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RESEARCH MEMORANDUM

TRANSIENT AND STEADY-STATE PERFORMANCE OF A SINGLE TURBOJET COMBUSTOR WITH FOUR DIFFERENT FUEL NOZZLES

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NATIONAL ADVISORY COMMITTEE
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TRANSIENT AND STEADY-STATE PERFORMANCE OF A SINGLE TURBOJET COMBUSTOR WITH FOUR DIFFERENT FUEL NOZZLES

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SUMMARY

Acceleration and steady-state performance of a single tubular combustor operating with four different fuel nozzles were determined at two simulated altitude, part-throttle conditions. The nozzles were the dual-entry duplex nozzle usually used in this combustor, a single-entry duplex type, and two simplex nozzles. Additional tests were made over a range of initial fuel flows (heat-release rate) while maintaining the combustor-inlet air variables constant at the two altitude - engine speed conditions.

The rates at which combustor temperature and pressure responded to fuel addition varied with the nozzles; an appreciable response lag was observed with all the nozzles. Limiting rates of change of fuel flow (acceleration limits) were observed only with the dual-entry nozzle; the observed combustion failures were attributed to an interrupted fuel-flow delivery during acceleration. At the particular altitude conditions used, heat release rate was not found to be an important factor in controlling acceleration limits as was suggested in a previous investigation. No combustion failures were observed during acceleration with three other nozzles that gave uniform flow delivery, excepting those accelerations to final fuel-air ratios producing steady-state rich blow-out. These results suggest that combustion failures during high-altitude acceleration are due to rich blow-out limits being exceeded during transient operation, or are due to discontinuity in fuel-flow delivery, which is a function of fuel nozzle used.

The best steady-state combustion efficiencies were obtained with the dual-entry duplex nozzle because of its superior atomization at these part-throttle conditions. As this nozzle also gave the poorest acceleration, steady-state efficiency performance is no reliable criterion of transient performance.

INTRODUCTION

Research is being conducted at the NACA Lewis laboratory to determine the factors that affect engine acceleration. As part of this research, an investigation of the effect of fuel-nozzle design on the combustion behavior during fuel-flow increase in a single tubular combustor is reported herein.

A study of one full-scale engine indicated that combustion flame-out was a factor limiting engine acceleration at altitudes above 35,000 feet (ref. 1). Precise control of the fuel input during acceleration was necessary in order to avoid unstable combustor operating conditions. An investigation describing combustion response to rapid fuel-flow changes is reported in reference 2. Limiting time rates of change of fuel flow (acceleration limits) were determined and the effects of certain air-flow variables were studied. Further studies indicated that small variations in the axial position of the liner with respect to the nozzle affected both transient and steady-state performance (ref. 3). These investigations (refs. 2 and 3) were conducted in a J35 combustor with a dual-entry duplex nozzle, which is the standard nozzle for this combustor.

The present investigation used a similar-type combustor with four different fuel-injection nozzles to determine effects of some variations in nozzle design on transient and steady-state combustion performance. The four nozzles provided a range of fuel-spray characteristics at any given fuel flow rate. The J47 combustor chosen for this investigation was so designed that variations in axial position of the liner with respect to the nozzle would not occur.

Data were obtained with the four fuel nozzles at combustor-inlet conditions simulating 58-percent rated rotor speed and altitudes of 35,000 and 45,000 feet. Additional tests were conducted to determine the effects of initial (before acceleration) outlet temperature, fuel-air ratio, and heat-release rate on the acceleration characteristics. The data are analyzed to indicate the effect of fuel-spray characteristics on steady-state combustion efficiencies and transient combustor behavior. Photographs of the fuel sprays provided by the four nozzles are also shown and discussed. Descriptions of the special apparatus and instrumentation used are presented.

APPARATUS AND INSTRUMENTATION

Combustor

The axial relation of the liner to the nozzle has been shown to be a variable factor influencing combustion performance in the J35 combustor (ref. 3). For this reason, a J47-GE-19 single combustor was chosen for this investigation. The liner of this combustor is anchored near the upstream end of the combustor at the cross-fire tubes; thus, only small axial movement of the liner with respect to the nozzle occurs as a result of liner thermal expansion. The combustor-outer-housing wall was reinforced with metal bands to eliminate structural failure at low interior pressures.

Combustor Installation

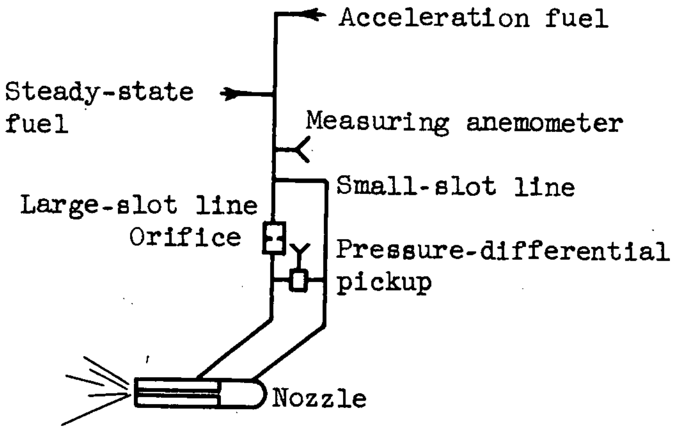
The combustor was connected to the laboratory air facilities as shown diagrammatically in figure 1. Air-flow rate and air pressure were regulated by remote-control valves upstream and downstream of the combustor. Air flow was measured by means of a variable-area orifice. In order to assure a uniform air and exhaust supply free of line surges, choke plates were placed in the inlet and exhaust ducting of the combustor. Location and construction of these choke plates are shown in figure 2. The inlet choke plate admitted air through fifty 1/4-inch-diameter holes. The outlet choke-plate assembly consisted of two slotted plates, one of which was movable with respect to the other, permitting a range of flow areas to be selected. The inlet choke plate and outlet choke assembly were installed in the ducting at positions corresponding to the last stage of the compressor and to the turbine nozzle diaphragm in the full-scale engine.

Fuel-Injector Systems

Two fuel systems were used to obtain the required flow rates for the steady-state and transient phases of the investigation. A conventional fuel system containing fuel storage drums, pumps, rotameters, piping, and manual regulating valves was used to obtain steady-state combustion data. A separate fuel system containing a pressurized container, motorized flow control valve, and surge chambers was used to obtain transient data. A detailed description of the fuel acceleration system is given in reference 2. The fuel used was MIL-F-5624A, grade JP-4 (NACA fuel 52-288).

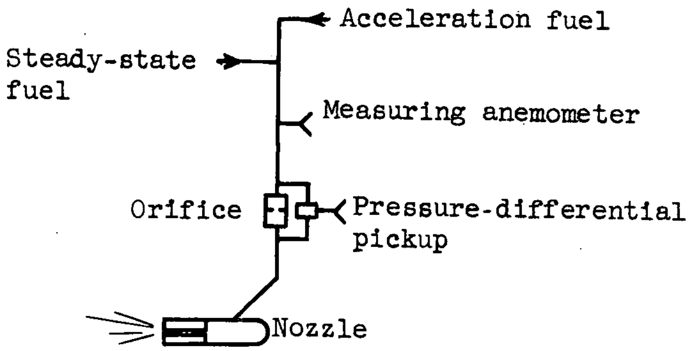
The four different fuel injectors used in this investigation were installed in the same relative position within the combustor. A description follows:

Dual-entry duplex nozzle. - The dual-entry duplex nozzle is used in the J47 turbojet engine. It has two internal flow paths, called large and small slots, which converge and feed out through a single orifice. An external flow divider splits the flow to each slot path in the engine installation. At low flow rates all the fuel goes through the small slots. When the pressure within the small-slot path exceeds a preset value, excess fuel is diverted to the large slots. An orifice in the large-slot supply line was used in the test apparatus to approximate the action of the external flow divider. The nozzle, supply piping, and location of fuel-measuring instruments are shown in the following sketch:



The transient fuel-flow rate was measured with a pressure-differential pickup and a constant-current hot-wire anemometer. The pressure-differential pickup was connected across the orifice in the large-slot fuel-supply line, as shown in the preceding sketch. The pressure pickup, properly calibrated, measured steady-state fuel flow accurately and was used to indicate the flow before and during acceleration. The anemometer, installed in the main fuel-supply line, had a higher frequency response but was less accurate; the anemometer was used to determine the time elapsed during the fuel-flow change. The signals obtained from both flow-measuring devices were recorded on an oscillograph.

Single-entry duplex nozzle. - This nozzle has two flow slot paths and a single orifice similar to the dual-entry duplex, but division of flow is done within the nozzle body. As the flow division is internal, one supply line feeds the nozzle as shown by the following sketch:



The flow-measuring anemometer and pressure pickup were installed in series in the single fuel-supply line.

Simplex-type nozzles. - Two different capacity simplex nozzles were used. They were constant-area, single-orifice units having 60.0 and 15.3 gallon-per-hour capacities at 100-pounds-per-square-inch pressure differential. The internal parts of a duplex nozzle were removed and the simplex units were attached to the end of the duplex body. The supply line arrangement was identical with the single-entry duplex arrangement.

Temperature and Pressure Instrumentation

Combustor-inlet air temperature was measured by two single-junction iron-constantan thermocouples located at station 1 (fig. 1). Steady-state combustor-inlet static pressure was measured by static taps located at station 2 (fig. 1). Transient combustor-inlet static pressure was measured at the same station (2) with a diaphragm-type differential pressure pickup and was recorded on an oscillograph.

Combustor-outlet gas temperature was measured by three five-junction chromel-alumel thermocouple rakes located at station 3 (fig. 1). These thermocouples were connected through an averaging circuit to a potentiometer and were used to indicate steady-state outlet temperatures before and after fuel accelerations. The rapid variations in combustor-outlet temperature during the acceleration process were indicated by a single thermocouple that was compensated for thermal lag. The single thermocouple, located between the rakes at station 3, consisted of 0.010-inch-diameter wires butt-welded between two heavier support wires. The position of the single thermocouple junction in the gas stream was selected to indicate the same temperature as the average reading of the 15 outlet thermocouples during steady-state operation. The temperature indications were recorded by an oscillograph. A detailed discussion of the methods of thermocouple compensation is given in reference 2. The theory of compensation is presented in reference 4.

PROCEDURE

Test Procedure

Transient combustion response characteristics and steady-state combustion efficiencies were studied at the following operating conditions:

Simulated flight conditions		Inlet static pressure, in. Hg abs	Inlet air temperature, °F	Inlet air flow, lb/sec	Reference velocity, ft/sec	Outlet temperature, °F
Altitude, ft	Rotor speed, percent rated					
35,000	58	18	85	2.0	95	520
45,000	58	11.5	85	1.3	96	510

These conditions simulated operation of the combustor in a 5.2-pressure-ratio turbojet engine at a flight Mach number of zero. Reference velocities are based on the maximum cross-sectional area of the combustor (0.48 sq ft), the inlet-air density, and the mass-air flow rate.

Combustor steady-state temperature-rise data were obtained with all four fuel nozzles at the two operating conditions noted. At each test condition, data were recorded for fuel-air ratios both higher and lower than those required for the outlet temperatures shown in the table.

Transient combustion response data were obtained in the following manner: Steady-state combustion was attained and the transient instrumentation was calibrated against the steady-state instrumentation. The acceleration fuel system was then adjusted and energized to increase fuel flow at the desired rate. For selected final values of fuel flow, the rate of fuel acceleration was increased by readjusting components of the accelerating system until combustion failed or the limit of the fuel system was reached. This procedure was repeated for each combustor test condition with each of the four fuel nozzles. Limited acceleration data were obtained over a range of initial fuel-air ratios to determine the effects of initial outlet temperature and fuel-air ratio on acceleration limits.

Method of Determining Fuel Acceleration Rates

The fuel acceleration rates referred to herein represent the fuel-flow slopes and were computed as the change of fuel-air ratio per unit time. Figure 3 shows a sketch of a typical fuel trace as recorded by the pressure-differential pickup. This oscillograph trace was obtained with the dual-entry duplex fuel nozzle. The acceleration rate was calculated by dividing the difference between initial fuel-air ratio and final fuel-air ratio by the amount of time (seconds) between the point on the trace where the acceleration begins and the point where the fuel flow first reaches the final flow rate.

RESULTS

Combustor Transient-Response Characteristics

The transient-combustion performance data obtained with the four nozzles at both simulated altitude - rotor speed conditions are presented in table I. Included in these tables are data indicating the rate of combustion response to fuel acceleration. Combustion "dead time" is defined as the time between the start of the acceleration and the point where temperature and pressure first exceed their initial values. Total response lag is the time required after the start of the acceleration for the combustor-inlet temperature (as indicated by the single compensated thermocouple) approximately to level off at the higher temperature at the end of the transient. Both lag and dead time are a combination of fuel transport and combustion process time.

Oscillograph records typical of those obtained at the simulated 35,000-foot altitude test condition are presented in figures 4 and 5. A composite plot of the data from figures 4 and 5 is presented in figure 6, which shows faired curves for the fuel-flow, combustor-outlet-temperature (as indicated by the single compensated thermocouple), and inlet-static-pressure variations during accelerations with each of the four nozzles. In most cases the fuel-supply system was adjusted to increase outlet temperature from 520° to 1500° F during the acceleration. With the smallest simplex nozzle (15.3-gal/hr) available supply pressure limited the final temperature to about 1250° F.

Results of two runs at different acceleration rates with the dual-entry duplex nozzle are shown in figure 6(a). The gap in the flow curves for both runs resulted from the trace exceeding the limits of the calibration. As fuel flow was increased, combustor-outlet temperature and inlet static pressure first decreased and then increased; dead time was about 1.58 seconds. An outlet temperature of about 1500° F was attained in about 2 seconds (total response lag). The dotted-line curves represent an unsuccessful acceleration; the more rapid increase in fuel flow resulted in a decrease in temperature and pressure with no recovery. Unsuccessful accelerations following this response path are referred to as "quench-out" points. Similar response characteristics of a J35 combustor operating with the same dual-entry duplex nozzle are reported in reference 2. Another unsuccessful response path, called "blow-out", is reported in reference 2. During acceleration to high final fuel-air ratios, the fuel addition would provide some increase in temperature rise before flame blow-out occurred. A possible explanation of these response paths is included later.

Results obtained in a typical run with the single-entry duplex nozzle are shown in figure 6(b). For this run, the change from initial to final flow rate occurred in about one-tenth of the time taken for the successful acceleration run with the dual-entry duplex nozzle (fig. 6(a)). Combustor-outlet temperature and inlet pressure responded immediately to the increase in fuel flow; no intermediate decreases were observed. The time required for outlet temperature to reach the final temperature of 1500° F was, however, approximately the same with both single- and dual-entry nozzles. Once the temperature began to respond to the increase in fuel flow, it rose more rapidly with the dual-entry nozzle.

Response curves for the 60.0- and 15.3-gallon-per-hour simplex nozzles are presented in figures 6(c) and (d), respectively. The fuel acceleration time with each nozzle was about the same as with the single-entry duplex nozzle. Temperature and pressure responded immediately with both simplex nozzles, but they increased more slowly than with the duplex nozzles. Total response lag was greater with the large capacity than with the smaller capacity nozzle. The conclusions obtained from the representative runs shown in figure 6 are supported by the response time data for all the runs (table I).

Limits of Fuel Acceleration

Effect of final fuel-air ratio. - Acceleration rate, calculated as the change in fuel-air ratio per unit time, is plotted against final fuel-air ratio in figure 7 for the simulated 35,000- and 45,000-foot-altitude conditions. All accelerations shown in figure 7 were started from fuel-air ratios required to give about 520° F for the 35,000-foot condition and 510° F for the 45,000-foot condition. The range of steady-state, rich blow-out fuel-air ratios observed at the higher altitude is included on figure 7(b). At the 35,000-foot altitude the rich blow-out fuel-air ratios were beyond the limits of the temperature instrumentation. The unsuccessful acceleration data were all quench-out points with the exception of those within the steady-state, rich blow-out region.

Unsuccessful accelerations were observed with the dual-entry duplex nozzle at both altitude conditions; lines are faired through the data to represent limits of successful acceleration. No unsuccessful accelerations were observed with the other three nozzles at either test condition except when the final fuel-air ratio was within the steady-state blow-out range (fig. 7(b)). At both altitude conditions, the range of final fuel-air ratio investigated provided outlet temperatures in excess of the maximum allowable turbine-inlet temperature, about 1600° F.

Effect of initial conditions before acceleration. - Acceleration data were obtained for a range of initial fuel-air ratios at both simulated altitudes. These accelerations were made to a final outlet temperature of about 1500° F. Acceleration rate is plotted against fuel-air ratio before acceleration in figure 8, and against combustor-outlet temperature and heat-release rate before acceleration in figure 9.

The dual-entry duplex nozzle gave unsuccessful accelerations at both altitude conditions. At the 35,000-foot condition, the limiting acceleration value increased rapidly as fuel-air ratio, outlet temperature, and heat-release rate before acceleration increased (figs. 8(a) and 9(a)). The trend was directly opposite at the 45,000-foot condition (figs. 8(b) and 9(b)).

No combustion blow-out or quench-out was observed with the single-entry duplex and the two simplex nozzles over the range of initial conditions represented by the data of figures 8 and 9. No data are shown on figures 8(a) and 9(a) for the 15.3-gallon-per-hour nozzle; the final temperature with this nozzle was limited by insufficient fuel-supply pressure. However, successful accelerations were obtained over the same range of initial conditions to about 1250° F final temperature with the 15.3-gallon-per-hour nozzle.

Steady-State Combustion Efficiency

Steady-state combustion performance data obtained at combustor-inlet conditions simulating part-throttle operation at 35,000- and 45,000-foot altitude are presented in table II. Data were obtained at the low fuel-air ratios that would exist during engine operation at part throttle at any altitude. Acceleration to higher fuel-air ratios would begin with these steady-state conditions. Combustor-outlet temperature is plotted against fuel-air-ratio, for each of the different fuel nozzles, in figure 10. Included in figure 10 are lines of constant combustion efficiency; by interpolating between these lines the combustion efficiency value of each data point can be estimated. These lines of constant efficiency were computed as the ratio of enthalpy rise through the combustor to heat content of the fuel.

