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RESEARCH MEMORANDUM

SIMULATED AFTERBURNER PERFORMANCE WITH HYDROGEN
PEROXIDE INJECTION FOR THRUST AUGMENTATION

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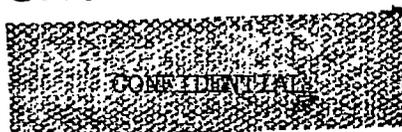
SUMMARY

The effect of injecting high-strength hydrogen peroxide into turbo-jet primary combustors on the combustion performance of three experimental afterburner configurations was investigated. Afterburner inlet conditions simulated turbine outlet conditions of a 5.3-compressor-pressure-ratio engine for altitude flight at a flight Mach number of 0.6. The effect of hydrogen peroxide on afterburner performance was evaluated by comparing the combustion efficiency and afterburner stability limits obtained with and without peroxide injection. Similar afterburner data obtained with water injection to the primary combustor were also compared.

The experimental data indicate that, at a test condition simulating flight at 32,500 feet, water-air ratios of only 0.04 caused combustion blowout in the afterburner. For the same conditions, afterburner combustion was stable and 90-percent efficient at hydrogen peroxide injection rates $7\frac{1}{2}$ times as great. Injection to peroxide-air ratios of about 0.3 increased combustion efficiency about 5 percent over that for no injection. Afterburner stability improvements were noted at peroxide-air ratios as low as 0.1. Two afterburner configurations that limited flame spreading and reduced combustion time were blowout limited at fuel-air ratios less than stoichiometric. At peroxide-air ratios of only 0.1, these units burned stably at stoichiometric fuel-air ratios of about 0.08.

Calculations for an afterburning engine indicated that at an augmented liquid ratio of about 6, which is the afterburner stability limit with water injection, the augmented net-thrust ratio with peroxide injection is about 6 percent greater than that with water injection. Augmented liquid ratios as high as 24 may be attained with peroxide injection, however, and augmented net-thrust ratios of 2.1 and 2.8 were calculated at augmented liquid ratios of 12 and 24, respectively.

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INTRODUCTION

Afterburner combustion efficiency and combustion stability are adversely affected when high rates of water-alcohol mixtures are injected for additional thrust augmentation. The investigation reported herein was conducted to determine the effect of high-strength hydrogen peroxide when used as a liquid injectant for thrust augmentation on afterburner combustion performance.

Thrust-augmentation systems are frequently used in turbojet aircraft requiring short periods of high-thrust-level operation. Coolant injection into the primary engine, afterburning, or a combination of the two are thrust-augmenting systems commonly used. High rates of coolant injection, however, hinder the combustion process in both the primary engine (refs. 1 to 3) and in the afterburner (ref. 4). The effect of coolant injection on the afterburner combustion process is particularly severe, and major losses in combustion efficiency and stability result.

The specific role of a coolant such as water in the afterburner combustion process is not clearly defined. The coolant may reduce the rate of the combustion reaction directly, or it may reduce the oxygen concentration by dilution, thus lowering the reaction rate. If the heat of vaporization of the coolant must be compensated by an engine-fuel-flow increase to maintain turbine-inlet temperature, the oxygen concentration of the afterburner inlet gases would be further reduced. Afterburner operating conditions of high gas velocity, high heat release, and relatively low pressure are, at best, difficult conditions for combustion. Therefore, the addition of a coolant to such a system results in a more pronounced deleterious effect than is encountered in the combustion system of the primary engine.

Reference 3 indicates that combustion problems of the primary-engine combustors may be overcome if high-strength hydrogen peroxide is used as the liquid injectant. Not only can a greater mass be injected, but combustion efficiency and stability are also improved over that for conventional coolant injection. Afterburner combustion problems arising from coolant injection might be similarly overcome. Furthermore, the oxygen released by the peroxide decomposition could be utilized in the afterburner to attain higher outlet temperatures, and hence, high thrust-augmentation ratios.

For this investigation, the test installation consisted of a primary combustor, into which augmenting fluids were injected, and a simulated afterburner installation. Three afterburner configurations were tested to determine the effect of peroxide injection on afterburner combustion with and without a flameholder, and on afterburner combustion with reduced length. Afterburner inlet pressure and temperature approximated turbine outlet conditions of an engine with a 5.3 compressor pressure

ratio operating at rated engine speed, a flight Mach number of 0.6, and altitudes of 32,500 and 45,000 feet. Data obtained with no liquid injection, with water injection, and with hydrogen peroxide injection are compared at these conditions. Afterburner performance was evaluated on the basis of the combustion efficiency and the combustion stability range of the configuration.

APPARATUS AND INSTRUMENTATION

Test Apparatus

The basic afterburner and diffuser configuration used for this investigation is shown in figures 1 and 2. The shell of the diffuser was a section of a cone, $17\frac{1}{2}$ inches long with an inlet diameter of 8 inches and an outlet diameter of 10 inches. The diffuser centerbody was a hollow, bullet-nosed body $3\frac{27}{32}$ inches in diameter at the diffuser exit and 16 inches long. The diffuser-area change over its total length was approximately 33 percent. Three fuel injectors were equally spaced circumferentially $3\frac{3}{4}$ inches from the upstream end of the diffuser. The injectors were 1/8-inch Inconel tubes with two 1/32-inch holes drilled near the tube end and were positioned for fuel injection in a plane normal to the diffuser axis. Fuel injection was at a point 1/8-inch from the surface of the centerbody. Representative afterburner inlet temperatures were obtained from a thermocouple rake positioned as shown in figure 2(a). The gas stream entering the afterburner was sampled by two 4-point sampling rakes positioned in the same plane as that of the inlet thermocouples.

A simple, single V-gutter, annular flameholder was positioned at the downstream flange of the diffuser. The flameholder is detailed in figure 1 and is also shown in figure 2(b). The blocked areas of the flameholder and the diffuser centerbody, based on the 10-inch afterburner inside diameter, are listed in the following table:

	Blocked area, sq in.	Diffuser outlet area blocked, percent
Centerbody	11.6	14.7
Flameholder	25.8	32.8

Three afterburner configurations were investigated. The basic configuration A, as shown in figure 1, had a 10-inch inside diameter, was 36

inches long, and approximately scaled to a full-scale unit described in reference 5. The second configuration B was identical to that shown in figure 1 except that no flameholder other than that provided by the diffuser centerbody was used. Configuration C had a 10-inch inside diameter, was 18 inches long, and had the basic V-gutter flameholder installed. For all configurations tested, the afterburner section was water cooled to prevent burnout.

Installation and Instrumentation

The afterburner was installed as shown diagrammatically in figure 3(a). A single combustor from a J47 engine was used as the primary combustor into which augmenting fluids were injected. A perforated plate, installed at the J47 outlet, simulated turbine pressure drop, thus permitting this combustor to be operated at inlet pressures and velocities approximately similar to those reported in reference 3, although the afterburner inlet pressures were only about one-third as high. The diffuser and the afterburner were installed immediately downstream of the perforated plate. Afterburner combustion was quenched at station 7 (fig. 3(a)) by a four-bar, air-atomized water spray positioned normal to the gas flow. The uniformity and effectiveness of the quenching was observed through a window located approximately 14 inches downstream of the spray bars. Following mixing, the bulk gas temperature was measured at station 8.

Combustion air flow was metered at the inlet of the test facility by means of a variable-area-orifice installation. Combustor-inlet air flow and afterburner inlet pressure were controlled by remote-operating throttle valves.

Augmenting fluids, water or 90-percent hydrogen peroxide, were injected into the primary combustor at station 3. The liquid-injection system was identical to that described in reference 3 and utilized the production water manifold that was integral with the combustor housing. Fluid flow was controlled by throttle valves and was metered by vane-type flowmeters. Fuel flow to both the primary combustor and to the afterburner was metered by calibrated rotameters. The fuel used was MIL-F-5624C, grade JP-4 (table I).

Instrumentation details are indicated in figure 3(b). Inlet temperatures and pressures were measured at stations 1 and 2 by a bare-wire, iron-constantan thermocouple and a static-pressure tap, respectively. Outlet gas temperatures from the primary combustor were measured at station 4 with 32 bare-wire chromel-alumel thermocouples positioned at centers of equal areas of the 8-inch-diameter duct. Afterburner inlet static pressure was measured at station 5; bulk gas temperature at station 8 was measured with 12 bare-wire chromel-alumel thermocouples positioned as

shown in the figure. All temperatures were indicated on self-balancing potentiometers and were not corrected for radiation. All pressures were indicated by mercury manometers. Oxygen concentration of the afterburner inlet gases was measured by a Pauling meter.

PROCEDURE

Test Conditions

The inlet operating conditions for the afterburner with no liquid injection are listed in the following table:

	Test condition	
	1	2
Air flow rate, lb/sec	4.3	2.5
Inlet static pressure, in. Hg abs	20.5	11.5
Inlet temperature, °F	1200	1200
Afterburner reference velocity, ft/sec	520	520
Over-all fuel-air ratio	Stoichiometric	Stoichiometric

The afterburner inlet test conditions 1 and 2 approximated turbine outlet conditions of an engine with a 5.3 compressor pressure ratio operated at rated engine speed at a flight Mach number of 0.6 at altitudes of 32,500 and 45,000 feet, respectively. The fuel-air ratio of the primary burner with no liquid injection approximated that of the engine at the flight conditions. Afterburner data were also obtained at inlet temperatures of 1000°, 1200°, and 1400° F at over-all fuel-air ratios ranging from 0.04 to 0.09 for the air flow rates and inlet pressures shown in the table.

All afterburner-performance data with liquid injection were obtained at stoichiometric conditions. The inlet pressures and temperatures specified in the table are the values for zero liquid injection; with liquid injection, afterburner inlet pressure and inlet temperature were adjusted to values higher than those indicated in the table to approximate turbine outlet conditions calculated for the condition of liquid injection into an engine.

Operating Procedure

For all test data, with or without liquid injection, afterburner inlet temperature, pressure, and fuel flow were set to predetermined values and the water-quench flow rate was set to maintain a bulk gas temperature of approximately 600° to 700° F at station 8. Data were recorded after

temperature equilibrium had been established. With peroxide injection, however, actual run time was limited by the peroxide storage facility to a maximum of 5 minutes. Since bulk gas temperature, after quenching, was maintained constant at the preset value, little error should have resulted from failure to maintain thermal equilibrium in the heat-balance section even though fuel flow was necessarily increased along with the peroxide injection to maintain stoichiometry. With peroxide injection, the calculated afterburner inlet pressures could not be maintained because of the limits of the test facility; however, they were within approximately 1.5 inches of the calculated values for an engine having liquid augmentation to the primary combustor.

