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RESEARCH MEMORANDUM

TURBOJET COMBUSTOR PERFORMANCE WITH INJECTION OF HYDROGEN PEROXIDE FOR THRUST AUGMENTATION

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RESEARCH MEMORANDUM

TURBOJET COMBUSTOR PERFORMANCE WITH INJECTION OF HYDROGEN PEROXIDE FOR THRUST AUGMENTATION

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SUMMARY

High-strength hydrogen peroxide, a possible thrust-augmenting liquid, was injected in a tubular combustor and the resulting performance was studied. Combustor-inlet pressure and mass flow, and combustor-outlet temperature simulated operation of a 5.2 compressor-pressure-ratio engine at a flight Mach number of 0.6 and altitudes of 32,500 and 45,000 feet. Performance data were compared with similar data obtained with water injection, with 35-percent hydrogen peroxide injection, and with no liquid injection.

Combustor performance with 90-percent hydrogen peroxide injection was found to be superior to that with either water or 35-percent hydrogen peroxide injection. Greater mass-flow rates could be injected with no loss in combustion efficiency and without the occurrence of combustor blow-out. At all conditions investigated, the 90-percent hydrogen peroxide was completely vaporized and 98 to 100 percent decomposed at the combustor outlet.

Calculations indicated that the injection of 90-percent hydrogen peroxide increases the potential engine thrust over that for water injection. The thrust increase is particularly large for engines employing afterburning because the oxygen released by the hydrogen peroxide decomposition makes burning at higher temperatures possible in the afterburner. Furthermore, for any afterburner combustion temperature, the additional oxygen should assist the combustion process.

INTRODUCTION

Turbojet engine thrust may be increased by liquid injection into the engine combustion chambers. As indicated in reference 1, such injection results in increased fluid mass and increased engine pressure ratio. The injection of water-alcohol mixtures into turbojet engines is currently used to increase the thrust output of the engine. However, this method of thrust augmentation has several inherent

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disadvantages. Fuel consumption increases and combustion efficiency decreases at high water-air ratios (refs. 2 and 3). For engines employing afterburners, the deleterious effect of water injection on the combustion process in the afterburners is particularly critical and is the direct result of the reduced oxygen concentration of the afterburner-inlet gas because of both dilution and the increased fuel flows required in the primary combustor.

Unpublished analytical studies by Wallace Velie of Lewis laboratory have indicated theoretical thrust advantages for 90-percent hydrogen peroxide injection into turbojet engines over that for water-alcohol injection. Also, because hydrogen peroxide reacts readily with jet fuel, hydrogen peroxide injection should alleviate combustion problems encountered with water-alcohol injection into combustion chambers. Ninety-percent hydrogen peroxide decomposes rapidly at high temperatures to steam and oxygen. The reaction is exothermic (1108 Btu/lb) and the adiabatic decomposition temperature of 1362° F closely approaches normal turbine-inlet temperatures. Therefore, if decomposition is complete, little additional fuel should be required to maintain turbine-inlet temperature. Also, since 42 percent by weight of a 90-percent hydrogen peroxide and water mixture is active oxygen, hydrogen peroxide injection and subsequent decomposition would enrich the gas mixture entering the afterburner. Such oxygen enrichment not only should increase afterburner combustion efficiency, but also would allow an increase in afterburner-exhaust temperature and jet velocity.

A program to investigate the effect of high-strength hydrogen peroxide on the performance of a single tubular combustor, and to investigate the suitability of a standard water-injection system for use with the hydrogen peroxide, was initiated at the Lewis laboratory. A single J47 combustor, with a production water-alcohol injection manifold and nozzles, was mounted in a direct-connect duct. The combustor was operated with inlet-air mass flow, inlet pressure, and combustor-outlet temperature simulating rated speed operation of a 5.2 compressor pressure-ratio engine operating at a flight Mach number of 0.6 and altitudes of 32,500 and 45,000 feet. An inlet air flow rate 50 percent greater than that at rated-speed condition at 45,000 feet was also investigated. The effect of the hydrogen peroxide on combustor efficiency was evaluated at various injection rates at the specified test conditions. Data obtained in preliminary tests with 35-percent hydrogen peroxide at similar conditions are included. The performance data are compared with similar data obtained with no liquid injection and with water injection.

APPARATUS AND INSTRUMENTATION

Combustor Installation

A single combustor from a J47 engine was installed in the research facility shown in figure 1. The inlet diffuser and exhaust ducting of the combustor simulated an actual engine installation; however, the exhaust gas was not choked at the normal position of the turbine. Fuel was sprayed into the burner through a single-entry duplex nozzle. Thrust augmenting fluids, water, 35-percent hydrogen peroxide, or 90-percent hydrogen peroxide, were pumped through a standard manifold integral with the combustor outer shell; they were injected into the combustor by four hollow cone nozzles (fig. 2) mounted flush with the liner wall and spaced 90° apart. Combustion air flow was metered at the inlet of the test facilities by means of a variable area orifice installation. Liquid flow rates were measured with calibrated rotameters and vane-type flowmeters. The combustor inlet-air pressure and air flow were controlled by remote operating throttle valves. The fuel used was MIL-F-5624C Grade JP-4 (table I).

The physical properties of various solutions of hydrogen peroxide and water are shown in table II. Additional physical and chemical data are presented in references 4 to 7.

Coolant Injection Systems

The standard coolant manifold and injection nozzles of the J47 combustor (fig. 2) were used in the test program with the exception that various high pressure-drop nozzles were used for some water injection runs to study the effects of atomization on burner performance. The only change in the standard combustor injection system involved the inlet elbow to the coolant manifold. The elbow had been silver soldered to the manifold, and, because silver solder will catalyze decomposition of hydrogen peroxide, the silver solder joint was removed, and the elbow was welded in position.

A schematic diagram of the coolant-injection systems is shown in figure 3. The entire coolant piping system was constructed with series 300 stainless-steel fittings and tubing. The hydrogen peroxide storage spheres were fabricated of a 90+-percent aluminum alloy. A gear pump was used to supply city water at a pressure of 150 pounds per square inch gage to a throttle valve which controlled water-injection flow rates into the combustor. Water was also used to cool the injection manifold prior to each hydrogen peroxide run and was used to purge the hydrogen peroxide piping system.

The hydrogen peroxide system was pressurized by means of helium from compressed gas cylinders, and the pressure to the hydrogen peroxide storage tanks was adjusted by means of a remote pressure control. A remote-controlled three-way valve connected the hydrogen peroxide tanks to an atmospheric vent during shutdown and to the helium pressure system during operation. The tanks were pressurized to 300 pounds per square inch gage. A pressure-relief valve, set to open at 350 pounds per square inch gage, prevented over-pressurization of the system. A dump valve, controlled automatically by a pressure switch preset at 450 pounds per square inch gage, was integrated into the system as a safety measure. If rapid hydrogen peroxide decomposition in the storage tanks occurred, the dump valve would open and the contents of the tanks would be forced into a drum of water for dilution. The dump valve could also be operated by remote control. The flow of hydrogen peroxide into the combustor was controlled by a throttle valve.

Instrumentation

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The instrumentation details of the test assembly are shown in figure 4. The combustor inlet and exhaust static pressures were measured by means of static taps at stations 2 and 3. Iron-constantan thermocouples at station 1 indicated the temperature of the inlet combustion air. The exhaust gas temperature was measured at station 3 with 35 chromel-alumel bare-wire thermocouples positioned at five radii representing the centers of equal area. Station 3 simulated the location of the turbine with reference to the combustor in the J47 engine. Pressures and temperatures were indicated by mercury manometers and self-balancing potentiometers, respectively. Exhaust gas samples were withdrawn at station 4 through a water-cooled, stainless-steel, single-point probe. Flow through the sample probe was measured by a wet-test meter. The samples were analyzed for hydrogen peroxide in order to determine the extent of decomposition at the turbine position.

PROCEDURE

Test Conditions

The three test-operating conditions A, B, and C used for this investigation are tabulated below:

Variable	Test condition		
	A	B	C
Air flow rate, lb/sec	2.5	3.8	4.3
Combustor-inlet static pressure, in. Hg abs	34	34	54
Combustor-inlet temperature, °F	Ambient	Ambient	Ambient
Combustor-outlet temperature, °F	1560	1560	1560
Combustor reference velocity, ft/sec	60	100	60

Test conditions A and C simulated inlet-air mass flow and pressure, and turbine-inlet temperature for a 5.2 compressor pressure-ratio engine at rated speed, a flight Mach number of 0.6, and at altitudes of 45,000 and 32,500 feet, respectively. Inlet air could not be preheated;

therefore, combustor fuel-air ratio and combustor temperature rise were necessarily higher than for engine operation since turbine-inlet temperatures were simulated. The increased inlet-air mass flow of condition B increased combustor reference velocity to approximately that for engine operation at 45,000 feet. Combustor calibration data were obtained at combustor-inlet conditions A, B, and C at exhaust tempertures from 700° to 1800° F.

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Operating Procedure

For all test runs, combustor-inlet-air mass flows and pressures, and combustor-outlet temperatures were preset to the values indicated for test conditions A, B, and C. After approximate equilibrium was attained, the augmenting liquid was injected. Fuel flow was varied as necessary to maintain a constant combustor-outlet temperature. With liquid injection, the combustor-inlet pressure was increased from the preset point to simulate turbine choking in an engine installation.

Test runs with hydrogen peroxide injection were limited to a maximum 5-minute-run time by the available supply of hydrogen peroxide. Therefore, this same maximum time limit was imposed upon all other runs as well. Nevertheless, temperature equilibrium was probably very closely approached in this period since the outlet temperature had been established prior to the liquid injection and was maintained constant.

The following data were recorded at each test condition: inlet and exhaust gas temperatures and pressures, injection temperatures and flow rates of fuel and augmenting liquids, and air orifice temperature and pressures. Combustion efficiency was calculated as the ratio of the actual enthalpy rise to the theoretical enthalpy rise by the method of reference 8. The actual combustor-outlet enthalpy was calculated from the average of 35 individual temperatures measured at station 3. For those data obtained with hydrogen peroxide injection, the theoretical enthalpy rise assumed complete decomposition of the hydrogen peroxide. Enthalpy data for hydrogen peroxide were obtained from reference 4. The quantity of the hydrogen peroxide decomposed was estimated from a chemical analysis of the exhaust gas samples using a permanganate titration method.

RESULTS

Operational data and results for all test runs are tabulated in table III. The combustor reference velocity indicated therein is based upon inlet-air mass flow and density and the maximum combustor cross-sectional area of 0.48 square feet.

Combustor Performance With No Augmentation

The combustion efficiencies of the J47 test burner with no augmenting liquid injection, at inlet-air mass flows of 2.5 and 3.8, and 4.3 pounds per second, and at inlet-air pressures of 34 and 54 inches of mercury absolute, respectively, were determined for fuel-air ratios from 0.010 to 0.030. The results are shown in figure 5. Tailed symbols indicate check runs. The fuel-air ratio range was extended to the practical upper temperature limit for the combustor-outlet instrumentation and was wide enough to assure a comparison with data obtained in later runs with liquid injection. As indicated in figure 5, large differences in combustion efficiency were obtained at lean fuel-air ratios for the three 3972 flow conditions investigated. At a fuel-air ratio of 0.013, efficiencies of 65, 80, and 88 percent were obtained for inlet-air mass flows of 2.5, 3.8, and 4.3 pounds per second, respectively. At higher fuel-air ratios near the design point of the combustor, however, this difference was decreased to about 5 percent at a fuel-air ratio of 0.024. These efficiency variations may be traced to effects of pressure and velocity on the combustion process. Also, since fuel-injection pressures increase with increasing fuel-air ratio and air flow, the resulting improved atomization at the higher fuel flow rates would be expected to increase the combustion efficiency. The higher inlet-air temperatures encountered in actual engine operation would also be expected to raise the efficiency level above that indicated in the figure. Generally, the combustion efficiency was unaffected by fuel-air ratio increases above 0.024 except for an air flow of 2.5 pounds per second, which showed a 5-percent increase in combustion efficiency between 0.024 and 0.030.

Rated-speed engine operation at the flight conditions approximated in these tests requires fuel-air ratios of 0.018 to 0.019 in order to maintain a turbine-inlet temperature of 1560° F. A fuel-air ratio of approximately 0.024 was required in these tests to maintain the combustor-outlet temperature because of the reduced combustor-inlet-air temperature. Thus, fuel-air ratios for normal turbine-inlet temperatures were approximately 25 percent greater than those required for engine operation.