A comparison of the combustion efficiencies obtained with each nozzle at both altitudes is presented in figure 11. The efficiencies are lower at the higher altitude. In general, the dual-entry duplex nozzle provided the highest efficiencies of the four nozzles studied. The 60.0-gallon-per-hour simplex nozzle gave the poorest performance, with efficiencies as much as 48 percent lower than the others at a given fuel-air ratio value.

Spray Characteristics

In an effort to explain the results obtained in this investigation, a cursory examination was made of the spray characteristics provided by each of the fuel nozzles. Motion pictures and still photographs were taken of each nozzle ejecting water at flow rates similar to those used in the combustion performance investigation. Both steady-state and transient flow observations were made. The combustor was removed from the test rig and the nozzles sprayed into the test room. The same injection systems that were used to provide fuel in the performance investigation supplied water to the nozzles.

Steady-state tests showed that at any given flow rate the different nozzles gave a wide range of spray angles and drop sizes. All the nozzles gave hollow-cone-type sprays when fully developed. The dual-entry duplex nozzle produced the finest atomization, with a spray angle of about 170° through the small slots at low flows. As flow increased and as the large slots came into operation, the spray angle converged to about 120°. The other nozzles emitted a narrow-angle bulb-type spray at low flows that diverged to a fully developed cone as flow increased. The fully developed spray angles were 110° for the single-entry duplex nozzle, 80° for the large-capacity simplex nozzle, and 70° for the small-capacity simplex nozzle. The large-capacity simplex nozzle produced the coarsest atomization.

Selected frames of the motion pictures taken of the single-entry and dual-entry duplex nozzle sprays during flow acceleration are presented in figures 12 and 13, respectively. The spray pattern development was the same during acceleration as during steady-state conditions for all nozzles except the dual-entry duplex. In figure 13 the spray from the dual-entry duplex nozzle is shown to converge from a wide angle to a more narrow angle, with the flow output ceasing completely for a period of about 0.02 to 0.04 second during the transition. This flow interruption occurred only when the spray was emitting from the small slots at the start of the acceleration; no flow interruption was observed when both slots were completely filled at higher flows. Since the fuel-measuring instrumentation indicated an increase in flow during this flow interruption, recirculation of the fuel within the nozzle and injection system probably occurred.

DISCUSSION

Operation of the single turbojet combustor with different fuel nozzles showed that both steady-state and transient performance were affected by nozzle design. Photographic studies of the sprays formed at both steady-state and transient conditions will be used to explain the results observed in previous investigations (refs. 2 and 3) and those reported herein. The discussion is divided into two parts: (1) acceleration and (2) steady-state combustion efficiency.

Acceleration

Response characteristics. - The previous investigation conducted in a J35 combustor with a dual-entry duplex nozzle showed that combustor response to a rapid increase in fuel flow followed one of three paths:

(1) Successful acceleration with sustained burning at higher levels of temperature, pressure, and fuel-air ratio

(2) Acceleration to higher levels of temperature, pressure, and fuel-air ratio momentarily, followed by combustion blow-out if the final conditions approached the steady-state, rich blow-out limit

(3) Immediate combustion blow-out (quench out) during very rapid rates of fuel-flow increase.

In paths (1) and (2) dead time was observed as the inlet-air pressure and outlet temperature first decreased and then increased with an increase in fuel-flow rate. Response delay was shown to be one of the factors that made acceleration of an engine difficult to control in the tests reported in reference 5. Delays of about 0.03 second, which consisted of fuel transport and combustion process time, were observed during acceleration at sea level. With the J35 and dual-entry nozzle combustion system, the observed dead time was 0.25 second at the 25,000-foot simulated altitude and about 2.0 seconds at 50,000 feet (ref. 2).

Similar response paths were observed in the present investigation with the J47 combustor and dual-entry nozzle; the observed dead time was 1.58 seconds at 35,000-foot simulated altitude (fig. 4(a), run 13). Also, a comparison of the response time data in tables I(a) and (b) shows that total response lag increased with all the nozzles as altitude increased from 35,000 to 45,000 feet. The response characteristics with the single-entry duplex and the two simplex nozzles were quite different (figs. 4(b), (c), and (d)). Combustor-outlet temperatures and inlet static pressures did not follow the dip-and-rise pattern in response to added fuel; during successful accelerations they increased immediately with no dead time. However, response lag was observed with these nozzles. The temperature and pressure during successful acceleration did not attain the higher levels as fast as the fuel could be added; the time required varied with the individual nozzle. For all the runs with the nozzle producing the slowest temperature response, the average response lag time was 7.8 seconds at the highest simulated altitude condition (table I(b)). This type of delay would probably not be as harmful as the dead-time type of response, since there would be less tendency to cause overshoot of the scheduled fuel flow during acceleration; but response lag times of this magnitude are obviously appreciable when compared to the 20 to 40 seconds that might be required for an engine acceleration at 45,000 feet.

The variation in type of response lag observed may be explained by considering the manner in which the nozzles spray fuel during acceleration. The photographs showed that the dual-entry duplex nozzle ceased flow output immediately after the start of acceleration. The other nozzles had no such interruption; their sprays diverged into a fully developed cone uniformly. This flow interruption with the dual-entry nozzle decreased the amount of fuel being burned during the initial stage of the acceleration, resulting in the momentary decreases in temperature and pressure. After the interruption, the fuel entered the combustion zone at a more rapid rate than the calculated acceleration time would indicate, as shown by the fuel flow traces of figure 4(a). Higher acceleration rates, then, resulted in overloading a primary combustion zone in which the heat-release rate had already been reduced by the interruption in fuel flow. Only a portion of the fuel would therefore burn before blow-out occurred (response path 2). The following two possible interpretations are suggested for quench-out (response path 3): (1) still faster accelerations would result in sudden, complete quench-out of the combustion with little or none of the added fuel being burned; and (2) the nature or duration of flow interruption may have changed as acceleration rate increased, resulting in combustion lean limit blow-out with not enough fuel present to support combustion. In reference 2, the initial decreases in temperature and pressure were attributed solely to the increased fuel vaporization occurring during the acceleration. While vaporization may have influenced the accelerations in the present investigation, the fact that no initial decrease was noted with the three single-entry nozzles indicates that flow interruption was the primary factor.

Acceleration limits. - No unsuccessful accelerations were obtained with the single-entry duplex and two simplex nozzles up to the maximum acceleration rates provided by the equipment (fig. 5), excepting those accelerations where the final fuel-air ratios were in the range of rich-limit steady-state blow-out. Acceleration limits were obtained with the dual-entry nozzle in both the J47 combustor used in this investigation and the J35 combustor used previously (refs. 2 and 3). These previous investigations indicated that the limiting acceleration rates increased as initial outlet temperature and heat-release rate increased; a similar result was observed at the 35,000-foot-simulated-altitude condition in this investigation (fig. 7(a)). These accelerations were all started in the fuel-flow range where interruption of the flow occurred. The increase in limiting acceleration rate indicates that the effects of fuel-spray interruption become of lesser importance as the volume of burning is larger or the nature of the flow interruption changes. At the 45,000-foot simulated altitude, increasing these inlet variables did not permit faster acceleration rates; instead, the limits decreased (figs. 6(b) and 7(b)). The more severe inlet-air conditions present at this higher altitude apparently resulted in unstable combustion, and rich-limit fuel-air ratios were reached in the primary zone during acceleration. Unsuccessful accelerations at the higher fuel-air ratios resulted from blow-out.

Axial position of the dual-entry duplex nozzle was shown in reference 3 to have a marked influence on acceleration performance at altitude conditions. For the complete range of nozzle positions and combustor-inlet conditions covered in reference 3, the data showed differences in acceleration limits of about one order of magnitude. The highest acceleration rates were observed when the tip of the nozzle was nearly flush with the contour of the dome inner wall. These high acceleration rates may be due to fuel wash on the liner dome that counteracted the effects of the fuel-flow interruption. The fuel on the walls may have acted as a reservoir to supply the combustion with fuel during the flow interruption. With the wide spray angle produced by the dual-entry nozzle, the amount of fuel impinging on the walls would be expected to increase as the nozzle was shifted upstream.

In summary, acceleration performance of the J47 combustor was governed by the manner in which the fuel nozzle operated during acceleration. Temperature and pressure response to fuel addition was different with the different nozzles; two types of response lag were observed. Unsuccessful accelerations to fuel-air ratios below steady-state rich limit blow-out were observed only with the nozzle that produced an interrupted flow during acceleration. Increases in initial heat-release rate did not consistently increase acceleration limits with this nozzle at the altitude conditions investigated, as was observed in previous tests (ref. 2). With fuel nozzles that provided uniform flow increases during acceleration, combustion failures occurred when the final fuel-air ratio was within the range of steady-state rich blow-out. This emphasizes the need for a sufficient margin between rich blow-out fuel-air ratios and the fuel-air ratio necessary to give enough temperature rise for engine acceleration.

These results apply only to the equipment, fuel, and range of variables investigated. Also, the results obtained with the dual-entry duplex nozzle may not apply rigidly to an engine using these nozzles. It is not known if the engine fuel supply and control apparatus used with the nozzles produce flow interruptions during transient fuel additions.

Combustion Efficiency

Of the four nozzles used, the dual-entry duplex nozzle gave the highest efficiencies and the large simplex the lowest at both altitude conditions (fig. 9). These efficiency data were obtained in the low fuel-air-ratio range that would correspond to part-throttle operation. At these fuel flows, the spray photographs showed that the dual-entry duplex gave the finest atomization and the widest spray angle, while the large simplex gave the poorest atomization and narrowest spray angle. The efficiencies were lower with the simplex nozzle because (1) the poorer atomization increased the time required for fuel vaporization, and (2) the narrow spray angle reduced fuel-air mixing in the primary combustion zone. With this nozzle, the efficiency increased rapidly with fuel-air ratio because of improvement in spray configuration and atomization at the higher fuel flows. The effects of fuel-spray characteristics on combustion performance have been investigated and discussed previously in references 6 and 7.

A comparison of steady-state efficiency and acceleration performance of the nozzles shows that acceleration performance did not depend on combustion efficiency at the initial conditions. Successful acceleration data were obtained at maximum acceleration rates with fuel nozzles giving large differences in combustion efficiency at the operating conditions preceding the acceleration.

SUMMARY OF RESULTS

Transient and steady-state combustion performance of a single tubular combustor with four different fuel nozzles was measured at simulated part-throttle altitude conditions. The nozzles were a dual-entry duplex type, a single-entry duplex, and two simplex nozzles. The results were as follows:

1. For a given acceleration rate, the manner and time in which the combustor-outlet temperature and inlet static pressure responded to fuel acceleration were affected by the nozzles. Two types of response lag were observed; with the dual-entry duplex nozzle a "dead time" was observed before the temperature and pressure increased above their initial values; with the other nozzles the temperature and pressure increased immediately but did not reach their final values as rapidly as did the fuel-flow rate. Both types of time lag consisted of fuel transport and combustion process time.

2. Limiting rates of acceleration were observed with the dual-entry duplex nozzle; these combustion failures were attributed to an interruption in fuel flow provided by this nozzle. Combustor-inlet air conditions and fuel flow were shown to affect these acceleration limits. The effect of initial fuel-air ratio (heat-release rate) on acceleration limits was not consistent at two altitude conditions and could not be used rigidly to control acceleration limits, as had been suggested in a previous investigation.

3. Except for steady-state rich-limit blow-out, no combustion failures were observed during acceleration with a single-entry duplex and two different capacity simplex nozzles. With these nozzles, the fuel flow to the combustor increased uniformly during acceleration.

4. At part-throttle operation, the highest combustion efficiencies were generally obtained with the dual-entry duplex nozzle, which produced the finest atomization and the widest spray angle at these conditions. Since this nozzle gave the poorest acceleration characteristics, it is apparent that steady-state efficiency performance is no criterion for judging transient performance.

CONCLUDING REMARKS

Acceleration performance was governed by the manner in which the fuel nozzles operated during acceleration. The only combustion failures observed resulted either from a steady-state, rich fuel-air-ratio limitation, or from a discontinuity in fuel flow during acceleration. These results show no effect of transient fuel flows on the ability of the combustion process to produce temperature rise allowing time for equilibrium; they suggest that combustion failures during acceleration are not a result of rate limitations for some phase of the combustion process, such as vaporization or kinetics, as long as steady-state operating limits are not exceeded.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 4, 1955

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TABLE I. - TRANSIENT COMBUSTION PERFORMANCE DATA WITH FOUR NOZZLES FOR SIMULATED ALTITUDES

[Simulated rotor speed, 58 percent rated; inlet static pressure, 18.0 in. Hg abs; air flow, 2.0 lb/sec; inlet temperature, 85° F; reference velocity, 95 ft/sec.]

(a) Altitude, 35,000 feet

Run	Initial fuel-air ratio	Final fuel-air ratio	Time for acceleration, sec	Acceleration rate, fuel-air-ratio change/sec	Combustion dead time, sec	Total response lag, sec	Combustion response[a]
Dual-entry duplex nozzle							
5	0.0062	0.0128	0.17	0.038	----	----	S
6	↓	.0128	.15	.044	----	----	Q
7		.0157	.44	.022	0.63	1.79	S
8		.0157	.34	.028	----	----	Q
9		.0194	.68	.019	----	----	Q
10		.0194	1.08	.012	1.40	2.02	S
11		.0212	.86	.017	1.64	2.16	S
12		.0212	.60	.025	----	----	Q
13		.0233	1.4	.013	1.58	2.00	S
14		.0233	.80	.021	----	----	Q
15		.0264	1.1	.018	2.04	2.88	S
16		.0264	.80	.025	----	----	Q
17		.0282	.84	.025	.90	2.06	S
18	↓	.0282	.66	.033	----	----	Q
19	.0069	.0230	.72	.022	.88	1.84	S
20	.0069	.0230	.55	.029	----	----	Q
21	.0083	.0224	.20	.070	.26	1.62	S
22	.0076	.0224	.24	.062	.28	1.62	S
23	.0072	.0224	.20	.076	----	----	Q

[a]S, successful; Q, unsuccessful (quench-out).

TABLE I. - Continued. TRANSIENT COMBUSTION PERFORMANCE DATA

WITH FOUR NOZZLES FOR SIMULATED ALTITUDES

[Simulated rotor speed, 58 percent rated; inlet static pressure, 18.0 in. Hg abs; air flow, 2.0 lb/sec; inlet temperature, 85° F; reference velocity, 95 ft/sec.]

(a) - Concluded. Altitude, 35,000 feet.

Run	Initial fuel-air ratio	Final fuel-air ratio	Time for acceleration, sec	Acceleration rate, fuel-air-ratio change/sec	Combustion dead time, sec	Total response lag, sec	Combustion response[a]
Single-entry duplex nozzle							
70	0.0079	0.0246	0.12	0.14	----	2.0	S
71	.0079	.0238	↓	.13	----	2.2	↓
72	.0094	.0236	↓	.12	----	1.4	↓
73	.0103	.0234	↓	.11	----	1.9	↓
74	.0069	.0230	↓	.13	----	1.0	↓
75	.0054	.0234	↓	.15	----	1.4	↓
76	.0038	.0232	.13	.15	----	2.0	↓
77	.0079	.0208	.14	.092	----	1.3	↓
78	.0078	.0172	.12	.078	----	1.9	↓
79	.0078	.0139	.11	.056	----	1.8	↓
60.0-gal/hr simplex nozzle							
85	0.010	0.0188	0.12	0.073	----	---	S
86	↓	.0199	.11	.090	----	---	↓
87	↓	.0216	.11	.10	----	9.0	↓
88	↓	.0234	.12	.11	----	6.0	↓
89	↓	.0243	.12	.12	----	6.5	↓
101	.0119	.0232	.12	.094	----	---	↓
102	.0088	.0229	.12	.12	----	---	↓
15.3-gal/hr simplex nozzle							
122	0.0074	0.0161	0.12	0.072	----	6.0	S
123	.0074	.0167	.12	.078	----	4.0	↓
124	.0074	.0149	.12	.062	----	8.0	↓
125	.0074	.0129	.12	.046	----	4.5	↓
126	.0082	.0167	.11	.077	----	3.5	↓
127	.0099	.0165	.13	.051	----	5.5	↓
128	.011	.0162	.12	.042	----	5.5	↓
129	.0050	.0162	.12	.093	----	6.5	↓

[a]S, successful; Q, unsuccessful (quench-out).

TABLE I. - Contined. TRANSIENT COMBUSTION PERFORMANCE DATA

WITH FOUR NOZZLES FOR SIMULATED ALTITUDES

[Simulated rotor speed, 58 percent rated; inlet static pressure, 11.5 in. Hg abs; air flow, 1.3 lb/sec; inlet temperature, 85° F; reference velocity, 96 ft/sec.]

(b) Altitude, 45,000 feet

Run	Initial fuel-air ratio	Final fuel-air ratio	Time for acceler-ation, sec	Accelera-tion rate, fuel-air-ratio change/sec	Combus-tion dead time, sec	Total response lag, sec	Combus-tion response[a]
Dual-entry duplex nozzle							
27	0.0070	0.0176	1.4	0.0076	2.6	5.1	S
28	.0070	.0176	1.1	.011	---	---	Q
29	.0068	.0186	1.2	.0098	2.0	4.5	S
30		.0186	.74	.016	---	---	Q
31		.0212	1.5	.0096	2.9	4.3	S
32		.0212	1.0	.014	---	---	Q
33		.0226	1.4	.011	2.5	4.9	S
34		.0226	1.0	.015	---	---	Q
35		.0248	1.6	.011	2.2	3.9	S
36		.0248	1.3	.014	---	---	Q
37		.0260	1.9	.010	2.2	4.1	S
38		.0260	1.4	.014	---	---	Q
39		.0278	2.0	.010	1.7	4.1	S
40		.0278	1.3	.016	---	---	Q
41		.0324	3.0	.0086	---	---	S
42		.0324	2.5	.010	---	---	Q
43		.0368	2.4	.012	---	---	B
44		.0357	5.5	.0052	---	---	B
45		.0207	2.0	.0070	2.6	4.1	S
46		.0207	1.2	.012	---	---	Q
47	.0085	.0207	1.5	.0081	1.4	3.2	S
48	.0085	.0207	1.2	.010	---	---	Q
49	.0107	.0214	1.4	.0076	2.2	---	B
50	.0107	.0214	2.2	.0049	5.3	---	B
51	.0128	.0214	2.5	.0034	4.4	---	B

[a]S, successful; Q, unsuccessful (quench-out); B, unsuccessful (blow-out).

