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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF THE EFFECT OF FUEL-INJECTION-SYSTEM DESIGN VARIABLES ON AFTERBURNER PERFORMANCE

By Emmert T. Jansen, Wallace W. Velie
and H. Dean Wilsted

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation was conducted on a full-scale afterburner test rig and two turbojet-engine afterburner configurations to determine criteria for the design of fuel systems for afterburners. The effect of various fuel-air ratio distributions at the flame holder on combustion performance was obtained along with the effects of variation in fuel-system design variables on the fuel-air ratio distribution. The data for the various configurations were obtained for a range of afterburner-inlet total pressures from 600 to 1600 pounds per square foot, afterburner-inlet gas velocities between 380 and 600 feet per second, and afterburner-inlet gas temperatures between 1550° and 1760° R.

For the afterburner configurations used in this investigation, it was determined that uniform fuel-air ratio distribution results in maximum combustion efficiency over the relatively wide range of afterburner fuel-air ratio between 0.04 and stoichiometric. For afterburner operation at fuel-air ratios leaner than 0.04, high peak combustion efficiency requires a radial fuel-air ratio gradient that provides rich zones in the vicinity of the flame holder. As would be expected, fuel-injection bars designed to distribute fuel in proportion to the radial gas mass-flow profile at the point of fuel injection will produce a reasonably flat radial fuel-air ratio distribution in the plane of the flame holder. In order to insure equal fuel flow through equal orifice areas, the flow area of the fuel-injection bar should be at least twice the total flow area of the fuel orifices.

INTRODUCTION

The trend of military aircraft towards higher flight speeds and higher altitudes demands a more complete exploitation of the thrust

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potentialities of afterburners. Such an exploitation requires the use of the optimum design criteria for each of the afterburner components. Considerable research and development have been conducted to establish afterburner design criteria. The knowledge the NACA had accumulated with regard to afterburner design variables up to the end of 1950 is summarized in reference 1. Since then several investigations (refs. 2 to 10) have been conducted to develop afterburners for specific turbojet engine applications and, although specific in nature, these investigations contributed to the general knowledge and understanding of afterburner design variables. The amount of work which has been done specifically on the fuel system is limited; however, some work has been reported in references 11 and 12.

As part of an over-all afterburning program, the present investigation was conducted with the purpose of broadening the information available concerning afterburner fuel systems by quantitatively indicating the effect of fuel-air ratio distribution on afterburner performance and by providing information pertinent to the design of a satisfactory fuel-injection system which uses radial fuel-injection bars. The effect of radial and circumferential fuel-air distribution and spray direction on combustion performance was determined along with the effect of the fuel distribution with respect to air-flow profile on the fuel-air ratio profile. Particular problems concerning the manufacturing techniques of fuel-injection bars were also investigated and discussed.

The investigation was conducted on a full-scale afterburner blower rig which is capable of simulating a range of afterburner-inlet conditions, and on two engine-afterburner installations in altitude test chambers. The range of conditions included afterburner-inlet temperatures between 1550° and 1760° R, afterburner-inlet total pressures from 600 to 1600 pounds per square foot, and diffuser-outlet gas velocities from 380 to 600 feet per second. The variations in fuel distribution near the upstream face of the flame holder were measured with an NACA fuel-air mixture analyzer.

INSTALLATION AND INSTRUMENTATION

Full-Scale Afterburner Test Rig

The general arrangement of the full-scale afterburner blower test rig is shown schematically in figure 1. The main components of the installation are a preheater, a mixing chamber, and an afterburner with various fixed-area exhaust nozzles. Air was supplied to the preheater and heated to a temperature of 1250° F before entering the gas mixing chamber. In the mixing chamber the hot gas was thoroughly mixed to promote a uniform temperature distribution before it entered the afterburner diffuser. The diffuser inner body, which was 60.5 inches long, was designed for a constant rate of area increase. The flame holders were mounted 7 inches aft of the rear end of the diffuser inner body. The longitudinal location of the fuel-injection bars was 29.5 inches upstream of the flame holders. The combustion chamber was 25.75 inches in diameter and approximately 53 inches long. A general description of the flame holders investigated, along with pertinent facts concerning the fuel systems, is given in table I. Details of the fuel systems will be discussed subsequently.

Full-Scale Engine-Afterburner Installation

The engine-afterburners were installed in similar altitude test chambers 10 feet in diameter and 60 feet in length. A bulkhead, which incorporated a labyrinth seal, around the forward end of the engine permitted the simulation of desired inlet and exhaust pressures.

Turbojet engine and afterburner I. - The turbojet engine-afterburner I had a sea-level nonafterburning thrust rating of 5425 pounds at rated engine speed and rated turbine-outlet temperature. The main components of the configuration were a can-type axial-flow turbojet engine with an afterburner which had a clamshell-type variable-area exhaust nozzle (fig. 2(a)). The length of the diffuser was 45.75 inches and the over-all length of the afterburner (including diffuser) was approximately 100 inches. The diameter of the combustion chamber at the flame-holder location was 32.25 inches. The flame holder was mounted on a rod which extended rearward from the aft end of the diffuser inner body and the fuel-injection bars were located 22 inches upstream of the flame holder (fig. 2(a) and table I). Cooling of the afterburner shell was accomplished by the use of a liner which extended from about 1 inch downstream of the fuel bars to within 1/2 inch of the fixed portion of the exhaust-nozzle outlet. The section of the liner between the flame holder and the nozzle exit was louvered to permit the flow of cooler turbine-outlet gas from the liner passage into the primary stream.

Turbojet engine and afterburner II. - The turbojet engine-afterburner II had a sea-level nonafterburning thrust rating of 3000 pounds at rated engine speed and rated turbine-outlet temperature. This engine was, in general, similar to engine I except that it had an annular-type combustor. The afterburner was also similar to afterburner I except that it was fitted with a fixed-area exhaust nozzle (fig. 2(b)). The length of the diffuser was 34 inches and the flame holder was mounted from the outer shell about 3 inches downstream of the aft end of the diffuser inner body. The fuel-injection bars were located 25 inches upstream of the flame holder. The combustion-chamber diameter at the flame holder was 22.8 inches and the length was 57 inches.

Afterburner Fuel-Injection Bar Configurations

A description of each configuration is presented in table I and a detailed sketch of each fuel bar used is shown in figure 3. The various fuel-system design variables investigated, along with the particular configurations on which they were used, are listed in the following table: 3093

Afterburner configurations	Fuel systems	Fuel-system design variables
A	1 2 3	Effect of various fuel-air ratio distributions on performance
B	1	Effect of various fuel-air ratio distributions on performance
C	4	Effect of various fuel-air ratio distributions on performance
D	5 6	Effect of fuel spray direction on combustion efficiency
E	4 5	Effect of fuel orifice size on combustion efficiency
F	7 8 9 10	Effect of varying fuel orifice size on fuel-air ratio distribution
G	11 12 13	Effect of varying fuel orifice location on fuel-air ratio distribution
H	14 15	Final spray pattern designed to match mass-flow profile

The first five afterburner configurations (A to E) were used to show the effect of fuel distribution on afterburner performance while the last three (F to H) show comparisons of some of the design techniques involved in the development of a satisfactory fuel-injection system.

Instrumentation

The location and amount of instrumentation at the various stations of the engines and afterburners are shown in figures 1 and 2. The pressures at the exhaust nozzle were measured with a water-cooled rake. The fuel used for all three afterburner configurations was MIL-F-5624A, grade JP-4. Fuel flow was measured by calibrated rotameters.

3093 An NACA mixture analyzer (ref. 13) was used to measure the fuel-air ratio distribution at the flame holder. A schematic sketch of the fuel-air ratio sampling system is shown in figure 4. For all three afterburners the fuel-air ratio profile was measured as near the upstream side of the flame holder as was possible. In order to obtain an accurate fuel-air ratio measurement, care must be taken to insure that the fuel-air sample is obtained at free-stream velocity (fig. 5(a)). If the sampling velocity is higher than the free-stream gas velocity, then the sampled fuel-air ratio mixture will be leaner than the true fuel-air mixture because of the additional air sucked into the sampling probe. Likewise if the sampling is done at too low a velocity a larger proportionate share of fuel droplets in relation to air will enter the sampling probe making the sampled mixture richer than the true fuel-air mixture. A second precaution necessary in order to obtain accurate fuel-air ratio measurements is that all the fuel must be vaporized and oxidized before the sample goes to the mixture analyzer. Figure 5(b) shows the electrical requirement necessary as supplied by an electric welder to the oxidizer when used with engine-afterburner I at a flight Mach number of 0.6 and altitude of 40,000 feet. The oxidizer (fig. 4) was 12 feet long and was constructed of 3/8-inch heavy-wall Inconel tubing. Insufficient electrical input to the oxidizer results in an indicated fuel-air ratio that is lower than the actual fuel-air ratio.

