calculation as presented in reference 7.

$$\eta_b = \frac{\left\{h_{a,7} + \left[\frac{f}{a_7}\left(\frac{Am+B}{m+1}\right)_7\right]_{540}^{T_7}\right\} - \left\{h_{a,5} + \left[\frac{f}{a_5}\left(\frac{Am+B}{m+1}\right)_5\right]_{540}^{T_5}\right\} + \left[\Delta h_w \frac{W_w}{W_a}\right]_{T_5}^{T_7}}{h_{c,alc}\frac{W_{alc}}{W_a}\left[1 - \eta_{alc}\right] + h_{c,f}\frac{W_b}{W_a}} \qquad \text{(B6)}$$

In the determination of the fuel-air ratios the alcohol present was reduced to an equivalent standard fuel through consideration of the equivalence ratios of the alcohol and tail-pipe burner fuel.

REFERENCES

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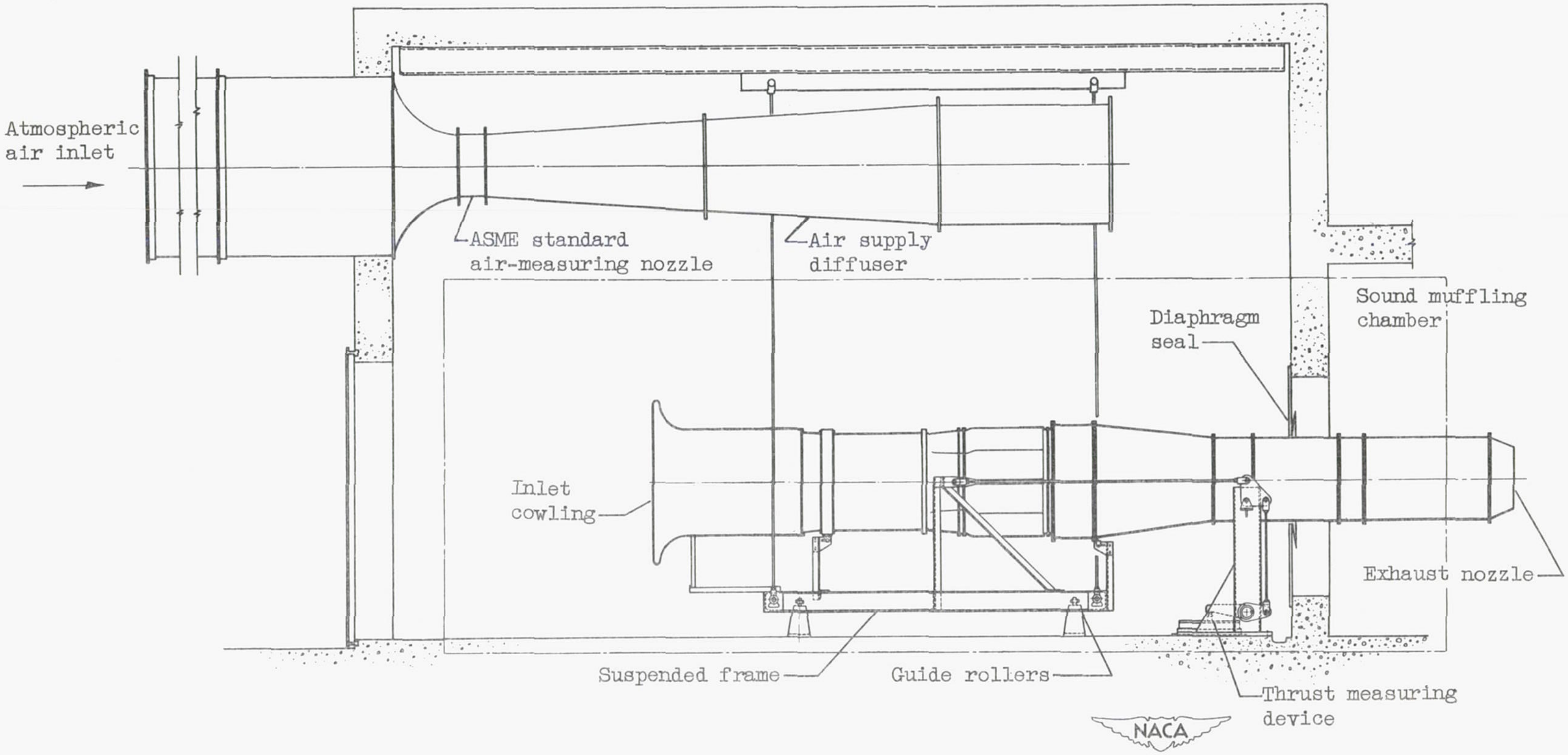


Figure 1. - Schematic diagram of engine installation.