Combustion-Efficiency Determination

For equivalence ratios less than stoichiometric, combustion efficiency of the primary burner and afterburner was calculated by the method of reference 6 as the ratio of the actual enthalpy rise to the theoretical enthalpy rise. Above stoichiometric, combustion efficiency of the afterburner was calculated as the ratio of the actual enthalpy rise to the heat content of the total fuel injected. For such mixtures, since the total heat content includes fuel that cannot be utilized for heat release, the highest efficiency obtainable is less than 100 percent. The actual enthalpy rise for the primary burner was calculated from the average of 32 individual temperatures measured at station 4. The actual enthalpy rise for the afterburner was calculated from a heat balance based upon inlet gas enthalpy, heat rejection to the water jacket, and heat absorption by the water-quench spray according to the relation

$$\Delta H = \Delta h_w + \Delta h_e + \Delta h_j$$

where

- ΔH total measured enthalpy rise, Btu/lb air
 Δh_w enthalpy rise of quench water, Btu/lb air
 Δh_e enthalpy rise of exhaust gas, Btu/lb air
 Δh_j enthalpy rise of jacket cooling water, Btu/lb air

For mixtures richer than stoichiometric, ΔH was corrected for excess fuel by the method of reference 7 by adding a fuel enthalpy term,

$$(f - f_{st}) \left[(Q_w)_{t_1} + c_{p,m} (t_e - t_1) \right]$$

where

- $(f - f_{st})$ fuel-air ratio in excess of stoichiometric
- $(Q_v)_{t_i}$ heat of vaporization of fuel at inlet temperature
- $(t_e - t_i)$ fuel temperature rise, inlet to exhaust-gas temperature, °F
- $c_{p,m}$ mean specific heat of fuel at constant pressure over temperature range

Afterburner theoretical enthalpy rise was based on the afterburner fuel flow plus the unburned fuel entering the afterburner from the primary burner. For those data with peroxide injection, complete decomposition in the primary burner, as indicated in reference 3, was assumed. Hydrogen peroxide enthalpy data were obtained from reference 8.

RESULTS

Afterburner Performance with No Liquid Injection

Combustion efficiencies obtained with afterburner configuration A (36-in. length with flameholder) at various afterburner fuel-air ratios and at inlet pressures of 11.5 and 20.5 inches of mercury absolute are shown in figure 4. Data were obtained at inlet temperatures of 1000°, 1200°, and 1400° F. Afterburner fuel-air ratios for over-all stoichiometry are indicated by arrows on the figure for the three inlet temperature conditions. The dashed curve shown in figure 4 represents complete combustion for fuel-air mixtures richer than stoichiometric. As previously indicated, the highest efficiency obtainable for such mixtures is less than 100 percent.

The afterburner configuration tested favored lean operation. Combustion efficiencies generally decreased rapidly at afterburner fuel-air ratios greater than 0.035 for all inlet conditions investigated. Combustion efficiency decreased approximately 10 percent at an inlet pressure of 20.5 inches of mercury absolute (fig. 4(a)) for fuel-air ratios ranging from 0.035 to stoichiometric. The trend is similar at lower pressures (fig. 4(b)), but the efficiency decreased about 13 percent for a similar fuel-air-ratio range. Richer mixtures caused further losses in combustion efficiency and resulted in eventual combustor blowout. At an inlet temperature of 1200° F, the rich limit was reduced from an afterburner fuel-air ratio of about 0.075 to 0.052 when the inlet pressure was reduced from 20.5 to 11.5 inches of mercury absolute. Similar reductions in rich-limit operation were noted at inlet temperatures of 1000° and 1400° F. Nevertheless, even at the more severe pressure condition, stable operation at over-all stoichiometric fuel-air ratios was possible.

The combustion-efficiency losses noted with rich operation probably result from uneven fuel distribution in the flameholder region. A rich pilot zone in the wake of the centerbody is suspected to have existed with the fuel-injection system used. More even fuel distribution at the flameholder cross section may have improved combustion efficiencies at the richer-mixture conditions; however, other injector designs were not investigated.

As shown in figure 4, increasing the inlet gas temperature resulted in reduced afterburner combustion efficiency at afterburner fuel-air ratios greater than 0.04. The effect was not clearly defined at leaner fuel-air ratios, however. At the constant-air-flow conditions of these tests, changing the inlet temperature altered both the afterburner inlet oxygen concentration and inlet velocity. For inlet temperatures ranging from 1000° to 1400° F, afterburner inlet oxygen concentrations varied from about 16.5 to 14 percent, respectively, and inlet reference velocities from 440 to about 608 feet per second, respectively. The decreased oxygen concentration and increased mixture velocity at the higher temperature hinder the combustion reaction. Also, although increased inlet temperature favors fuel vaporization and chemical reaction, it may also alter the effective fuel-air ratio in the region of the flameholder and cause localized overenrichment.

Combustion efficiency obtained with configurations A, B, and C at an inlet temperature of 1200° F and at an inlet pressure of 11.5 inches of mercury absolute is shown in figure 5. The severity of the conditions for the combustion process was increased in configurations B and C by the removal of the flameholder and by reducing the combustor length, respectively. With configuration B, flame seating could occur only in the wake of the diffuser centerbody, and flame spreading could thus occur only from this region. Configuration C represented a 50-percent reduction in combustor length, and, hence, in combustion time. The more severe combustion conditions, as represented by these configurations, resulted in generally poorer afterburner performance. When the flameholder was removed from configuration A, combustion efficiency decreased 9 to 14 percent and rich-limit blowout occurred at an afterburner fuel-air ratio of only 0.038 (over-all, 0.059). Thus, with configuration B, stable operation was limited to over-all fuel-air ratios less than 87 percent of stoichiometric. A 50-percent reduction in combustion length (or combustion time) from that of configuration A also resulted in efficiency losses and in restricted operating limits. Efficiencies of only 83 percent were obtained with configuration C as compared with about 97 percent for configuration A. The fuel-air ratio for rich-limit operation was greater than that for configuration B, but was still less (0.065) than that required for stoichiometric operation. Afterburner operation near the fuel-air-ratio limit was unstable and was characterized by partial blowout and relight.

Comparison of the curves of figure 5 indicates the contribution of increased flame spreading and of combustion time to afterburner performance. Increased flame spreading from suitably situated flameholders not only improved combustion efficiency, but also contributed appreciably to the stability of the combustor. On the other hand, combustion time, as represented by combustor length, primarily affected the efficiency of the combustion process.

Afterburner Performance with Water Injection

Stoichiometric afterburning with water injection was possible only with configuration A operating at test condition 1. The data are shown in figure 6. Water injection to a water-air ratio of 0.04 caused a 5-percent loss in combustion efficiency. At this point, combustor operation became unstable, and blowout occurred shortly thereafter. At the lower pressure of test condition 2, water injection at water-air ratios of less than 0.01 caused blowout of test configuration A at an over-all stoichiometric fuel-air ratio. Similarly, although the operating characteristics of configurations B and C precluded water injection at stoichiometric conditions, water-air ratios of less than 0.01 caused afterburner blowout at over-all fuel-air ratios of only 0.05. Generally, the water-injection limits were improved either by increased afterburner pressure or by reduced over-all fuel-air ratios. However, such improvements were not major, and configurations B and C were still limited to water-air ratios less than 0.03 even at over-all fuel-air ratios of 0.05 and afterburner inlet pressures of 20.5 inches of mercury absolute.

Afterburner Performance with 90-Percent Hydrogen Peroxide Injection

Afterburner combustion efficiencies with hydrogen peroxide injection are shown in figure 7 for the three test configurations investigated. Data are shown for test conditions 1 and 2 for afterburner configuration A. All other data are for test condition 2 only. For all data, over-all stoichiometric fuel-air ratios were approached. Thus, with peroxide injection to peroxide-air ratios of 0.1 and 0.3, over-all fuel-air ratios of approximately 0.08 and 0.11, respectively, were maintained. For comparison, the water-injection data of figure 6 are included in figure 7.

For all afterburner configurations investigated, hydrogen peroxide injection increased afterburner combustion efficiency. The efficiency of configuration A at the high-pressure test condition 1 was 90 percent at a peroxide-air ratio of 0.3 as compared with 84 percent with no liquid injection. The efficiency of the high-flow data point (injectant-air ratio of 0.32) for this configuration is estimated to be about 3 percent high since the over-all fuel-air ratio for this point was below stoichiometric. Lower rates of injection resulted in correspondingly smaller efficiency increases.

Similar results were obtained for all afterburner configurations at the low-pressure test condition 2. Injection to peroxide-air ratios of 0.3 resulted in efficiency increases of at least 5 percent over that for no injection. At the more severe combustion conditions in configurations B and C the increases were greater. Although these configurations were normally inoperable at stoichiometric conditions with no liquid injection, injection to peroxide-air ratios of 0.3 resulted in combustion efficiencies of 82 and 84-percent, respectively.

Although stable operation of afterburner configuration A with water injection was possible at the stoichiometric conditions of test condition 1, rapid efficiency loss and combustor blowout resulted from such injection. At the same test condition, $7\frac{1}{2}$ times as much 90-percent hydrogen peroxide was injected without encountering combustion blowout in the afterburner. Injection was limited to a peroxide-air ratio of about 0.3 by the system storage capacity, test-facility capacity, and run time rather than by combustion stability limits. At the low-pressure test condition 2, stoichiometric combustion with water injection was impossible with any of the afterburner configurations investigated. However, all configurations burned stably with hydrogen peroxide injection to injectant-air ratios as high as 0.3. Even at peroxide-air ratios as low as 0.1, the stability of configurations B and C was greatly improved. With no injection, combustion blowout occurred with configurations B and C at fuel-air ratios less than 0.0675 (fig. 5), but with hydrogen peroxide injection to an injectant-air ratio of only 0.1, combustion was stable to an over-all stoichiometric fuel-air ratio of 0.08.

DISCUSSION

Effect of Hydrogen Peroxide on Combustion Performance

The effect of hydrogen peroxide injection on the performance of a turbojet combustor and on the performance of a simulated afterburner has been evaluated at two simulated flight conditions. Performance data for the primary combustor are reported in reference 3, and these results showed that at least three times as much peroxide as water could be injected without suffering penalties in combustion efficiency or stability. The results of the present afterburner-performance investigation showed similar results. Although even low rates of water injection could not be tolerated by the afterburner, it was possible to inject hydrogen peroxide at a rate limited only by the test facility without penalizing afterburner efficiency.