PROCEDURE

For the fuel systems and afterburner configurations of the full-scale afterburner test rig (configurations A to E), performance data were obtained over a range of afterburner-inlet pressures ranging from 600 to 1400 pounds per square foot and flame-holder inlet gas velocities from 380 to 600 feet per second with an inlet air temperature of 1710° R. At each simulated afterburner-inlet setting condition, data were taken over a range of afterburner fuel-air ratio for a given fixed-area exhaust nozzle. (The afterburner fuel-air ratio is defined as the ratio of afterburner fuel to unburned air entering the afterburner.) Where possible, the lean blow-out limits of the various configurations were determined.

Data were taken for each configuration of engine-afterburner I at a single flight condition and afterburner fuel flow which corresponded to an afterburner-inlet total pressure of 1100 pounds per square foot, average diffuser-outlet gas velocity of 500 feet per second, and afterburner-inlet air temperature of 1760° R; while for engine-afterburner II data were taken at a single flight condition and afterburner fuel flow which corresponded to an afterburner-inlet total pressure of 1590 pounds per square foot, diffuser-outlet velocity of 560 feet per second, and afterburner-inlet air temperature of 1550° R.

Fuel-air ratio surveys were taken ahead of the flame holders for 3093
each configuration investigated on both engine-afterburner installations, while surveys on the afterburner test rig were obtained only when deemed advisable by the investigators. Two surveys were taken on each configuration, one at the flame-holder inlet directly downstream of a fuel-injection bar and the other at the same flame-holder inlet location but midway between the projected location of two adjacent fuel-injection bars.

RESULTS AND DISCUSSION

In addition to the optimum fuel-air distribution, the attainment of good afterburner combustion performance is dependent, among other things, upon a stable flame seat, sufficient fuel mixing length, and, in general, afterburner-inlet gas velocities at the flame holder not in excess of 600 feet per second. It is therefore obvious that an optimum fuel-air distribution or an adequate flame-holder configuration will give good afterburner performance only if all other factors which affect the performance are satisfactory. The configurations for which afterburner performance data are presented herein (afterburner test rig) had a fuel mixing length of 29.5 inches; for any given comparison the flame holder, which generally provided a satisfactory flame seat, remained unchanged.

Effect of Fuel-Air Ratio Distribution on Afterburner Performance

Typical variations in afterburner-inlet conditions and gas velocity profile at the diffuser outlet for the full-scale afterburner test rig which employed a fixed-area exhaust nozzle are shown in figure 6. The afterburner-inlet total pressure increased and afterburner-inlet velocity decreased as the fuel-air ratio was increased. These variations in pressure and velocity are substantial but because no comparisons between configurations are made at two different fuel-air ratios, the variations do not affect the comparative results. For any given afterburner fuel-air ratio the variation in afterburner-inlet pressure or diffuser-outlet gas velocity among configurations was less than 3 percent and thus would have essentially no effect on the afterburner performance comparisons. Similar variations in afterburner-inlet conditions existed for all configurations investigated on the full-scale afterburner test rig. However, even though the average gas velocity varied as the afterburner fuel-air ratio was varied for any given fixed-area exhaust nozzle, the shape of the velocity profile, which is typical of the profiles existing in current production afterburners, remained unaltered.

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<u>Circumferential and radial fuel distributions at two ranges of diffuser-outlet velocities.</u> - Three fuel-air ratio distributions (fuel systems 1, 2, and 3 of afterburner configuration A) that were investigated to determine the effect of circumferential and radial variations in fuel-air ratio distribution on combustion performance are presented in figure 7. Fuel system 1 produced a uniform fuel-air distribution both radially and circumferentially. In order to show the effect of an adverse fuel-air ratio distribution, fuel system 2, which was otherwise identical to configuration 1, had every other fuel bar removed in order to produce lean fuel-air ratio regions circumferentially; fuel system 3 was identical to fuel system 1 except that the pair of fuel orifices at the location nearest the outer shell was removed in order to produce lean fuel-air ratio regions at the outer radial location of the annulus. The curves for fuel systems 1 and 3 are representative of two surveys at the flame-holder inlet: one directly downstream of a fuel bar, and the other midway between the projected location of two adjacent fuel bars. The two surveys for fuel system 2 are presented to show the circumferential variation in the fuel-air ratio distribution. The profile of the survey taken directly downstream of a fuel bar for fuel system 2 is identical to that of configuration 1 but at a higher level, while the survey taken between the projected location of two adjacent fuel bars is similar to the profile for configuration 3.

The effect of the circumferential and radial variations in fuel-air ratio distribution on afterburner performance is shown in figure 8 for the range of diffuser-outlet gas velocities from 500 to 600 feet per second and afterburner-inlet total pressures from 800 to 980 pounds per square foot. At an afterburner fuel-air ratio higher than about 0.040, a uniform fuel-air ratio distribution gave the highest combustion efficiency and exhaust-gas temperatures, but below a fuel-air ratio of 0.035 both nonuniform fuel-air ratio distributions gave slightly higher combustion efficiencies. This characteristic results from the fact that with the nonuniform fuel-air ratio distributions there exist locally fuel-rich regions which are more favorable for good combustion at these low over-all fuel-air ratios. These locally fuel-rich regions also cause the fall-off in combustion efficiency at the higher fuel-air ratio because the local fuel-air mixture is above stoichiometric. It is therefore evident that a uniform fuel-air ratio distribution is desirable except for an afterburner developed primarily for low-temperature-rise operation.

The afterburner combustion efficiency for the same three fuel systems of figure 7 (afterburner configuration A) is shown in figure 9 for the lower diffuser-outlet gas velocity range (380 to 480 ft/sec). The uniform fuel-air ratio distribution had the highest combustion efficiency above an afterburner fuel-air ratio of about 0.04 and the relative loss in efficiency between a uniform and a nonuniform radial 3083
fuel-air ratio distribution (above an afterburner fuel-air ratio of 0.04) remained relatively unchanged. The difference in performance between the nonuniform circumferential fuel-air ratio distribution and the uniform fuel-air ratio distribution was not so great at the lower diffuser-outlet gas velocities as it was at the higher gas velocities with a drop of only about 0.01 to 0.02 in combustion efficiency. The reason that the decrease in diffuser-outlet gas velocity improved the performance of the nonuniform circumferential distribution is that the fuel was injected normal to the gas stream in a circumferential direction. Decreasing the gas velocity tended to increase the penetration and mixing time of the fuel and thus to decrease the small nonuniform regions of the circumferential distribution. Obviously for the nonuniform radial distribution the amount of increased mixing and penetration due to the decrease in gas velocity aided very little in moving the fuel out radially to the large lean-fuel-air region near the outer shell and the performance remained relatively unaffected.

For both the uniform and nonuniform circumferential fuel-air distribution the fuel-air ratio at which lean blow-out occurred was about 0.03 for the high velocity range and about 0.027 for the low velocity range. For the nonuniform radial fuel-air ratio distribution, however, the lean blow-out occurred at fuel-air ratios of 0.024 and 0.015 for the high and low velocity ranges, respectively. These results indicate that, for an afterburner with a low lean blow-out limit, the desired fuel-air ratio distribution is one having a large region of rich fuel-air mixture (such as a nonuniform radial distribution but continuous uniform circumferential distribution) rather than one consisting of a large number of small regions having rich fuel-air mixtures (such as nonuniform circumferentially).

Even though a fuel system may be designed to give a desired fuel-air ratio distribution, it is possible that other factors may influence the actual distribution to a considerable extent. One of these factors is the plugging of the fuel bar orifices with foreign particles introduced with the fuel or from an unclean fuel system in conjunction with an inadequate fuel filter. A comparison of the fuel-air ratio distribution and the combustion efficiency both before and after foreign particles (iron oxide) plugged some of the fuel orifices (fuel system 1) is presented in figures 10 and 11. The small difference in fuel-air ratio distribution between the uniform distributions presented in figures 10 and 7 is caused by the difference in flame-holder inlet gas velocity.

For the comparisons presented in figures 10 and 11, the plugging of the fuel orifices occurred at the tips of the fuel bars (near the diffuser inner body); a flow check of the fuel bars after the plugging occurred indicated that the two fuel orifices located at the tip of the bar were consistently plugged on all of the fuel bars. Therefore, the resulting fuel-air ratio distribution after plugging by foreign materials (fig. 10) is similar to the nonuniform radial fuel-air ratio distribution (fuel system 3) just discussed except that the rich region of fuel-air mixture is at the outer radial location of the annulus.

Comparing the performance of fuel system 1 after plugging (fig. 11) and fuel system 3 (fig. 9) with the results obtained with uniform fuel-air ratio distribution shows almost identical trends in each case. In both cases the performance with nonuniform radial fuel-air ratio distribution is considerably inferior to that with the uniform fuel-air ratio distribution above a fuel-air ratio of 0.035. However, below a fuel-air ratio of 0.035 the nonuniform radial distributions are superior in both combustion efficiency and lean blow-out limits.

As has been pointed out, a nonuniform fuel-air ratio distribution improves the performance of the afterburner in the range of lean fuel-air ratio operation. Therefore, fuel system 4 (afterburner configuration C) was designed to have a severe radial fuel-air ratio gradient and mild circumferential fuel-air ratio gradient (fig. 12). This fuel-air ratio distribution was accomplished by using 12 fuel bars, each bar having only four fuel orifices located in pairs at two radial positions so as to place the rich region of fuel-air mixture at the radial position of the single-ring V-gutter flame holder.