2312

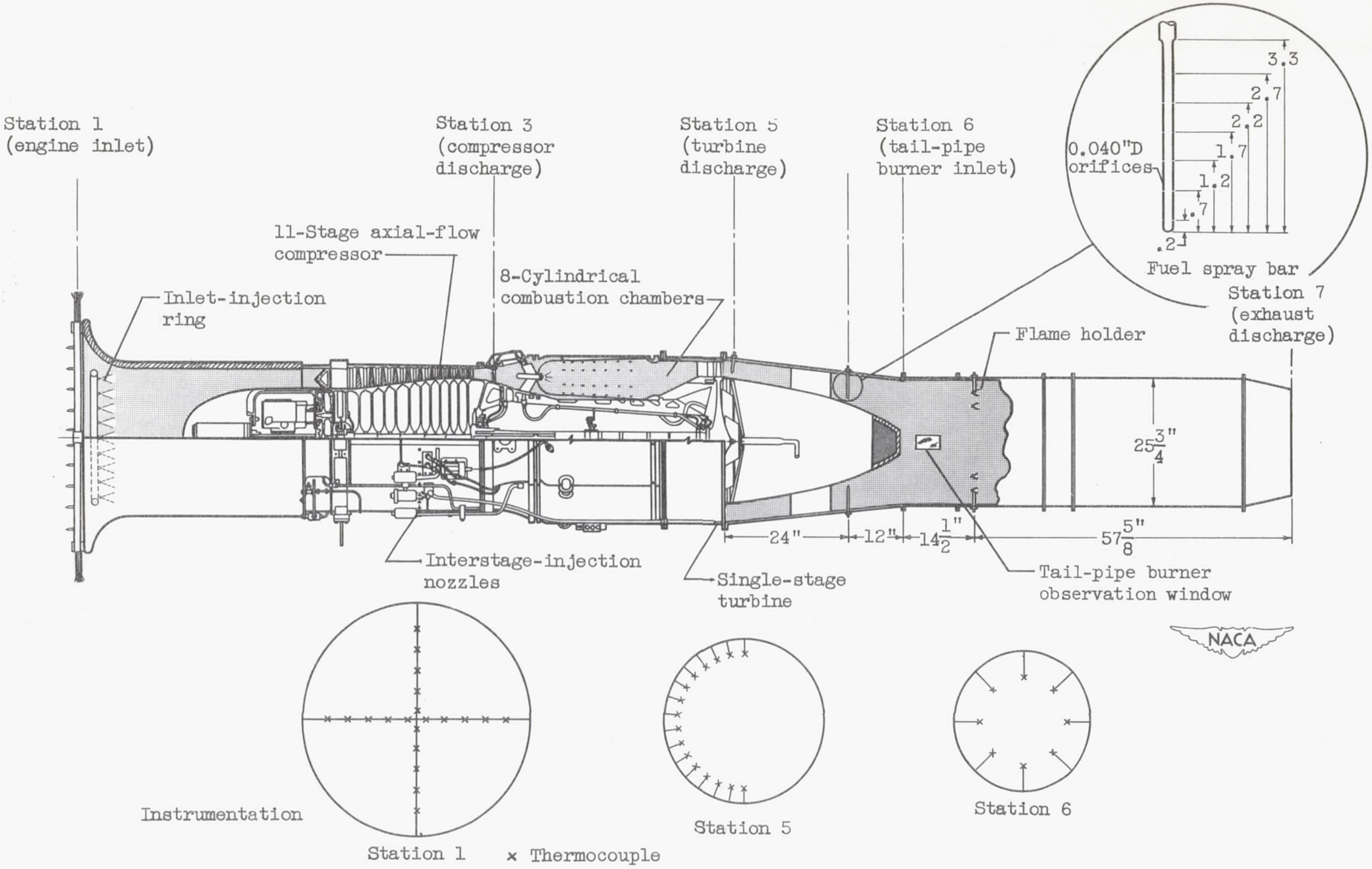