Combustor performance, then, of either the primary engine combustor or of the afterburner does not limit the amount of hydrogen peroxide that may be injected for thrust-augmenting purposes. Combustor performance

was, in fact, improved for both the engine combustor and for the afterburner. Afterburner stability, especially, was improved by peroxide injection. Even low rates of hydrogen peroxide injection stabilized combustion in normally inoperative afterburner configurations. Such marked improvements in afterburner performance resulting from hydrogen peroxide injection may permit the design and efficient operation of afterburners having a higher inlet velocity, lower internal drag, and shorter over-all lengths than those now in use. Appreciable improvements in powerplant weight and over-all performance might thus be realized.

Effect of Peroxide Injection on Engine Thrust

The thrust of a turbojet engine may be increased by increasing either the fluid mass of the jet or by increasing its temperature. An ideal augmentation system would increase both without attendant losses in combustion efficiency or combustion stability to compromise the mass increase. Hydrogen peroxide approaches such an ideal liquid injectant for thrust augmentation since both mass and temperature of the jet may be increased without incurring large combustion performance losses as are incurred with water injection.

Fluid mass increase. - Since hydrogen peroxide injection does not penalize combustion in either the primary combustor or in the afterburner, large quantities may be injected, and, hence, large increases in jet fluid mass may be attained. Also, since the decomposition of the peroxide increases the afterburner inlet oxygen concentration as shown in figure 8, fuel flow to the afterburner may be increased accordingly. Stoichiometric fuel-air ratio for JP-4 fuel increases from 0.0675 with no peroxide injection to 0.104 at a peroxide-air ratio of 0.3 since 0.123 pound of additional fuel is required to burn the oxygen released by 1 pound of 90-percent hydrogen peroxide. Thus, even greater increases in mass may be attained. A practical limit for peroxide injection, however, is imposed by compressor surge and occurs near a peroxide-air ratio of 0.32 for a typical 5.3-compressor-pressure-ratio engine at rated speed, zero Mach number, and sea level conditions. This may be compared with the injection limit imposed by combustion instability at a water-air ratio of 0.065 with water-alcohol injection at stoichiometric conditions (ref. 9).

Equilibrium temperature increase. - A comparison of the effect of water or hydrogen peroxide on the calculated equilibrium temperature for a stoichiometric JP-4 fuel - air injectant system is shown in figure 9. These curves were calculated by the method of reference 10 for an initial reactant temperature of 437° R and include the effect of product dissociation. With peroxide injection, the reaction temperature increases as a result of the heat of decomposition of the peroxide, the increased oxygen concentration, and, hence, increased fuel flow at stoichiometry. With water injection, combustion temperature falls sharply, since fuel flow is

constant ($f = 0.0675$), and heat is absorbed by the heating and vaporization of the injected water. Thus, at the compressor-limited peroxide-air ratio of 0.32, the reaction temperature approaches 4290° R as compared with 3700° R at a stability-limited water-air ratio of 0.065. In practice, however, the temperature difference between the two systems would be even greater at these points because of the combustion-efficiency losses associated with water injection.

Augmented net-thrust-ratio increase. - The augmented-net-thrust ratio was calculated for liquid injection to a 5.3-compressor-pressure-ratio engine with an afterburner. The results are shown in figures 10 and 11. For these calculations, the following assumptions were made: rated engine speed at altitude at a flight Mach number of 0.6; choked turbine and exhaust nozzle; primary combustor pressure loss, 5 percent; afterburner pressure loss, 12 percent; complete ram-pressure recovery; theoretical equilibrium reaction temperatures (fig. 9); and experimental afterburner combustion efficiencies (fig. 7) with stoichiometric afterburning. The data are plotted on the basis of augmented liquid ratio, defined as the ratio of the total liquid consumption to the primary-combustor fuel flow with no liquid augmentation.

The results of these calculations using the data from test configuration A for an altitude of 32,500 feet with water and hydrogen peroxide injection are shown in figure 10. For comparison, an additional calculated point for stoichiometric afterburning of a magnesium-slurry fuel is included.

At an augmented liquid ratio of about 6, the augmented net-thrust ratio of an afterburning engine with water injection is limited to about 1.68 by combustion blowout in the afterburner. With peroxide injection at the same augmented liquid ratio, the augmented net-thrust ratio is about 1.79, which is 6 percent greater than that with water injection. However, at injection rates limited by compressor surge (augmented liquid ratio, 24) for peroxide injection and limited by afterburner instability (augmented liquid ratio, 6) for water injection, the augmented net-thrust ratio of 2.78 attainable with peroxide injection is 65 percent greater than that calculated for water injection.

The thrust advantage for peroxide injection is apparent from an examination of the slopes of the two curves of figure 10. Efficient high-temperature afterburner performance with peroxide injection is the prime factor contributing to the increased slope of that curve; thus, appreciably more favorable thrust - liquid consumption ratios are calculated for peroxide injection than for water injection. At higher rates of liquid consumption, the difference in thrust obtainable with these two systems also increases since combustion losses attendant with water injection become increasingly severe.

Figure 11 shows the results of similar calculations for altitude flight at 45,000 feet for peroxide augmentation of the three afterburner configurations tested. At this condition, measurable quantities of water could not be injected without causing afterburner blowout in any of the test configurations. The calculations for configurations B and C are further restricted to fuel-air ratios less than stoichiometric because of afterburner instability. With peroxide injection, however, the calculated augmented net-thrust ratios for all three configurations tested are closely similar and are within approximately 10 percent of the theoretical ratios calculated for this flight condition.

SUMMARY OF RESULTS

The effect of the injection of water or 90-percent hydrogen peroxide for thrust augmentation on the combustion performance of three different afterburner configurations was determined at simulated altitude flight conditions. The following results were obtained:

1. With no liquid injection, increased afterburner inlet pressure, increased afterburner length, and improved flame spreading with flameholders generally increased afterburner efficiency and fuel-air-ratio range for stable operation. At an inlet pressure of 11.5 inches of mercury absolute, the maximum fuel-air ratios for stable operation for an afterburner with a flameholder, one having no flameholder, and one reduced in length by 50 percent were 0.075, 0.059, and 0.065, respectively.

2. At afterburner inlet conditions simulating flight at 32,500 feet with stoichiometric afterburning, water injection to a water-air ratio of 0.04 caused combustion blowout in the afterburner. Reduced pressure, limited flame spreading, or reduced combustion time limited water injection rates to water-air ratios less than 0.01.

3. At least $7\frac{1}{2}$ times as much hydrogen peroxide as water could be injected into all configurations tested without the occurrence of afterburner instability or combustion blowout. Even injection to peroxide-air ratios as low as 0.1 stabilized combustion in normally unstable afterburner configurations having limited flame spreading or limited combustion time.

4. Hydrogen peroxide injection to peroxide-air ratios of 0.3 resulted in combustion efficiencies of 82 to 90 percent, representing an increase of at least 5 percentage points over that for no injection.

CONCLUDING REMARKS

High-strength hydrogen peroxide has been proposed as a liquid injectant superior to water for injection into engine combustors for thrust augmentation. Combustion tests recently concluded have indicated that

combustion performance losses associated with water injection do not occur when peroxide is used as the injectant. The combustion efficiency of both the primary combustor and of the afterburner increases with peroxide injection. However, improvements in combustion stability with peroxide injection are especially great. Thus, even low rates of peroxide injection may greatly improve the performance of normally unstable combustors.

Calculations have indicated that, with peroxide injection, large increases in augmented net-thrust ratios are possible because of improved combustion performance. However, at maximum rates of liquid augmentation of an afterburning engine with hydrogen peroxide, total liquid consumption may increase by a factor of 6 over that for stoichiometric afterburning alone, so that up to 42 percent of the total fluid passing through the powerplant would be fuel and peroxide. This must necessarily be considered a portion of aircraft gross weight and may unduly penalize aircraft performance. Therefore, because of the weight penalty, for a given flight plan, it may be more advantageous to operate below maximum attainable thrust to minimize the attendant weight penalty associated with liquid augmentation. For the case of augmentation on takeoff only, the penalty may not be as severe, since the additional fluid weight would be dissipated by the time the aircraft is airborne.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 31, 1956

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TABLE I. - FUEL ANALYSIS

	MIL-F-5624C, grade JP-4
A.S.T.M. Distillation D86-46, °F	
Initial boiling point	152
Percent evaporated	
5	214
10	239
20	257
30	270
40	282
50	294
60	305
70	317
80	334
90	356
95	379
Final boiling point	421
Residue, percent	1.0
Loss, percent	0.5
Reid vapor pressure, lb/sq in.	2.6
Specific gravity, 60°/60° F	0.763
Hydrogen-carbon ratio	0.171
Net heat of combustion, Btu/lb	18,710
Aniline point, °F	135.7