The fuel-air ratio at which lean blow-out occurred was 0.0043 and the peak combustion efficiency of 0.90 occurred at a fuel-air ratio of 0.01 (fig. 13). Above a fuel-air ratio of 0.01, the combustion efficiency fell off very rapidly to about 0.42 at a fuel-air ratio of 0.025 and then remained fairly constant as the fuel-air ratio continued to increase.

Fuel-injection direction. - The effect on combustion efficiency of injecting the fuel normal, upstream, and downstream with respect to the gas flow (afterburner configuration D) from a radial fuel bar is presented in figure 14. Fuel system 5, which gave a uniform fuel-air ratio distribution both radially and circumferentially, was used to inject the fuel normal to the gas stream (in two directions 180° apart) and fuel system 6 was used to inject the fuel in either the upstream or the downstream direction. Because fuel system 6 injected fuel in only one direction, the number of fuel orifices was reduced by half; therefore, the area of each orifice was approximately doubled in order to maintain the fuel injection pressures about the same.

Varying the direction of fuel injection from a normal direction to
either upstream or downstream injection decreased the combustion effi-
ciency over the entire range of fuel-air ratios investigated. For exam-
ple, combustion efficiency at stoichiometric fuel-air ratio, when either 3093
upstream or downstream fuel injection was used, was about 0.09 lower
than that obtained with normal fuel injection. These results indicate
that even though the penetration of the fuel jet into the gas stream
may be small it is evident that the direction has a measurable effect
on the fuel-air ratio distribution and should be considered. Changing
the fuel injection to either upstream or downstream direction from a
normal direction practically eliminated all normal penetration of
the fuel so that if the same fuel-air ratio distribution is desired
the number of fuel bars will have to be increased. Reference 1,
which showed essentially no effect of fuel injection direction on
combustion efficiency, used a nonuniform circumferential fuel-air
ratio distribution instead of a uniform distribution as is used in
this report. Close inspection of the data presented in this refer-
ence, however, indicates that at the higher afterburner fuel-air ratios
normal fuel injection direction is superior to either the upstream
or the downstream injection direction.

Fuel orifice area. - The effect of fuel orifice area on combustion efficiency is presented in figure 15 for fuel which is injected normal to the gas stream. Fuel systems 1 and 5 (afterburner configuration E) were the same except that fuel system 1 had orifices 0.030 inch in diameter while fuel system 5 had orifices 0.020 inch in diameter. The ratio of total fuel orifice area to inside area of the fuel bar was 0.11 and 0.05 for fuel systems 1 and 5, respectively. These ratios will subsequently be shown to be entirely satisfactory in order to insure equal fuel flows through each orifice along a fuel bar. Therefore, the only effect on combustion efficiency caused by varying the fuel orifice diameter will be due to the change in fuel manifold pressures, which in turn affects the degree of penetration of the fuel into the high-velocity gas stream.

Decreasing the fuel orifice diameter from 0.030 to 0.20 inch (increasing the fuel manifold pressure tending to increase the fuel penetration into the gas stream) has very little effect on combustion efficiency between fuel-air ratios of 0.055 and 0.07. However, for the range of fuel-air ratios from 0.055 to the fuel-air ratio at which lean blow-out occurred, the fuel system having 0.030-inch-diameter fuel orifices gave combustion efficiencies about 5 points higher than the fuel system having 0.020-inch-diameter fuel orifices. The improved combustion efficiency at the low fuel-air ratio range as the fuel orifice diameter was increased is attributed to a less uniform fuel-air ratio distribution. The less uniform fuel-air ratio distribution as the fuel orifice diameter is increased results from the lower fuel manifold pressures which tend to decrease the penetration of the fuel and to cause richer local regions of fuel-air mixture directly behind each fuel bar.

There are other considerations in the selection of fuel orifice diameter which may be more important than the effect of orifice diameter on fuel penetration and fuel-air ratio distribution. Two of these effects (for both of which a large orifice area is desirable) are orifice plugging due to impurities in the fuel and drilling of the fuel orifices.

Techniques and Considerations in the Development of a Satisfactory Fuel-Air Ratio Distribution

Because of the difficulties in getting good fuel-air ratio distributions with nonuniform radial mass-flow profiles leaving the turbine, considerable attention has been given to the design techniques of a fuel-bar system which will result in optimum fuel-air ratio distribution at the flame holder. Generally, two techniques can be employed in the design of a fuel-bar configuration in order to obtain a desired fuel-air ratio distribution. The first technique would involve a trial-and-error method in which an arbitrary fuel-bar configuration is varied either by altering the fuel orifice diameters or by altering the fuel orifice radial locations until the desired fuel-air ratio distribution is obtained. The second technique requires an accurate mass-flow-profile measurement at the fuel-bar location from which the fuel-bar orifice size and spacing can be calculated so as to give the desired fuel-air ratio distribution. Actually the first technique could be used to refine a fuel-bar configuration designed by the second technique. All three afterburner series considered in this section have as a goal the attainment of a uniform fuel-air ratio distribution both radially and circumferentially at the flame-holder inlet.

Trial-and-error technique to obtain desired fuel-air ratio distribution. - The effect of varying fuel-orifice diameter (fuel systems 7 to 10, afterburner configuration F) on fuel-air ratio distribution is presented in figure 16. Generally, varying the fuel orifice diameter while maintaining fixed radial positions for the fuel orifices does not appear to be a very predictable method in obtaining

a desired fuel-air ratio distribution (as will be shown in the following discussion). The alteration to the fuel orifice diameters from one fuel system to the next was based on the deviation of the measured fuel-air ratio distribution from a uniform fuel-air ratio distribution. Fuel system 7 had the fuel orifices located on equal areas but with varying orifice diameters in order to produce greater fuel flows in the regions near the inner and outer surfaces of the annulus. Because the fuel-air ratios in the inner and outer regions of the annulus were still lean, fuel system 8 was constructed, which satisfactorily enriched the outer region but overcorrected the inner region and result-
ed in a hump in the fuel-air ratio profile near the inner body. Fuel 3093
system 9 was an unsuccessful attempt to remove the hump near the inner body. Fuel system 10, which was also designed to remove the hump, actually overcorrected, resulting in a lean region of fuel-air ratio near the inner body and a dip in the fuel-air ratio profile at the center of the annulus.

The trial-and-error method of varying the fuel orifice radial locations in obtaining the desired fuel-air ratio distribution is presented in figure 17. Fuel system 11 was a modification of a fuel system in which the fuel orifices were so located that each pair of orifices represented their proportionate share of the total area of the annulus. In modifying the fuel system two additional orifices were added near the liner in the outer region of the annulus and one additional orifice (injecting fuel upstream) was added near the inner body in order to keep the fuel-air ratios in the boundary regions of the annulus from being too lean. The resulting fuel-air ratio distribution from this fuel system was relatively satisfactory near the boundaries of the annulus, but the distribution had a dip in the center of the passage. In an attempt to remove the dip and decrease the hump near the inner body, the locations of three sets of fuel orifices were altered (shown in fig. 3). The resulting profile for fuel system 12 had a variation in the fuel-air ratio of less than ± 0.005 over approximately two-thirds of the annular passage from the inner body to the cooling liner. It appears from the number of attempts made that moving fuel orifices while maintaining constant orifice diameters holds more promise in the trial-and-error design of fuel system configurations than does varying the fuel orifice diameter while holding orifice location fixed.

<u>Fuel-injection bar designed to match weight-flow distribution.</u> - The first technique in designing a fuel-system configuration which has been discussed requires some method of measuring the fuel-air ratio distribution at the flame-holder inlet in order to determine what modifications to the fuel bar, if any, are required to obtain the desired fuel-air ratio distribution. The desirable characteristic for any method of designing a fuel system would be one in which the resulting fuel-air distrubution would always match the design

fuel-air distribution. This is possible if the fuel bar is designed so that the fuel distribution matches the weight-flow profile at the fuel bar location. By use of the measured weight-flow profile of engine-afterburner II (fig. 18), two fuel-system configurations were designed to produce a uniform fuel-air ratio distribution across the annular passage. Fuel system 13 had eight fuel orifices located in pairs at four radial positions along each bar. The resulting fuel-air ratio profile (fig. 19) was as uniform as any obtained by either of the
3093 first two trial-and-error methods discussed. However, because the penetration distance of a fuel jet normal to the gas stream is extremely small for the condition covered by afterburner operation, it would appear more practicable not to locate the fuel orifices in pairs but to stagger their positions along the fuel bar. This staggering of the fuel orifices, such as for fuel system 14, would increase the number of sources of fuel and thus decrease the mixing required between the fuel and air. A comparison of the fuel-air ratio distribution for fuel systems 13 and 14 shows that fuel system 14 produced a smoother distribution than fuel system 13 and had a fuel-air ratio variation of less than ±0.005 over 75 percent of the annulus. It must be realized that it is generally difficult to maintain a uniform fuel-air ratio distribution across the entire annular passage at the flame-holder inlet because the overlapping effect of the diffused fuel from one orifice on that from an adjacent orifice is not present on the wall side of the end orifice on any fuel bar. This lack of overlapping effect is generally desirable because the afterburner wall would overheat if a high degree of combustion took place near the wall.