TABLE I. - Concluded. TRANSIENT COMBUSTION PERFORMANCE DATA

WITH FOUR NOZZLES FOR SIMULATED ALTITUDES

[Simulated rotor speed, 58 percent rated; inlet static pressure, 11.5 in. Hg abs; air flow, 1.3 lb/sec; inlet temperature, 85° F; reference velocity, 96 ft/sec.]

(b) - Concluded. Altitude, 45,000 feet.

Run	Initial fuel-air ratio	Final fuel-air ratio	Time for acceleration, sec	Acceleration rate, fuel-air-ratio change/sec	Combustion dead time, sec	Total response lag, sec	Combustion response[a]
Single-entry duplex nozzle							
55	0.0094	0.0237	0.15	0.095	---	3.4	S
56	↓	.0269	.14	.12	---	2.8	S
57	↓	.0291	.15	.13	---	2.2	S
58	↓	.0312	.11	.20	---	2.8	S
59	.0096	.0334	.13	.18	---	3.3	S
60	.0096	.0344	.13	.19	---	---	B
61	.0096	.0366	.13	.21	---	---	B
62	.0113	.0246	.13	.10	---	---	S
63	.0113	.0259	.13	.11	---	3.2	S
64	.0113	.0269	.13	.12	---	3.4	S
65	.0122	.0267	.13	.11	---	---	S
60.0-gal/hr simplex nozzle							
93	0.0128	0.0368	0.12	0.20	---	5.0	B
94	.0128	.0348	.12	.18	---	6.0	B
95	.0128	.0288	.13	.12	---	8.0	S
96	.0128	.0268	.12	.12	---	7.2	S
97	.0152	.0261	.12	.091	---	8.3	S
98	.0107	.0261	.10	.15	---	8.0	S
99	.0128	.0229	.11	.092	---	9.5	S
100	.0128	.0208	.13	.062	---	10.5	S
15.3-gal/hr simplex nozzle							
106	0.009	0.0160	0.08	0.087	---	5.5	S
107	.009	.0176	.11	.078	---	6.1	↓
108	.009	.0198	.11	.098	---	5.0	↓
109	.009	.0222	.12	.11	---	9.0	↓
110	.0107	.0220	.11	.11	---	8.2	↓
111	.0118	.0216	.12	.089	---	5.2	↓
112	.0073	.0212	.12	.12	---	7.0	↓
113	.0048	.0212	.11	.14	---	7.5	↓
114	.009	.0231	.12	.13	---	8.4	↓
115	.009	.0246	.12	.13	---	7.0	↓
116	.009	.0256	.12	.14	---	6.0	↓

[a]S, successful; Q, unsuccessful (quench-out); B, unsuccessful (blow-out).

TABLE II. - STEADY-STATE COMBUSTION PERFORMANCE DATA

[Simulated rotor speed, 58 percent rated.]

Run	Simulated altitude, ft	Combustor-inlet static pressure, in. Hg abs	Combustor-inlet temperature, °F	Air flow, lb/sec	Combustor reference velocity, ft/sec	Fuel flow, lb/hr	Fuel-air ratio	Mean combustor outlet temperature, °F	Combustion efficiency
Dual-entry duplex nozzle									
1	35,000	18.0	90	2.0	96	37	0.0051	420	0.82
2	35,000	18.0	90	2.0	96	45	.0062	530	.91
3	35,000	18.0	90	2.0	96	65	.0090	730	.96
4	35,000	18.0	90	2.0	96	90	.0125	940	.94
24	45,000	11.5	90	1.3	97	34	.0073	500	.75
25	45,000	11.5	90	1.3	97	48	.0102	660	.76
26	45,000	11.5	90	1.3	97	54	.0115	730	.76
Single-entry duplex nozzle									
66	35,000	18.0	85	2.0	95	48	0.0067	410	0.63
67	35,000	18.0	85	2.0	95	60	.0083	595	.81
68	35,000	18.0	85	2.0	95	75	.0104	750	.86
69	35,000	18.0	85	2.0	95	84	.0117	840	.88
52	45,000	11.5	90	1.3	97	40	.0085	430	.52
53	45,000	11.5	90	1.3	97	47	.0100	630	.74
54	45,000	11.5	90	1.3	97	51	.0109	730	.80
60.0-gal/hr simplex nozzle									
80	35,000	18.0	90	2.0	96	100	0.0139	930	0.84
81	35,000	18.0	90	2.0	96	86	.0119	745	.75
82	35,000	18.0	90	2.0	96	80	.0111	635	.67
83	35,000	18.0	90	2.0	96	74	.0103	540	.60
84	35,000	18.0	90	2.0	96	64	.0089	410	.48
90	45,000	11.5	85	1.3	96	71	.0152	805	.65
91	45,000	11.5	85	1.3	96	63	.0134	600	.52
92	45,000	11.5	85	1.3	96	54	.0115	410	.37
15.3-gal/hr simplex nozzle									
117	35,000	18.0	85	2.0	95	93	0.0129	950	0.94
118	35,000	18.0	85	2.0	95	81	.0112	860	.94
119	35,000	18.0	85	2.0	95	66	.0092	715	.93
120	35,000	18.0	85	2.0	95	54	.0075	550	.82
121	35,000	18.0	85	2.0	95	45	.0062	405	.66
103	45,000	11.5	85	1.3	96	56	.0120	820	.84
104	45,000	11.5	85	1.3	96	46	.0098	635	.75
105	45,000	11.5	85	1.3	96	36	.0077	435	.60

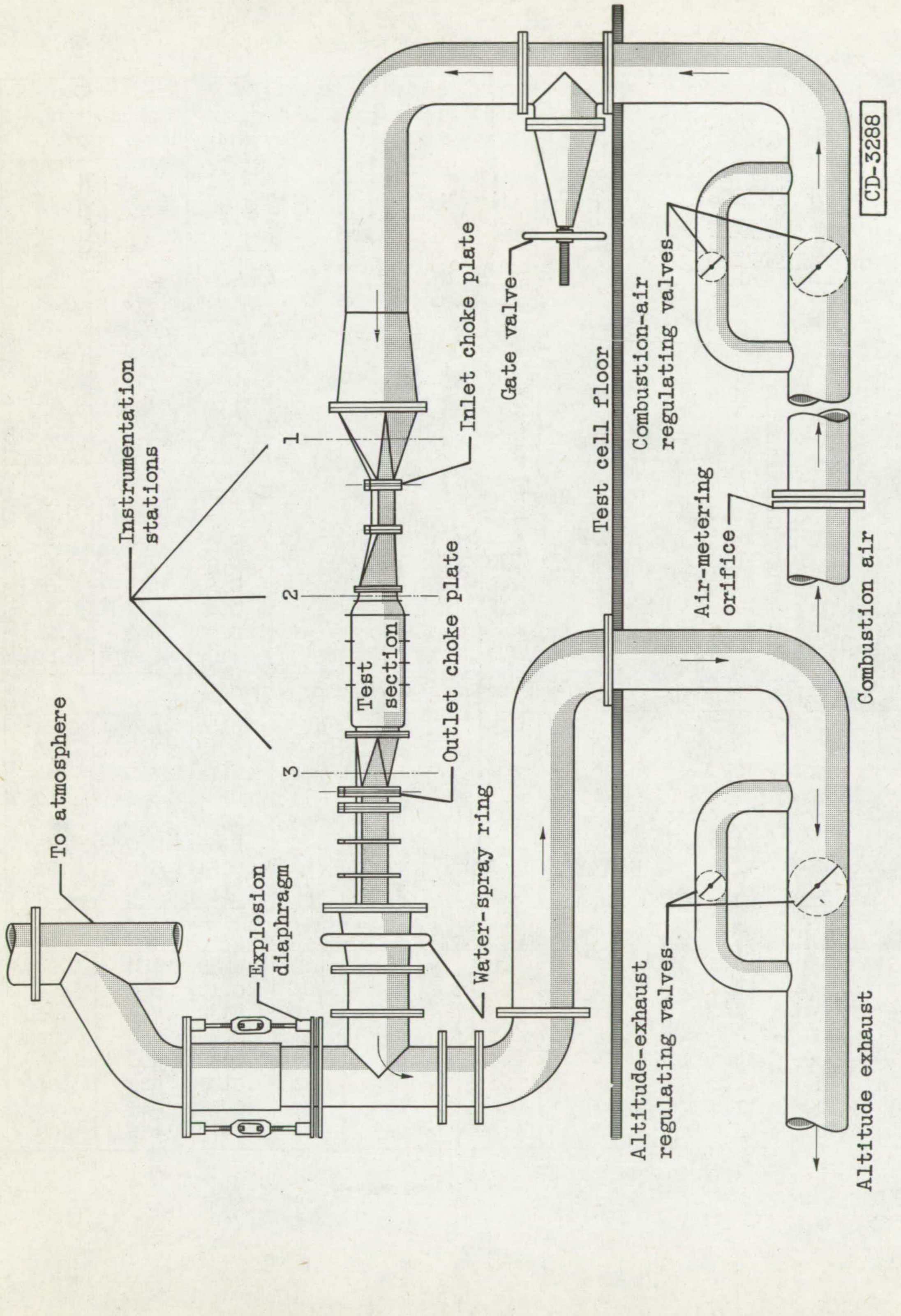


Figure 1. - Single tubular combustor installation.

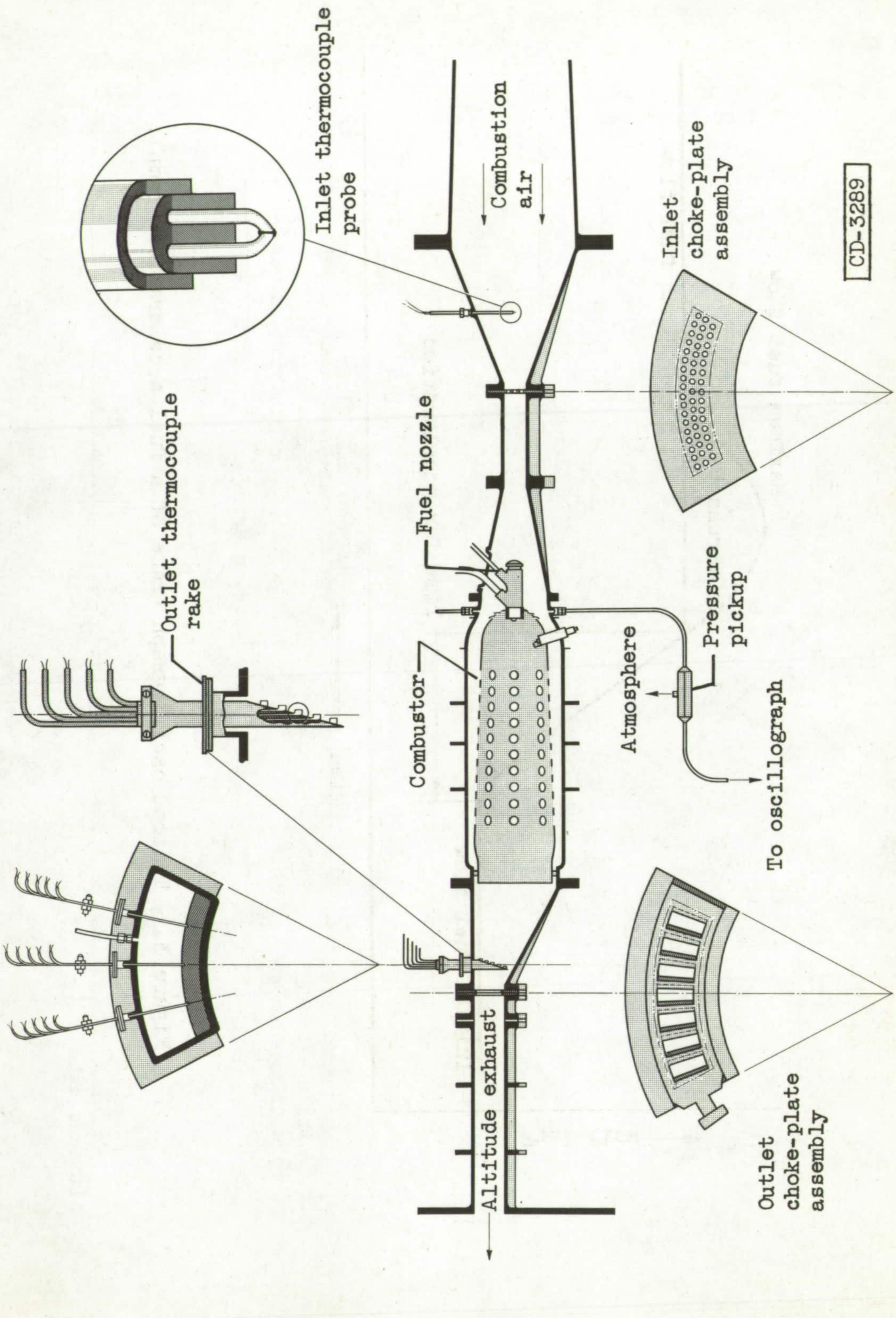


Figure 2. - Instrumentation for acceleration studies.

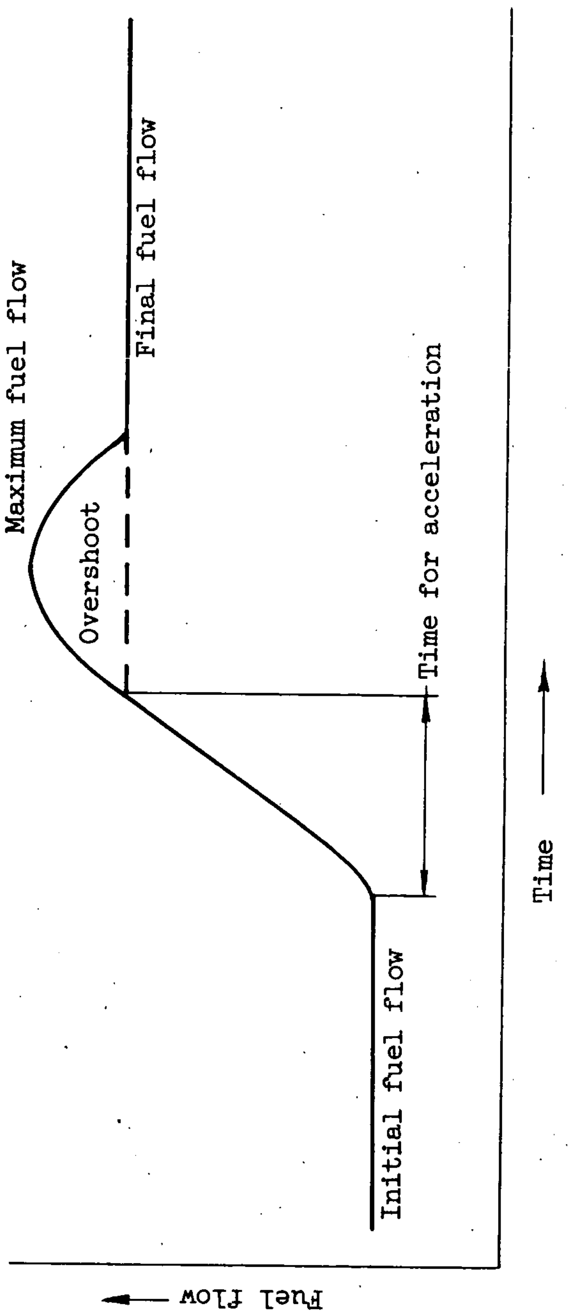
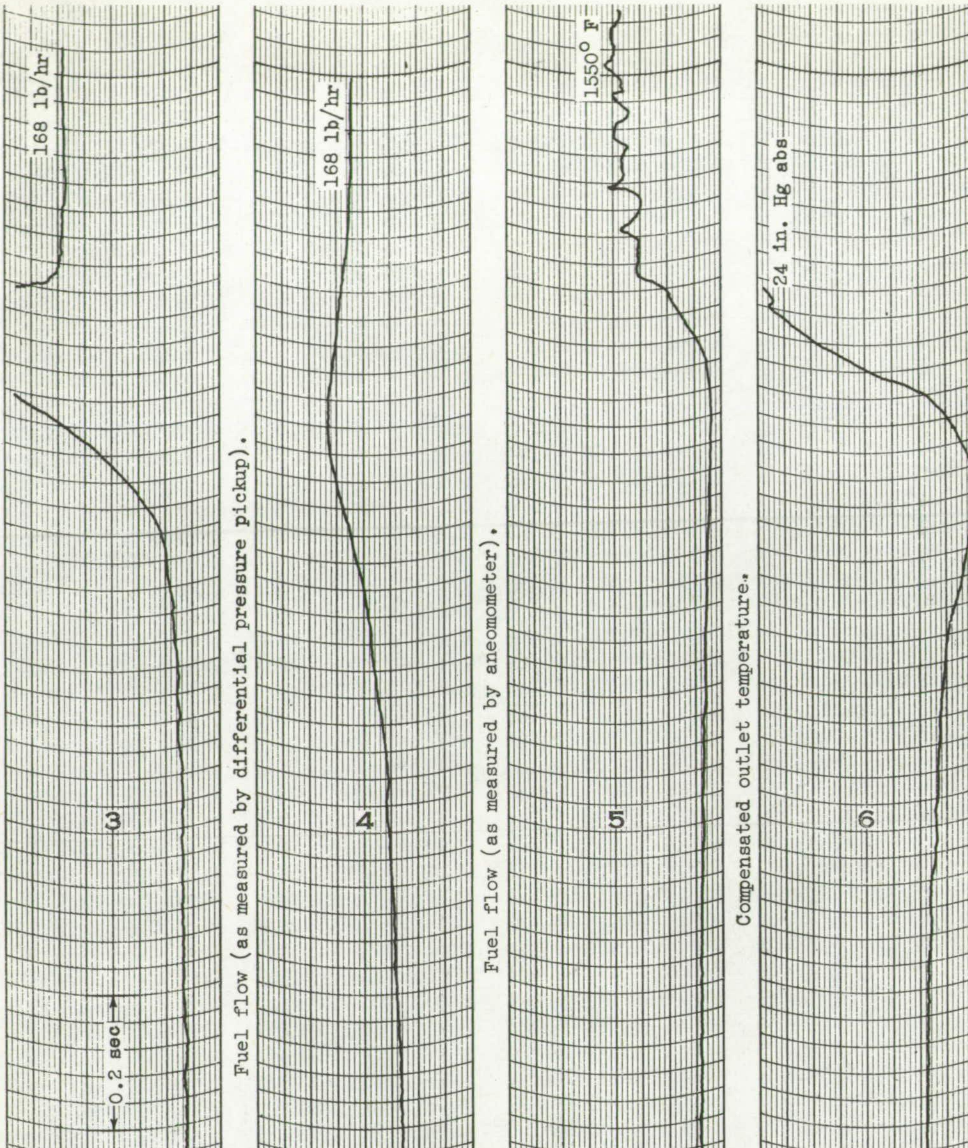


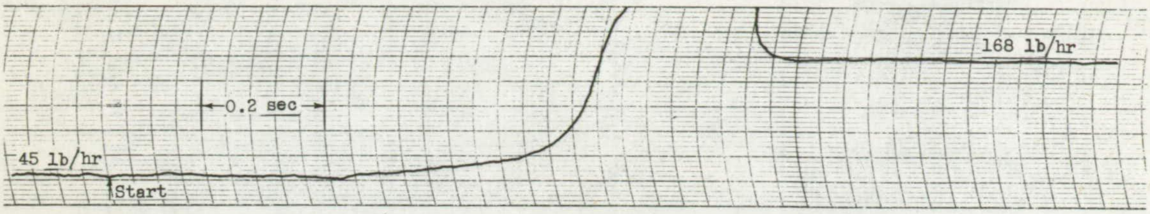
Figure 3. - Typical oscillograph trace of a fuel acceleration (ramp).