TABLE II. - AFTERBURNER COMBUSTION PERFORMANCE DATA

After-burner configuration	Com-bustor inlet air flow, lb/sec	After-burner inlet pressure, in. Hg abs	After-burner inlet temperature, °F	Primary burner fuel-air ratio	After-burner fuel flow, lb/hr	After-burner fuel-air ratio	Over-all fuel-air ratio	Injectant flow rate, lb/hr	Injectant-air ratio	After-burner combustion efficiency, percent	After-burner reference velocity, ft/sec	Figure		
No liquid injection														
A	4.32	20.5	1005	0.0148	730	0.0508	0.0656			85.1	456	4(a)		
	4.31	20.5	1010	.0148	1100	.0709	.0857			64.0	464			
	4.32	20.5	1000	.0150	520	.0334	.0484			92.1	445			
	4.32	20.6	1000	.0152	330	.0212	.0364			83.6	440			
	4.33	20.6	1200	.0172	760	.0488	.0659			86.7	515			
	4.36	20.7	1195	.0170	763	.0486	.0656			84.0	515			
	4.29	20.3	1200	.0171	1075	.0696	.0867			61.1	527			
	4.30	20.4	1200	.0172	520	.0336	.0507			96.2	509			
	4.31	20.5	1200	.0172	295	.0190	.0363			97.8	548			
	4.30	20.5	1205	.0172	775	.0501	.0673			85.4	516			
	4.32	20.5	1200	.0171	520	.0334	.0505			96.5	509			
	4.32	20.5	1200	.0172	308	.0198	.0370			97.6	502			
	4.32	20.5	1210	.0172	1048	.0674	.0846			64.4	529			
	4.31	20.5	1400	.0207	725	.0467	.0674			83.1	578			
	4.31	20.5	1400	.0198	465	.0300	.0428			92.7	564			
	4.30	20.5	1400	.0199	615	.0397	.0597			87.1	573			
	4.30	20.5	1400	.0199	760	.0491	.0690			77.7	567			
	4.30	20.5	1400	.0199	938	.0606	.0805			65.1	584			
	A	2.50	11.3	995	.0189	308	.0342	.0531			84.2		470	4(b)
		2.50	11.6	1000	.0176	440	.0489	.0665			82.1		465	
2.50		11.5	1000	.0174	302	.0336	.0510			95.5	462			
2.50		11.7	1000	.0173	480	.0533	.0707			77.7	463			
2.49		11.8	1000	.0170	310	.0415	.0584			92.0	452			
2.48		11.8	1000	.0170	370	.0450	.0679			92.4	454			
2.50		11.7	1000	.0173	490	.0544	.0717			Blowout				
2.53		11.5	1190	.0207	415	.0456	.0663			79.9	536			
2.51		11.6	1190	.0206	460	.0509	.0715			74.8	530			
2.50		11.4	1185	.0207	310	.0344	.0552			97.4	527			
2.50		11.8	1200	.0201	428	.0476	.0676			83.8	520			
2.49		11.5	1200	.0202	320	.0357	.0559			93.1	526			
2.50		11.8	1200	.0201	375	.0417	.0617			87.0	517			
2.49		11.7	1200	.0200	430	.0480	.0680			79.9	523			
2.50		11.8	1200	.0201	475	.0525	.0726			Blowout				
2.50		11.3	1400	.0238	385	.0428	.0665			80.2	608			
2.50		11.5	1400	.0229	405	.0450	.0679			79.7	598			
2.50		11.5	1405	.0229	350	.0389	.0618			87.2	596			
2.50		11.6	1405	.0229	300	.0333	.0562			93.0	588			
2.50		11.5	1400	.0229	414	.0460	.0689			Blowout				
B	2.47	11.1	1200	.0197	200	.0225	.0422			78.8	533	5		
	2.50	11.6	1200	.0196	285	.0317	.0513			87.0	521			
	2.50	11.4	1200	.0194	340	.0378	.0572			81.7	533			
	2.52	11.6	1200	.0195	315	.0347	.0542			88.5	525			
	2.50	11.5	1200	.0201	325	.0361	.0562			81.9	528			
	2.51	11.6	1210	.0201	265	.0293	.0495			89.6	525			
C	2.53	11.6	1200	.0206	322	.0354	.0560			80.6	530	5		
	2.54	11.6	1200	.0205	392	.0429	.0633			73.8	535			
	2.53	11.6	1205	.0206	380	.0417	.0623			77.4	534			
	2.50	11.6	1205	.0206	395	.0439	.0644			77.9	529			
	2.52	11.5	1200	.0205	320	.0353	.0557			85.3	532			
Water injection														
A	4.32	21.1	1200	.0202	730	.0469	.0671	417.3	0.0268	82.9	515	6		
	4.31	21.5	1200	.0219	695	.0448	.0667	579.8	.0374	82.2	509			
	4.30	21.0	1195	.0200	735	.0475	.0675	579.8	.0245	78.6	516			
	4.30	21.3	1190	.0232	690	.0446	.0677	599.8	.0387	77.5	510			
4.32	21.0	1200	.0217	690	.0444	.0660	499.8	.0321	81.8	519				
Hydrogen peroxide injection														
A	4.30	29.0	1235	.0191	1190	.0769	.0959	4693	.3033	92.8	487	7		
	4.32	23.5	1205	.0183	955	.0614	.0797	1855	.1193	85.4	508			
	4.31	27.0	1225	.0185	1155	.0744	.0929	3091	.1993	86.8	481			
	2.50	14.5	1200	.0216	530	.0589	.0805	857.17	.0952	85.8	466			
2.50	18.5	1210	.0221	745	.0828	.1049	2698.0	.2998	86.8	439				
B	2.51	17.0	1200	.0229	745	.0824	.1053	2683.9	.2970	81.9	476	7		
	2.52	13.5	1200	.0223	540	.0595	.0818	913.4	.1007	72.2	507			
C	2.50	18.0	1230	.0224	745	.0827	.1052	2689.9	.2968	83.9	456	7		
	2.52	14.3	1205	.0216	538	.0593	.0809	955.5	.1053	78.1	482			

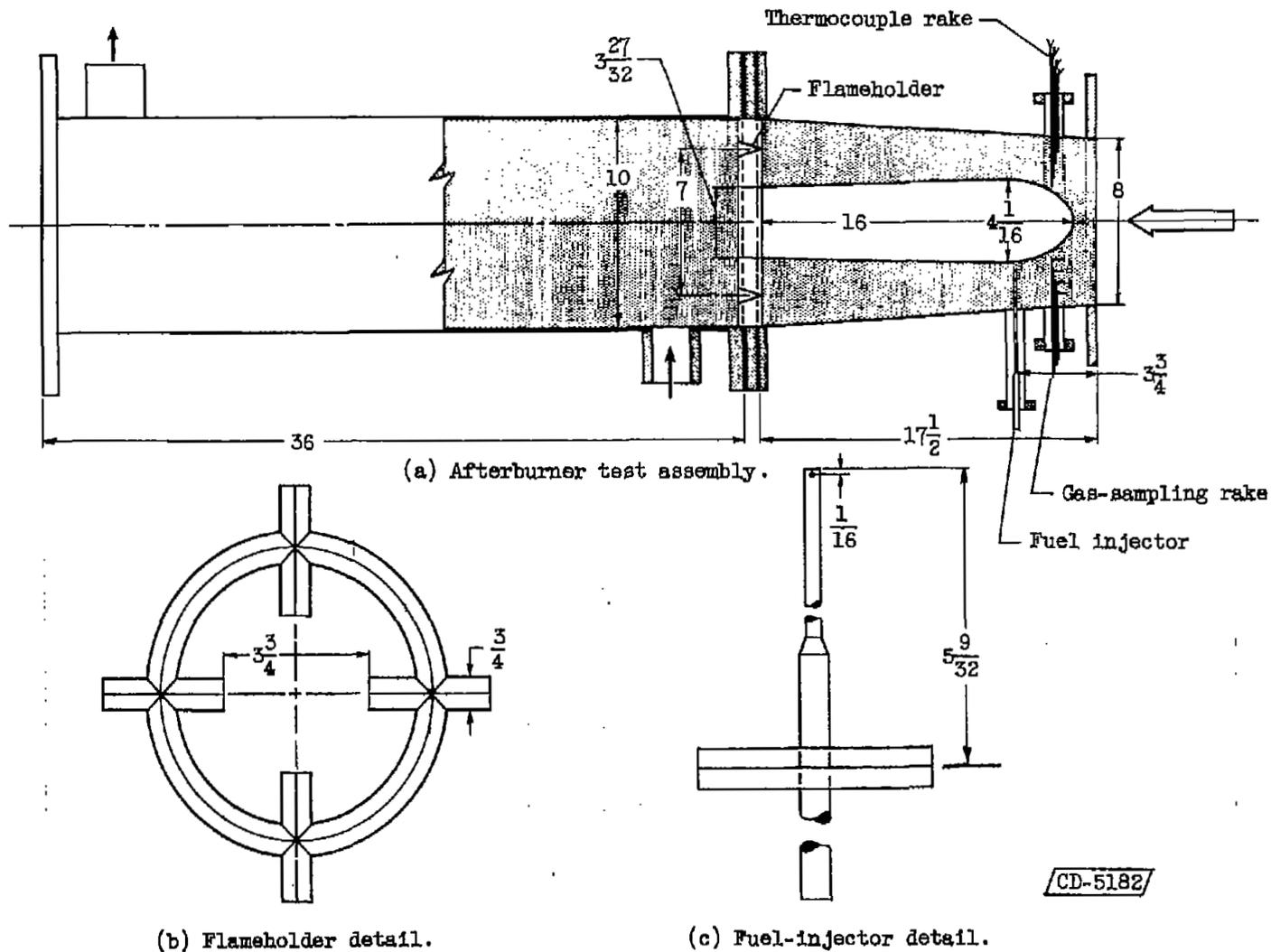
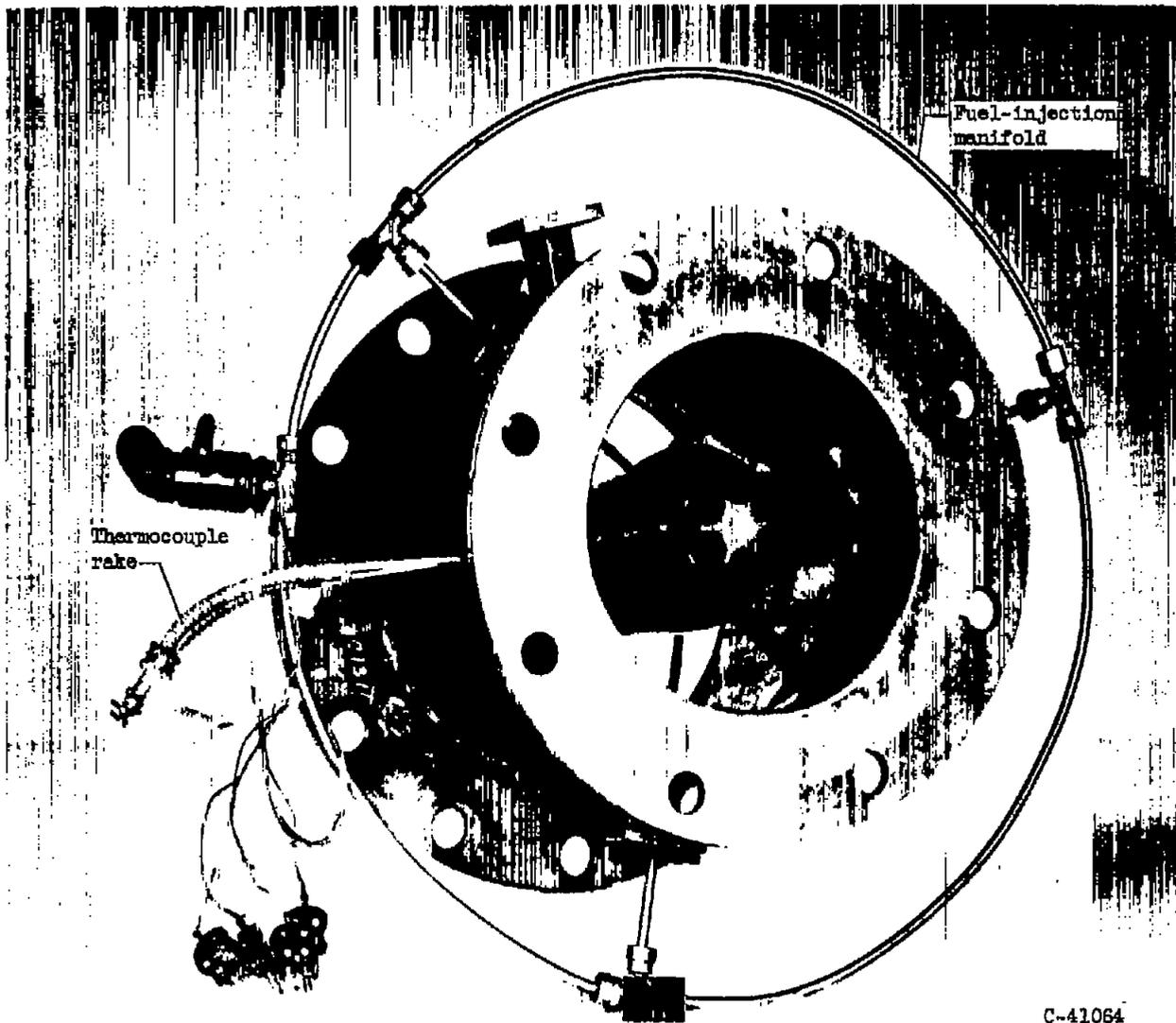