Effect of fuel-injection-bar dimensional changes and manufacturing technique on fuel orifice flow characteristics. - In the selection of the fuel bar and number of fuel orifices per bar to be used, several factors must be considered. The first precaution to take in order to obtain consistent fuel flows is to design the fuel bar so that the inside flow area of the fuel bar is at least twice the total area of the orifices. Figure 20(a) shows that as the ratio of total fuel orifice area to fuel-bar flow area is reduced from 0.953 to 0.424, the maximum variation in fuel flow through the orifices decreased from about 44 to 7 percent. The reduction in flow variation is caused by the decrease in velocity head of the fuel moving in the fuel bar. This velocity head variation both varies the static pressure of the fuel (as shown in fig. 20(b)) and alters the effective flow area or flow coefficient of the fuel orifices near the fuel-bar shank. The change in flow area is a result of the inertia of the fuel flowing at right angles to the orifice axis.

Effort spent on the design of a fuel bar to give the desired fuel-air ratio distribution can be almost completely offset by inaccuracies in the actual orifice diameters. In the selection of the orifice diameters to be used, consideration should be given to the fuel-bar wall

thickness and the technique in the actual drilling of the orifices so that the orifice-flow-area variations are held to a minimum. For the range of fuel orifice diameters most commonly used in afterburner fuel systems, decreasing the length-diameter ratio of the fuel orifice either by decreasing the fuel-bar wall thickness or by increasing the orifice diameter decreased the average flow variation for any set of fuel orifices (fig. 21). Another technique which tended to reduce the variation in fuel orifice diameters for any length-diameter ratio was to drill the orifice undersize and then ream to the desired size. As
shown in figure 21, this technique produced the greatest uniformity of 3093
flow from one orifice to another.

CONCLUDING REMARKS

The results of an investigation conducted on a full-scale afterburner test rig and on two engine-afterburner configurations in an altitude test chamber show the importance of several design factors that must be considered in order to obtain optimum performance from an afterburner fuel-spray system having radial fuel-injection bars.

Considering only the fuel system, the value of the design fuel-air ratio will determine the shape of the radial fuel distribution curve necessary to produce peak efficiencies at the design point. Uniform fuel-air ratio distribution results in maximum combustion efficiency over a relatively wide range of fuel-air ratios (from approximately 0.040 to stoichiometric). For afterburner operation at fuel-air ratios leaner than 0.035, high peak combustion efficiency requires a radial fuel-air ratio gradient with the rich zones existing generally in the vicinity of the flame holder. For a given number of fuel-injection bars, higher combustion efficiency can be realized by injecting the fuel normal to the gas flow than by either upstream or downstream fuel injection. Increasing the afterburner-inlet gas velocity tends to reduce the penetration and mixing time of the fuel, resulting in less uniformity for any given fuel-air ratio distribution. When radial fuel-injection bars are used, the effect of velocity on fuel-air ratio distribution is more severe on the circumferential variation than on the radial variation.

Fuel-injection bars designed to distribute fuel in proportion to the radial gas weight-flow profile at the point of injection produced a radial fuel-air distribution that was reasonably flat over 75 percent of the annulus with the fuel-air ratio falling off near the inner and outer walls of the annulus. When an attempt was made to improve the fuel-air profile of an arbitrary fuel-injection system by a trial-and-error method, the results obtained by altering the radial location of orifices along the fuel-injection bar appear to be more effective and predictable than the results obtained by changing the orifice area. This is generally more satisfactory from a production standpoint because one orifice size can be maintained throughout the fuel-injection bar.

To insure equal fuel flow through equal orifice areas, the internal flow area of the fuel bar should be at least twice the total flow area of the orifices. The variation in fuel flow through any set of equal fuel orifices generally can be decreased by either increasing orifice size or decreasing fuel-injection-bar wall thickness, which in turn allows the holding of closer tolerances.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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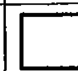
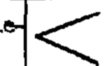
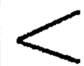
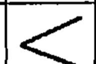
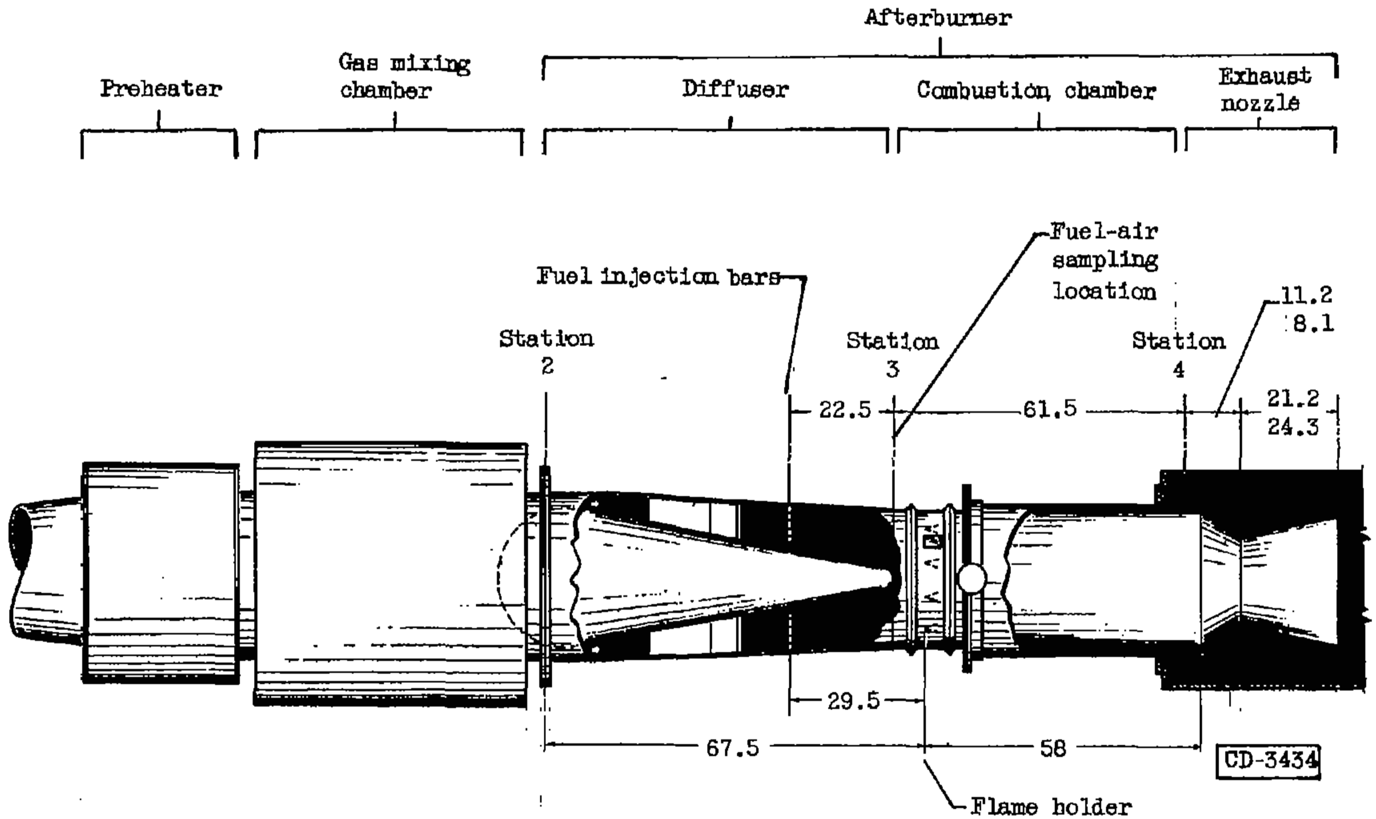
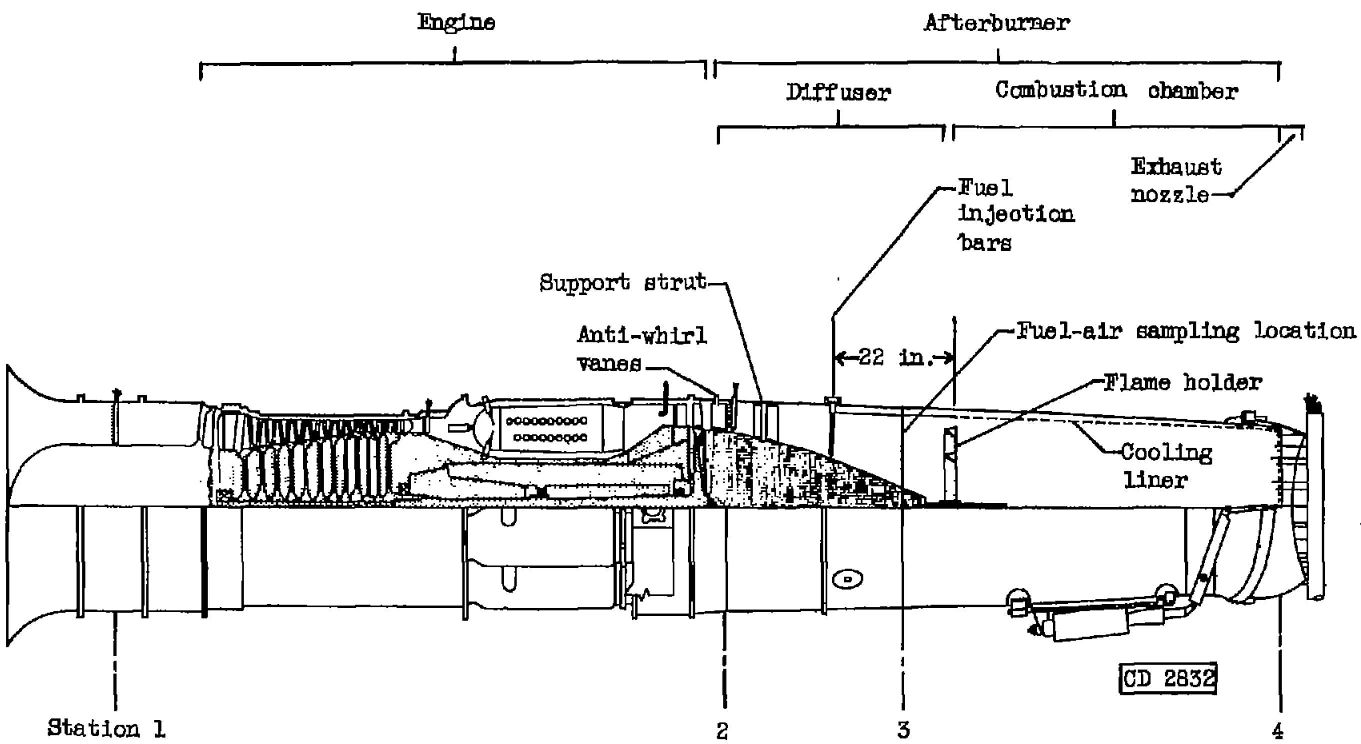
TABLE I. - GENERAL DESCRIPTION OF FUEL SYSTEMS AND FLAME HOLDERS