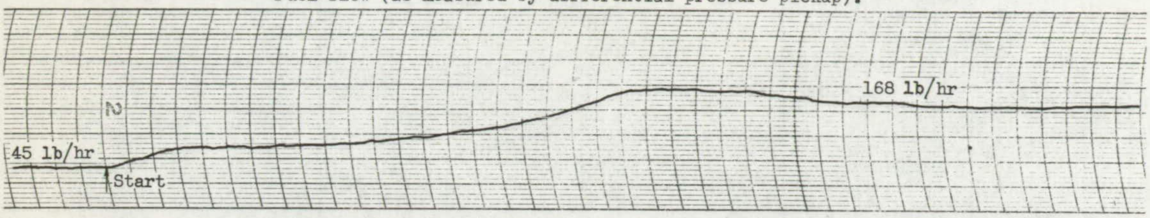
Inlet static pressure.

(a) Successful acceleration; run 13.

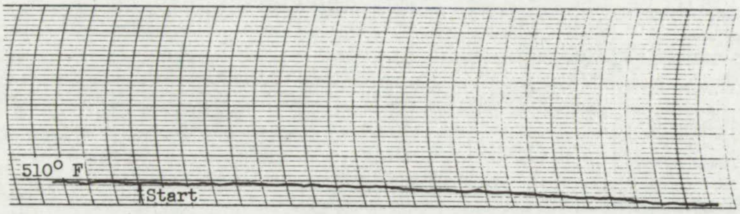
Figure 4. - Oscillograph trace of combustor variables during fuel acceleration with dual-entry duplex nozzle. Simulated altitude, 35,000 feet; rotor speed, 58 percent rated. Chart speed, 25 divisions per second.



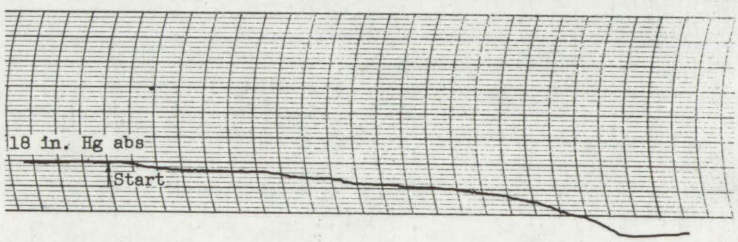
Fuel flow (as measured by differential pressure pickup).



Fuel flow (as measured by aneomometer).



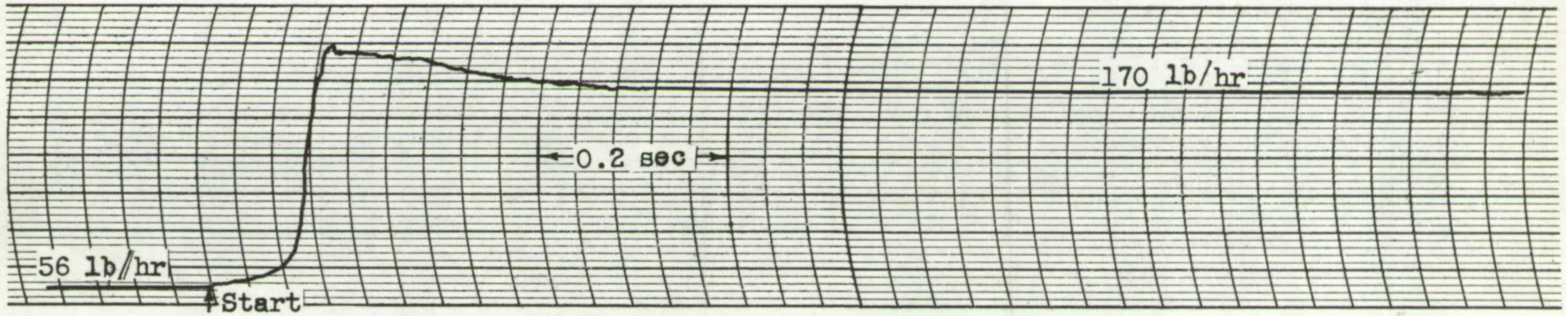
Compensated outlet temperature.



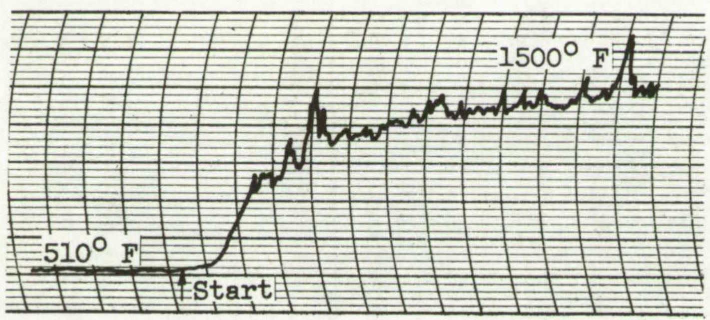
Inlet static pressure.

(b) Unsuccessful acceleration; run 14.

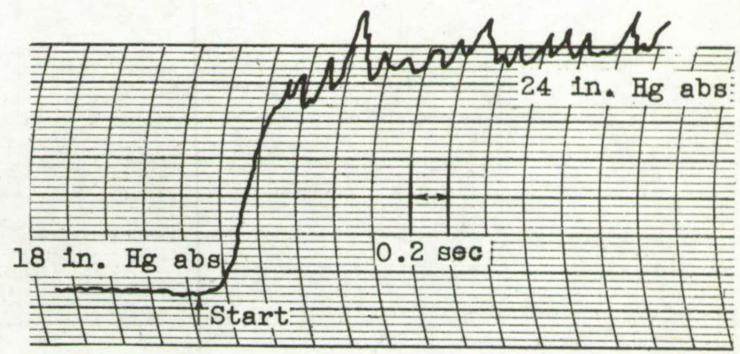
Figure 4. - Concluded. Oscillograph trace of combustor variables during fuel acceleration with dual-entry duplex nozzle. Simulated altitude, 35,000 feet; rotor speed, 58 percent rated. Chart speed, 25 divisions per second.



Fuel flow (as measured by differential pressure pickup). Chart speed, 25 divisions per second



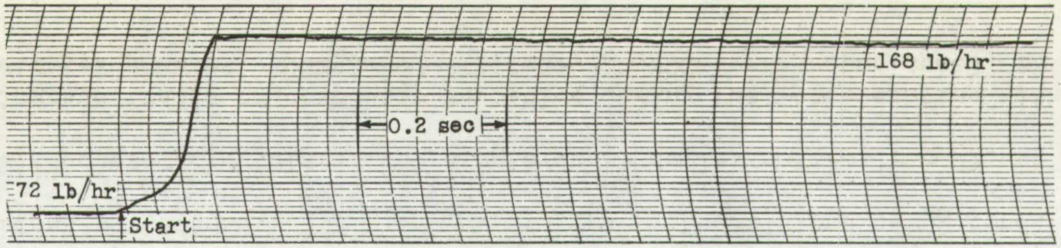
Compensated outlet temperature. Chart speed, 5 divisions per second.



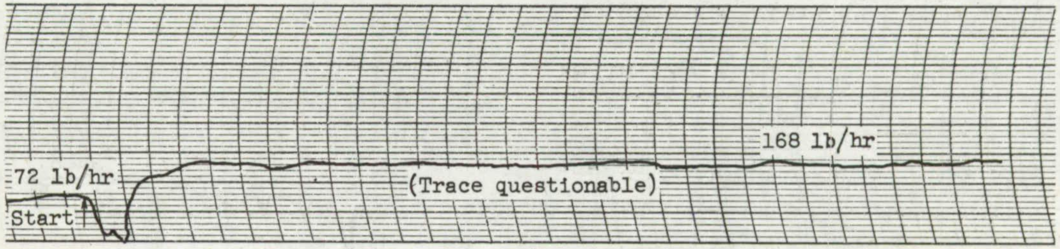
Inlet static pressure. Chart speed, 5 divisions per second.

(a) Successful acceleration; single-entry duplex nozzle; run 71.

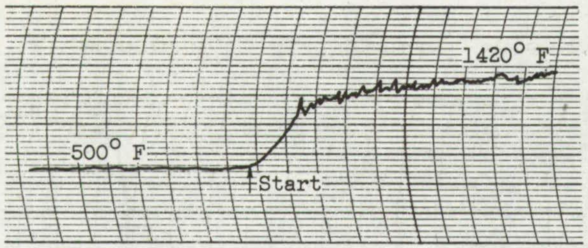
Figure 5. - Oscillograph traces of combustor variables during fuel acceleration with single-entry duplex and two simplex nozzles. Simulated altitude, 35,000 feet; rotor speed, 58 percent rated.



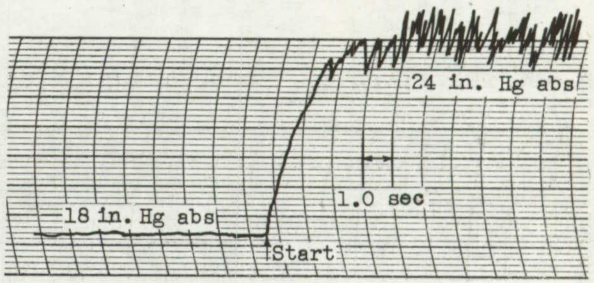
Fuel flow (as measured by differential pressure pickup). Chart speed, 25 divisions per second.



Fuel flow (as measured by anemometer). Chart speed, 25 divisions per second.



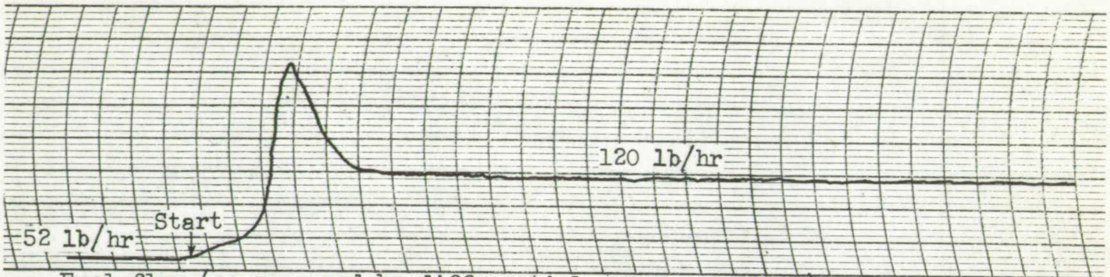
Compensated outlet temperature. Chart speed, 1 division per second.



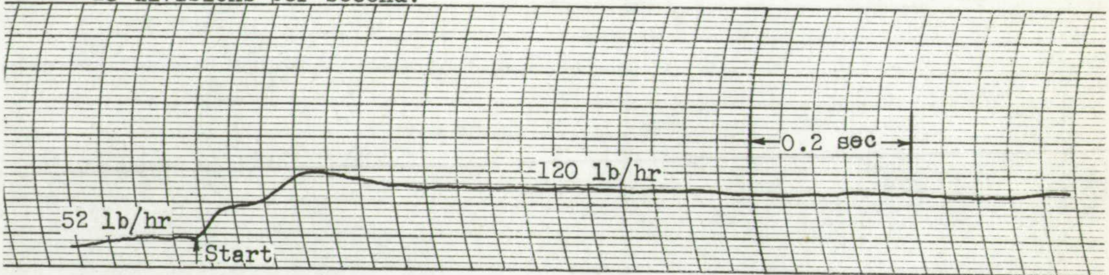
Inlet static pressure. Chart speed, 1 division per second.

(b) Successful acceleration; 60.0-gallon-per-hour simplex nozzle; run 88.

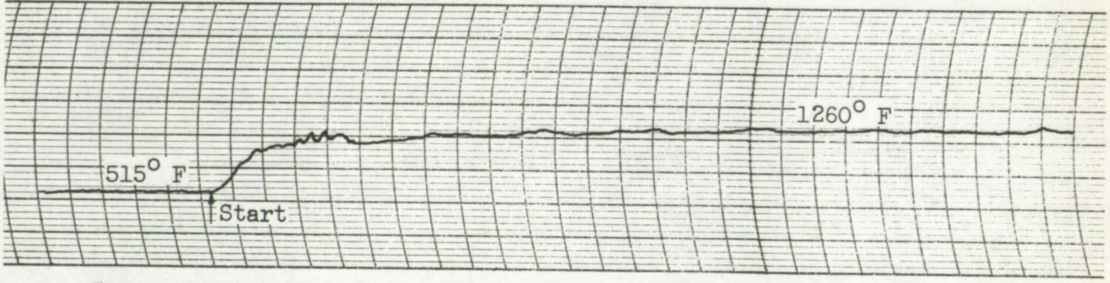
Figure 5. - Continued. Oscillograph traces of combustor variables during fuel acceleration with single-entry duplex and two simplex nozzles. Simulated altitude, 35,000 feet; rotor speed, 58 percent rated.



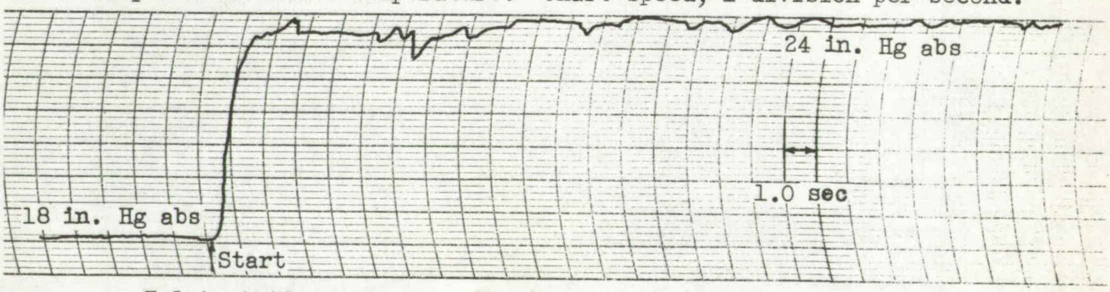
Fuel flow (as measured by differential pressure pickup). Chart speed, 25 divisions per second.



Fuel flow (as measured by anemometer). Chart speed, 25 divisions per second.