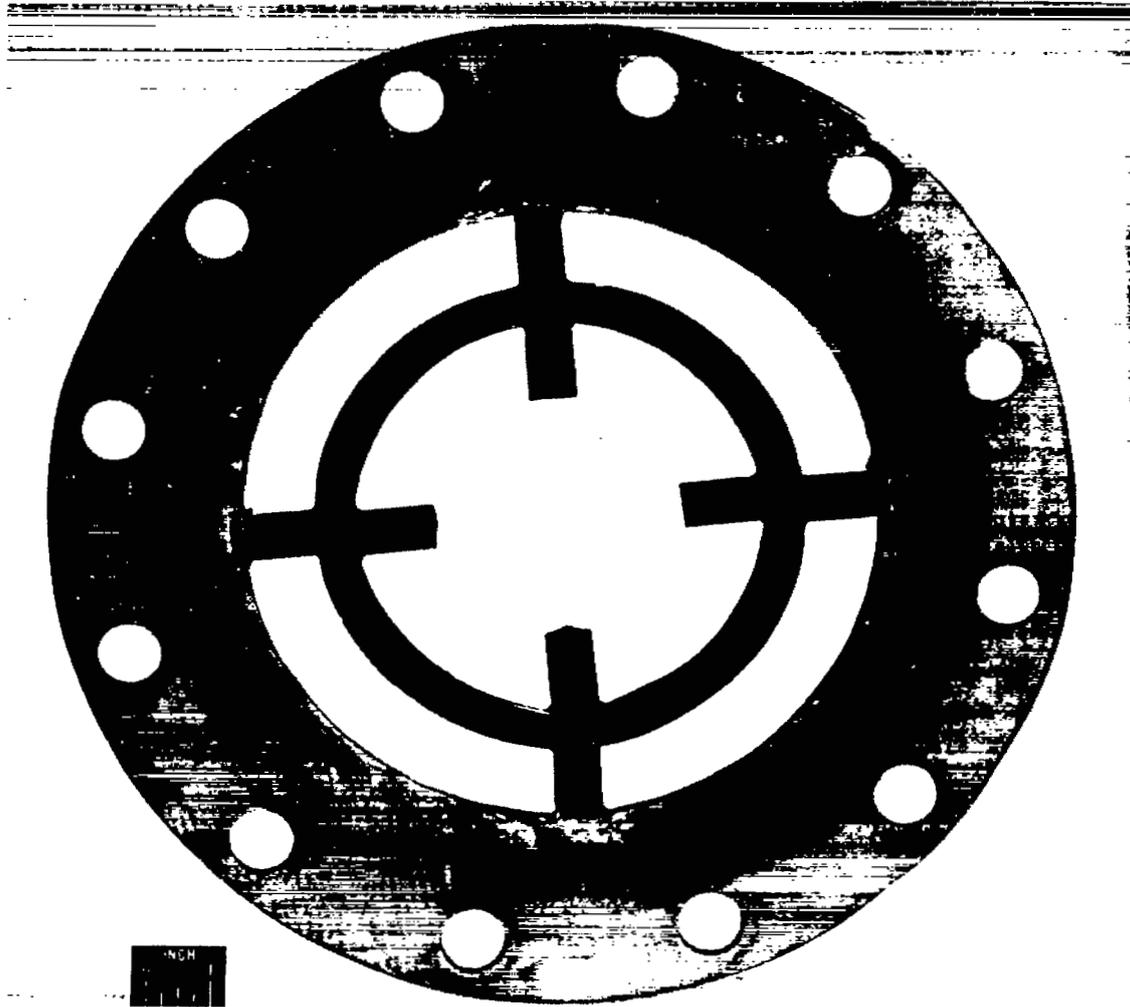
Figure 1. - Afterburner test configuration A and inlet diffuser section showing details of assembly, injection, and instrumentation. (All dimensions in inches.)

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(a) Diffuser section showing fuel-injector positions.

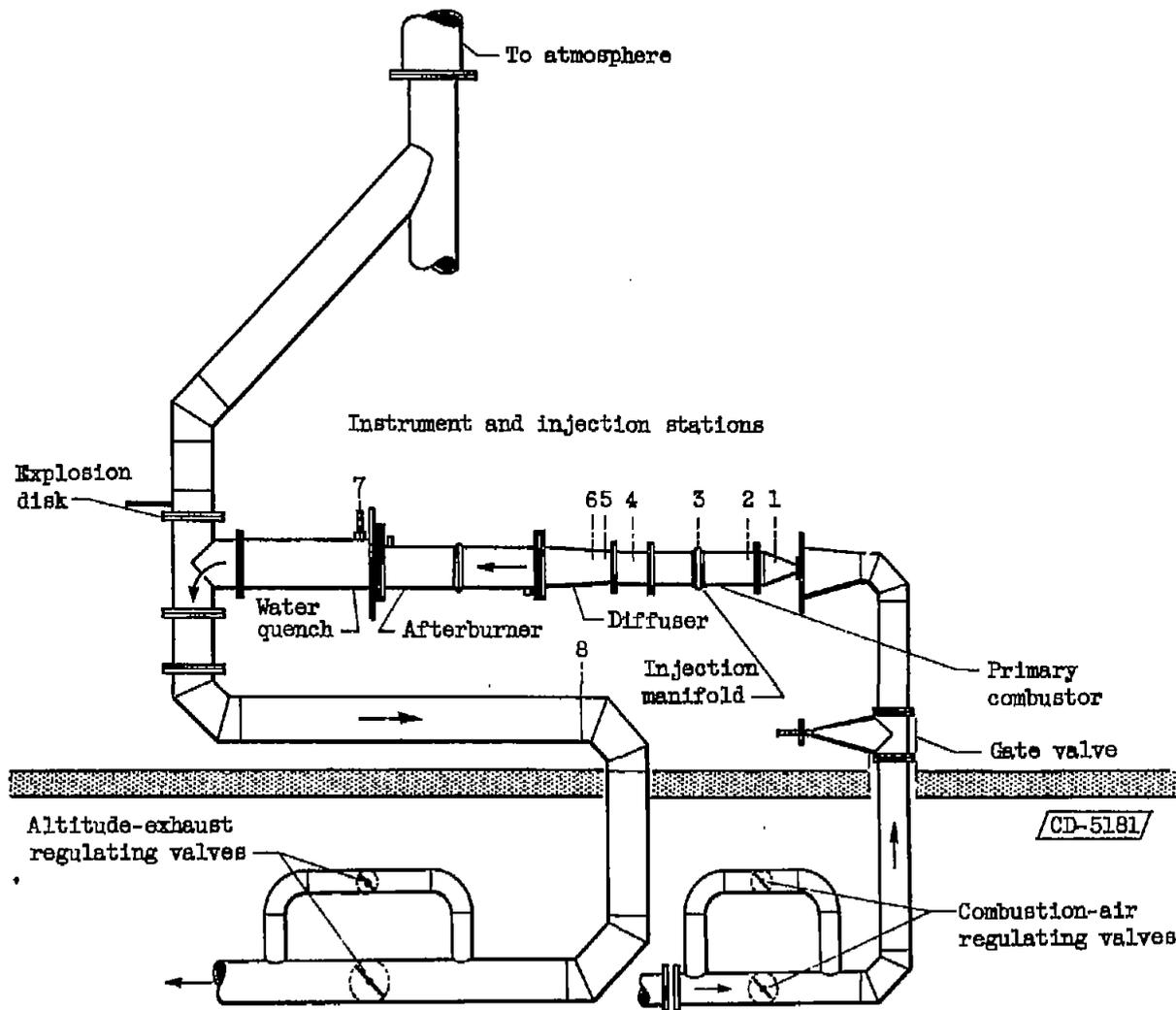
Figure 2. - Diffuser section and 3/4-inch V-gutter flameholder used for test configurations A and C.