	Afterburner configuration	Fuel system					Flame holder		
		Fuel-system configuration	Number of fuel-injection bars	Number of orifices per fuel injection bar	Direction of fuel injection	Fuel mixing length, in.	Type of gutter	Gutter shape	Blocked area, percent
Full-scale afterburner test rig	A	1 2 3	24 12 24	8 8 6	Normal	29.5 29.5 29.5	Conventional 2-ring V-gutter with rounded tabs		29
	B	1 1	24 24	8 8	Normal	29.5 29.5	2-ring channel gutter		29
	C	4	12	4	Normal	29.5	Conventional single-ring V-gutter		23
	D	5 6 6	24 24 24	8 4 4	Normal Upstream Downstream	29.5 29.5 29.5	Conventional 3-ring V-gutter		48
	E	1 5	24 24	8 8	Normal	29.5 29.5	Conventional 2-ring V-gutter with rounded tabs		29
Engine-afterburner I	F	7 8 9 10	20 20 20 20	16 18 18 18	Normal	22 22 22 22	Conventional 2-ring V-gutter		28
	G	11 12	20 20	19 19	Normal	22 22	Conventional 2-ring V-gutter		28
Engine-afterburner II	H	13 14	24 24	8 7	Normal	25 25	Conventional 2-ring V-gutter		30



Station	Number of probes		
	Total pressures	Wall and rake static pressures	Thermocouple
2	18	14	20
3	24	12	--
4	12	2	--

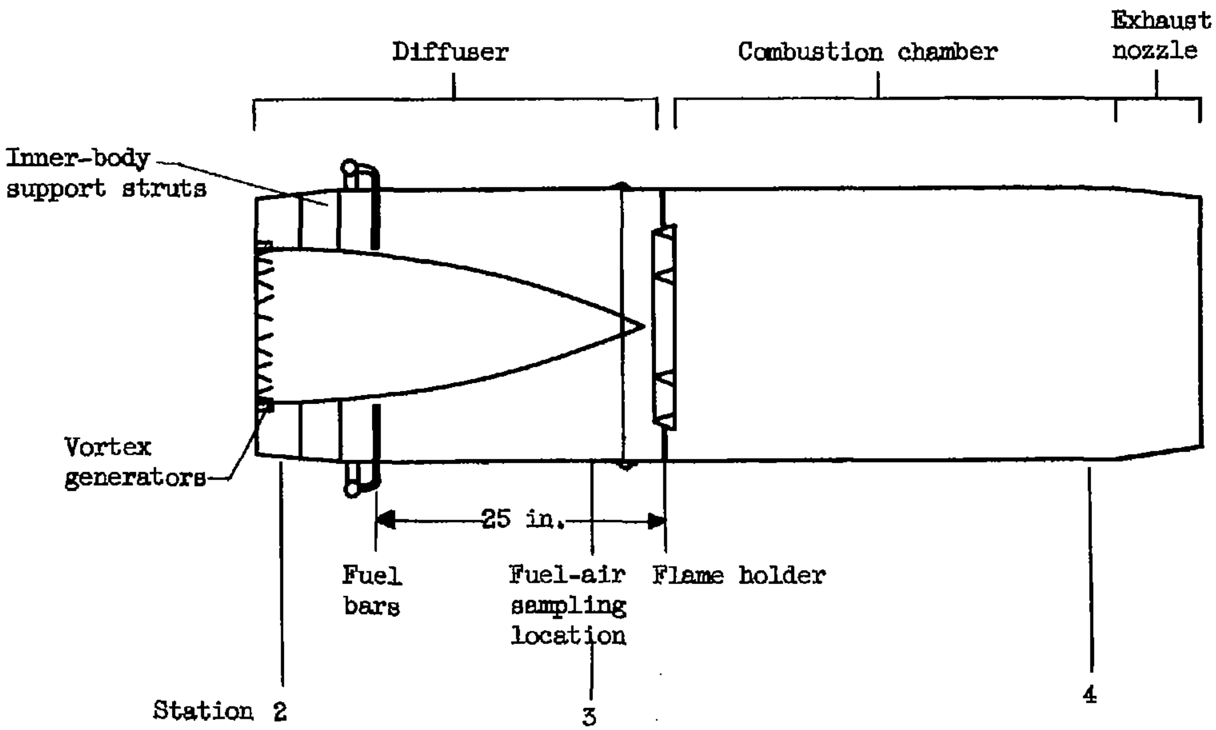
Figure 1. - Schematic diagram of full-scale afterburner test rig. (All dimensions are in inches.)



Station	Number of probes		
	Total pressures	Wall and rake static pressures	Thermocouples
1	24	10	12
2 (Diffuser inlet)	15	3	24
4 (Nozzle inlet)	13	4	--

(a) Engine-afterburner I.

Figure 2. - Schematic diagram of engine-afterburner configurations.



Station	Number of probes		
	Total pressure	Wall and rake static pressure	Thermocouple
2 (Diffuser inlet)	20	4	48
4 (Nozzle inlet)	13	-	--

(b) Afterburner II.

Figure 2. - Schematic diagram at engine-afterburner configurations.

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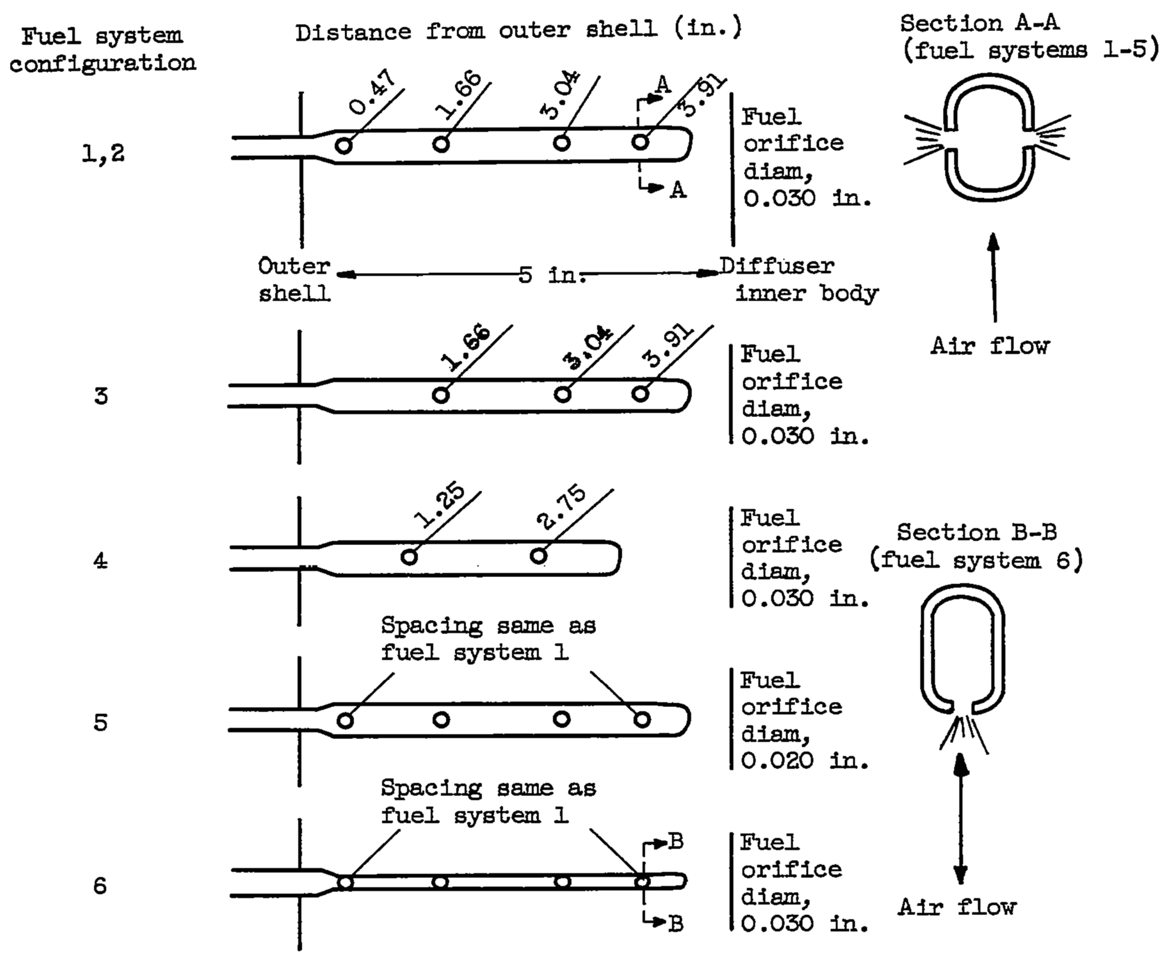