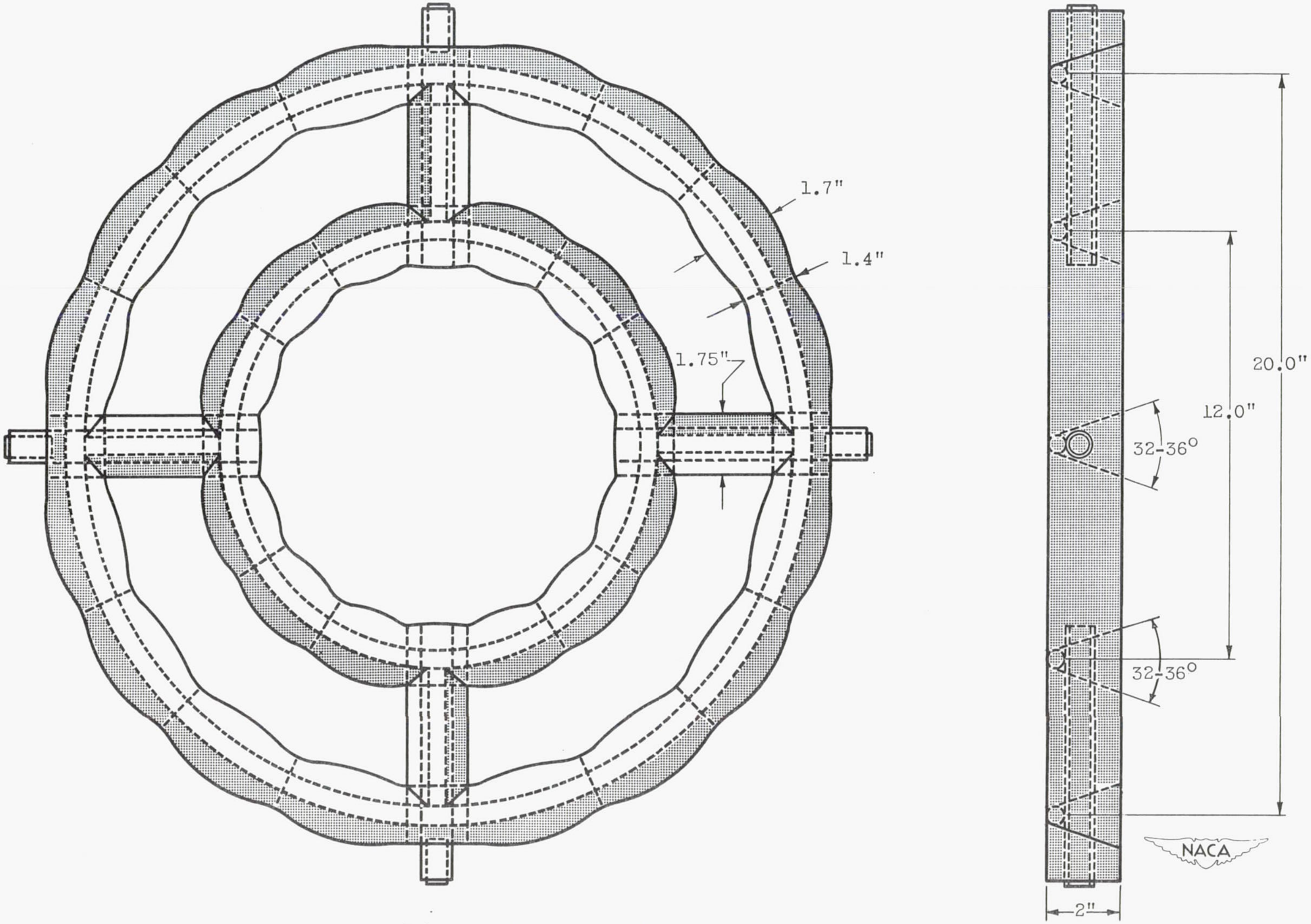