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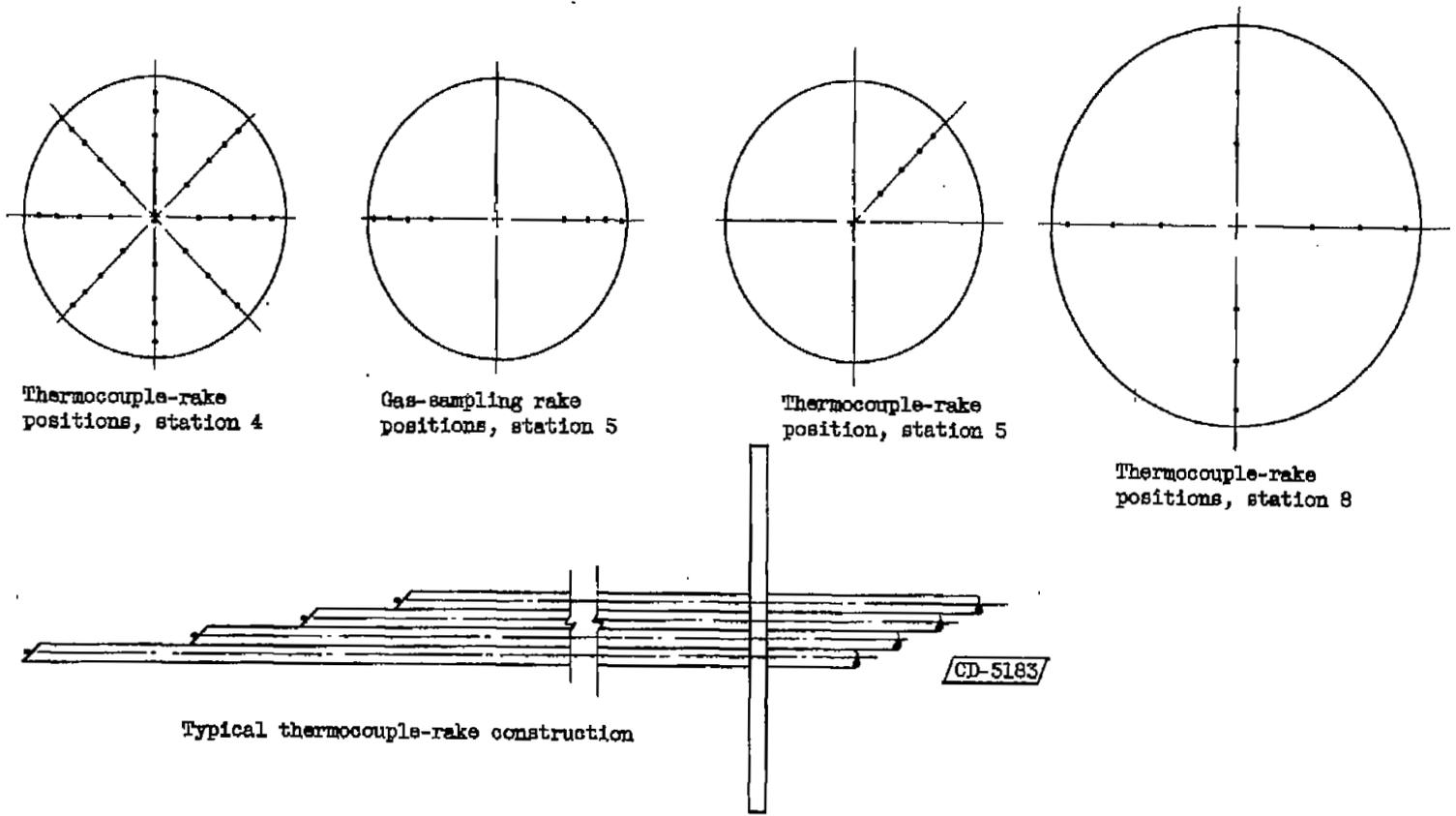
(b) Single V-gutter annular flameholder.

Figure 2. - Concluded. Diffuser section and 3/4-inch V-gutter flameholder used for test configurations A and C.



(a) Test facility.

Figure 3. - Apparatus and instrumentation details for afterburner performance investigation.



Thermocouple-rake positions, station 4

Gas-sampling rake positions, station 5

Thermocouple-rake position, station 5

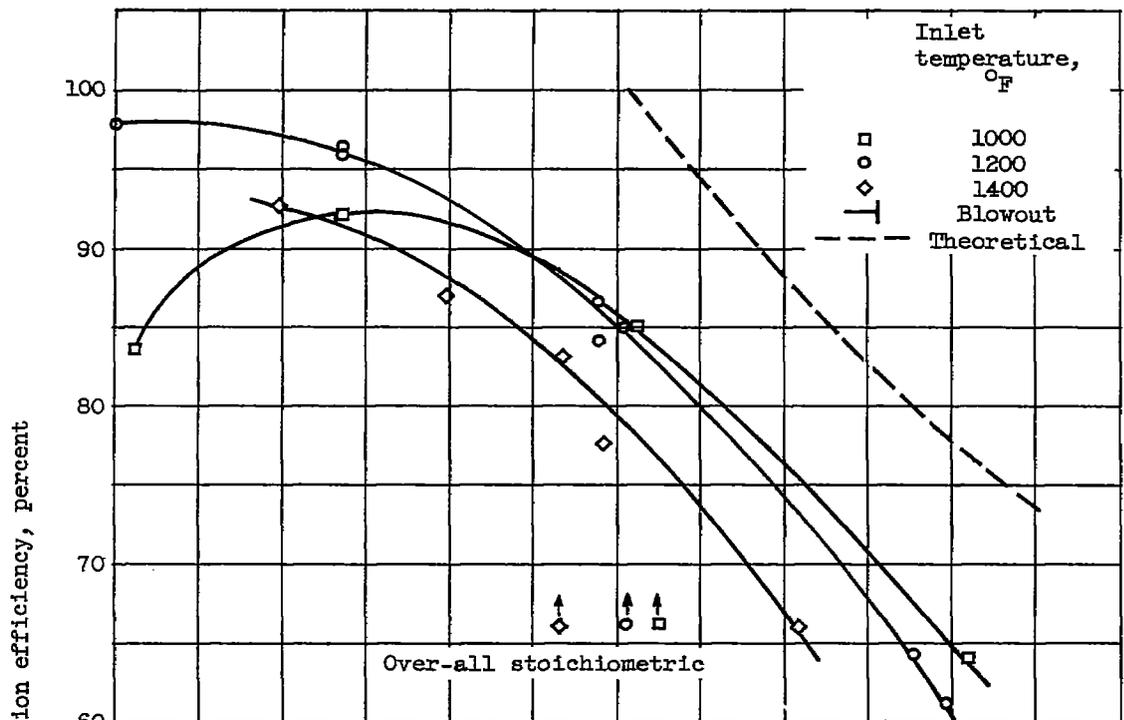
Thermocouple-rake positions, station 8

Typical thermocouple-rake construction

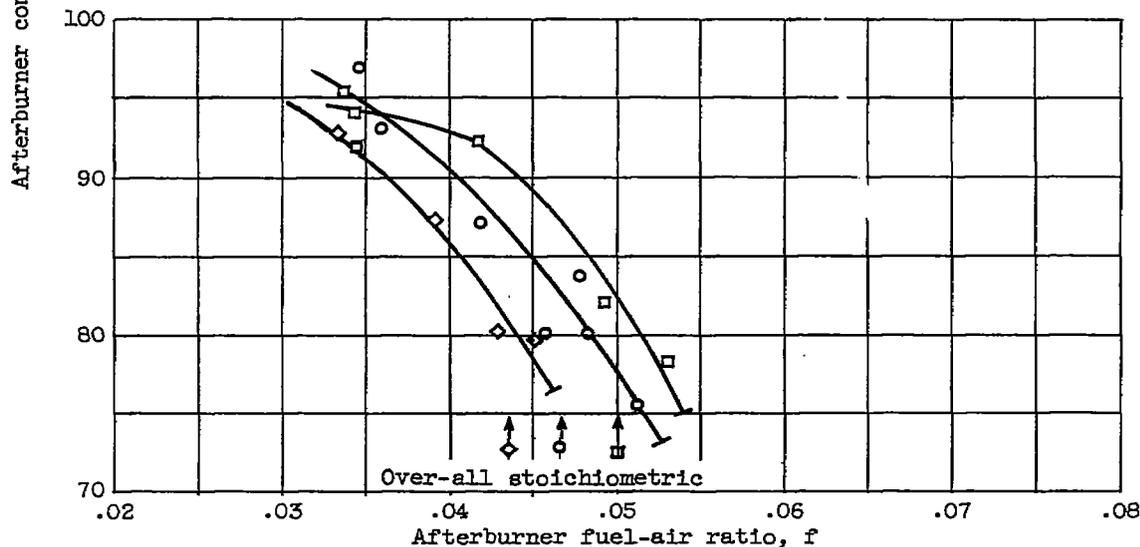
(b) Instrumentation details.

Figure 3. - Concluded. Apparatus and instrumentation details for afterburner performance investigation.

4159



(a) Inlet pressure, 20.5 inches of mercury absolute.



(b) Inlet pressure, 11.5 inches of mercury absolute.

Figure 4. - Performance of afterburner configuration A for three inlet temperatures and two inlet pressures. No liquid injection.

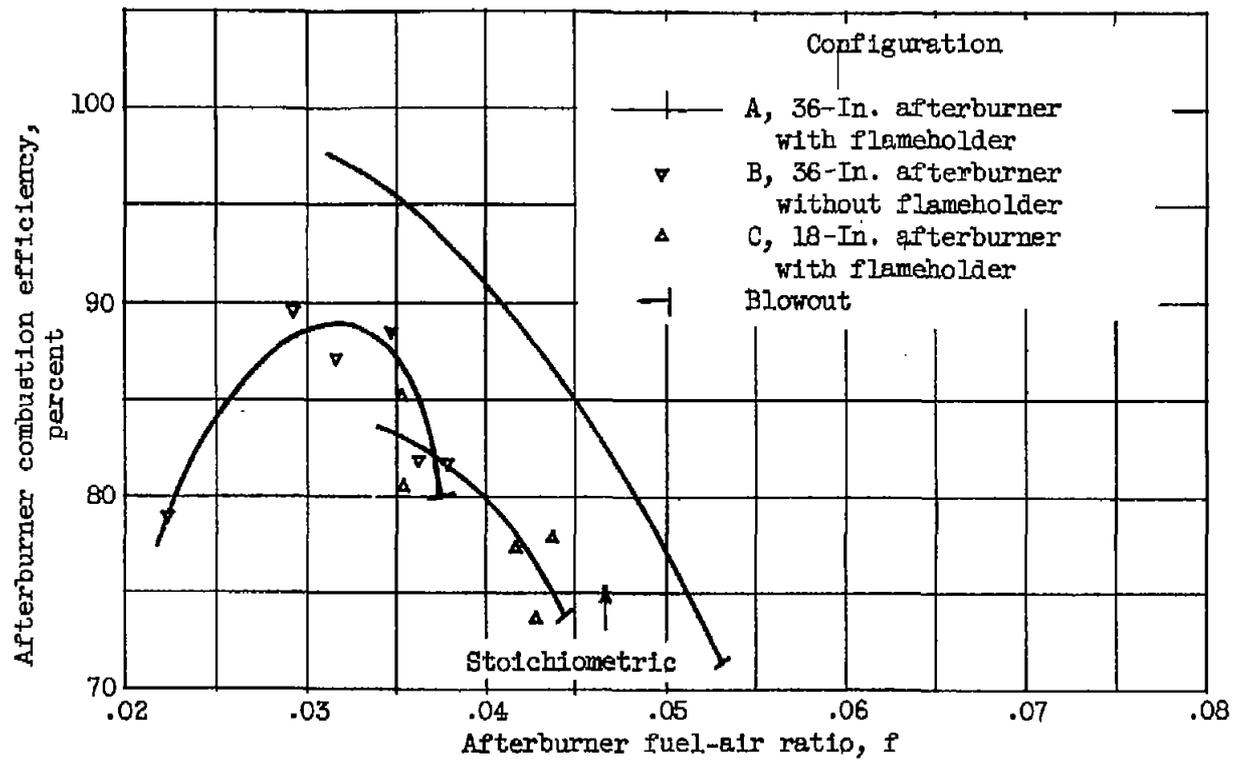


Figure 5. - Comparison of performance of afterburner configurations A, B, and C. No liquid injection; inlet pressure, 11.5 inches of mercury absolute; inlet temperature, 1200° F.