(a) Afterburner test rig fuel-injection configurations.

Figure 3. - Details of fuel-injection bar design.

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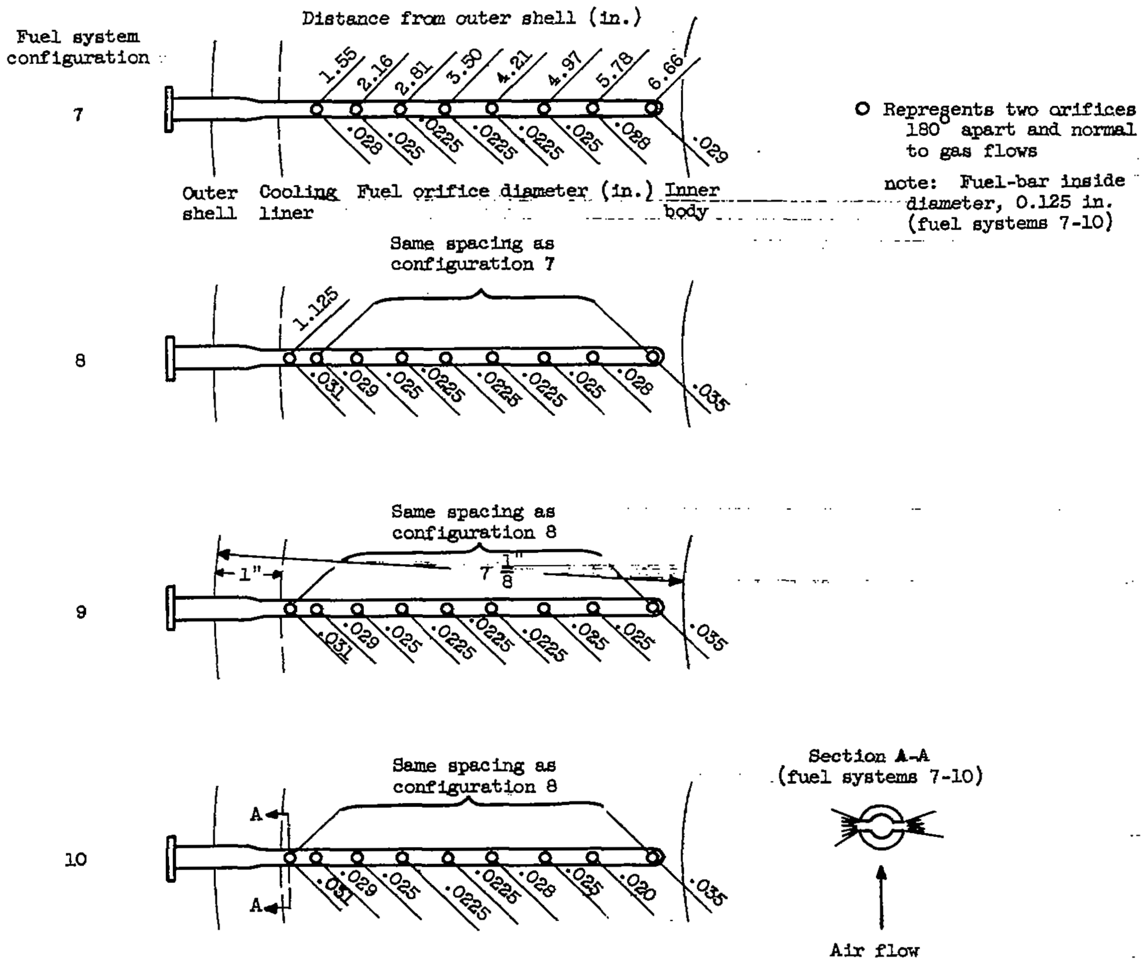

(b) Engine-afterburner I fuel-injection configurations 7 to 10.

Figure 3. - Continued. Details of fuel-injection-bar design.

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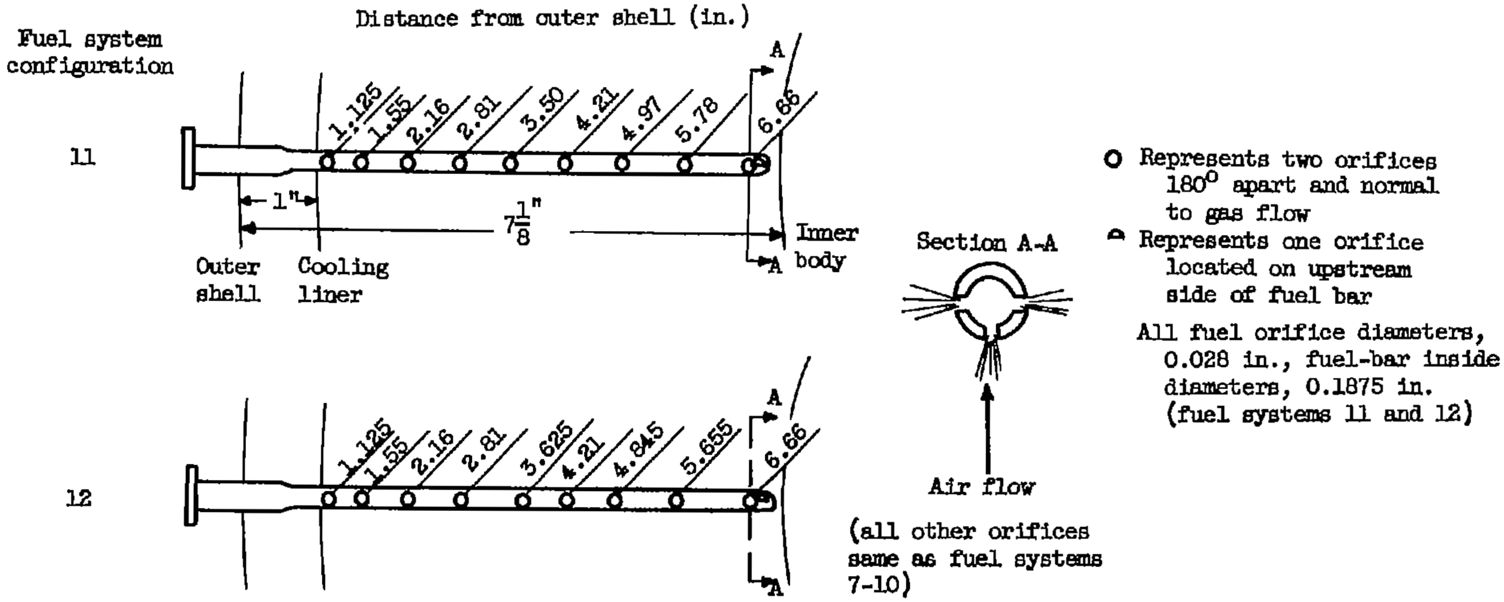

(c) Engine-afterburner I fuel-injection configurations 11 and 12.

Figure 3. - Continued. Details of fuel-injection bar design.