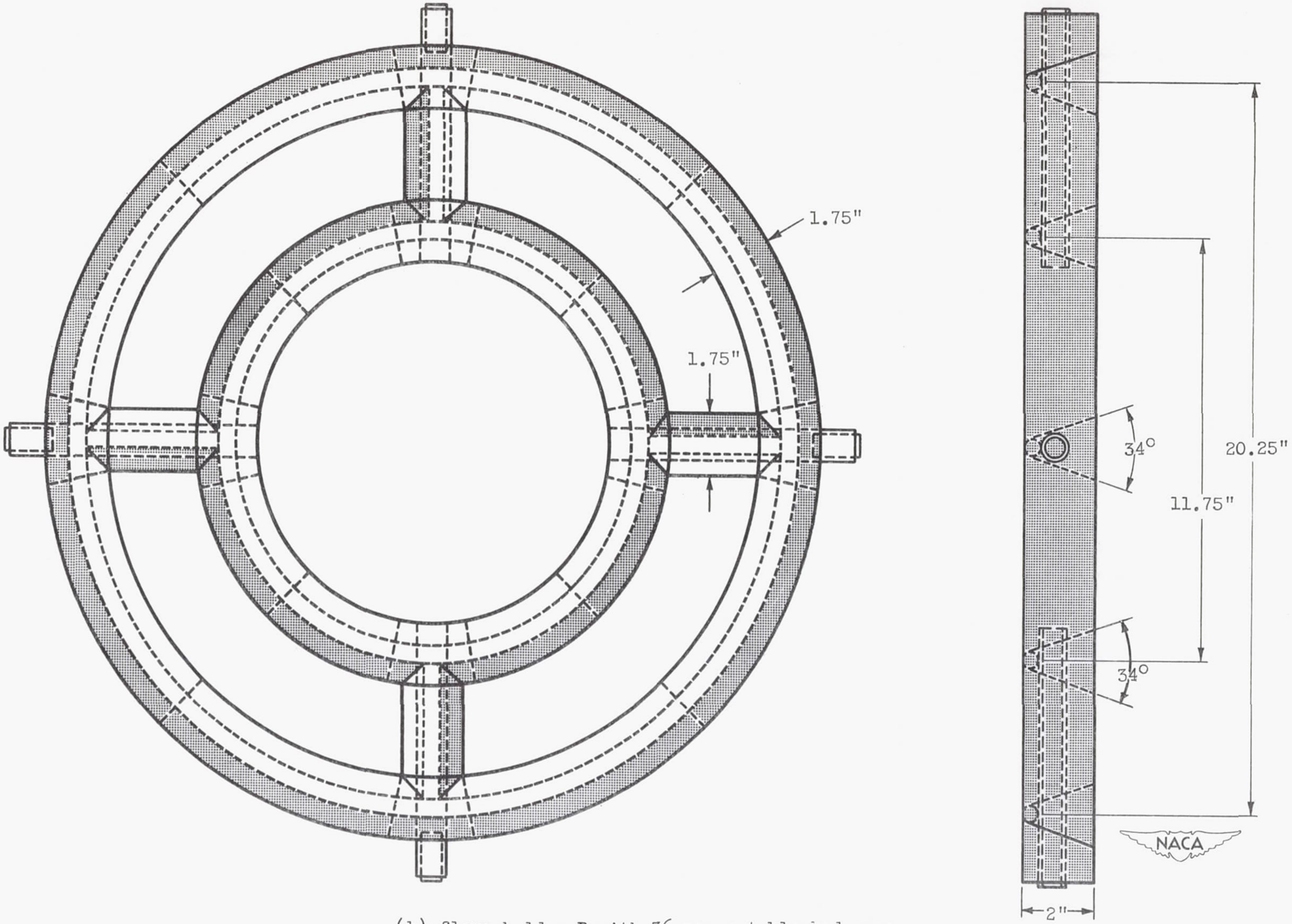
Figure 2. - Engine and tail-pipe burner configuration and instrumentation.



(a) Flame holder A with 31 percent blocked area.

Figure 3. - Flame holders for tail-pipe burner.

2274



(b) flame holder B with 36 percent blocked area.

Figure 3. - Concluded. Flame holders for tail-pipe burner.