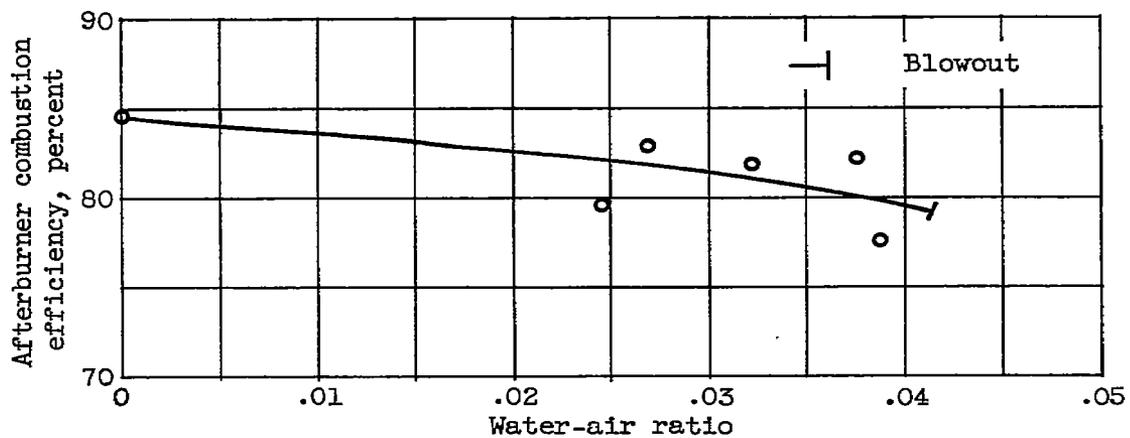


Figure 6. - Combustion efficiency of test configuration A with water injection at over-all stoichiometric fuel-air ratio at test condition 1.

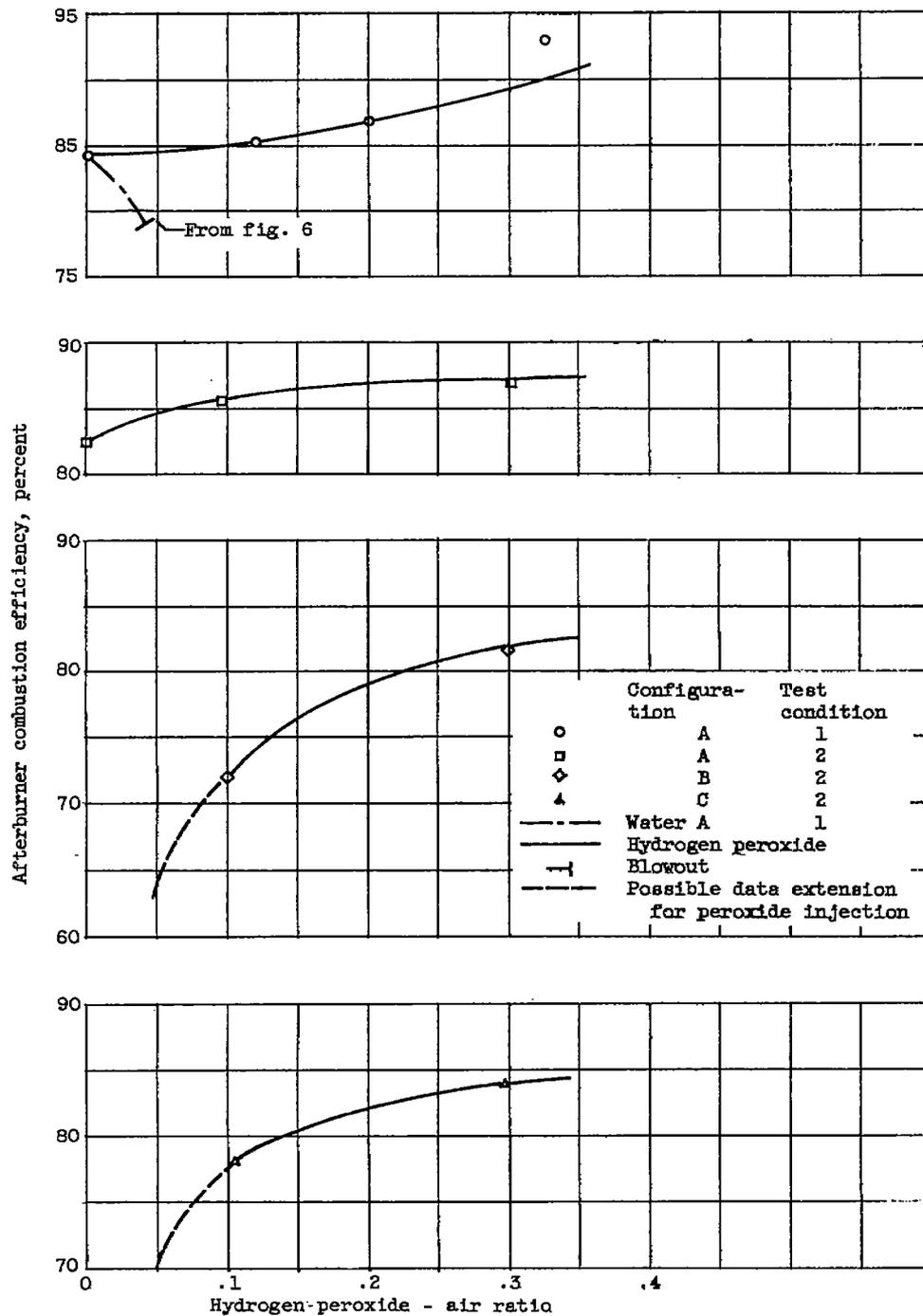


Figure 7. - Combustion efficiency of test configurations A, B, and C at over-all stoichiometric fuel-air ratio with hydrogen peroxide injection. Inlet temperature, 1190° to 1240° F.

4159

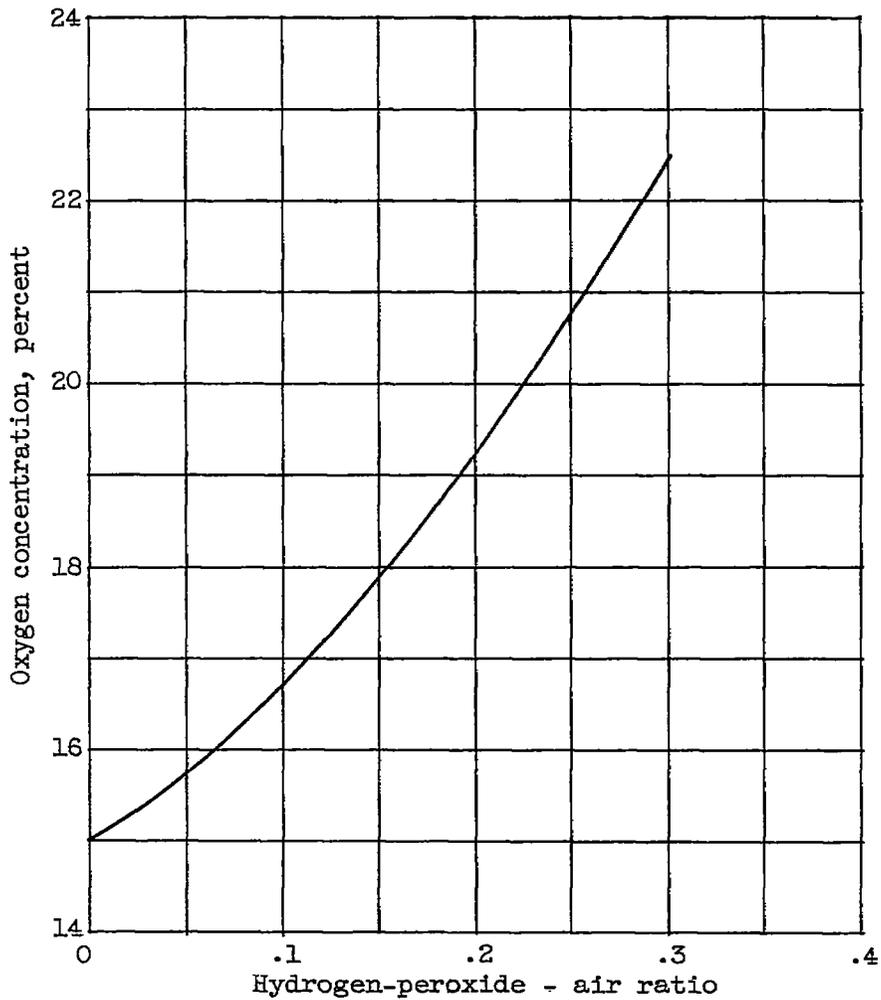
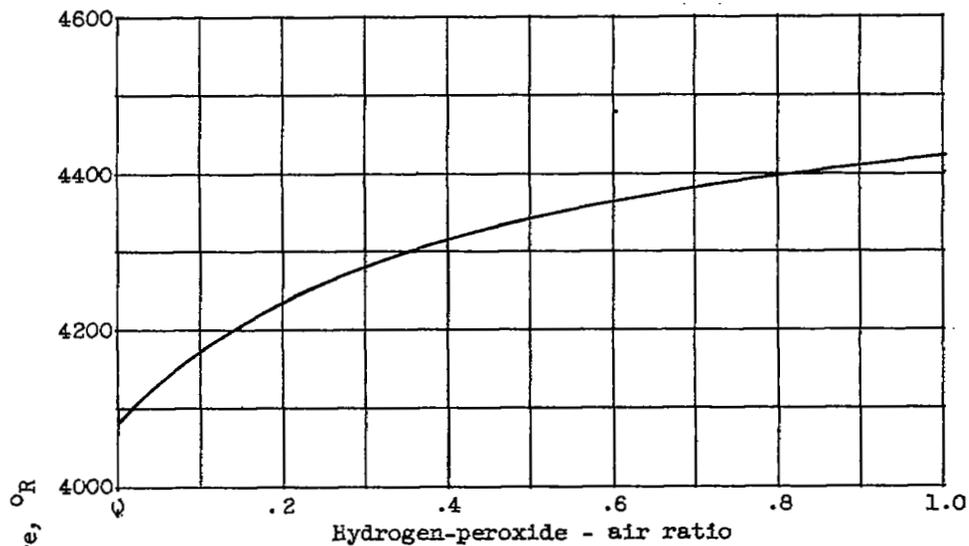
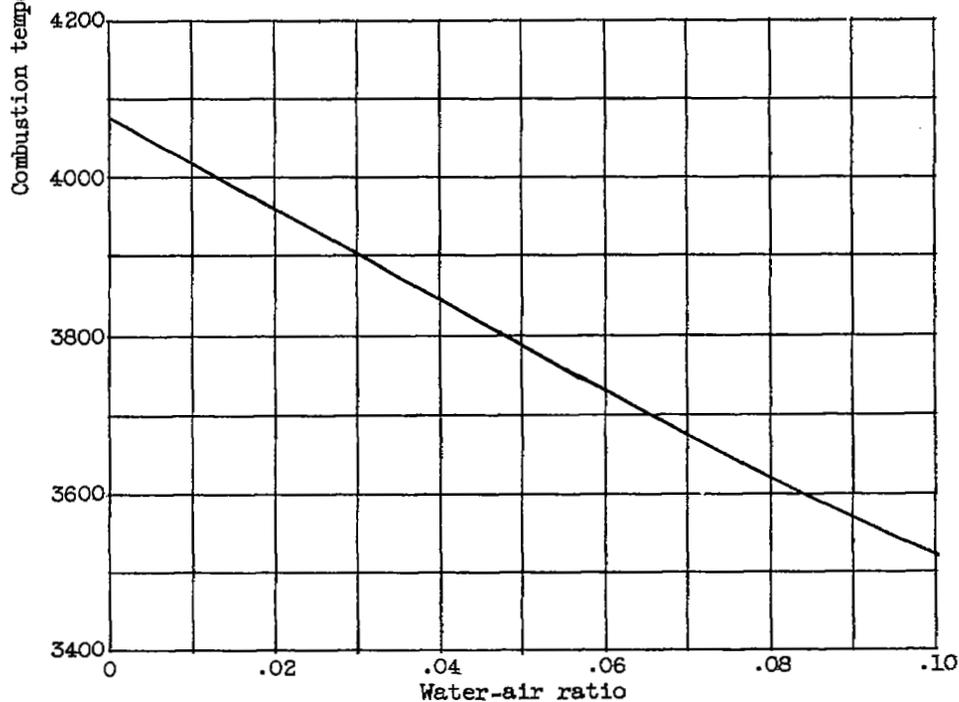