Combustor Performance With Water Injection

Data obtained with water injection are shown in figure 6. The fuel-air ratio was maintained constant at a value equivalent to that required for operation at normal turbine-inlet temperature with no water injection. Therefore, with increasing water-air ratios, turbine temperature decreased. No serious loss in combustion efficiency was noted with increasing water injection rates up to the region of incomplete vaporization indicated on figure 6 by the broken lines. Efficiencies calculated for injection rates within this area were unreliable and were low by an indeterminate quantity because of thermocouple cooling by water impingement.

Complete vaporization of the water was obtained for water-air ratios to 0.06, for air flow rates of 2.5 and 4.3 pounds per second, flow rates that provided a reference velocity of approximately 60 feet per second. At the condition of increased velocity at an air-flow rate of 3.8 pounds per second, complete vaporization was obtained for water-air ratios to only 0.04. With respect to the lowering of the water-air ratio, the relative importance of the residence time of the water in the combustor or of the quenching effect of water injection on the combustion reaction was not determined. Both, however, may be equally suspected.

Combustion efficiency and fuel-air ratio data obtained at test conditions A, B, and C at a constant combustor-outlet temperature of 1560° F and with water injection to water-air ratios of 0.11 are plotted in figure 7. For these data, it was necessary to increase fuel flow with increasing water injection rates in order to vaporize the water and raise the enthalpy of the steam formed so that a constant combustor-outlet temperature could be maintained. The required fuel-air ratio increase with water injection is shown in figure 7. At water-air ratios of 0.06 and 0.11, combustor fuel-air ratios of 0.03 and 0.04, respectively, were required. This represents a fuel-flow increase of 25 to 65 percent over that required for no liquid injection. Except for the high reference velocity condition B, combustion efficiency was relatively unaffected by water injection for water-air ratios to about 0.08. A further increase in water-injection rate was accompanied by incomplete vaporization and decreases in efficiency. Blow-out occurred at a water-air ratio of about 0.11. The apparent increase in combustion efficiency for water-air ratios to 0.08 for condition A is the result of the combustion-efficiency - fuel-air ratio relation for this combustor in this fuel-air region (fig. 5).

Water injection rapidly decreased combustion efficiency for test-condition B, and blow-out occurred at a water-air ratio of 0.03. The fuel-air ratio approximated 0.029. With no water injection, combustion instability was noted at a fuel-air ratio of 0.028. Therefore, blow-out probably resulted from overenrichment of the primary zone rather than from combustion quenching by the injected water.

Except for a few runs at water injection rates of 1000 pounds per hour, or greater, nozzle injection pressures were below 15 pounds per square inch gage. Substitution of low capacity, hollow cone nozzles maintained injection pressures of 25 to 125 pounds per square inch gage and the results of these tests are shown in figure 8. Solid lines are high pressure-drop injector data, and broken lines represent data with the standard low pressure-drop injector. Combustion efficiency was apparently unaffected by the degree of water atomization. However, the improved atomization of the high pressure-drop injectors was more effective in quenching the combustion reaction and resulted in blow out at lower water-air ratios.

Combustion Performance With Hydrogen Peroxide Injection

Hydrogen peroxide concentrations of less than 65 percent do not appear practical as augmenting fluids. The active oxygen concentration is proportional to concentration, of course; therefore, some performance gain might be expected. However, the adiabatic decomposition temperature for these concentrations only ranges to about 225° F and combustion quenching may be encountered. However, since a small quantity of 35-percent hydrogen peroxide was available for test, these data were obtained and are included herein to indicate the relative effect of hydrogen peroxide concentration on combustor performance. 3972

Combustor performance data obtained with the injection of 90-percent and 35-percent hydrogen peroxide at rated turbine-inlet temperatures are shown in figure 9. Combustion efficiency was calculated on the assumption of complete hydrogen peroxide decomposition. Quantitative analysis of gas samples withdrawn at the turbine position indicated approximately 98 percent decomposition of the 90-percent hydrogen peroxide. Therefore, except for those cases where vaporization was incomplete, the maximum error in calculated combustion efficiencies is estimated to be -3 to -5 percent.

Figure 9(a) presents the data obtained with 90-percent hydrogen peroxide injection for hydrogen peroxide-air ratios to 0.38 for test conditions A, B, and C. Although combustor blow-out occurred at water-air ratios of 0.12 or less (fig. 7), combustor operation was stable at hydrogen peroxide-air ratios at least three times greater. Also, for the test conditions investigated, combustion efficiency increased some 3 to 6 percent for increasing hydrogen peroxide injection rates. Combustor efficiencies greater than 95 percent were obtained at hydrogen peroxide-air ratios of 0.38. The higher inlet pressure of condition C resulted in higher efficiencies. The poor performance at the high velocity condition B that was noted with water injection was eliminated completely and the efficiencies with hydrogen peroxide injection were comparable to the low reference velocity conditions at all injection rates. For all data, combustor fuel-air ratio remained approximately constant, which indicated a high degree of hydrogen peroxide decomposition. Hydrogen peroxide injection temperature at the point of injection was approximately constant at 85° F; injection pressures ranged to 300 pounds per square inch gage.

As shown in figure 9(b), combustor performance with the 35-percent hydrogen peroxide was similar to that with water injection with respect to limiting liquid-air ratios at combustor blow-out and with respect to combustion efficiency. Fuel requirements, however, were slightly lower because of the exothermic decomposition of the hydrogen peroxide.

Turbine-Inlet Temperature Distribution With Liquid Injection

Typical turbine-inlet temperature profiles obtained at high liquid injection rates with the three liquids tested are shown in figure 10. Although these data were obtained at test condition C, they are typical for those obtained at the other test conditions as well. Near the limiting rates of injection of water or low strength hydrogen peroxide, incomplete vaporization of the liquid at the turbine position occurred; low temperature and mixed phase regions on the bottom of the outlet annulus resulted. With injection rates of 90-percent hydrogen peroxide that were three times greater than limiting water injection rates, no liquid was present, and turbine position temperature profiles were considerably more uniform.

DISCUSSION

Experimental Combustor Performance with Liquid Augmentation

The effects of the injection of water, 35-percent hydrogen peroxide, and 90-percent hydrogen peroxide on the performance of the single tubular test combustor are compared in figure 11 for three test conditions at a simulated turbine-inlet temperature of 1560° F. Combustor performance data at similar test conditions with no liquid injection are also included. In most cases, performance data with the low strength hydrogen peroxide injection are very similar to the data with water injection; therefore they will not be discussed separately.

In all cases, combustor performance with 90-percent peroxide injection is superior to that with water injection. Combustor operation with water injection is blow-out limited at injectant-air ratios of 0.12 or less. Blow-out limits with 90-percent hydrogen peroxide injection, however, were not encountered even at injection rates approximately three times greater than those for water. Also, with 90-percent hydrogen peroxide injection, the efficiency of the primary combustor was not impaired at any of the flow conditions investigated, whereas water injection showed efficiency losses at all water-air ratios for condition B and at water-air ratios over 0.08 for conditions A and C. As noted from figure 12, the combustor performance gains with high strength hydrogen peroxide were obtained with no increase in primary fuel flow. This is in marked contrast to the water injection data which exhibited a 65 percent fuel flow increase for a liquid injection rate less than one third that for hydrogen peroxide. Although these data are specifically from test condition A, they are typical of other conditions as well.

At high injection rates, the presence of liquid water at the combustor outlet was indicated by cold thermocouple readings, but 90-percent hydrogen peroxide was completely vaporized and exhibited outlet temperature profiles which were considerably more uniform (fig. 10). Gas analysis of samples withdrawn at the turbine position indicated that the 90-percent hydrogen peroxide was not only vaporized, but was approximately 98 percent decomposed after passage through the combustor. Since the combustor-outlet temperature is more uniform and free of cold spots because of the presence of liquid, turbine-blade stress problems should be alleviated.

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Theoretical Aspects of Liquid Augmentation

Effect of hydrogen peroxide and water injection on jet thrust. The physical and chemical properties of 90-percent hydrogen peroxide present some advantages over water for its use as an injectant for thrust augmentation. Its high density and low viscosity are advantageous. Its decomposition properties, however, are the most promising. The adiabatic decomposition temperature of 1362° F is high enough to minimize combustion quenching and requires little or no additional fuel to maintain turbine-inlet temperature. Further, the oxygen released upon decomposition may be utilized in the afterburner to obtain increased afterburner efficiency and exhaust gas temperatures. These gains should all be possible since it appears that the hydrogen peroxide decomposition can be obtained at no expense to primary burner performance. However, the evaluation of the relative merits of water and high strength hydrogen peroxide as thrust augmenting fluids must be considered from the standpoint of both the primary engine and of the engine plus afterburner. At constant rated-speed engine operation, thrust gains obtained by liquid augmentation of the primary engine result only from the increased mass handled by the turbine and the resulting compressor pressure ratio increase, since the gas temperature is fixed by the turbine and is essentially constant. Therefore, high strength hydrogen peroxide would be expected to exhibit greater allowable thrust gains than water since considerably higher mass flows may be injected into the engine.

If liquid injection into an engine plus afterburner is considered, the same two prime factors of pressure and mass will similarly tend to increase engine thrust. However, a third factor, exhaust gas temperature, must also be considered. Liquid injection can have a marked effect on this temperature.

With no liquid injection, an engine-afterburner combination using JP-4 fuel, operating at an over-all stoichiometric fuel-air ratio would have an afterburner fuel-air ratio of 0.052 if the primary combustor were performing with 100-percent efficiency at a fuel-air ratio of 0.0156. If water were injected into the primary engine, fuel flow would have to be increased to maintain turbine temperature. Stoichiometry would dictate a similar decrease in afterburner fuel flow. These trends are shown in figure 13 for these assumptions. At a water-air ratio of 0.05, the primary fuel flow would have to be increased approximately 30 percent and that to the afterburner decreased about 8 percent. At a water-air ratio of 0.15, the primary fuel would have to be doubled and that to the afterburner decreased 27 percent. The resulting reduction in afterburner gas temperature would offset some of the thrust gains expected from increased fluid mass and increased engine pressure ratio.

On the other hand, hydrogen peroxide injection would require only small fuel flow increases in the primary engine and would permit increased fuel flow to the afterburner. At an injectant-air ratio of 0.40, only a 10-percent increase in primary fuel flow would be required. Also, since the active oxygen release of 90-percent hydrogen peroxide is equivalent to approximately 0.12 pounds of JP-4 fuel per pound of hydrogen peroxide, at stoichiometric conditions afterburner fuel-air ratio would rise rapidly. As indicated in figure 13, afterburner fuel flow could be increased almost 100 percent, to a fuel-air ratio of 0.10 at a hydrogen peroxide-air ratio of 0.40. Outlet gas temperature would also rise, but because of dissociation would not rise proportionately. Major thrust gains would be expected with hydrogen peroxide injection since mass, temperature, and engine pressure ratio would all increase markedly.

Effect of hydrogen peroxide injection on afterburner oxygen concentration. - The combustion process in the primary burner depletes the oxygen concentration of the gas mixture entering the afterburner. As shown in figure 14, a primary combustor operating at 100-percent efficiency and a fuel-air ratio of 0.0156 would reduce the oxygen concentration of the air at the afterburner inlet approximately 23 percent to a concentration of about 17.5 weight percent. The increased fuel requirements imposed by water injection into this combustor would result in a further decrease in the oxygen concentration. The magnitude of this reduction would depend upon the rate of water injection and hence the fuel flow requirement for constant turbine temperature. However, the resulting oxygen concentration might approach only 14 to 15 weight percent. Such a reduction in afterburner-inlet oxygen concentration may seriously penalize afterburner performance. Combustion efficiency losses of approximately 20 percent in a propane-air system in which the oxygen concentration had been reduced only 3 percent are indicated in reference 9. Except for cases of special afterburner fuels, afterburner efficiency losses of 20 percent are common (ref. 10). As indicated in figure 14, the problem of reduced oxygen concentration at the afterburner inlet may be alleviated or overcome by hydrogen peroxide injection. The data (fig. 14) were calculated on the assumption of a primary combustor fuel-air ratio of 0.0156 and shows the increase in the oxygen concentration at the afterburner inlet for various rates of hydrogen peroxide injection. An oxygen concentration of 23 weight percent for air is indicated for reference. Injection to a hydrogen peroxide-air ratio of 0.20 would enrich the afterburner inlet concentration about 4 percent and for a hydrogen peroxide-air ratio of about 0.40, the enrichment would approach 7 percent. Thus, afterburner-inlet oxygen concentrations might conceivably equal or exceed that in pure air. Since increases in oxygen concentration favorably affect fundamental combustion properties such as flame speed and reaction rate, improvement in afterburner efficiency might be expected with hydrogen peroxide injection.