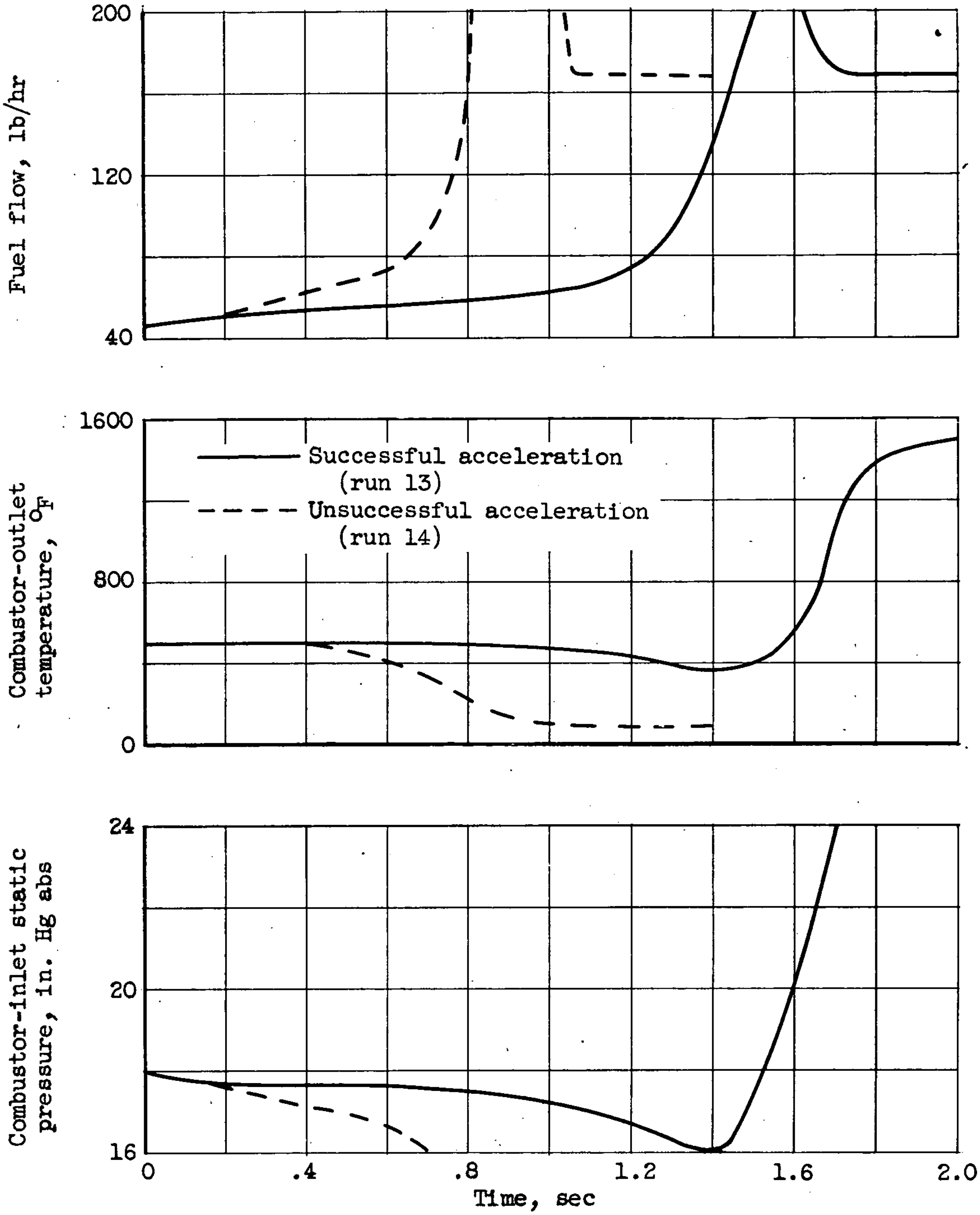
Compensated outlet temperature. Chart speed, 1 division per second.



Inlet static pressure. Chart speed, 1 division per second.

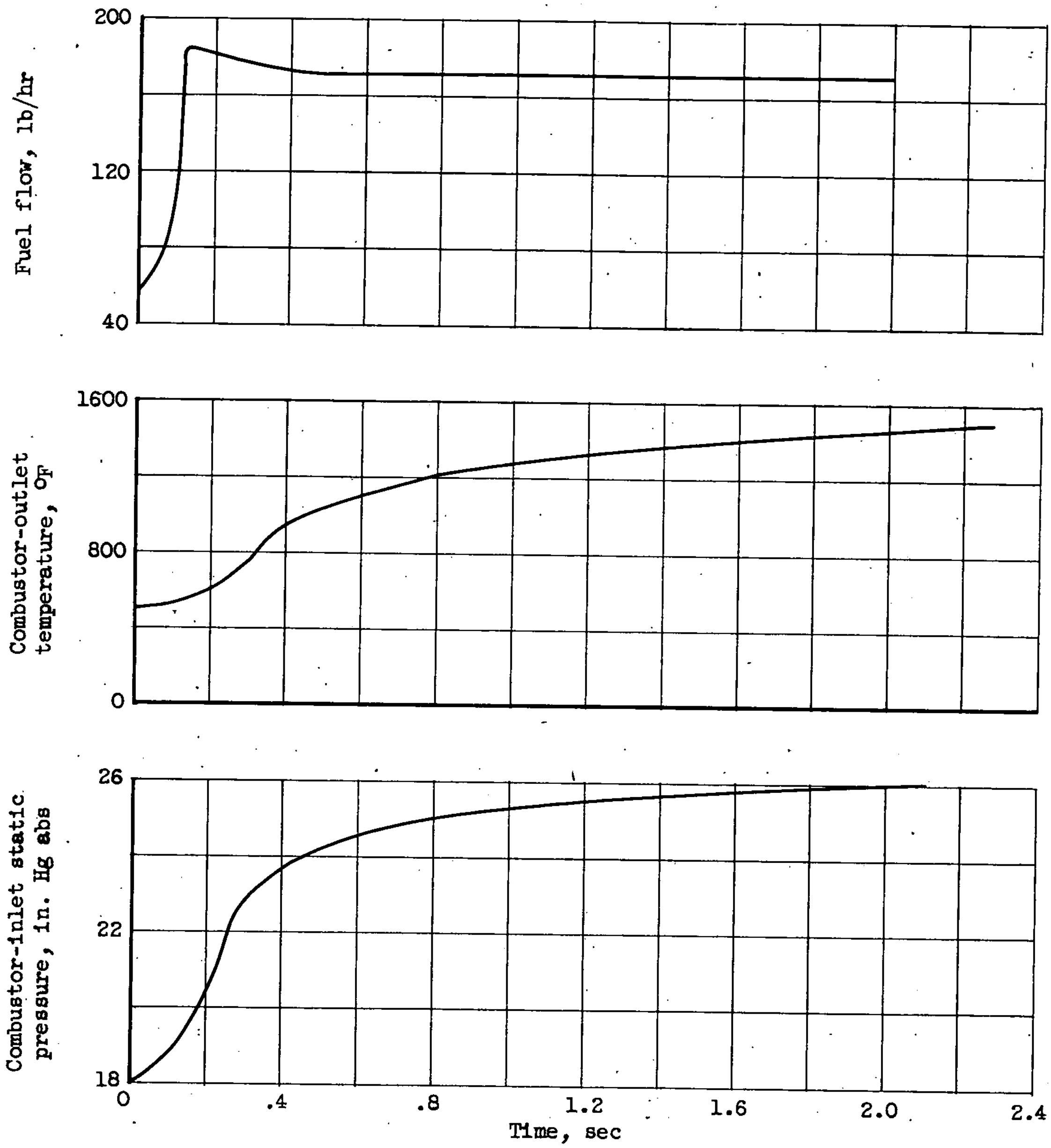
(c) Successful acceleration; 15.3-gallon-per-hour simplex nozzle; run 123.

Figure 5. - Concluded. Oscillograph traces of combustor variables during fuel acceleration with single-entry duplex and two simplex nozzles. Simulated altitude, 35,000 feet; rotor speed, 58 percent rated.



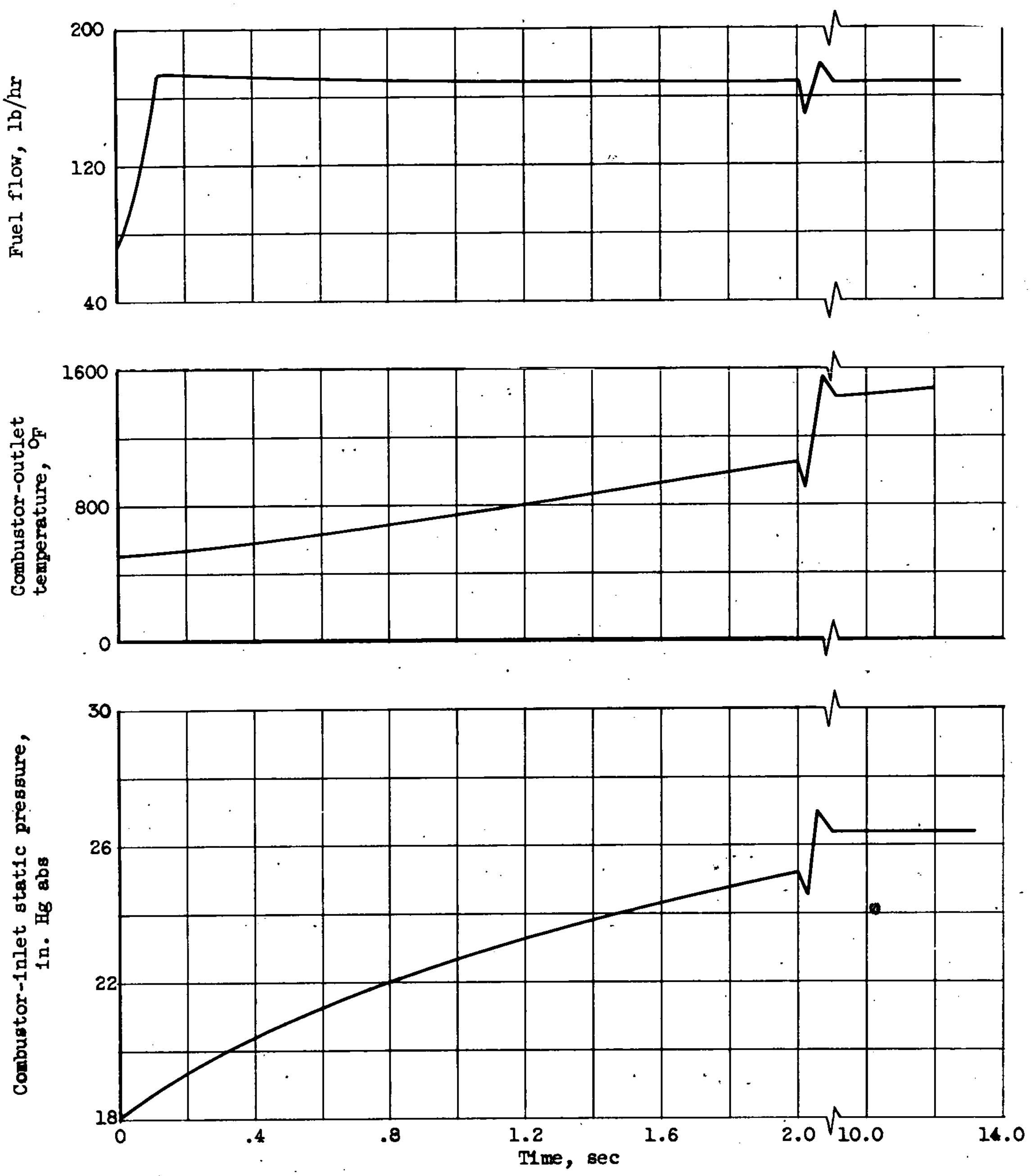
(a) Dual-entry duplex nozzle

Figure 6. - Comparison of combustor-outlet temperature and inlet-static-pressure response to fuel acceleration with four fuel nozzles. Simulated altitude, 35,000 feet; rotor speed, 58 percent rated.



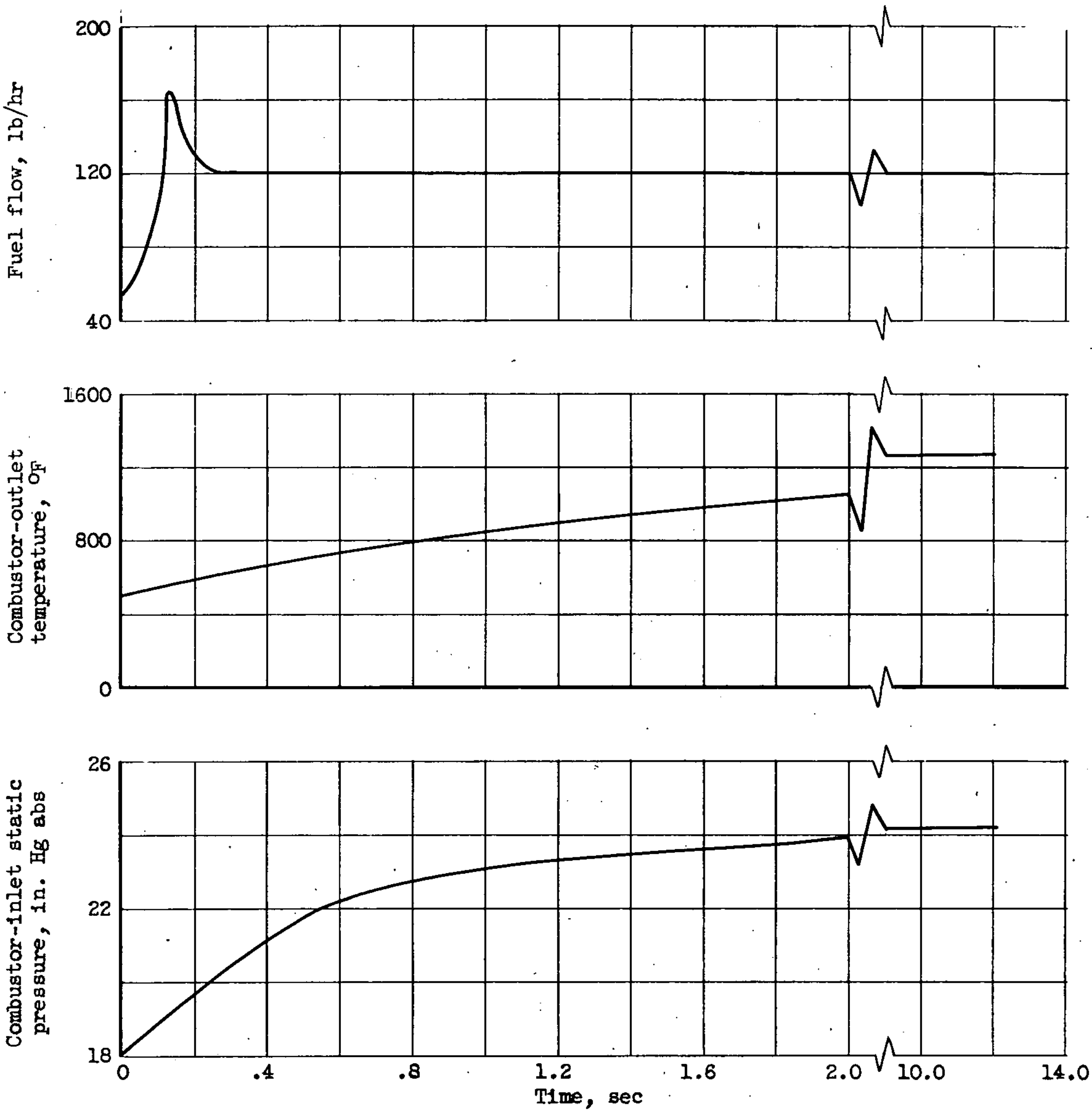
(b) Successful acceleration; single-entry duplex nozzle; run 71.

Figure 6. - Continued. Comparison of combustor-outlet temperature and inlet-static-pressure response to fuel acceleration with four fuel nozzles. Simulated altitude, 35,000 feet; rotor speed, 58 percent rated.



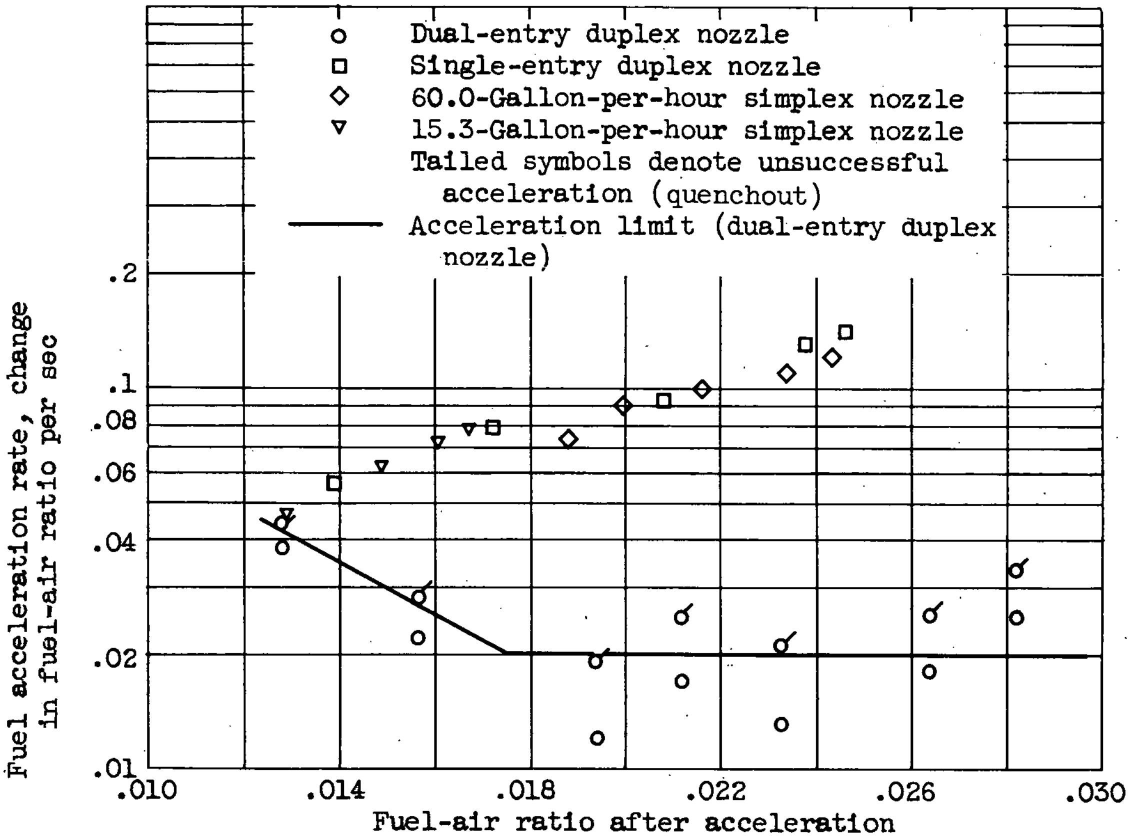
(c) Successful acceleration; 60.0-gallon-per-hour simplex nozzle, run 88.

Figure 6. - Continued. Comparison of combustor-outlet temperature and inlet-static-pressure response to fuel acceleration with four fuel nozzles. Simulated altitude, 35,000 feet; rotor speed, 58 percent rated.