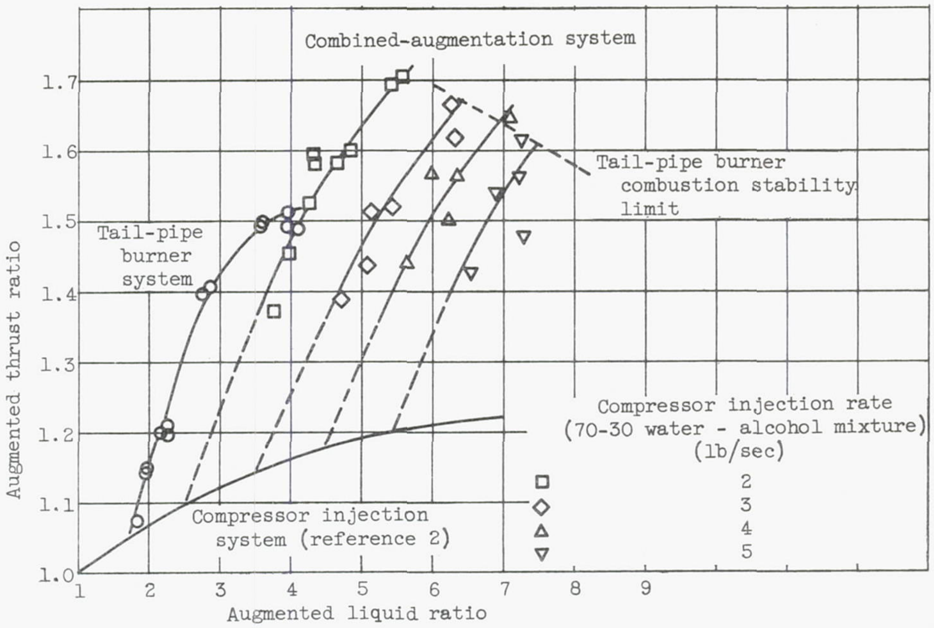


Figure 4. - Turbojet-engine performance with compressor coolant injection, tail-pipe burning, and combined tail-pipe burning and compressor coolant injection at sea-level, zero ram conditions; engine speed 7610 rpm, turbine-discharge gas temperature 1200° F, average engine-inlet temperature 80° F.