Calculated Thrust Augmentation

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The increases in calculated net-thrust ratio for an afterburning and a nonafterburning engine using water or 90-percent hydrogen peroxide injection are shown in figure 15. The analysis was based upon references 10 and 11, and the following was assumed: compressor pressure ratio, 5.3; zero flight Mach number at sea level; choked exhaust nozzle; rated speed, 7950 rpm; over-all stoichiometric burning at 100 percent efficiency; and 15 percent over-all pressure loss. The analysis was not rigorous. Nevertheless, the magnitude of the thrust increases possible with hydrogen peroxide are apparent for the two engine combinations considered.

The net-thrust increase with water or hydrogen peroxide injection into a nonafterburning engine may be represented by a single curve since the increase in engine thrust is dependent only on the increase in the fluid mass handled by the turbine and on the compressor characteristics at the fixed turbine temperature. However, hydrogen peroxide injection with afterburning results in increased engine thrust over that possible with water injection for similar liquid injection rates. This increase results primarily from the temperature increase of the fluid possible with hydrogen peroxide injection, since the increase in fluid mass and compressor pressure ratio for water or hydrogen peroxide would be approximately equal for a given injection rate.

The practical limits for liquid injection as imposed by compressor stall or tailpipe size were not considered for the calculations of figure 15. Such limits would vary with engine type. References 12 and 13, however, indicate that a J47 engine at rated speed at sea level is surge limited at a compressor pressure ratio of about 6.7 - a value which would have been exceeded by the experimental hydrogen peroxide-air ratio of 0.4. If the curves of figure 15 are compared in the light of this surge limit, a more realistic comparison is possible. Maximum water injection rates were limited by blow-out of the primary combustor at augmented liquid ratios of 8 to 10. Augmented liquid ratio is a measure of the total liquid consumption of an engine and is the ratio of the total liquid consumption to the primary engine fuel flow with no augmentation. Hydrogen peroxide injection rates on the other hand would be limited by compressor surge at an augmented liquid ratio of about 21 for no afterburning. Therefore, as indicated in the figure, at injection rates limited by blow-out or compressor surge, about 23 percent more thrust may be obtained with hydrogen peroxide injection than with water injection. This gain, however, would be obtained only at the expense of increase total liquid consumption.

With an afterburning engine, greater thrust gains appear possible. At an augmented liquid ratio of about 11, which approximates the water blow-out limit, thrust ratios with hydrogen peroxide injection approach 1.85 which represents an approximate 10 percent increase over water. At an injection rate limited by compressor surge, which is equivalent to an augmented liquid ratio of 27, the thrust ratio approximates 2.6. Therefore, with hydrogen peroxide injection at a rate limited by compressor surge, engine thrust approximately 50 percent greater than the maximum thrust obtainable with conventional water injection appears possible.

CONCLUDING REMARKS

A 90-percent hydrogen peroxide was successfully injected into a J47 combustor using the standard water injection manifold and nozzles. The use of high strength hydrogen peroxide as a possible thrust-augmenting fluid appears promising for turbojet application, especially for afterburning engines where full use can be made of the active oxygen released by the hydrogen peroxide decomposition.

The thrust gains possible with hydrogen peroxide injection require increased liquid consumption and a more complex liquid handling system. The decomposition properties and fire hazard of the hydrogen peroxide would make handling difficult for operational use; special handling techniques and liquid transfer methods would be imperative. However, much experience in hydrogen peroxide handling has already been obtained by the military services who have used it in rocket engines. Such experience would also be valuable for its use for turbojet application.

The results have also indicated that hydrogen peroxide injection has a stabilizing influence on the primary combustor. It is possible that such injection may also alleviate some of the combustion difficulties of high velocity combustors. Such application, however, would necessitate further research.

SUMMARY OF RESULTS

An investigation of the effect of water, 35-percent hydrogen peroxide, and 90-percent hydrogen peroxide injection on the performance of a single tubular combustor was conducted. Inlet mass flows to the combustor and combustor-inlet pressures simulated operation of a 5.2 compressor-pressure-ratio engine at 32,500 and 45,000 feet altitude, rated speed, and 0.6 Mach flight speed. Combustor-outlet temperatures simulated turbine-inlet temperatures at these flight conditions. The following results were obtained:

1. At a constant combustor-outlet temperature of 1560° F, and 60 feet per second combustor reference velocity, water injection with water-air ratios of approximately 0.07 did not penalize combustion efficiency of the test burner. Higher injection rates decreased efficiencies and caused flame blow-out.

2. Water injection to water-air ratios of 0.06 and 0.11 required fuel flow increases of 25 and 65 percent, respectively, to maintain turbine-inlet temperature of 1560° F.

3. Injection of 35-percent hydrogen peroxide indicated no improvement in burner performance over that obtained with water injection. 3972

4. Approximately three to four times as much 90-percent hydrogen peroxide as water could be injected into the combustor with no resulting efficiency loss. The hydrogen peroxide was almost completely decomposed at the combustor outlet and thus required no fuel flow increase to maintain combustor-outlet temperature.

5. Combustor operation was stabilized by 90-percent hydrogen peroxide injection. Stable combustion was obtained at hydrogen peroxide - air ratios as high as 0.38.

6. The standard combustor coolant injection system was suitable for use with 90-percent hydrogen peroxide with only one minor alteration.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 23, 1956

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TABLE I. - FUEL ANALYSIS

Fuel properties	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 at 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. - THE PHYSICAL PROPERTIES OF SOLUTIONS OF HYDROGEN PEROXIDE AND WATER

Physical property	H_2O_2, percent by weight											
	100	90	80	70	60	50	40	35	30	20	10	0
Density at 77° F, lb/gal	12.04	11.57	11.13	10.71	10.32	9.94	9.59	9.42	9.25	8.92	8.61	8.32
Viscosity, centipoises at 20° C	1.25	1.27	1.27	1.24	1.22	1.17	1.13	1.10	1.08	1.04	1.02	1.00
Normal boiling point, °F	302.4	286.2	271.0	257.8	246.2	237.0	229.3	226.0	223.3	218.5	214.7	212.0
Heat of vaporization at normal boiling point, Btu/lb	584	630	675	718	759	798	835	853	871	905	938	970
Freezing point, °F	31.3	11.3	-12.6	-40.5	-67.9	-62.0	-42.5	-27.4	-14.3	5.7	20.5	32.0
Mean heat capacity, 0-27° C, Btu/lb solution °F	0.628	0.660	0.692	0.725	0.757	0.790	0.823	0.841	0.860	0.899	0.945	1.002
Heat of decomposition at 77° F and 1 atm, Btu/lb of solution	1240.1	1108.4	979.1	851.9	726.7	603.1	481.1	420.5	360.0	239.7	119.7	0.0
Active oxygen, percent by weight	47.04	42.3	37.6	32.9	28.2	23.5	18.8	16.5	14.1	9.4	4.7	0.0
Adiabatic decomposition temperature at 1 atm, °F	1722	1362	860	400		266		212				

TABLE III. - COMBUSTION PERFORMANCE DATA

[B.O. denotes blow-out. M denotes high pressure-drop nozzles.]

Run	Combustor-inlet pressure, in. Hg abs	Combustor-inlet temperature, °F	Air flow rate, lb/sec	Fuel flow rate, lb/hr	Coolant flow rate, lb/hr	Coolant flow temperature, °F	Fuel-air ratio	Liquid-air ratio	Combustor-outlet temperature, °F	Combustion efficiency, percent	Combustor reference velocity, ft/sec	Coolant injector	Injection pressure, lb/sq in. gage	Hydrogen peroxide, percent decomposed
							No liquid injection							
34	53.7	93	4.29	335.0	---	---	0.0217	---	1550	97.5	69	---	---	---
41	53.8	104	4.29	341.0	---	---	.0221	---	1565	98.2	68	---	---	---
61	54.0	93	4.30	337.5	---	---	.0218	---	1560	98.0	69	---	---	---
72	54.0	83	4.26	339.0	---	---	.0221	---	1570	97.8	70	---	---	---
113	54.3	94	4.29	157.5	---	---	.0102	---	715	81.9	69	---	---	---
114	54.3	94	4.30	208.0	---	---	.0134	---	960	88.8	69	---	---	---
115	54.0	94	4.31	252.5	---	---	.0163	---	1175	93.0	69	---	---	---
116	53.8	93	4.32	306.0	---	---	.0197	---	1400	95.0	70	---	---	---
117	54.0	92	4.31	354.5	---	---	.0229	---	1585	95.1	69	---	---	---
118	54.1	91	4.31	429.5	---	---	.0277	---	1835	94.2	69	---	---	---
12	33.4	91	2.51	218.0	---	---	.0242	---	1545	87.7	65	---	---	---
27	34.5	94	2.50	219.1	---	---	.0244	---	1560	87.8	63	---	---	---
39	34.2	102	2.47	213.5	---	---	.0240	---	1560	88.8	64	---	---	---
47	34.0	90	2.53	216.0	---	---	.0239	---	1560	90.5	64	---	---	---
98	34.3	91	2.51	114.5	---	---	.0127	---	700	64.9	63	---	---	---
99	34.2	91	2.52	147.0	---	---	.0162	---	965	74.6	64	---	---	---
100	34.2	92	2.51	170.0	---	---	.0188	---	1160	80.0	64	---	---	---
101	34.4	91	2.51	189.5	---	---	.0221	---	1420	86.7	63	---	---	---
102	34.1	91	2.51	219.5	---	---	.0243	---	1605	91.1	64	---	---	---
103	34.2	90	2.51	249.5	---	---	.0276	---	1810	93.1	63	---	---	---
104	34.3	90	2.51	267.0	---	---	.0296	---	1950	95.0	63	---	---	---
8	33.3	96	3.61	306.2	---	---	.0236	---	1570	91.2	95	---	---	---
9	33.5	90	3.65	332.5	---	---	.0253	---	1560	85.1	94	---	---	---
30	34.4	95	3.84	316.5	---	---	.0229	---	1570	94.7	97	---	---	---
44	34.1	104	3.81	311.8	---	---	.0227	---	1555	93.1	99	---	---	---
105	34.1	90	3.80	153.0	---	---	.0112	---	725	76.4	96	---	---	---
106	33.9	90	3.81	191.0	---	---	.0138	---	925	82.5	97	---	---	---
107	34.2	90	3.80	231.5	---	---	.0169	---	1150	87.9	98	---	---	---
108	34.0	80	3.81	279.5	---	---	.0204	---	1400	92.1	96	---	---	---
109	33.9	90	3.81	300.5	---	---	.0219	---	1500	93.2	97	---	---	---
110	34.2	90	3.80	335.5	---	---	.0245	---	1620	91.6	96	---	---	---
111	33.9	90	3.79	357.3	---	---	.0262	---	1720	92.2	97	---	---	---
112	34.6	89	3.79	382.5	---	---	.0280	---	1830	92.7	94	---	---	---
							Water injection							
5	57.8	98	4.30	445.0	1011.2	78	0.0287	0.0653	1540	95.8	65	Standard	30	---
6	59.6	97	4.35	615.0	1511.8	78	.0393	.0966	1525	78.1	64	Standard	40	---
7	62.0	97	4.35	678.0	1792.1	78	.0433	.1144	1550	76.5	62	Standard	50	---
42	57.2	104	4.29	408.0	750.9	80	.0264	.0486	1565	99.0	64	Standard	---	---
43	61.7	106	4.30	618.0	1511.8	80	.0399	.0977	1540	77.7	62	Standard	---	---
62	54.0	93	4.30	337.5	249.9	77	.0218	.0161	1500	100.4	69	Standard	---	---
63	54.0	93	4.30	337.5	499.8	77	.0218	.0323	1370	97.3	69	Standard	---	---
64	54.0	93	4.30	337.5	749.7	77	.0218	.0484	1290	97.9	69	Standard	---	---
86	35.0	86	3.80	308.2	500.5	76	.0225	.0366	1240	87.2	93	30 M	30	---
94	35.3	88	3.80	352.0	250.2	76	.0257	.0183	1560	95.5	93	10.5 M	70	---
95	35.9	88	3.80	352.0	300.3	76	.0257	.0219	---	B.O.	93	10.5 M	---	---
13	34.8	92	2.52	239.0	230.5	64	.0263	.0254	1565	91.6	63	Standard	---	---
14	35.9	82	2.52	257.0	520.6	64	.0283	.0574	1555	95.8	61	Standard	---	---
15	36.4	92	2.52	274.0	740.9	63	.0302	.0817	1540	96.9	60	Standard	---	---
16	38.5	93	2.52	361.8	1011.2	62	.0399	.1114	1555	82.4	57	Standard	---	---
17	36.7	93	2.50	276.0	760.9	63	.0307	.0847	1565	97.8	59	Standard	---	---
38	35.5	102	2.47	244.5	500.5	82	.0275	.0563	1550	97.1	62	Standard	---	---
40	39.5	103	2.47	339.0	1001.0	80	.0381	.1126	1525	84.2	55	Standard	---	---
48	34.0	90	2.53	216.0	499.8	84	.0237	.0549	1270	91.5	64	Standard	---	---
82	35.1	84	2.54	261.2	500.5	78	.0288	.0552	1580	95.2	62	30 M	25	---
83	36.0	84	2.54	322.5	600.6	78	.0356	.0662		B.O.	60	30 M	---	---
84	35.2	86	2.52	218.5	500.5	78	.0239	.0552	1210	86.9	61	30 M	30	---
10	34.3	91	3.62	381.0	245.3	82	.0277	.0188	1575	85.5	91	Standard	---	---
11	34.8	91	3.64	374.0	355.4	66	.0285	.0271	1550	84.8	90	Standard	---	---
45	35.2	104	3.81	343.0	250.2	79	.0250	.0182	1580	92.3	95	Standard	---	---
46	35.6	105	3.81	360.0	325.4	79	.0262	.0237	1555	90.0	95	Standard	---	---
58	33.8	94	3.77	297.5	249.9	78	.0218	.0184	1390	92.3	97	Standard	---	---
96	35.3	88	3.80	318.5	250.2	76	.0233	.0183	1410	89.1	93	10.5 M	70	---
97	35.3	88	3.81	318.6	350.3	76	.0232	.0256	1230	79.8	93	10.5 M	140	---
73	56.2	82	4.27	378.5	600.6	76	.0246	.0326	1570	101.0	65	30 M	50	---
74	58.8	83	4.25	500.0	900.9	78	.0327	.0589	1570	85.0	62	30 M	120	---
75	54.0	84	4.27	339.0	500.5	78	.0221	.0326	1375	97.2	68	30 M	50	---
							35-Percent hydrogen peroxide							
24	61.8	90	4.22	430.0	1124.2	73	0.0283	0.0738	1550	95.8	59	Standard	25	Incomplete
25	63.5	91	4.30	567.0	1940.2	74	.0366	.1253	1525	80.4	59	Standard	45	Incomplete
18	36.1	90	2.50	227.0	682.1	74	.0252	.0647	1505	97.0	60	Standard	---	Incomplete
19	39.8	90	2.50	306.0	1141.3	77	.0340	.1268	1575	88.6	55	Standard	---	Incomplete
21	36.1	91	3.61	349.0	570.7	74	.0269	.0439	1560	90.4	86	Standard	---	Incomplete
22	37.2	91	3.61	385.0	776.1	74	.0296	.0597	1690	87.8	84	Standard	---	Incomplete
							90-Percent hydrogen peroxide							
35	64.1	95	4.30	347.0	2855.2	82	0.0224	0.1845	1560	97.9	59	Standard	70	--
36	74.5	96	4.27	353.0	5835.1	81	.0230	.3800	1560	98.0	50	Standard	250	99
37	63.3	97	4.27	349.0	2841.3	79	.0227	.1848	1560	97.1	59	Standard	70	97
28	39.7	94	2.55	218.0	1441.4	84	.0234	.1570	1560	95.3	56	Standard	16	92
29	46.2	96	2.51	224.0	3312.5	85	.0247	.3656	1540	94.2	47	Standard	90	97
31	40.1	94	3.84	318.0	2252.3	86	.0230	.1629	1550	95.8	83	Standard	45	--
32	47.0	94	3.85	330.0	4677.8	82	.0238	.3375	1550	96.4	71	Standard	150	96
33	40.1	93	3.85	324.0	2259.2	82	.0234	.1630	1560	95.5	83.0	Standard	50	98