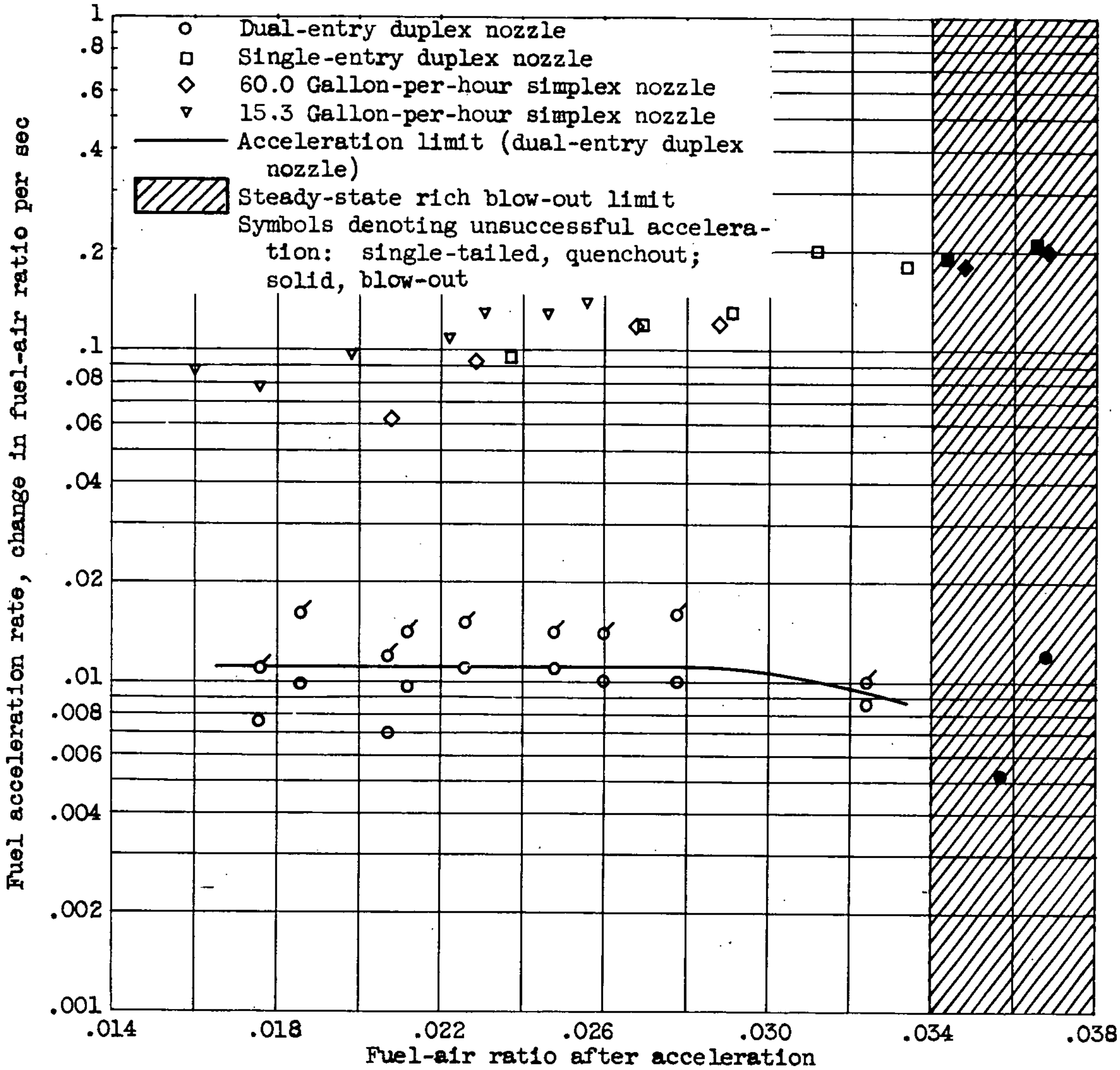
(d) Successful acceleration; 15.3-gallon-per-hour simplex nozzle run 123.

Figure 6. - Concluded. Comparison of combustor-outlet temperature and inlet-static-pressure response to fuel acceleration with four fuel nozzles. Simulated altitude, 35,000 feet; rotor speed, 58 percent rated.



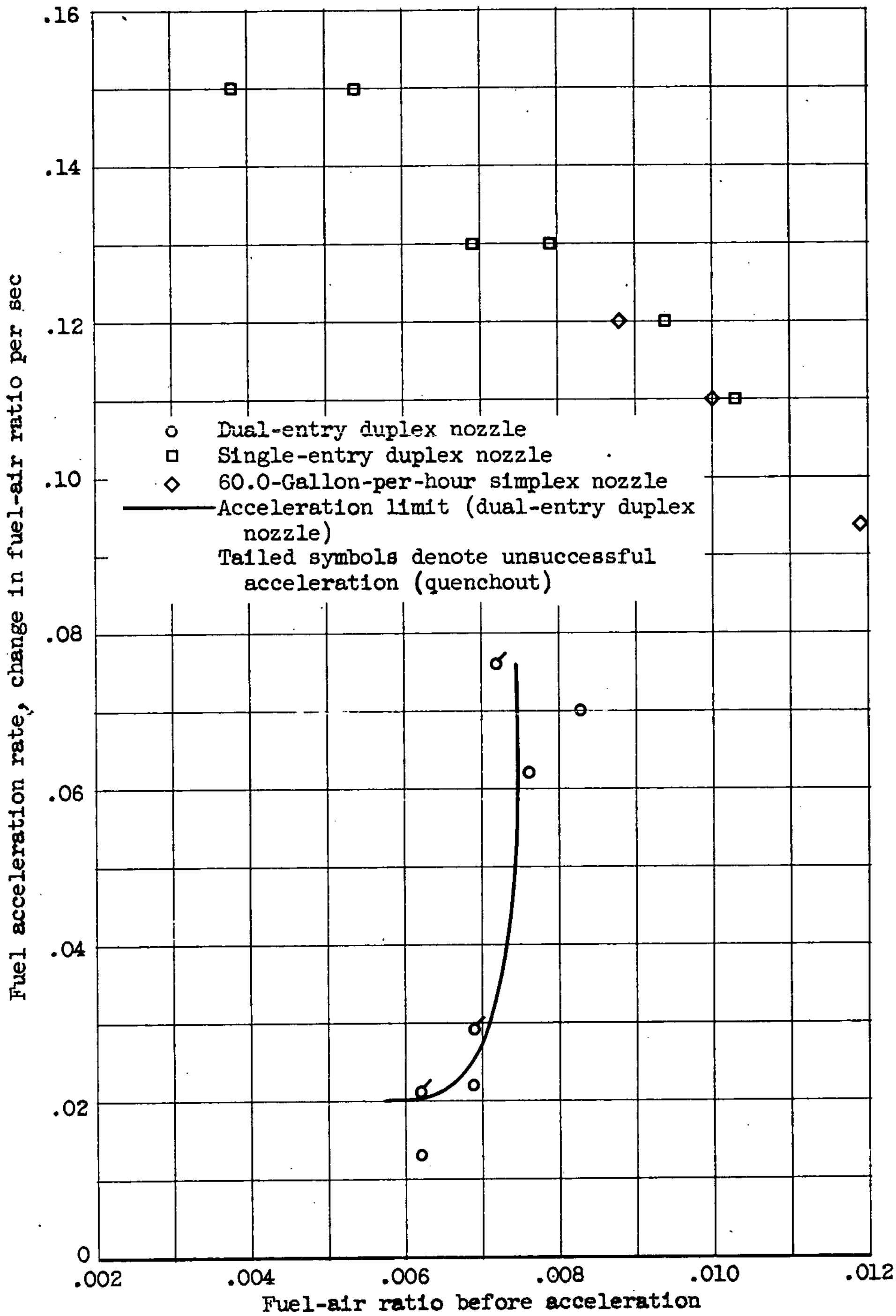
(a) Simulated altitude, 35,000 feet.

Figure 7. - Combustor fuel-acceleration data obtained with four nozzles at two simulated altitudes for a range of final fuel-air ratios. Rotor speed, 58 percent rated.



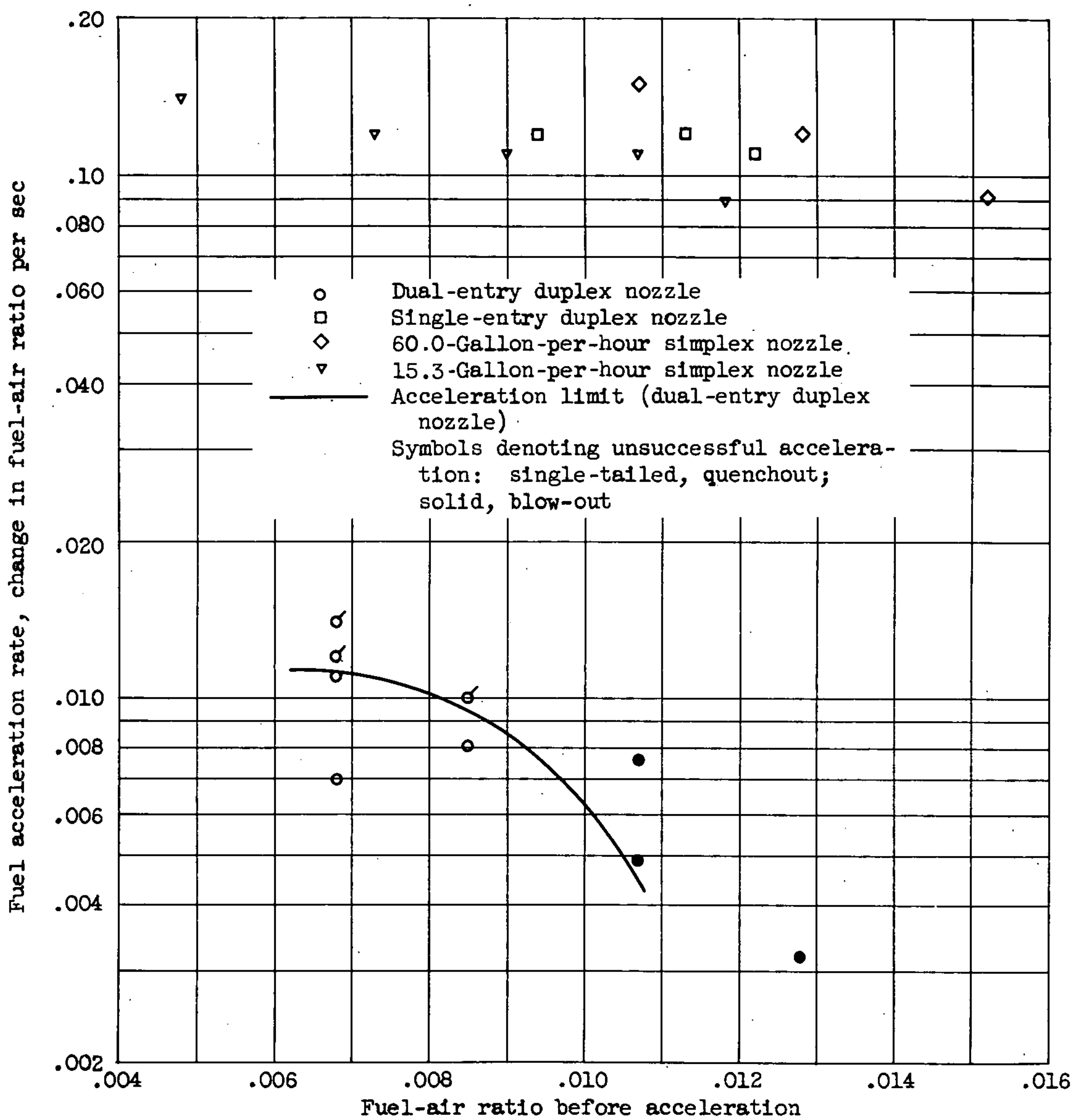
(b) Simulated altitude, 45,000 feet.

Figure 7. - Concluded. Combustor fuel-acceleration data obtained with four nozzles at two simulated altitudes for a range of final fuel-air ratios. Rotor speed, 58 percent rated.



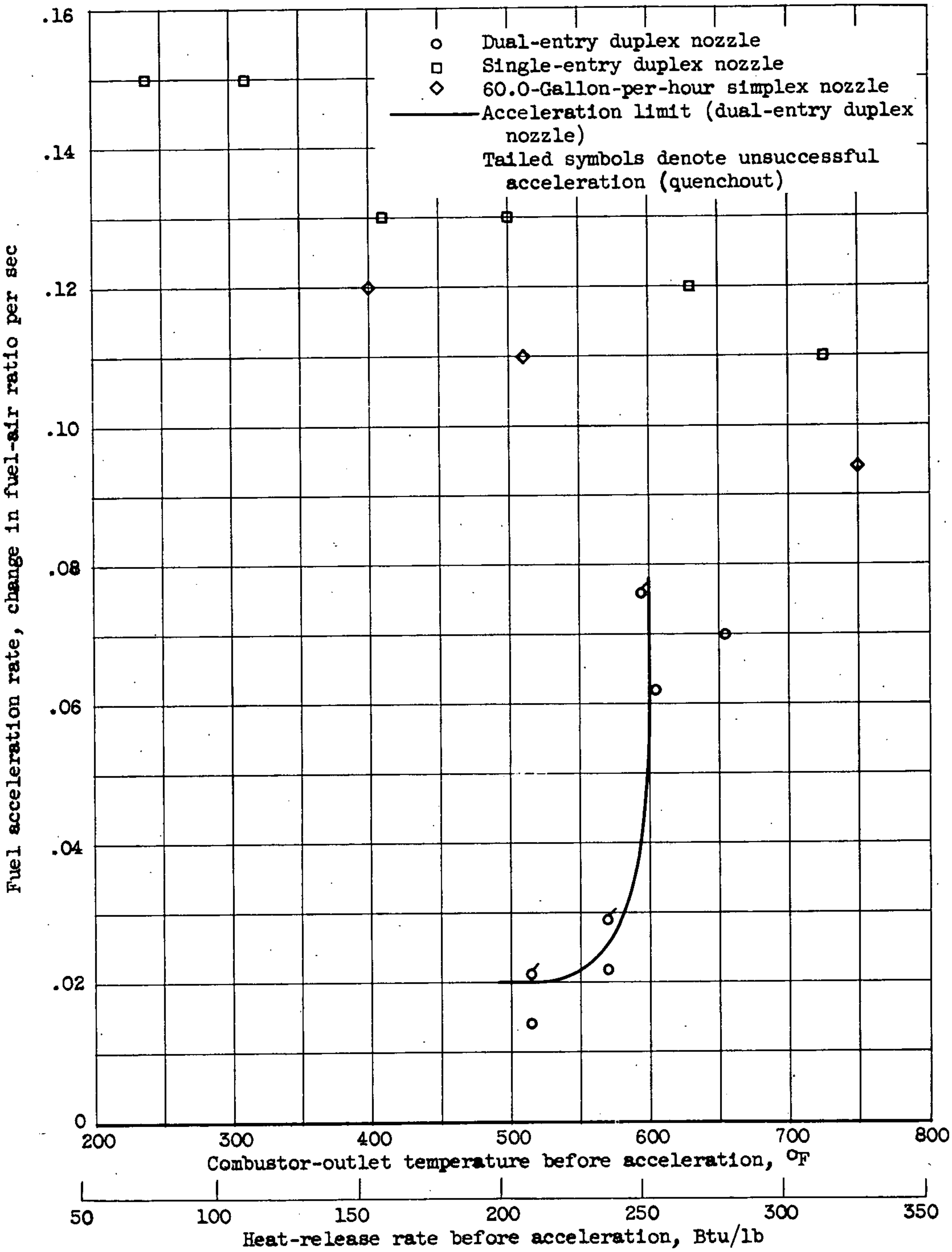
(a) Simulated altitude, 35,000 feet.

Figure 8. - Combustor fuel-acceleration data obtained with four nozzles at simulated altitudes for a range of initial fuel-air ratios. Rotor speed, 58 percent rated.



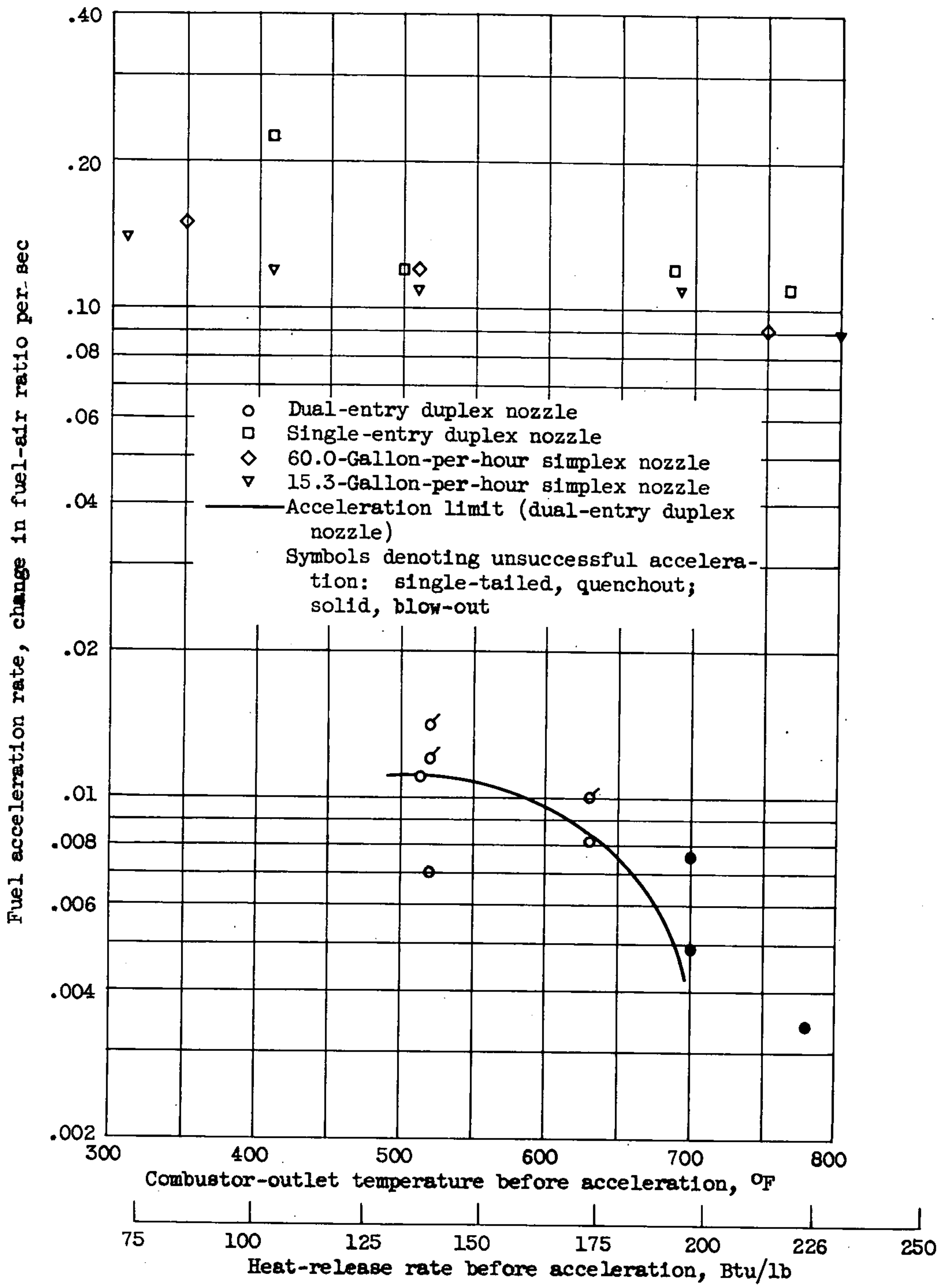
(b) Simulated altitude, 45,000 feet.