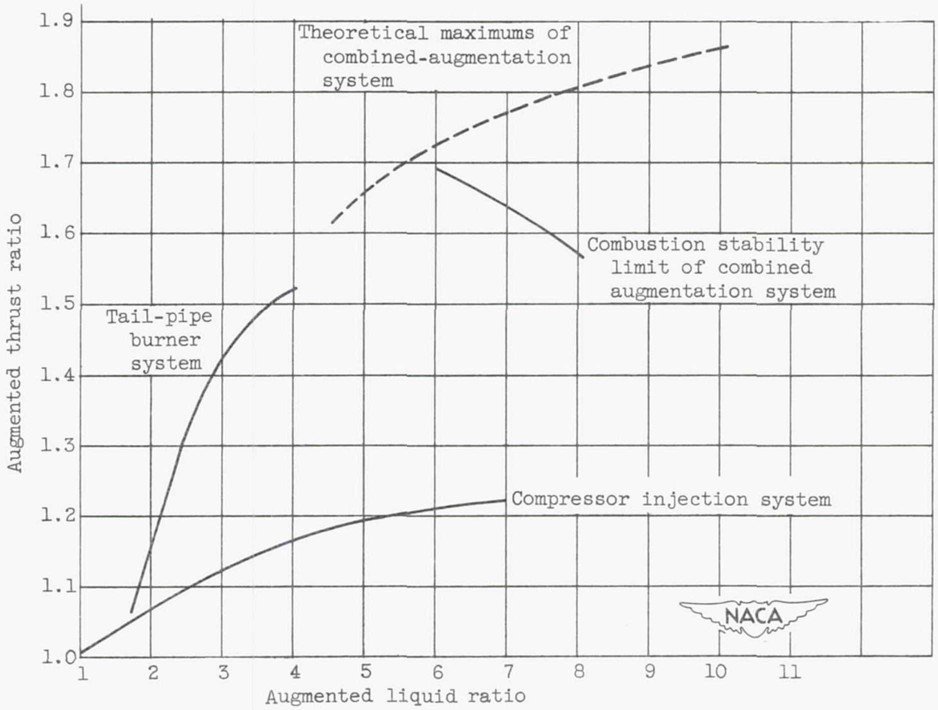
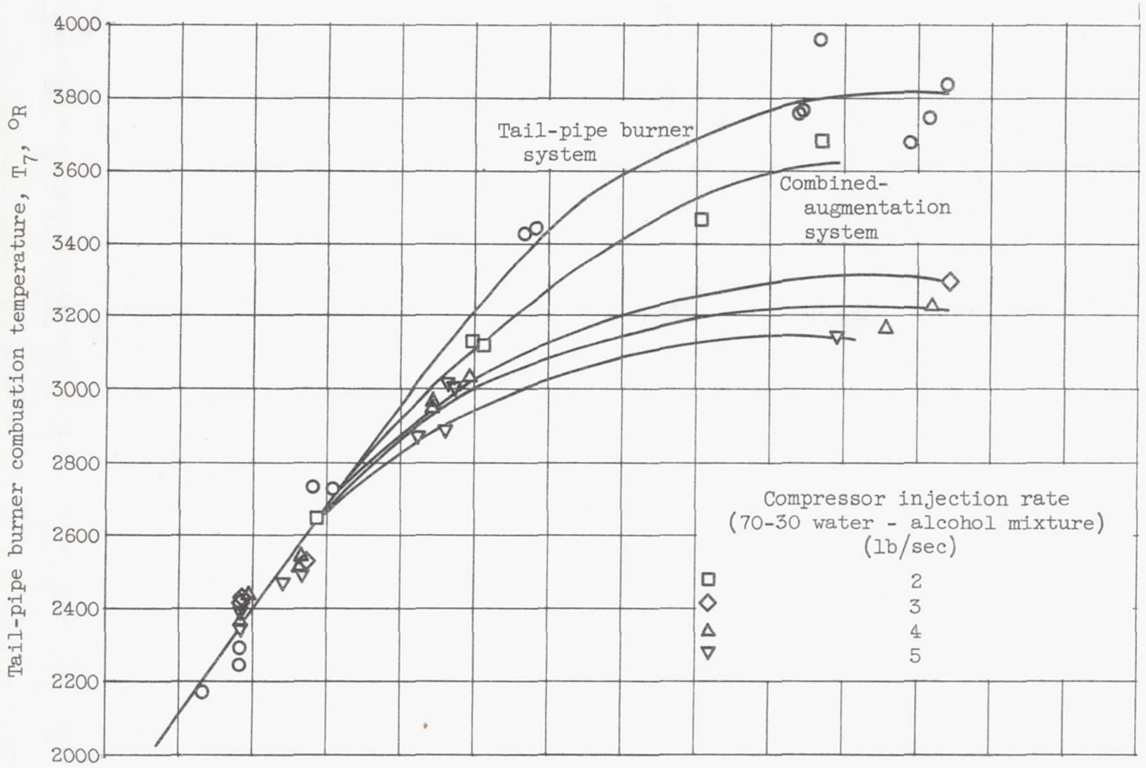
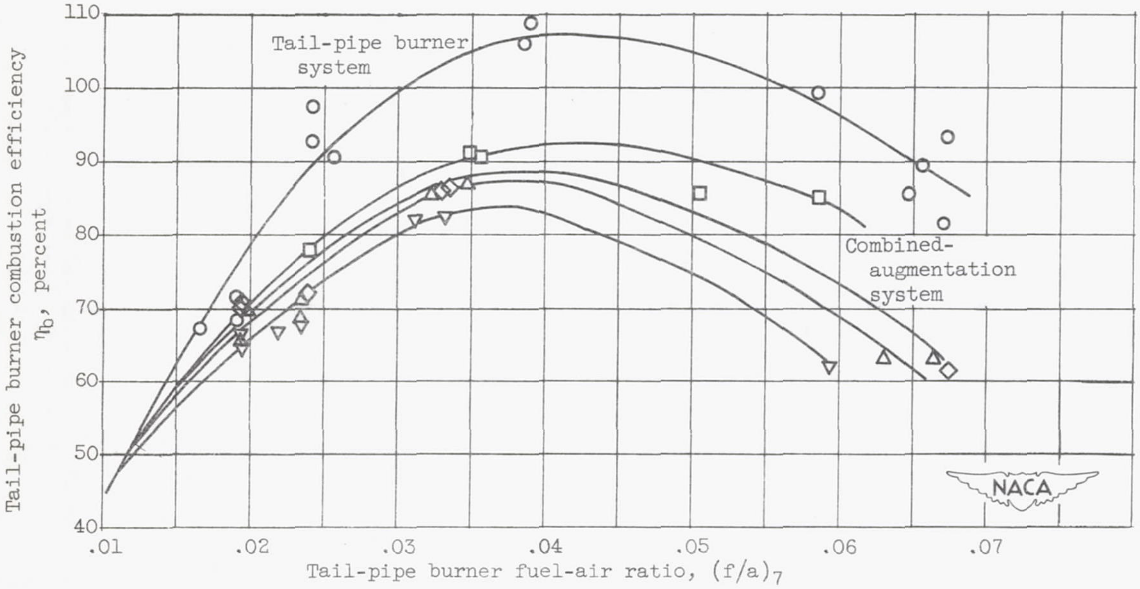


Figure 5. - Performance limitations of the compressor coolant injection, tail-pipe burning, and combined tail-pipe burning and compressor coolant injection.