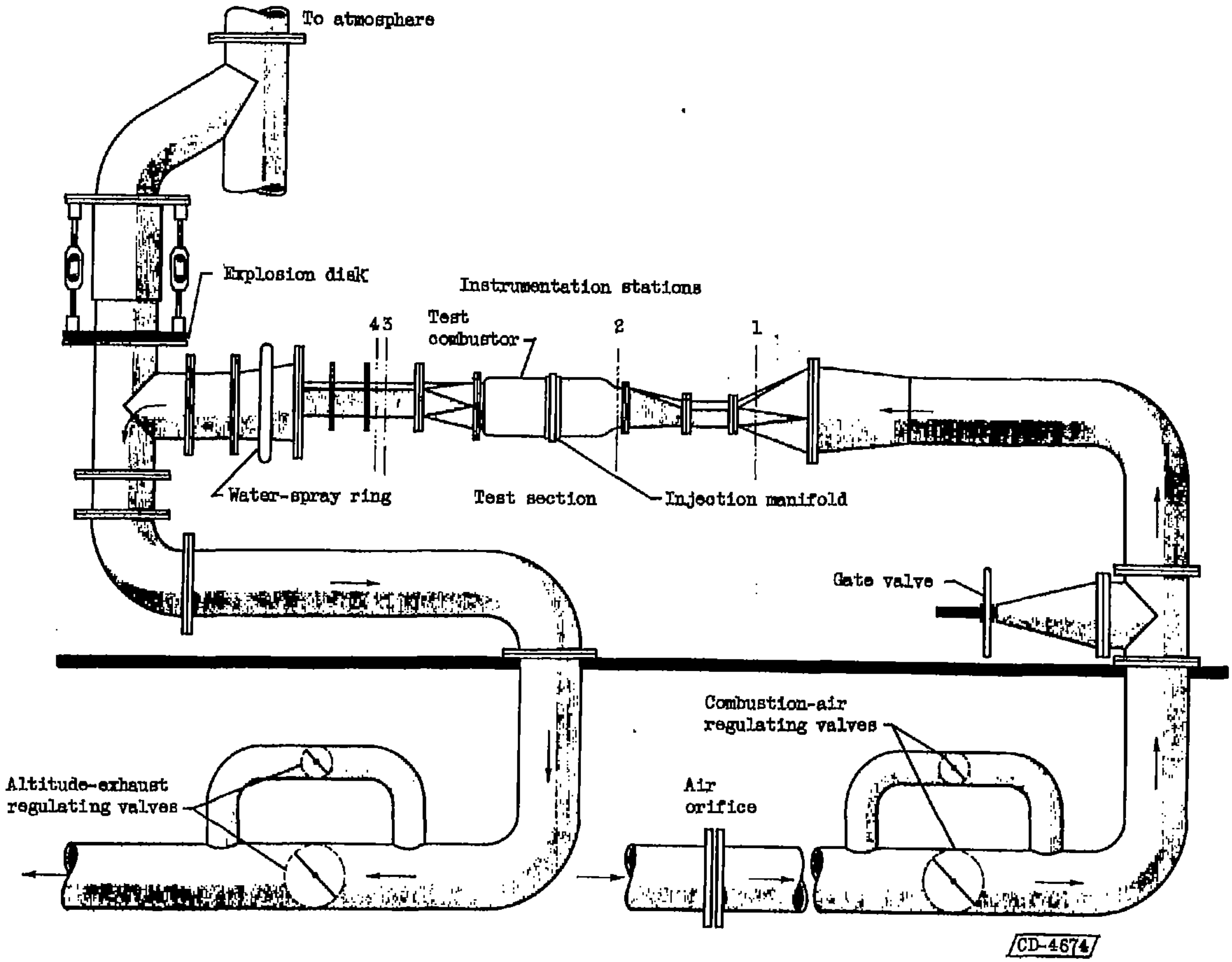

Figure 1. - Single tubular combustor installation.

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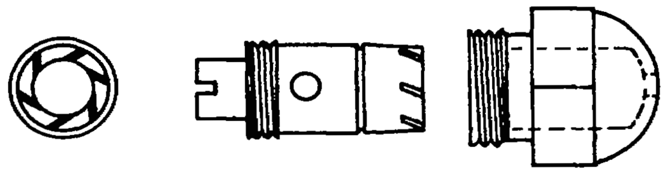
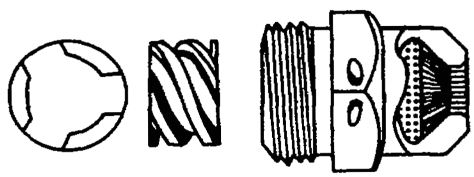
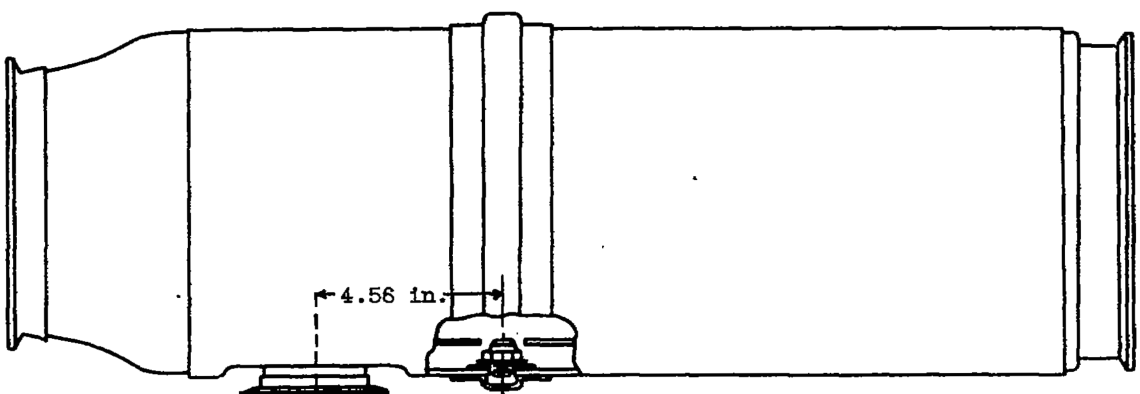


(a) High-pressure-drop nozzle.



(b) Standard injection nozzle.



(c) Location of nozzle in combustor housing.

Figure 2. - Injection nozzle and its location in combustion chamber.

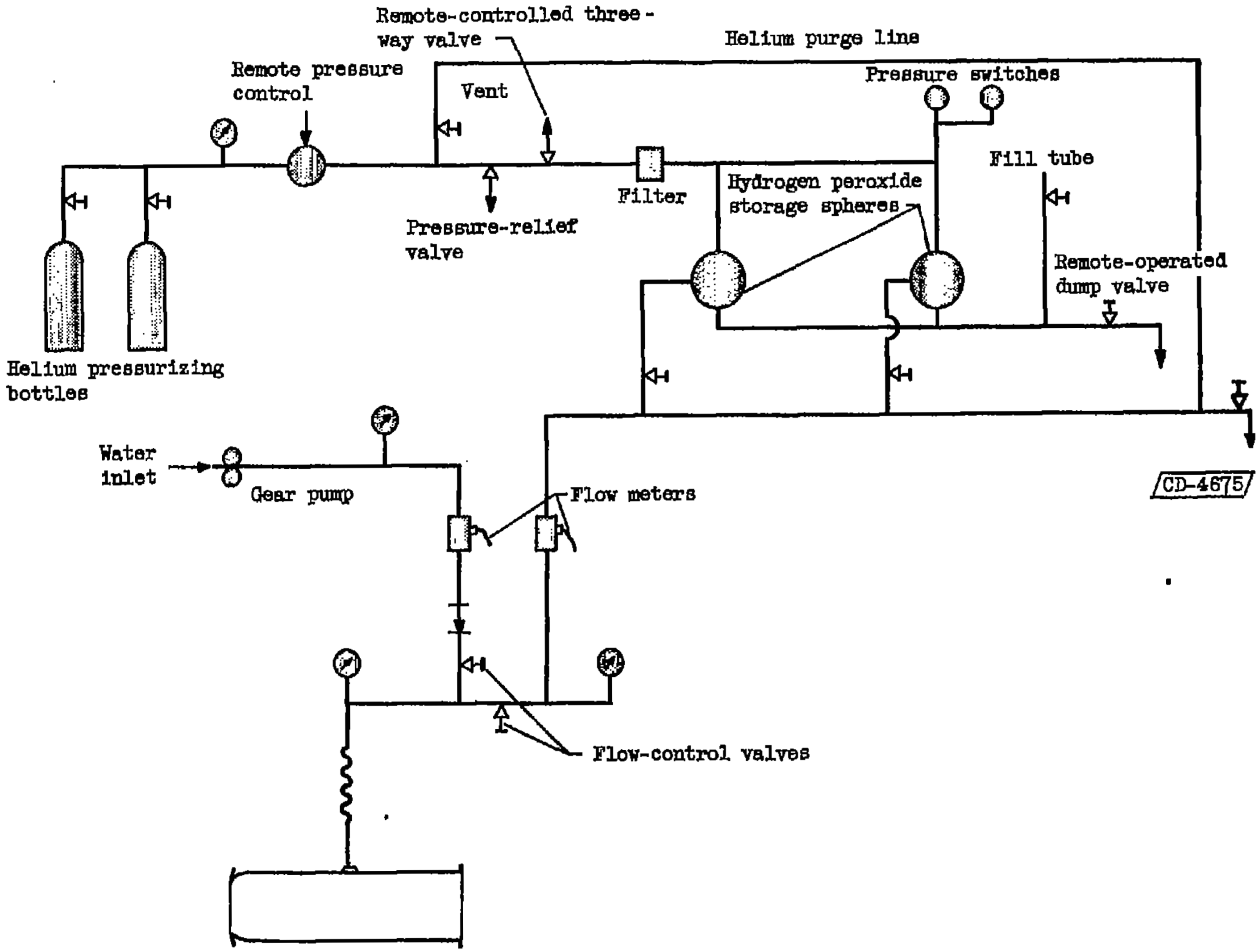


Figure 3. - Coolant-injection systems.