Figure 8. - Concluded. Combustor fuel-acceleration data obtained with four nozzles at simulated altitudes for a range of initial fuel-air ratios. Rotor speed, 58 percent rated.



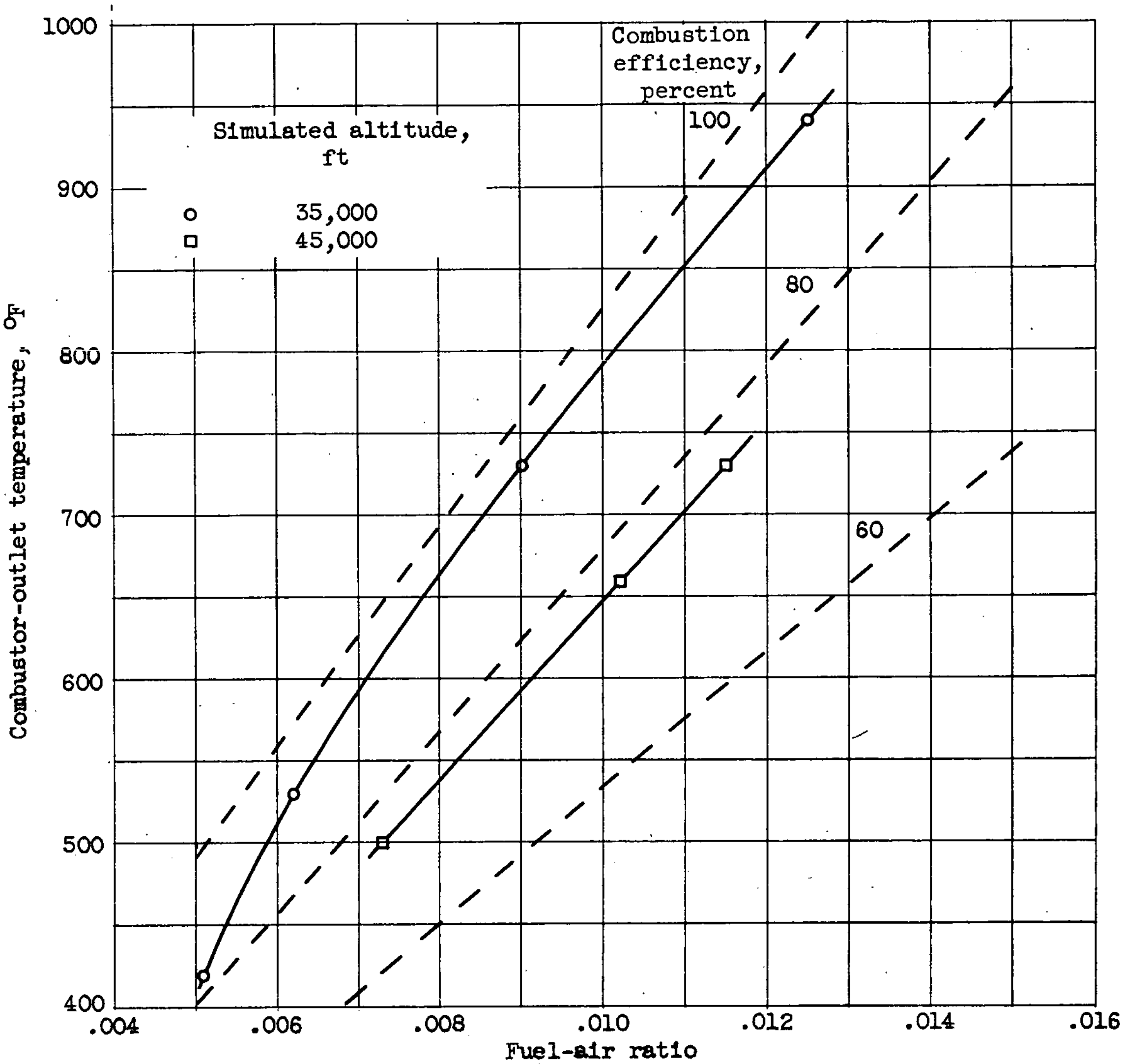
(a) Simulated altitude, 35,000 feet.

Figure 9. - Combustor fuel-acceleration data obtained with four nozzles at simulated altitudes for a range of combustor-outlet temperatures and heat-release rates before acceleration. Rotor speed, 58 percent rated.



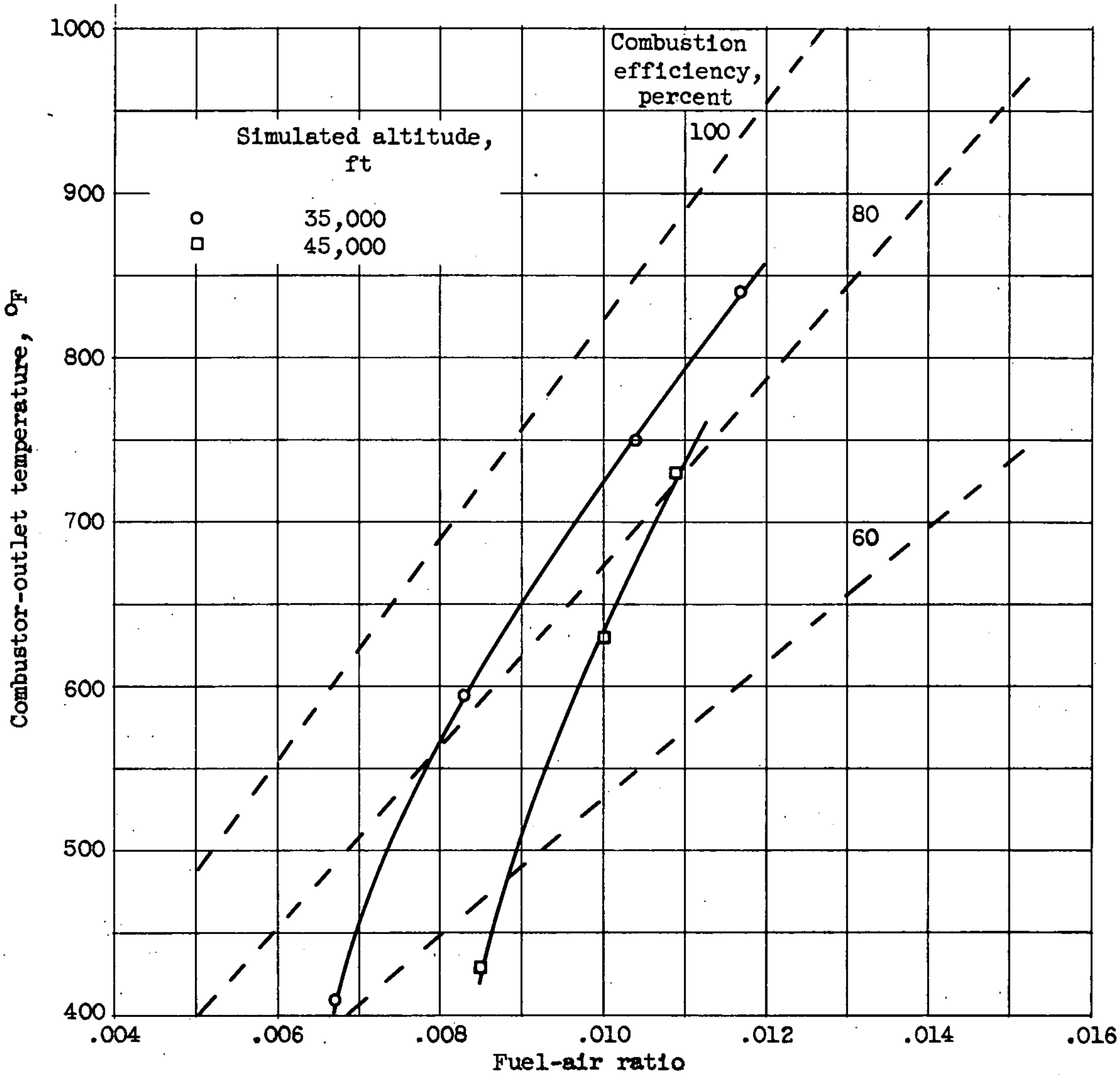
(b) Simulated altitude, 45,000 feet.

Figure 9. - Concluded. Combustor fuel-acceleration data obtained with four nozzles at simulated altitudes for a range of combustor-outlet temperatures and heat-release rates before acceleration. Rotor speed, 58 percent rated.



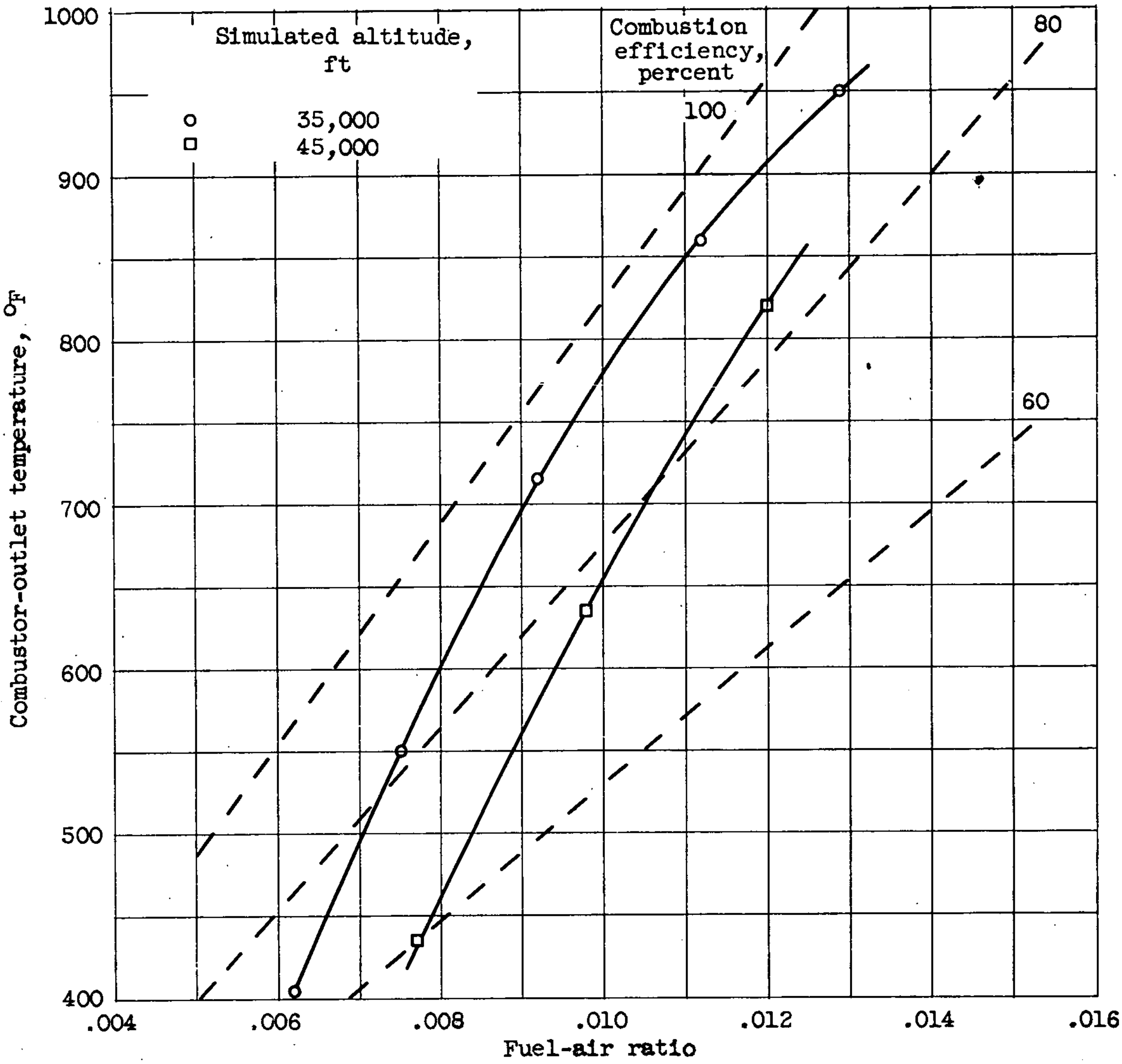
(a) Dual-entry duplex nozzle.

Figure 10. - Variation of steady-state combustor-outlet temperature with fuel-air ratio at simulated altitudes with four fuel nozzles. Rotor speed, 58 percent rated.



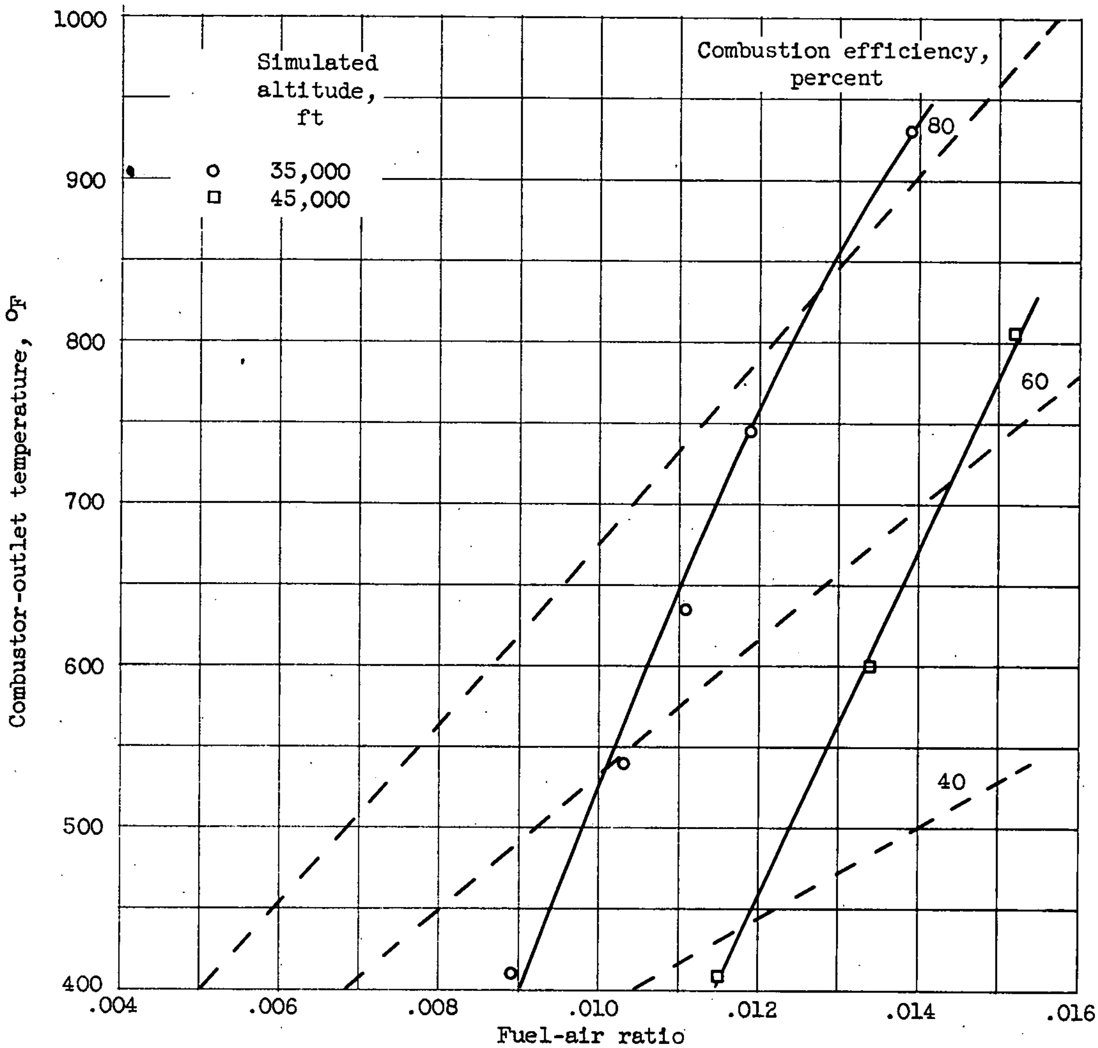
(b) Single-entry duplex nozzle.

Figure 10. - Continued. Variation of steady-state combustor-outlet temperature with fuel-air ratio at simulated altitudes with four fuel nozzles. Rotor speed, 58 percent rated.