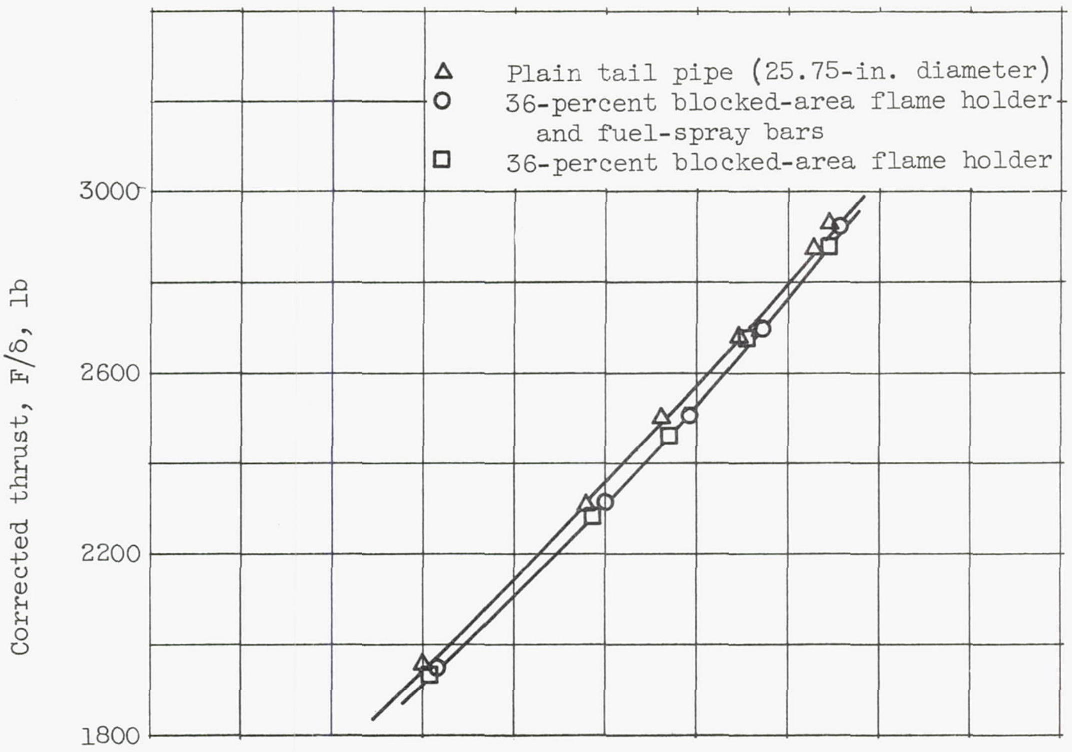


(a) Tail-pipe burner combustion temperature.