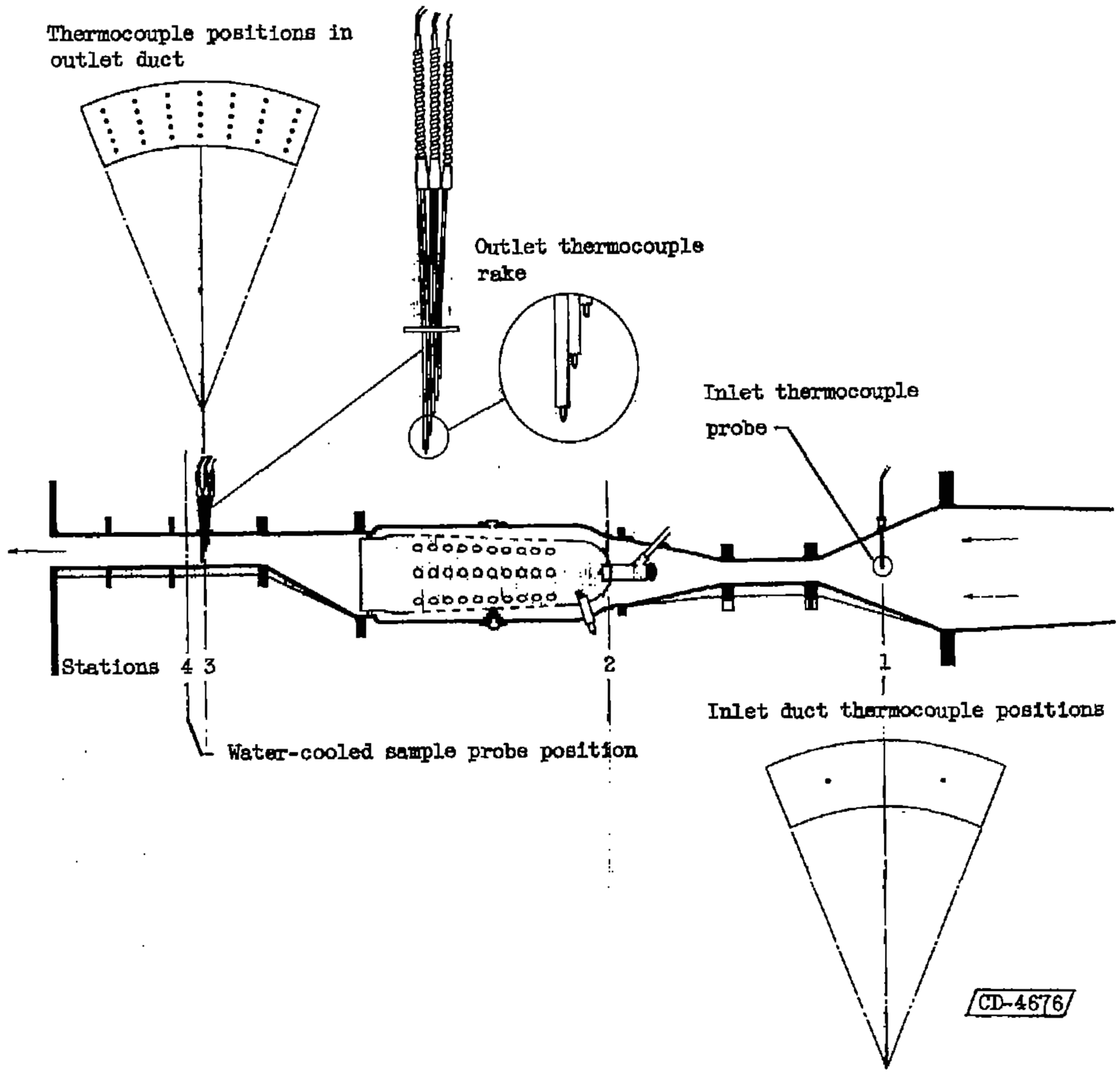


Figure 4. - Instrumentation details for test assembly for coolant-injection study.

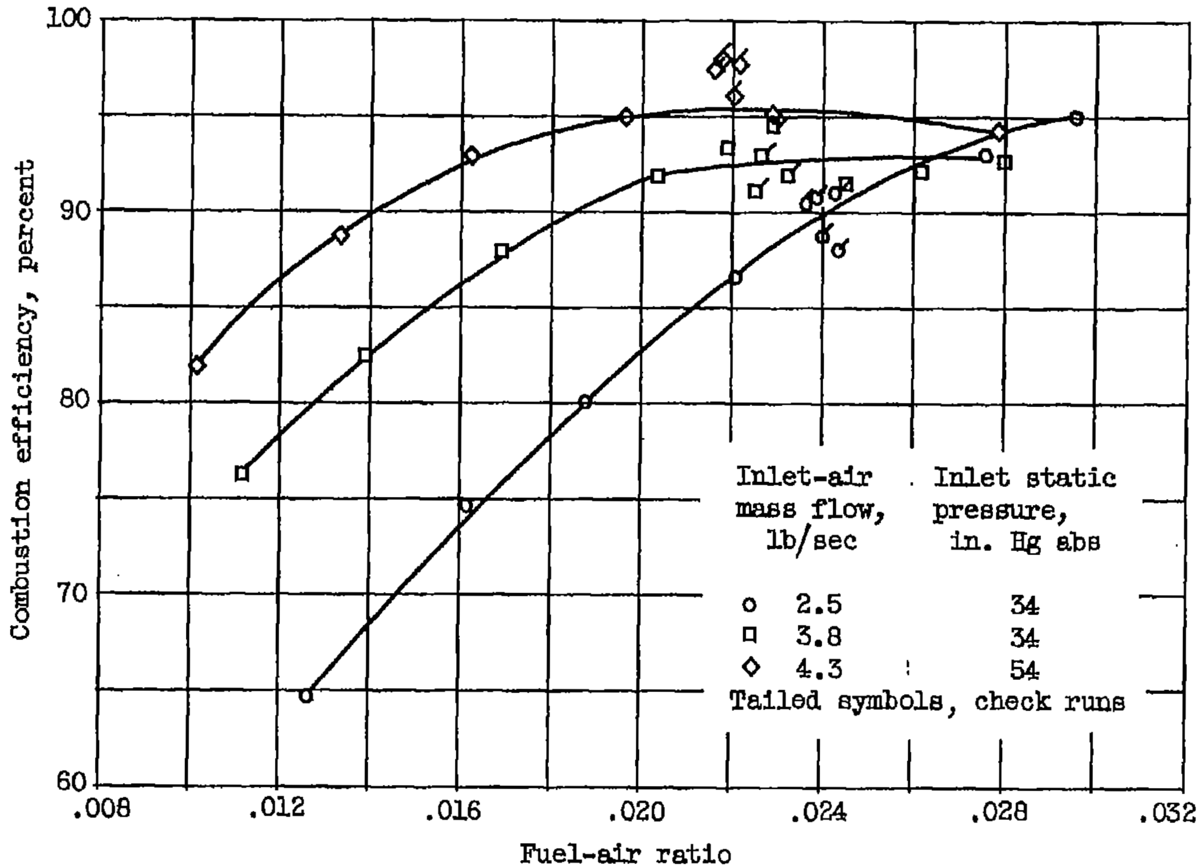


Figure 5. - Variation of combustion efficiency of the test combustor with fuel-air ratio. No coolant injection.

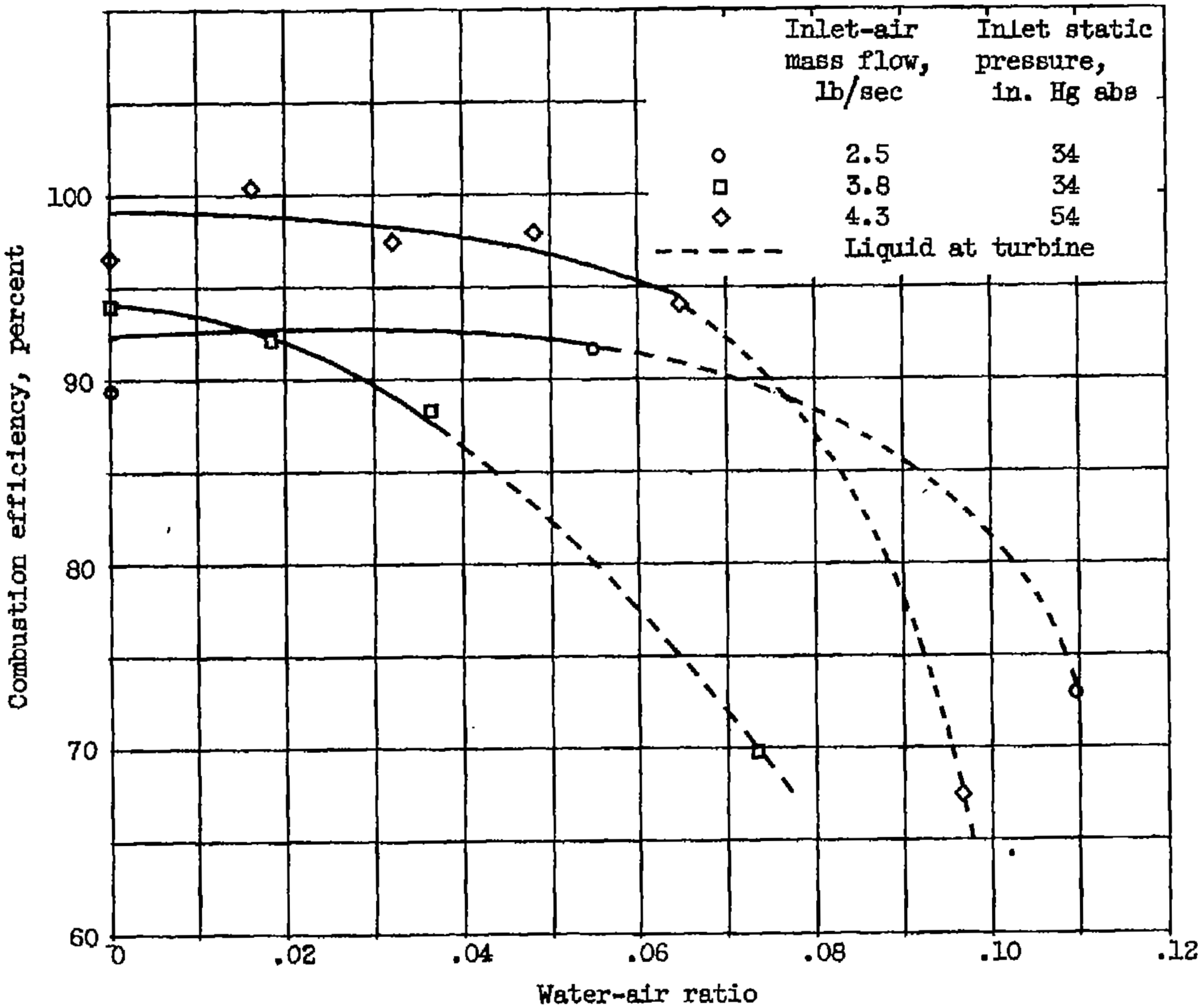


Figure 6. - The effect of water injection on combustion efficiency with constant combustor fuel-air ratio for three test conditions. Fuel-air ratio, approximately 0.022 to 0.024.