Figure 8. - Typical variation of afterburner inlet oxygen concentration with hydrogen peroxide injection.



(a) Hydrogen peroxide injection.



(b) Water injection.

Figure 9. - Theoretical stoichiometric combustion temperature of JP-4 fuel and air with hydrogen peroxide or water as the liquid injectant. Base temperature, 437° R.

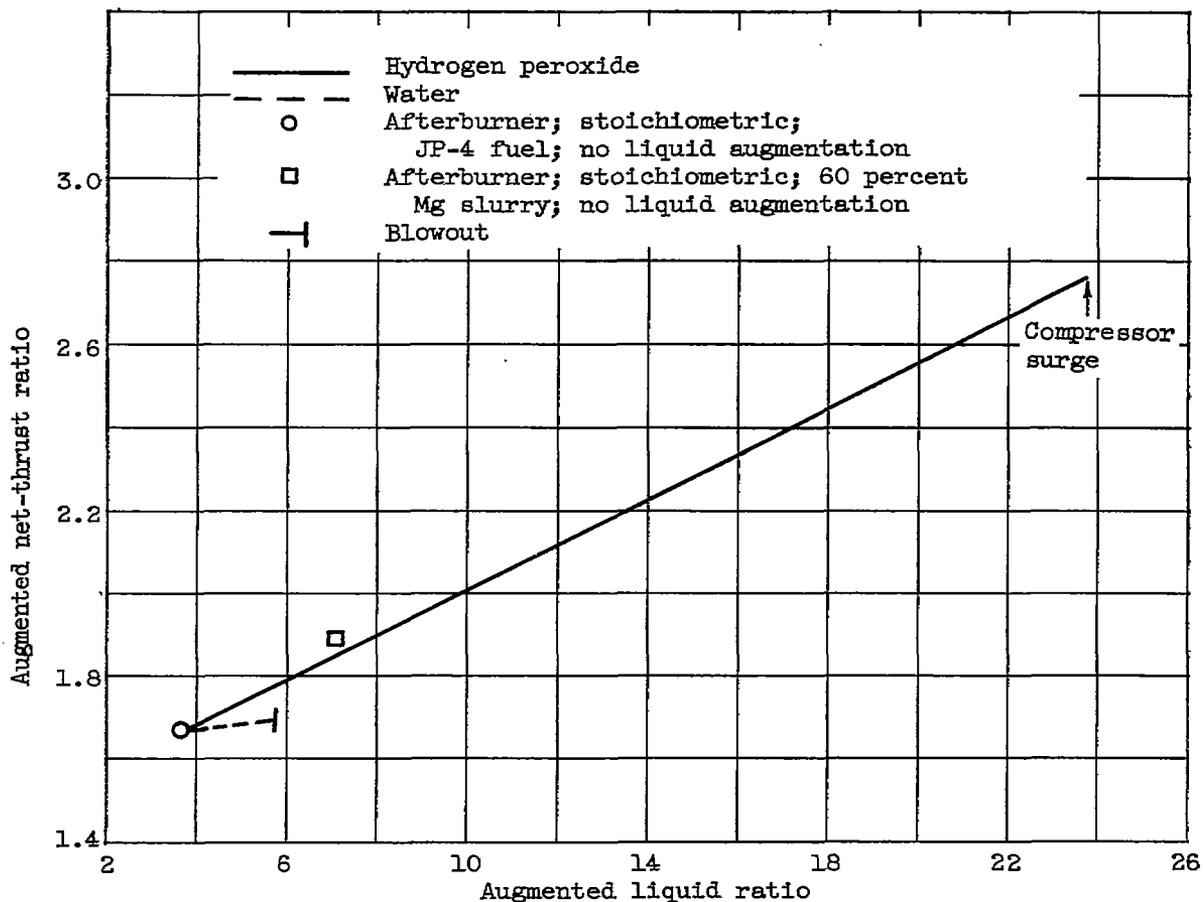


Figure 10. - Comparison of calculated net-thrust ratio for test configuration A with water and hydrogen peroxide injection. Engine compressor pressure ratio, 5.3; engine speed, 7950 rpm; flight Mach number, 0.6; altitude, 32,500 feet; afterburner efficiency from figure 7; liquid injection into combustor; choked turbine and exhaust nozzle.

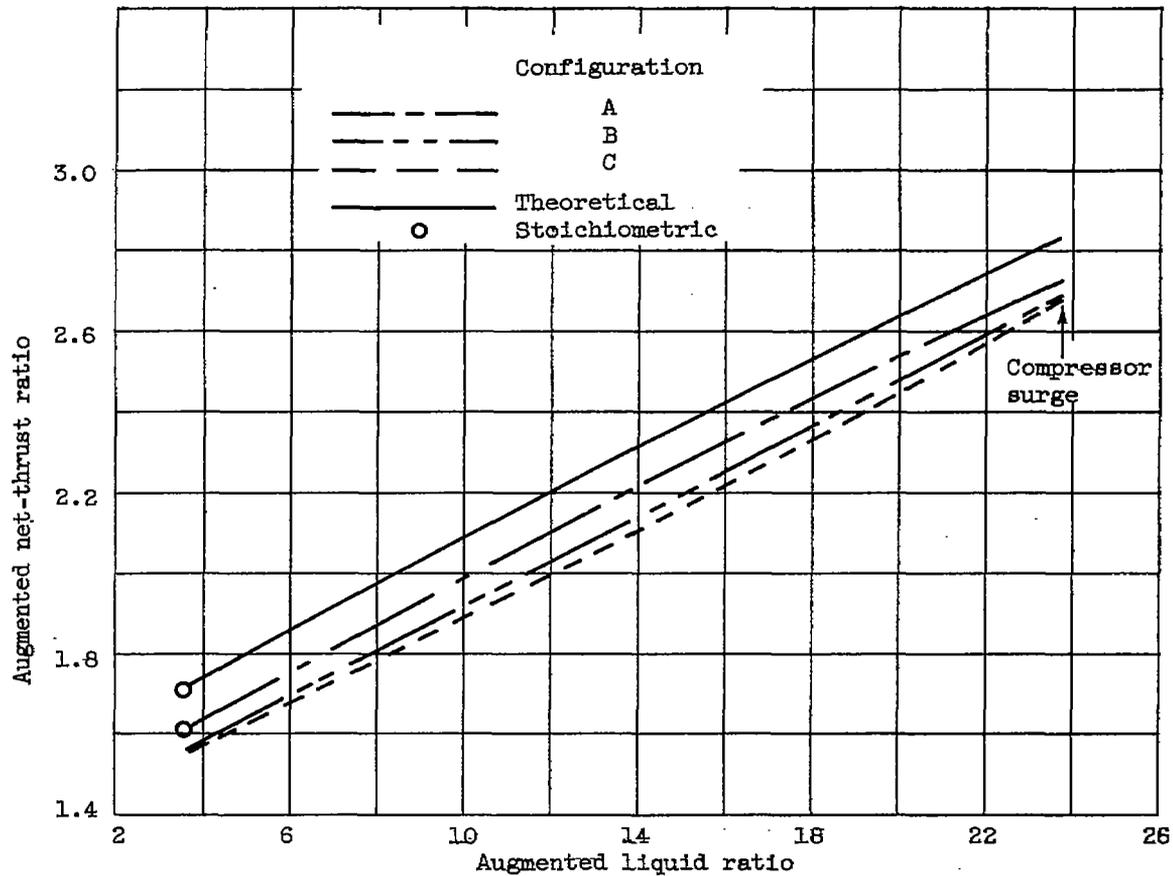


Figure 11. - Comparison of calculated net-thrust ratios for three test afterburner configurations with hydrogen peroxide injection into primary engine combustor. Engine compressor pressure ratio, 5.3; engine speed, 7950 rpm; flight Mach number, 0.6; altitude, 45,000 feet; turbine and exhaust nozzle choked.

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