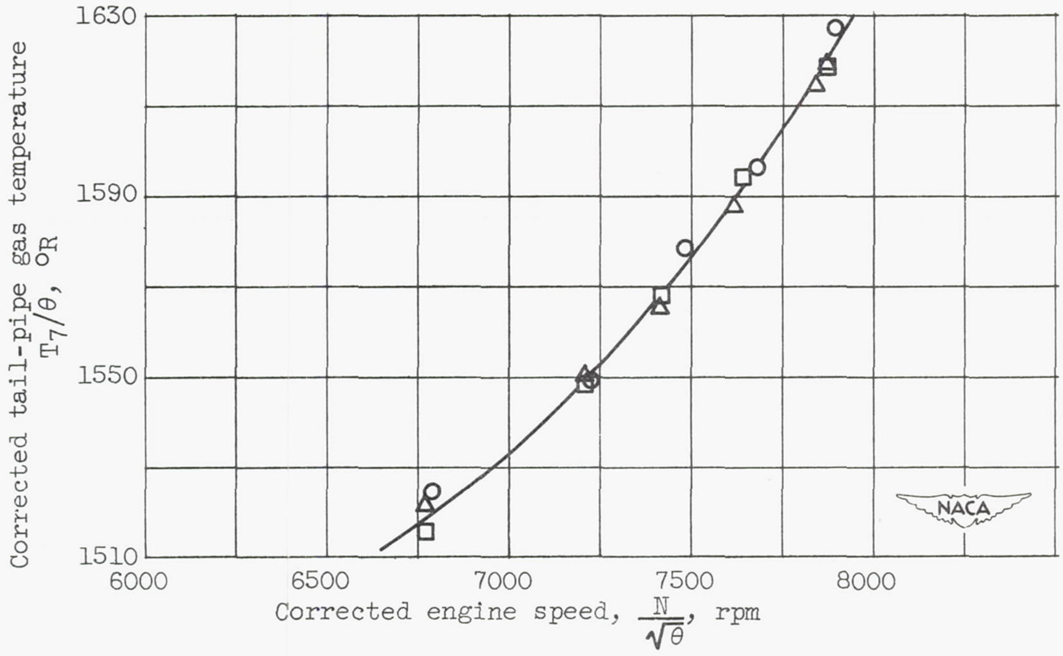


(b) Tail-pipe burner combustion efficiency.

Figure 6. - Combustion performance of tail-pipe burner during independent operation and in combination with compressor coolant injection; burner inlet temperature 1200° F, sea-level, zero ram conditions.



(a) Corrected thrust.



(b) Corrected tail-pipe gas temperature.

Figure 7. - Effect of tail-pipe burner components on turbojet-engine normal performance with $25\frac{3}{4}$-inch diameter tail pipe and variable-area exhaust nozzle.

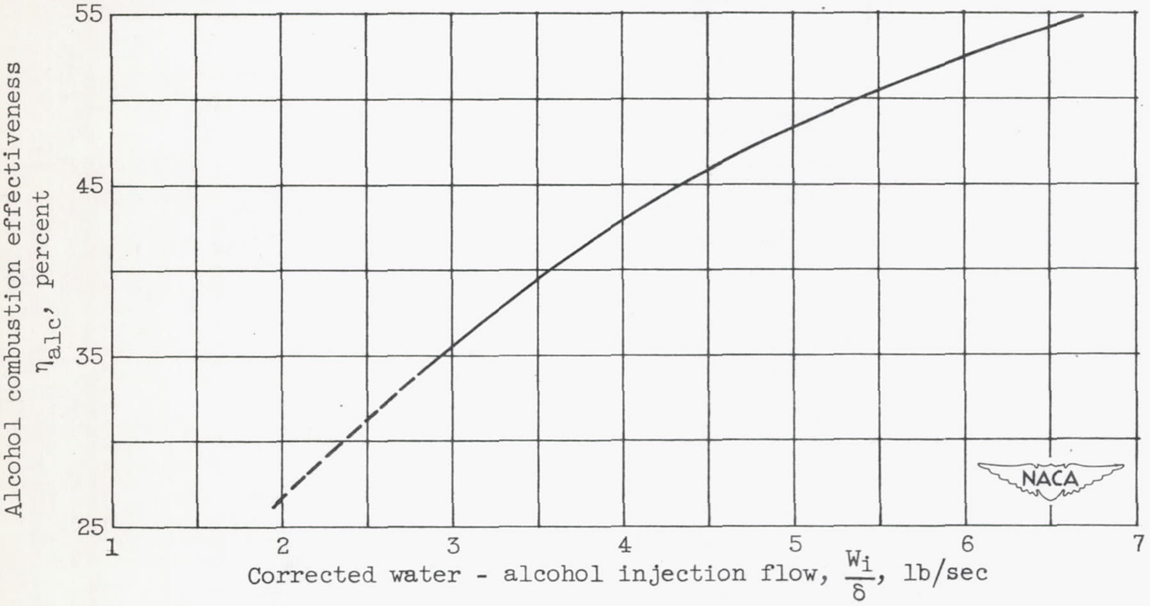


Figure 8. - Alcohol-combustion effectiveness as a function of corrected water - alcohol mixture injection flow rate. Mixture of 70-percent water and 30-percent alcohol by volume. Alcohol blend of 50-percent ethanol and 50-percent methanol.