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CJ-4

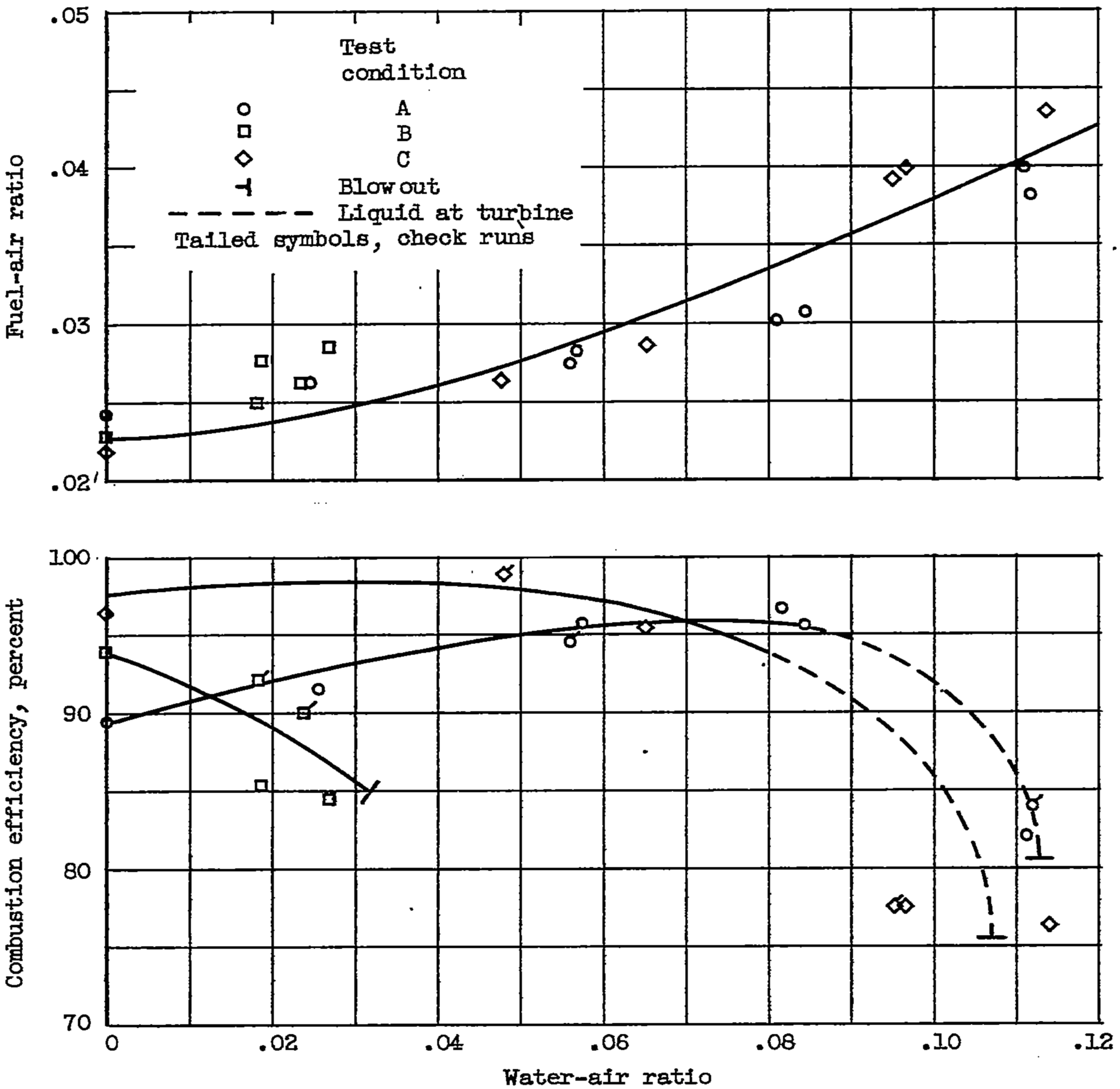

Figure 7. - Comparison of the effect of water injection on combustion efficiency and fuel-air ratio. Constant combustor-outlet temperature, 1560° F; test conditions, A, B, and C.

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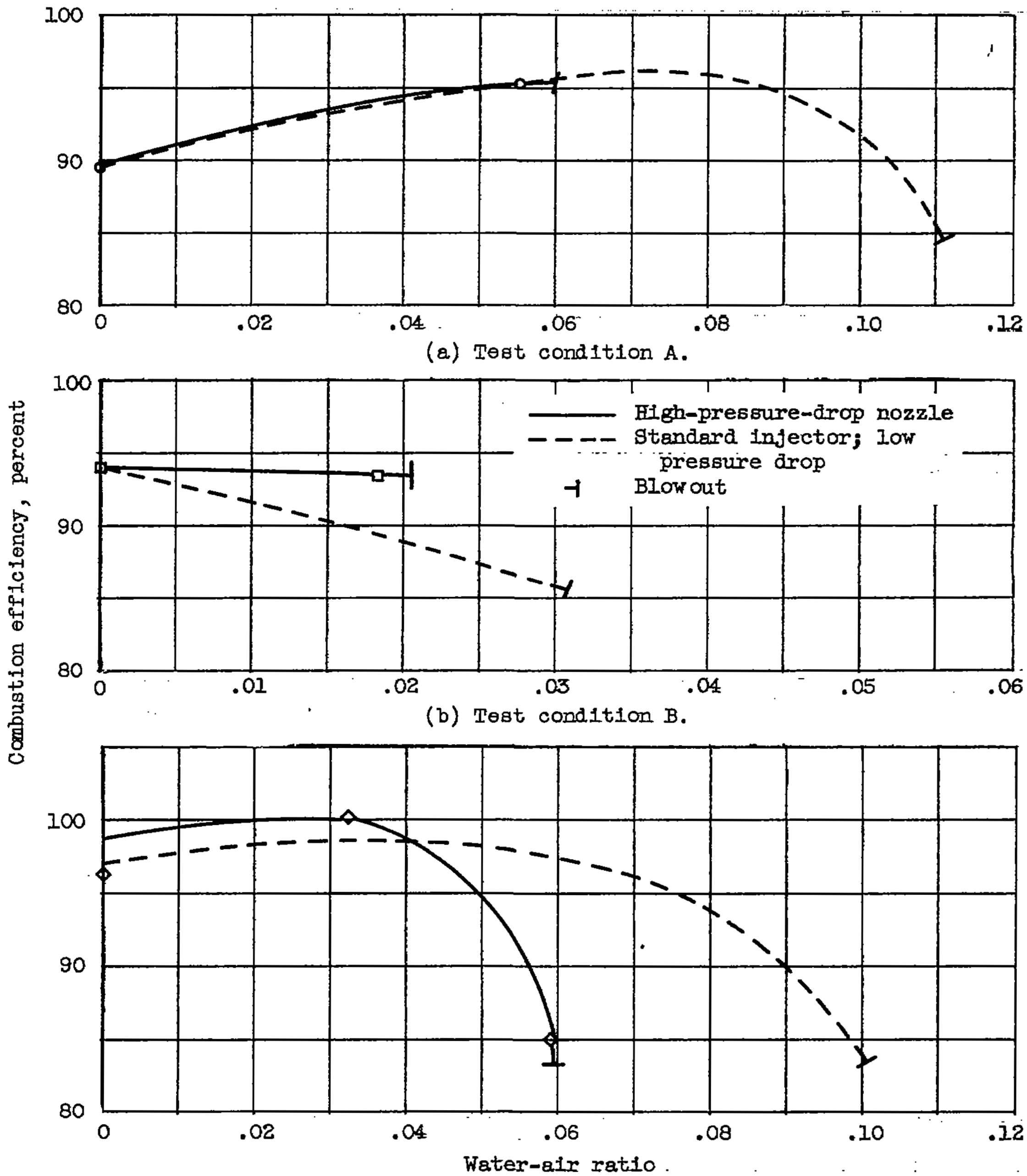
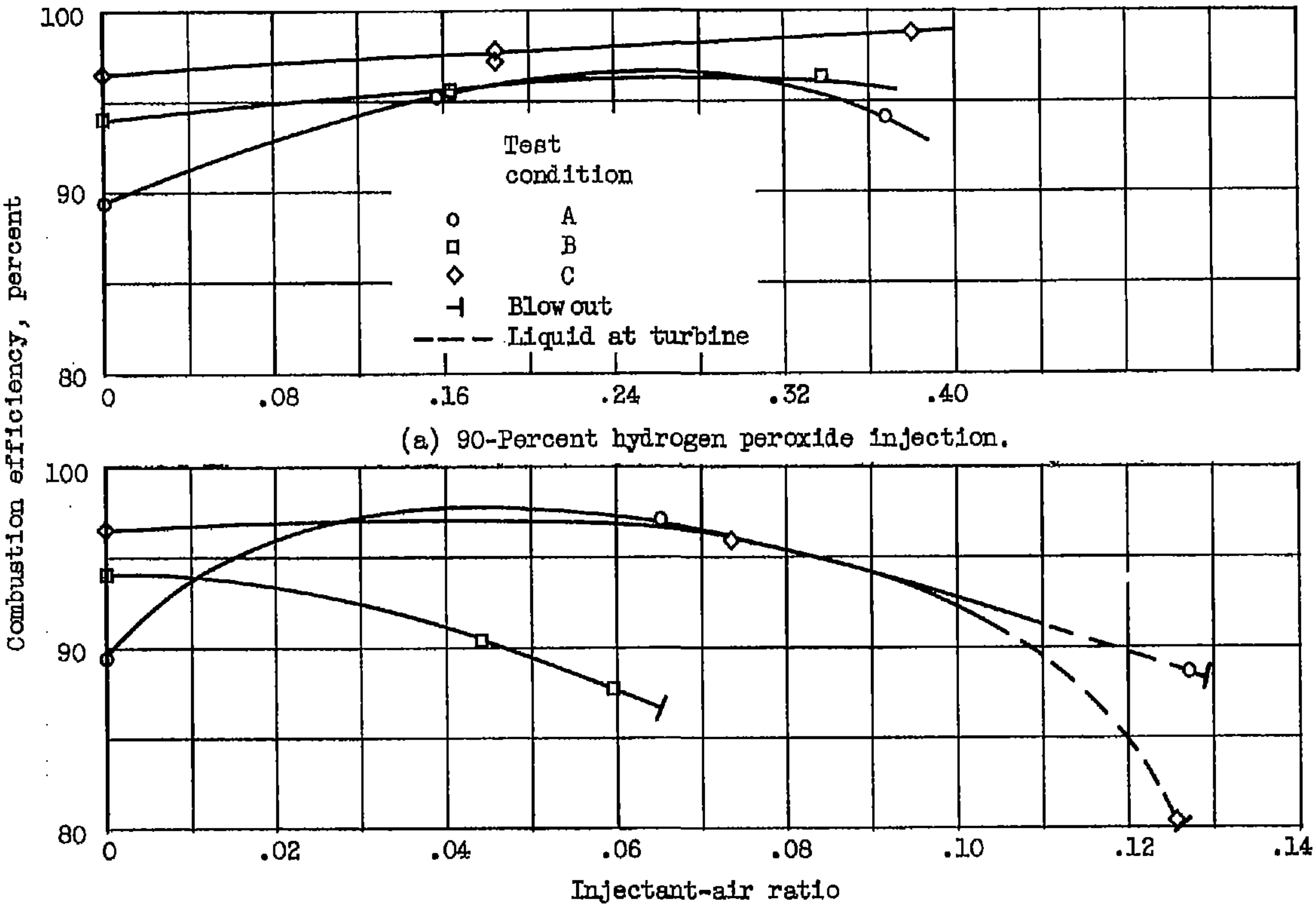


(c) Test condition C.

Figure 8. - Combustion-efficiency - water-air ratio relations for high and low pressure-drop injection nozzles. Combustor-outlet temperature, 1560° F.

[redacted]



(a) 90-Percent hydrogen peroxide injection.

(b) 35-Percent hydrogen peroxide injection.