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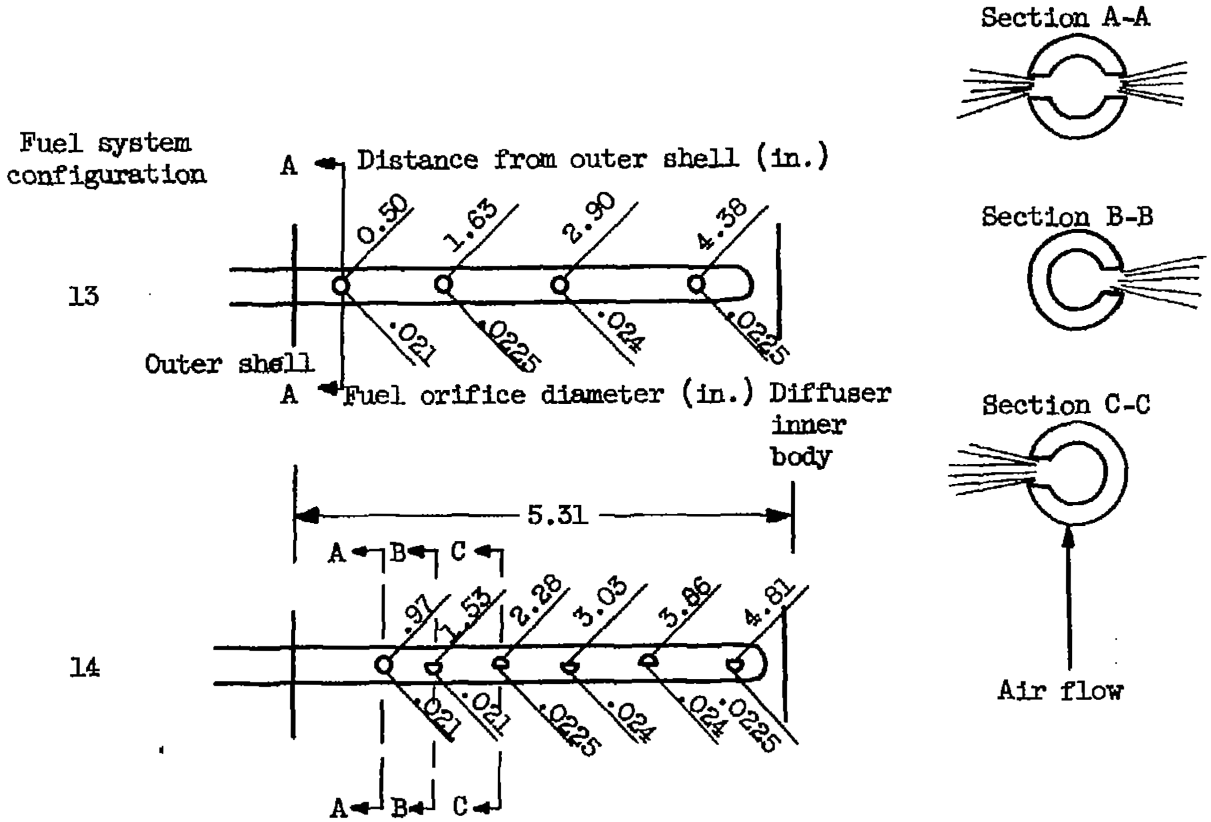

○ Represents two fuel orifices 180° apart
◓ Represents one fuel orifice
Fuel-bar inside diameter, 0.25 in.

(d) Engine-afterburner II fuel-injection configurations.

Figure 3. - Concluded. Details of fuel-injection bar design.

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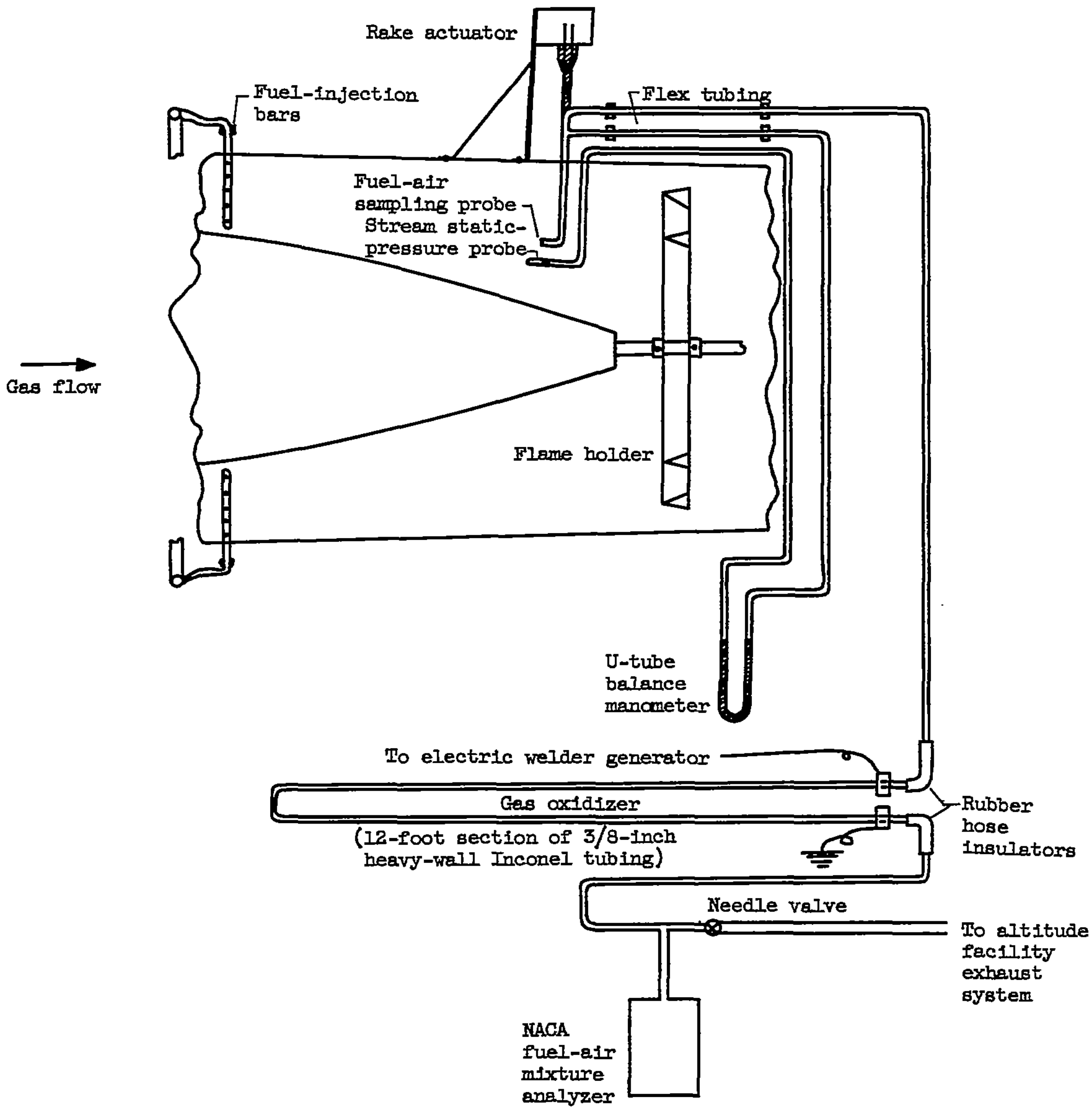

Figure 4. - Schematic sketch of fuel-air mixture sampling system.