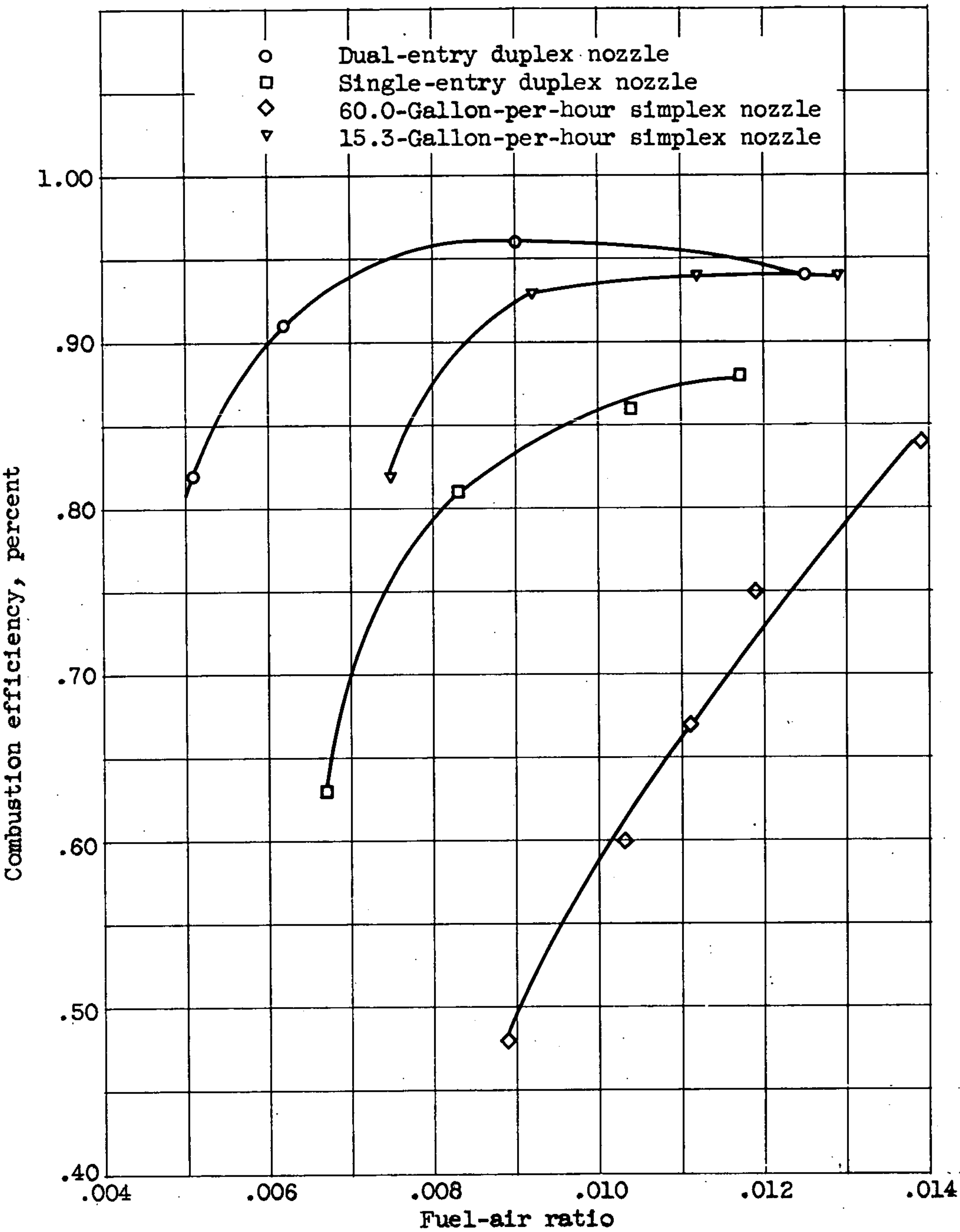
(d) 15.3 Gallon-per-hour simplex nozzle.

Figure 10. - Concluded. Variation of steady-state combustor-outlet temperature with fuel-air ratio at simulated altitudes with four fuel nozzles. Rotor speed, 58 percent rated.



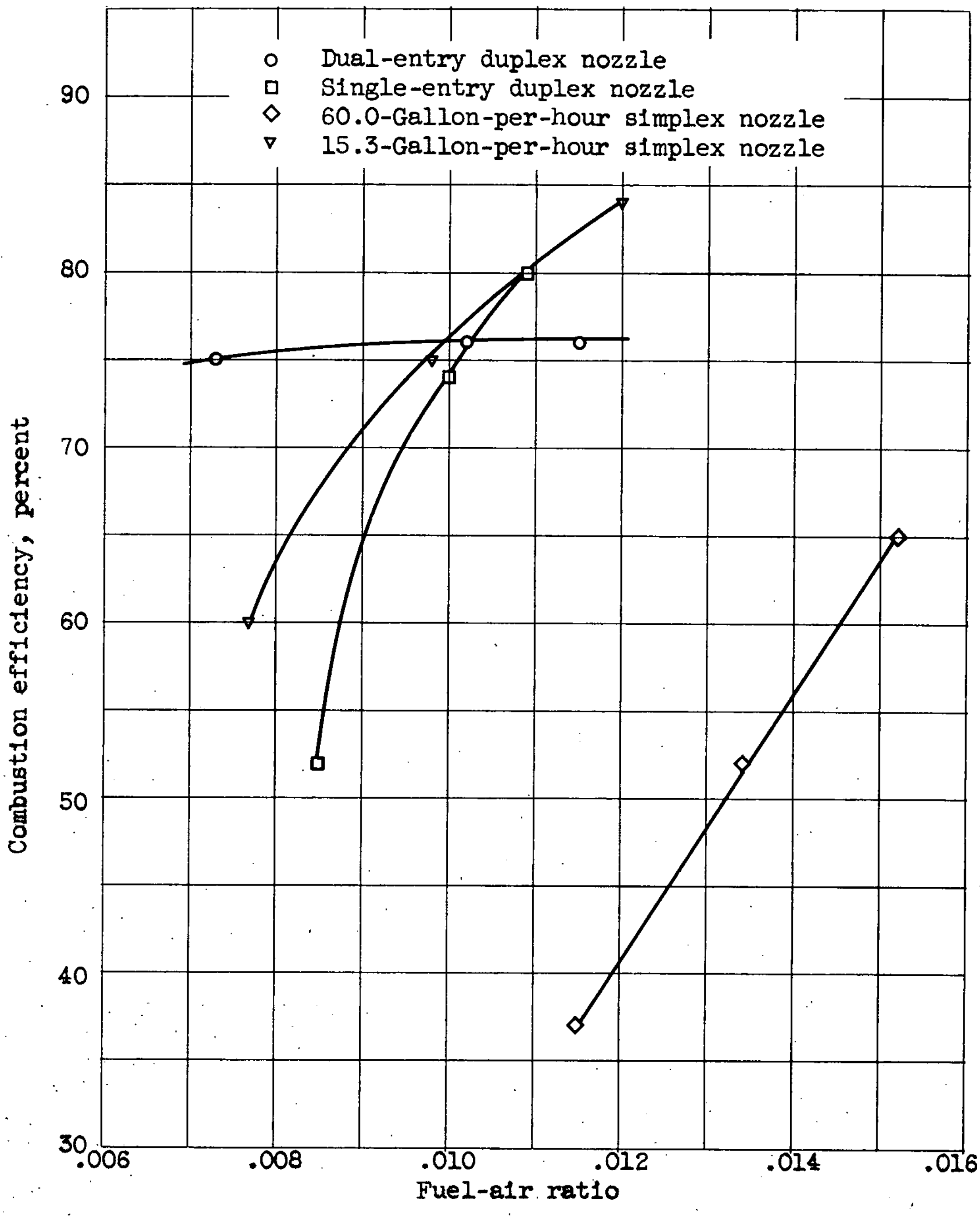
(c) 60.0 Gallon-per-hour simplex nozzle.

Figure 10. - Continued. Variation of steady-state combustor-outlet temperature with fuel-air ratio at simulated altitudes with four fuel nozzles. Rotor speed, 58 percent rated.



(a) Simulated altitude, 35,000 feet.

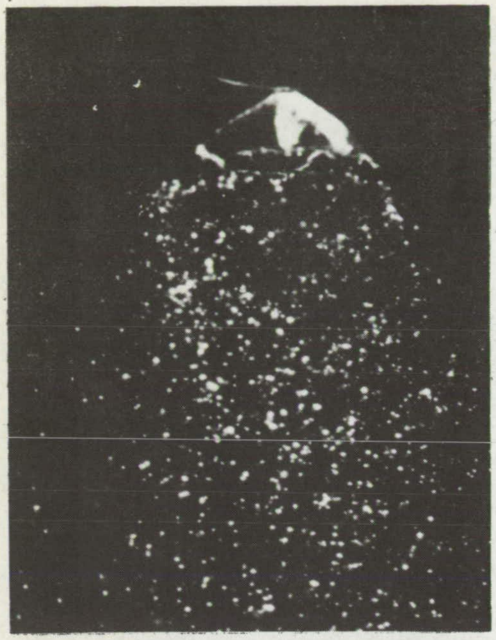
Figure 11. - Comparison of combustion efficiency obtained with four nozzles over a range of fuel-air ratios at simulated altitudes. Rotor speed, 58 percent rated.



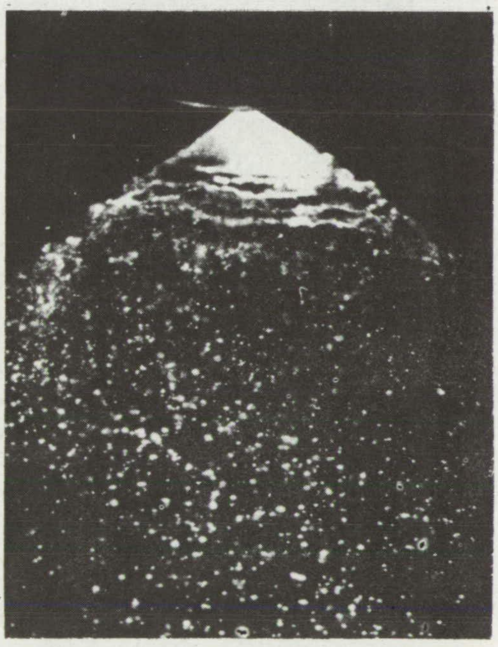
(b) Simulated altitude, 45,000 feet.

Figure 11. - Concluded. Comparison of combustion efficiency obtained with four nozzles over a range of fuel-air ratios at simulated altitudes. Rotor speed, 58 percent rated.

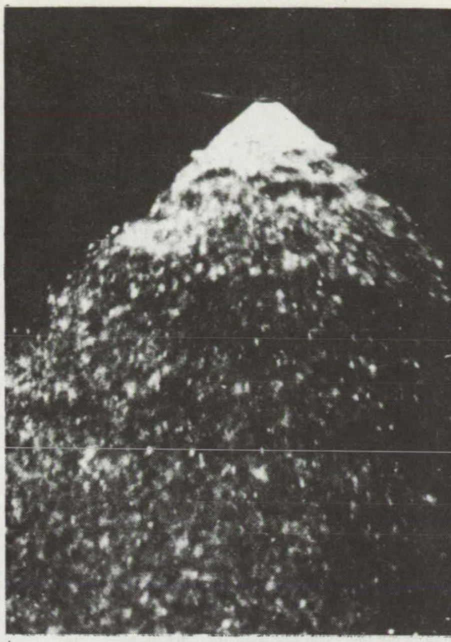
(a) Start of acceleration.



(b) 0.015 Second after start



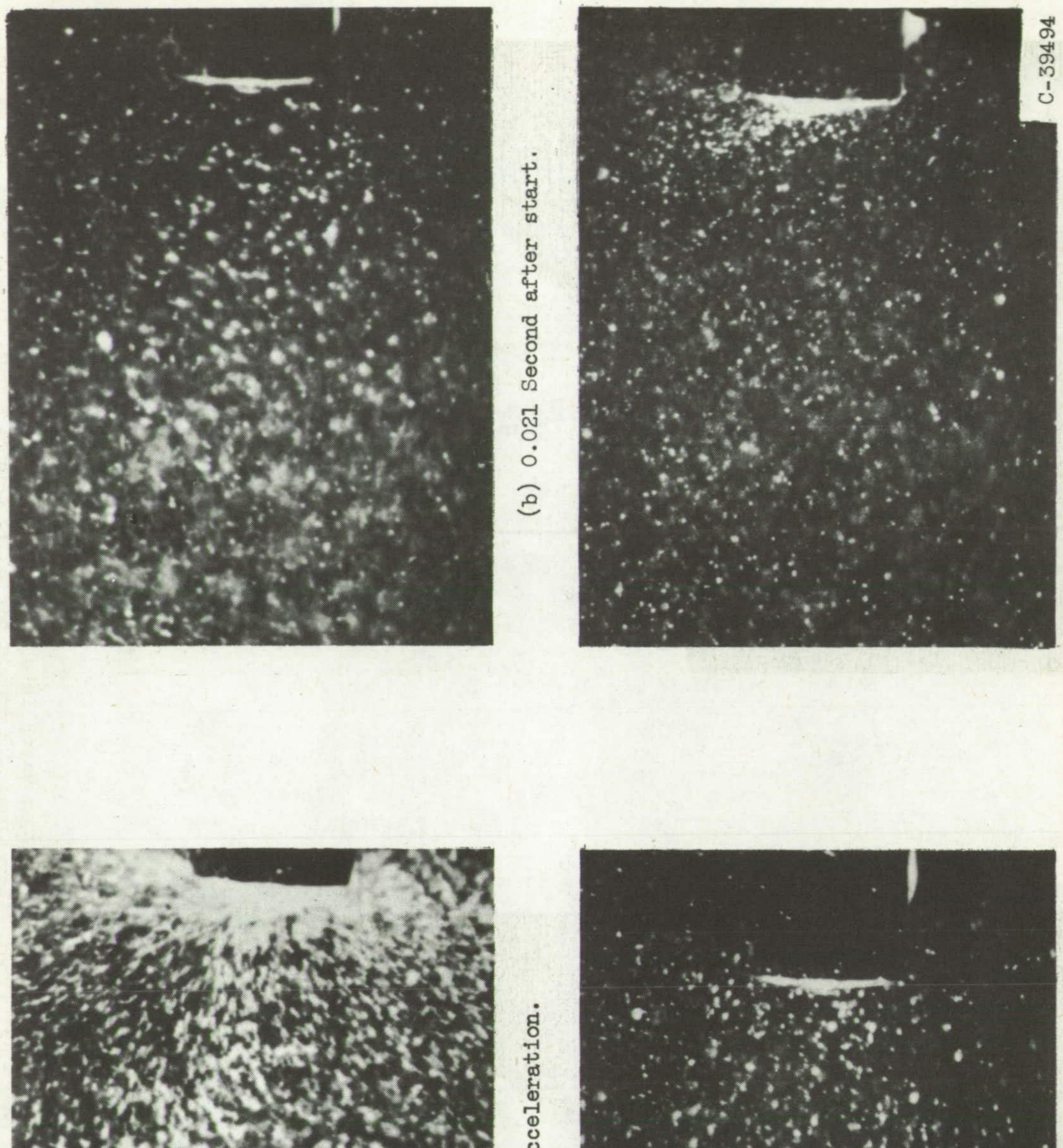
(c) 0.037 Second after start.



(d) 0.12 Second after start.

C-39493

Figure 12. - Single-entry duplex nozzle spraying water into quiescent air during flow acceleration. Initial water flow, 50 pounds per hour; final water flow, 170 pounds per hour; camera speed, 2400 frames per second.



(a) Start of acceleration.

(b) 0.021 Second after start.

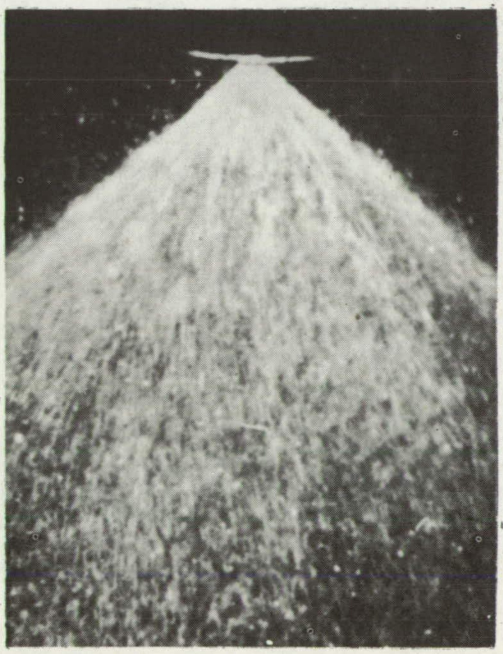
c) 0.035 Second after start.

(d) 0.050 Second after start.

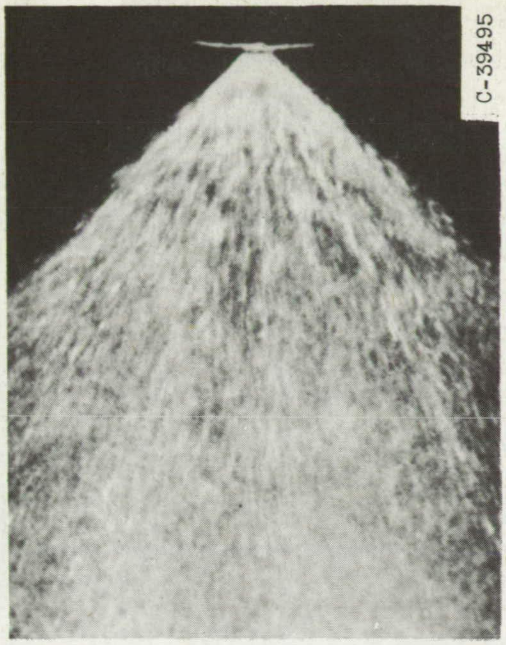
Figure 13. - Duel-entry duplex nozzle spraying water into quiescent air during flow acceleration. Initial water flow, 60 pounds per hour; final water flow, 192 pounds per hour; camera speed, 1080 frames per second.

(e) 0.065 Second after start.

(f) 0.078 Second after start.



(g) 0.086 Second after start.



C-39495

(h) 0.11 Second after start.

Figure 13. - Concluded. Duel-entry duplex nozzle spraying water into quiescent air during flow acceleration. Initial water flow, 60 pounds per hour; final water flow, 192 pounds per hour; camera speed, 1080 frames per second.