Figure 9. - Effect of hydrogen peroxide injection on combustion efficiency assuming complete hydrogen peroxide decomposition. Turbine-inlet temperature, 1560° F.

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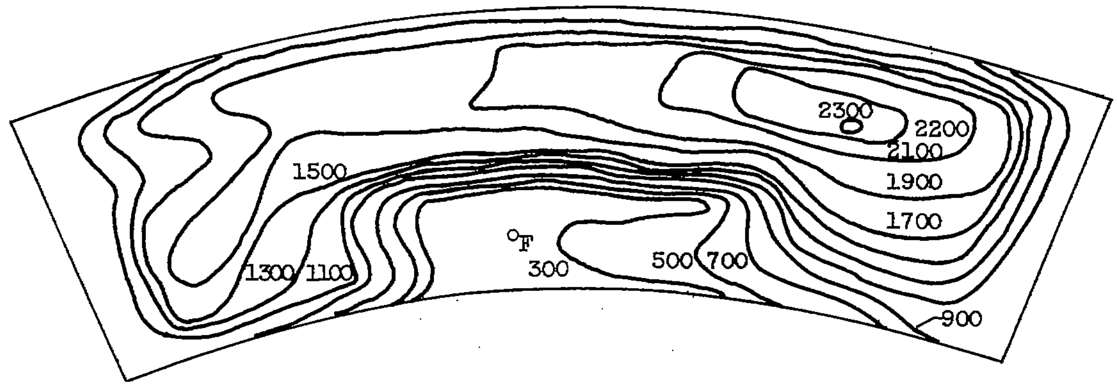
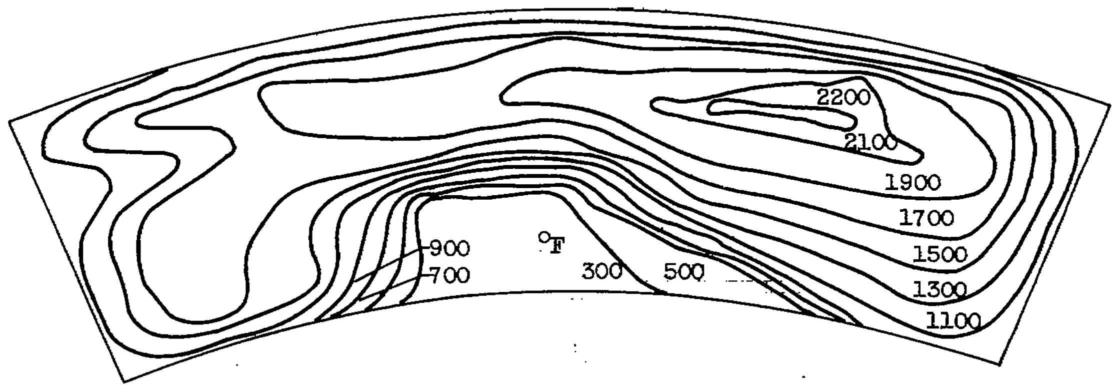
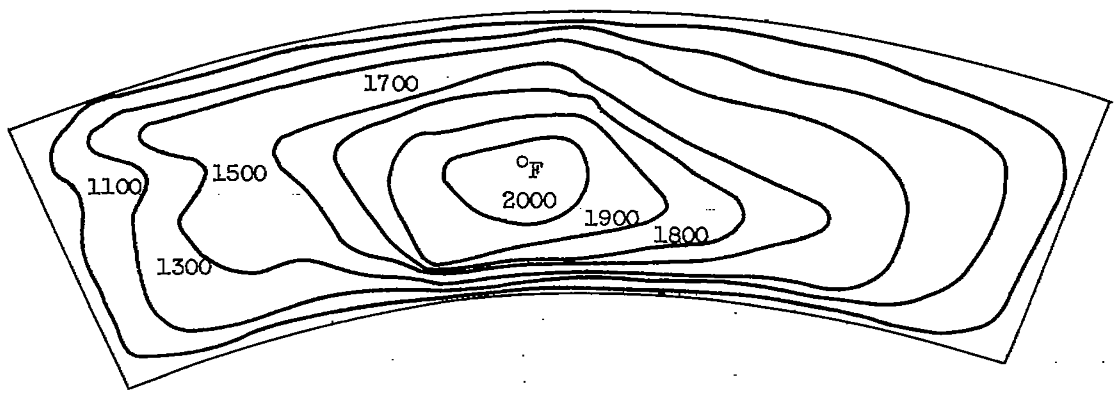


(a) Water-air ratio, 0.0966.



(b) 35-Percent hydrogen peroxide - air ratio, 0.1253.



(c) 90-Percent hydrogen peroxide - air ratio, 0.3800.

Figure 10. - Turbine-inlet temperature profiles at high injectant-air ratio for water and for hydrogen peroxide injection. Combustor-inlet temperature, 90° F; turbine-inlet temperature 1560° F; condition C.

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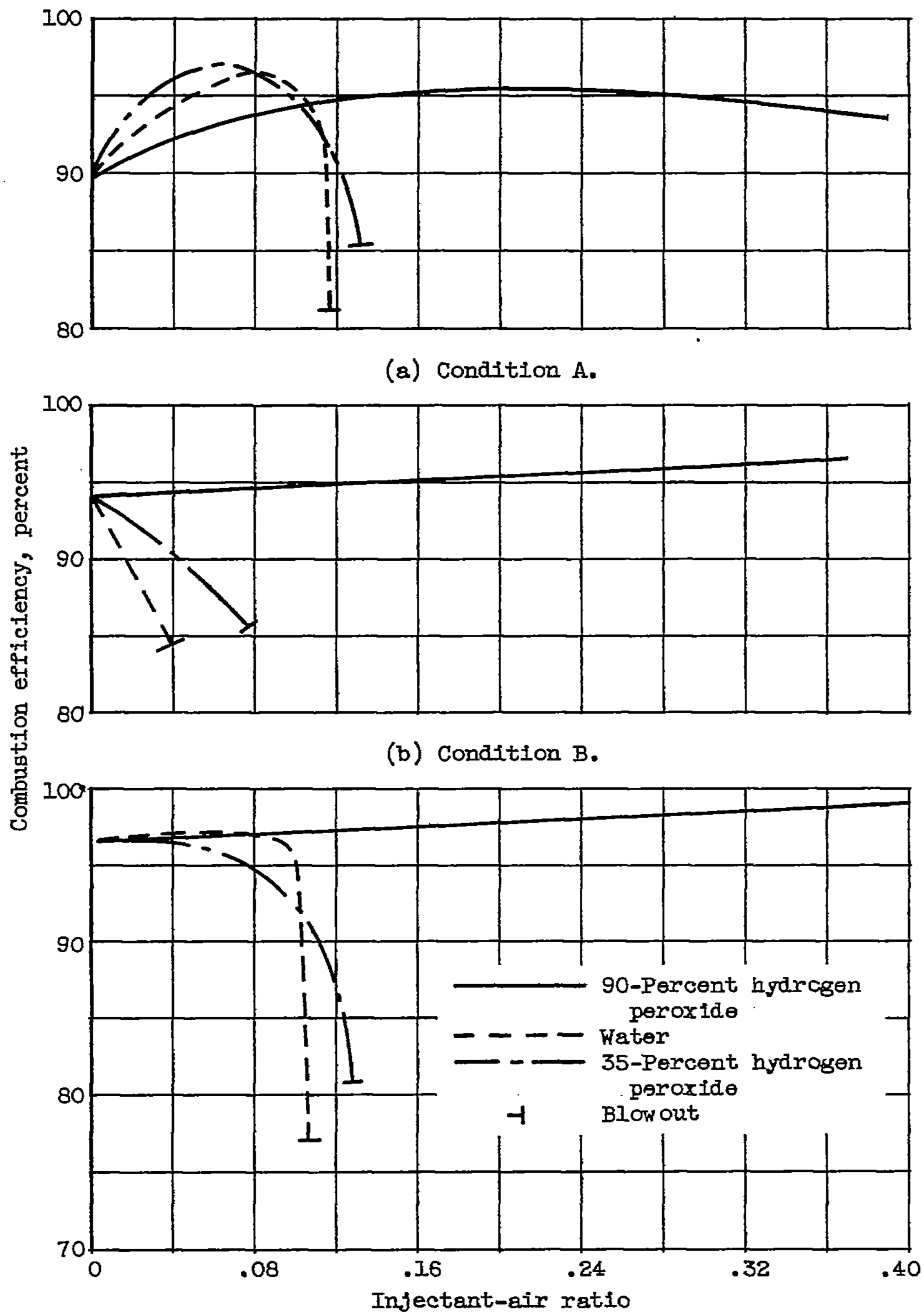

(a) Condition A.

(b) Condition B.

(c) Condition C.

Figure 11. - Comparison of combustion efficiency at conditions A, B, and C for water or hydrogen peroxide injection into combustor. Turbine-inlet temperature, 1560° F.

[redacted]

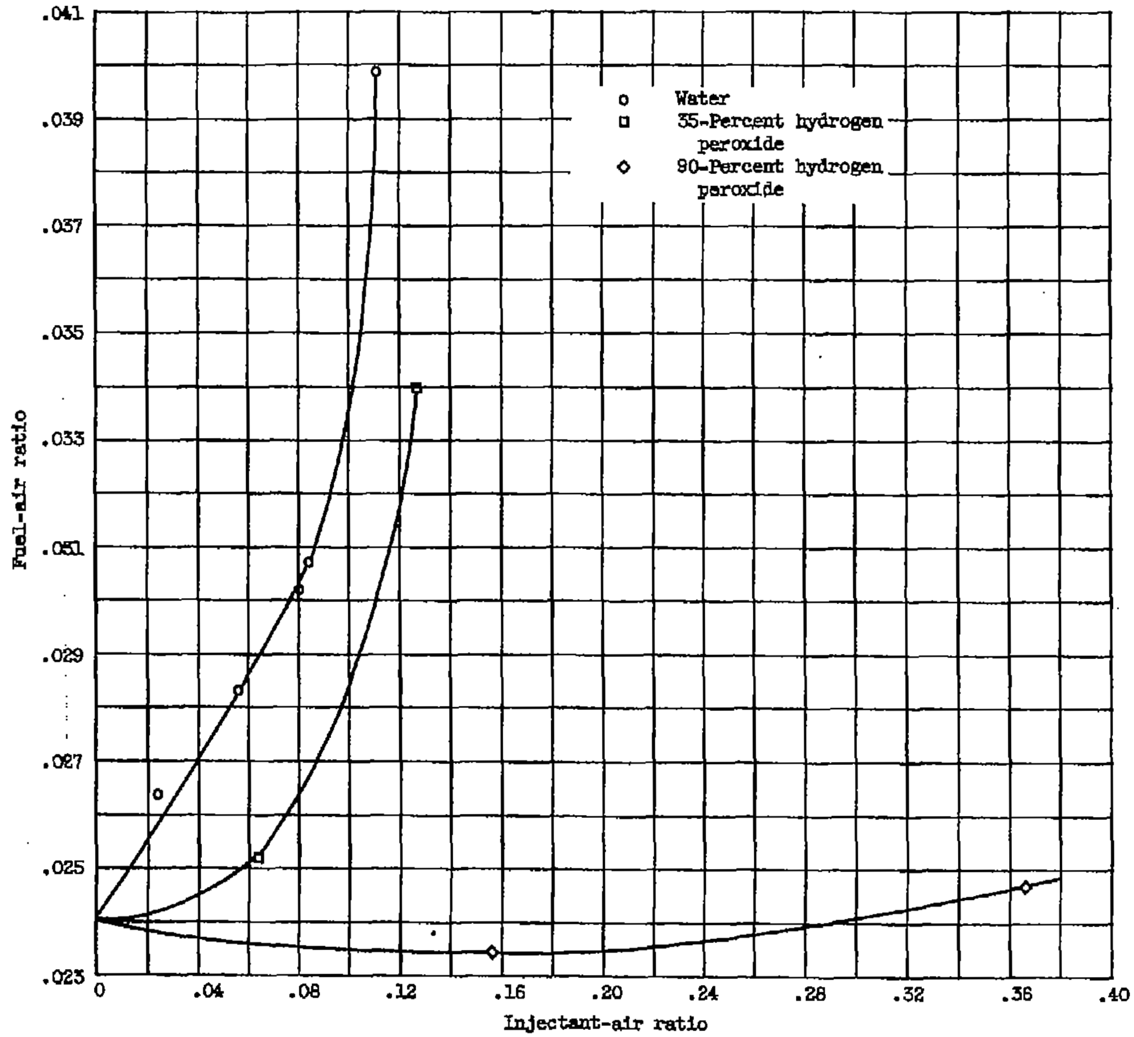

Figure 12. - Comparison of combustor fuel-air ratio required to maintain turbine-inlet temperature of 1560° F for injection of water or hydrogen peroxide at condition A. Combustor-inlet temperature, 90° F.

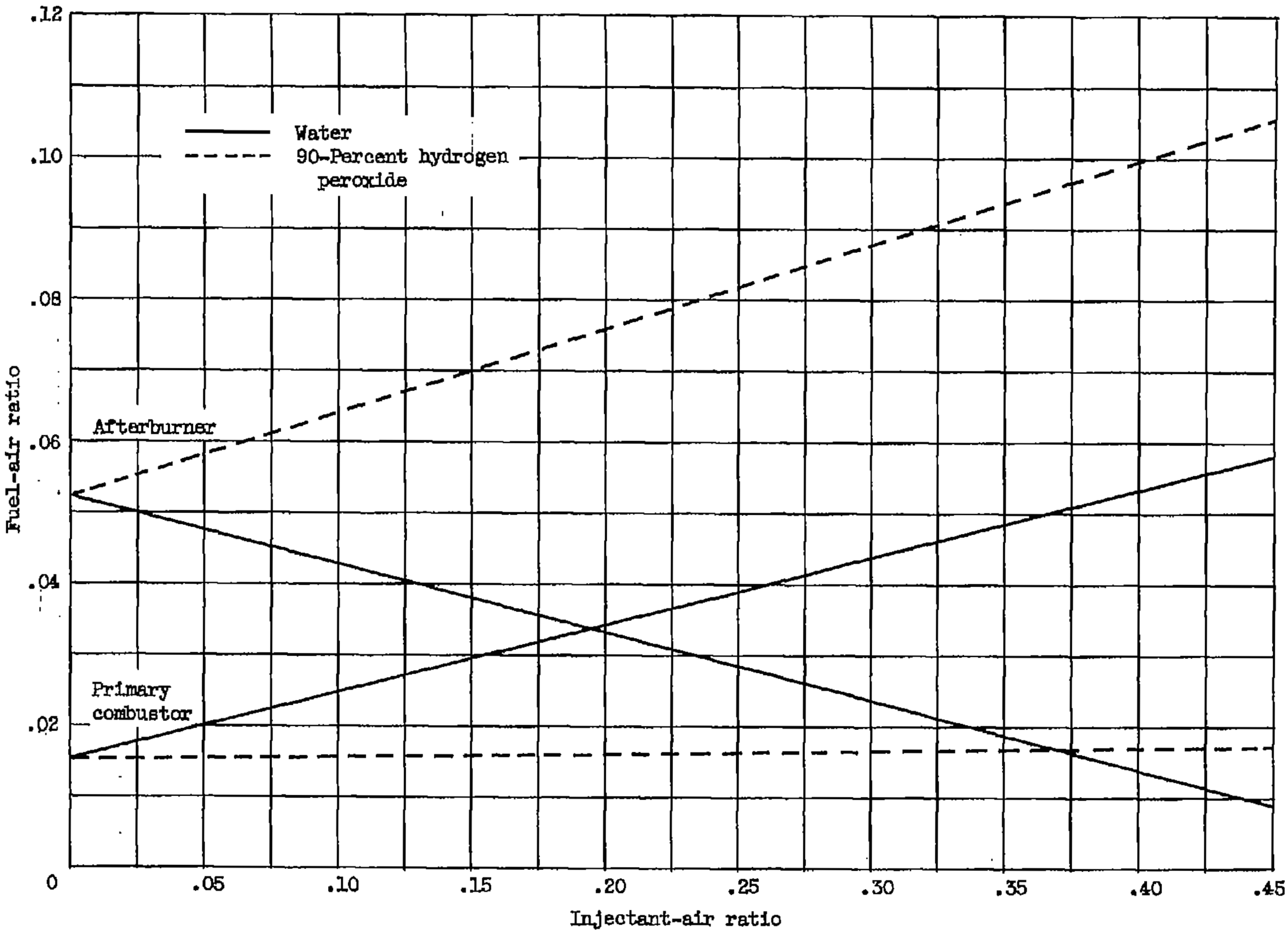

Figure 13. - Theoretical primary combustor and afterburner fuel-air ratios for various injection rates of water and hydrogen peroxide. Assumptions: Primary fuel-air ratio, 0.0156; turbine-inlet temperature, 1520° F; combustion efficiency, 100 percent; stoichiometric afterburning.

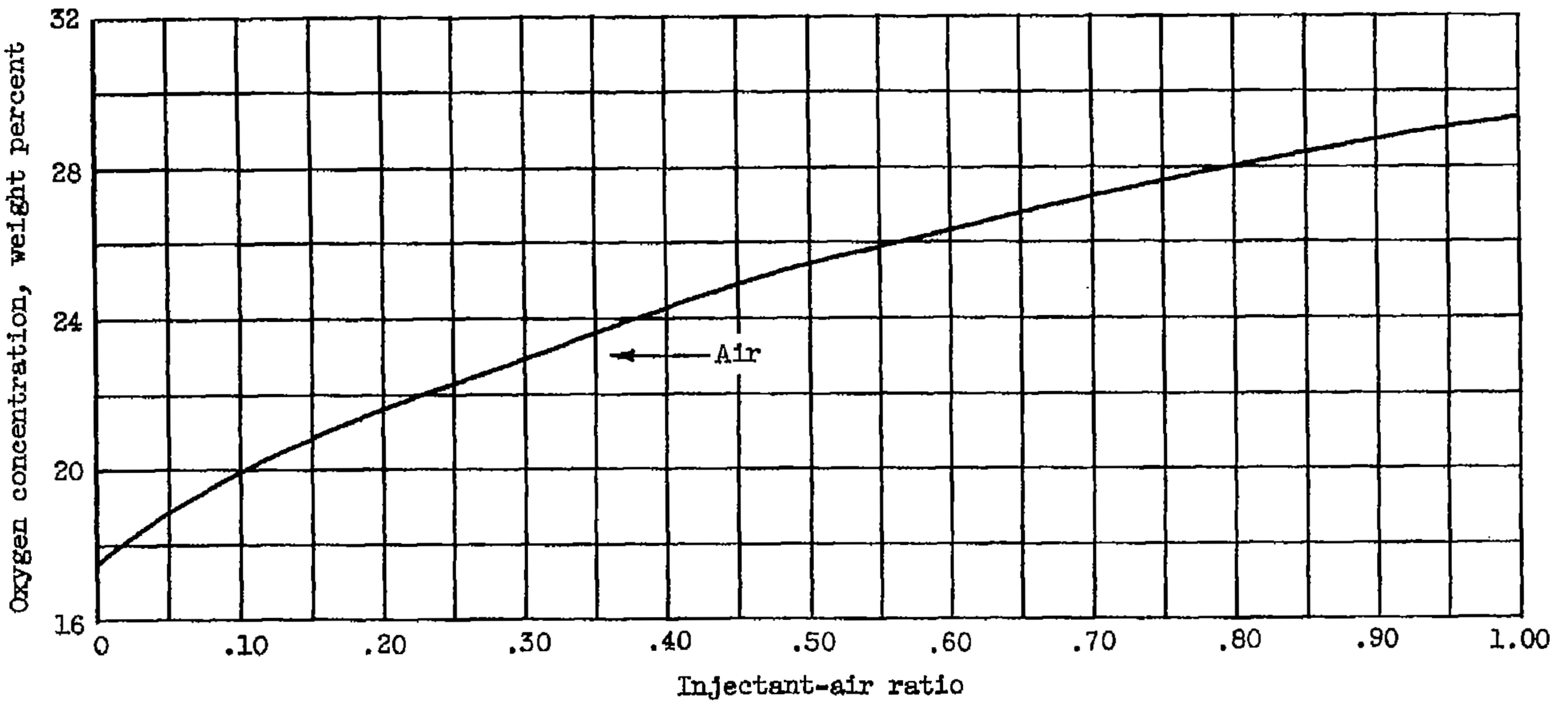

Figure 14. - Afterburner-inlet oxygen concentration resulting from 90-percent hydrogen peroxide decomposition for various hydrogen peroxide-air ratios: Primary combustor fuel-air ratio, 0.0156; combustion efficiency, 100 percent; complete hydrogen peroxide decomposition assumed.

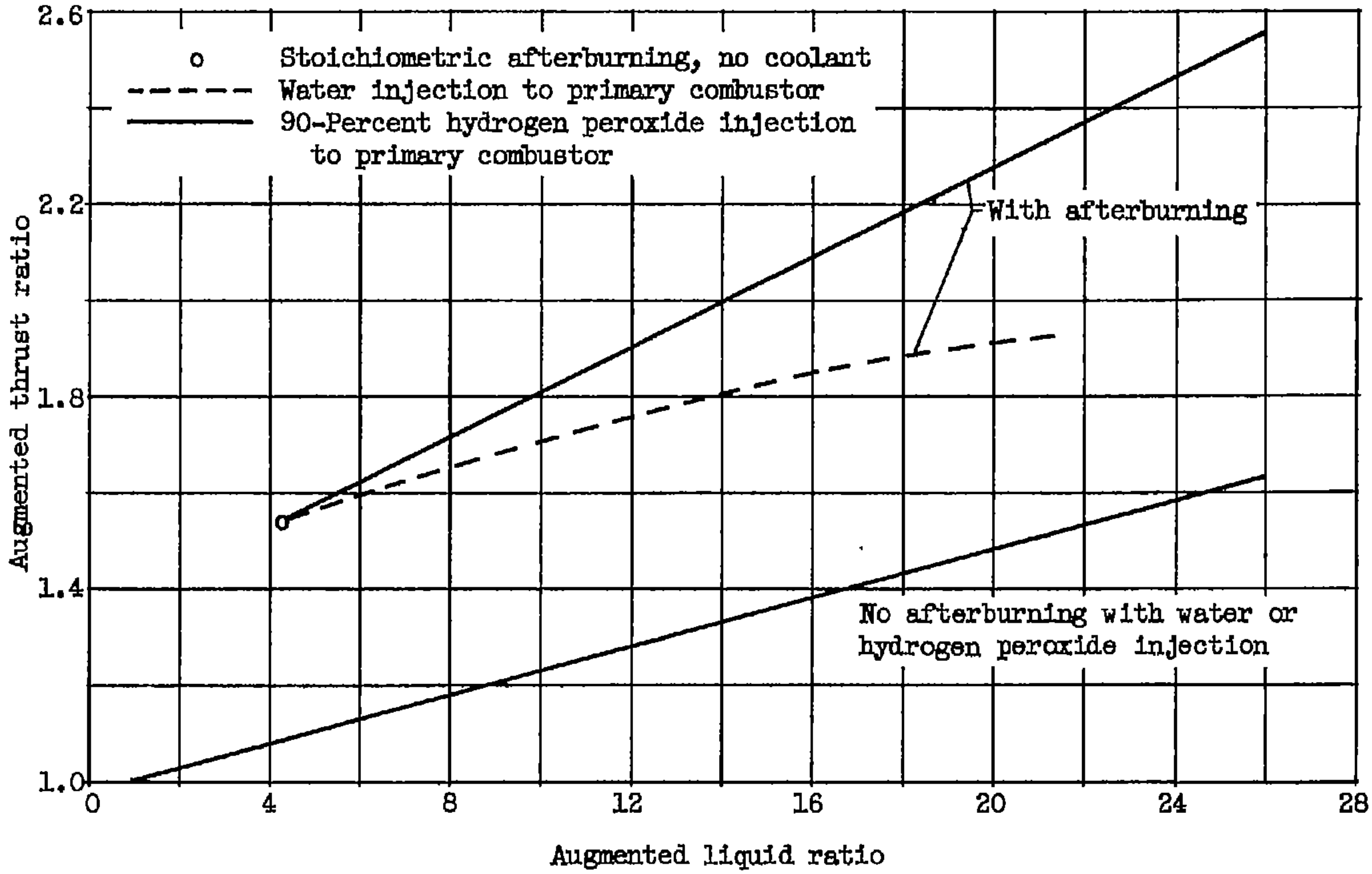

Figure 15. - Approximate theoretical net thrust ratios for various rates of injection of water or 90-percent hydrogen peroxide into the primary combustor of a 5.3 compressor-pressure-ratio engine with and without afterburning. Zero flight Mach number, sea level; rated speed, 7950 rpm, and choked exhaust nozzle.