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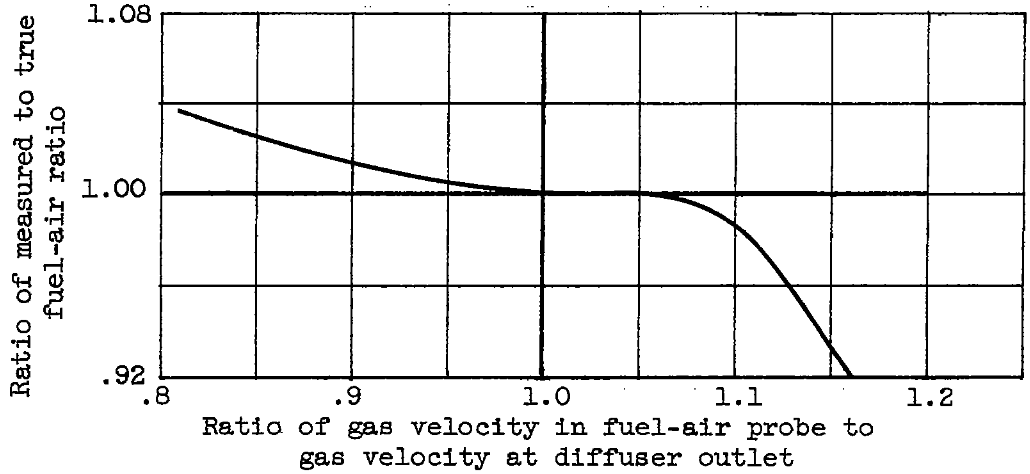
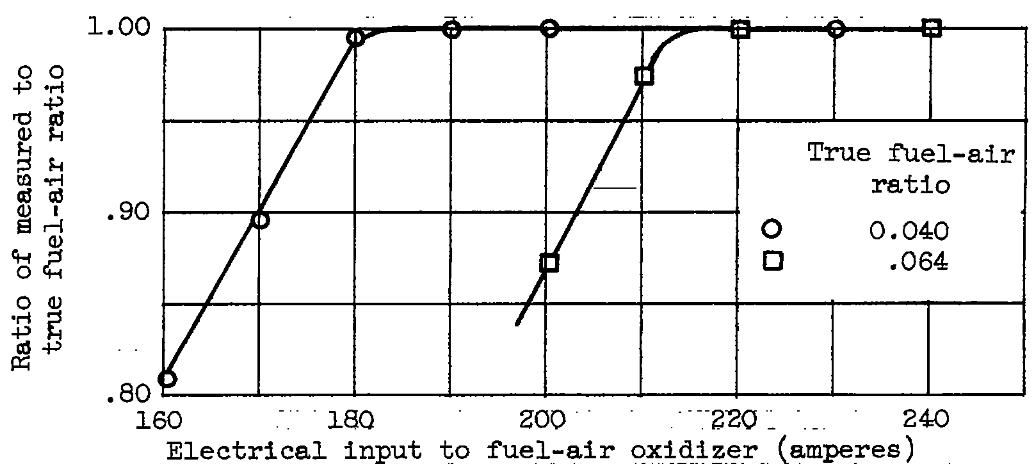
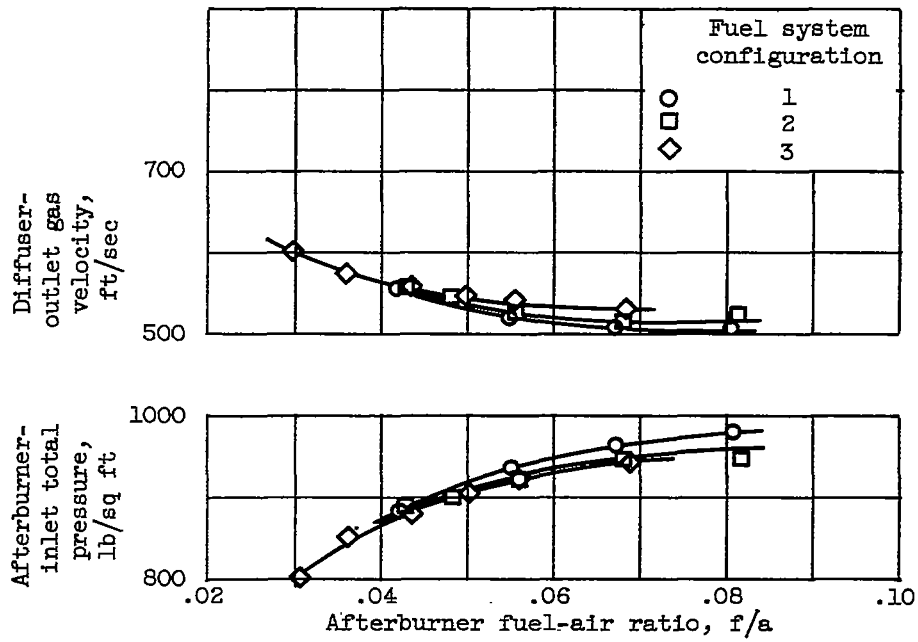


(a) Sampling velocity. True fuel-air ratio, 0.0675; average diffuser-outlet velocity, 500 feet per second.

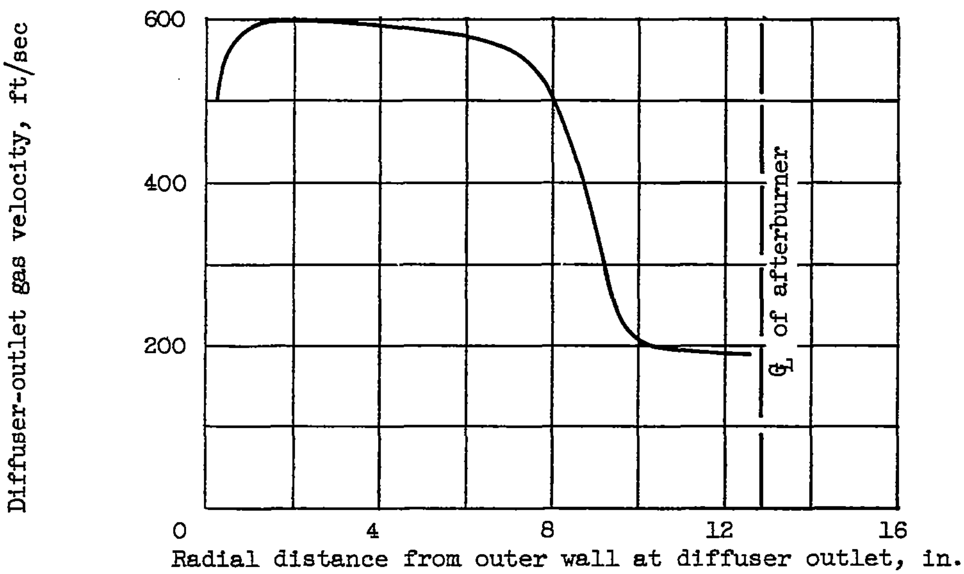


(b) Oxidizer electrical requirements.

Figure 5. - Variables to be considered in design of fuel-air sampling system. Engine-afterburner I; altitude, 40,000 feet; flight Mach number, 0.6.



(a) Afterburner-inlet conditions.



(b) Typical diffuser-outlet gas velocity profile.

Figure 6. - Typical variations in afterburner-inlet conditions as afterburner fuel-air ratio is varied, along with typical velocity profile at diffuser outlet for full-scale afterburner test rig. Afterburner-inlet total temperature, 1710° R.

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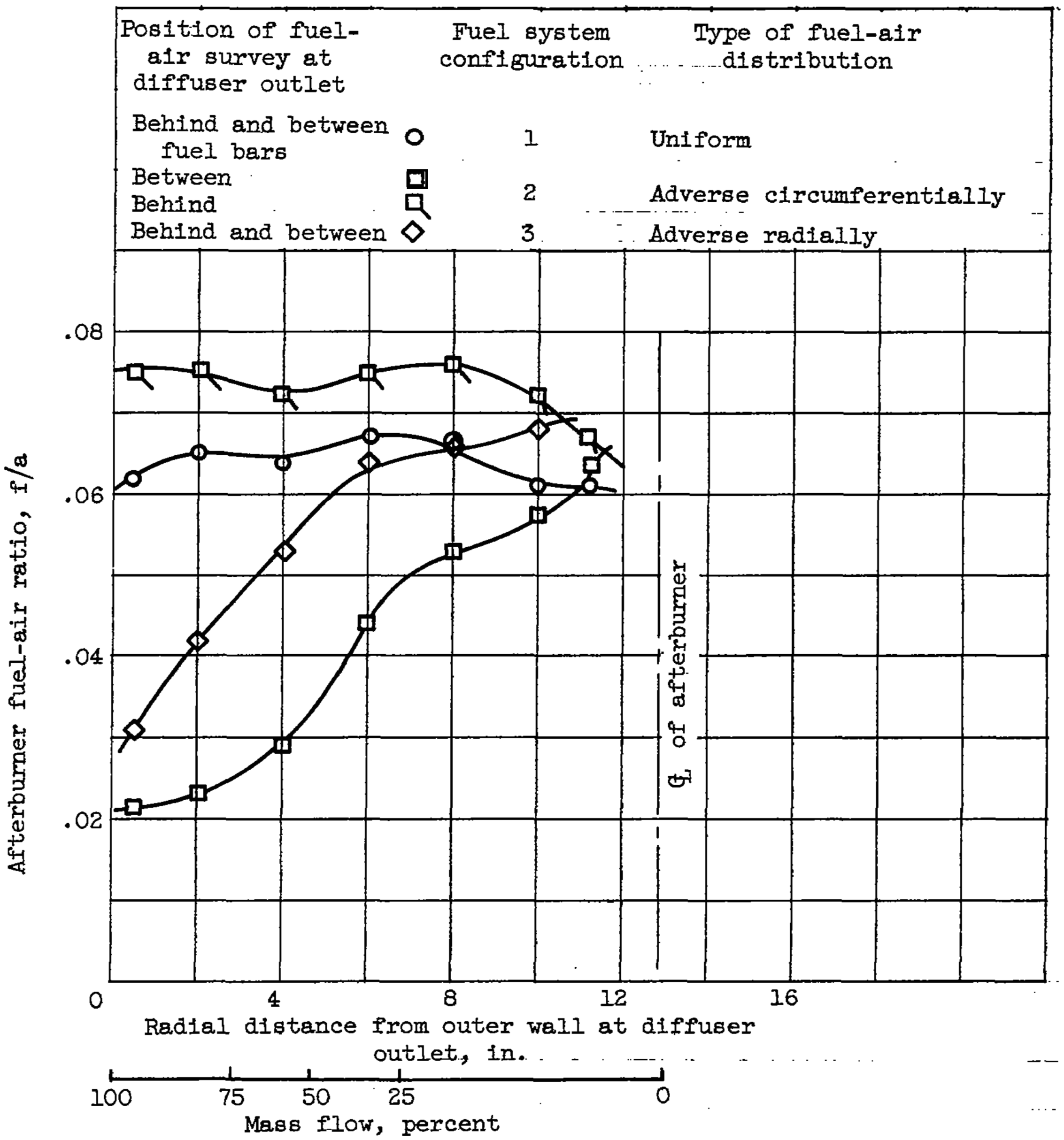

Figure 7. - Effect of fuel-distribution variations on fuel-air ratio profile at flame-holder. Afterburner configuration A; diffuser-outlet gas velocity, 520 feet per second; afterburner-inlet total pressure, 940 pounds per square foot; afterburner-inlet total temperature, 1710° R.

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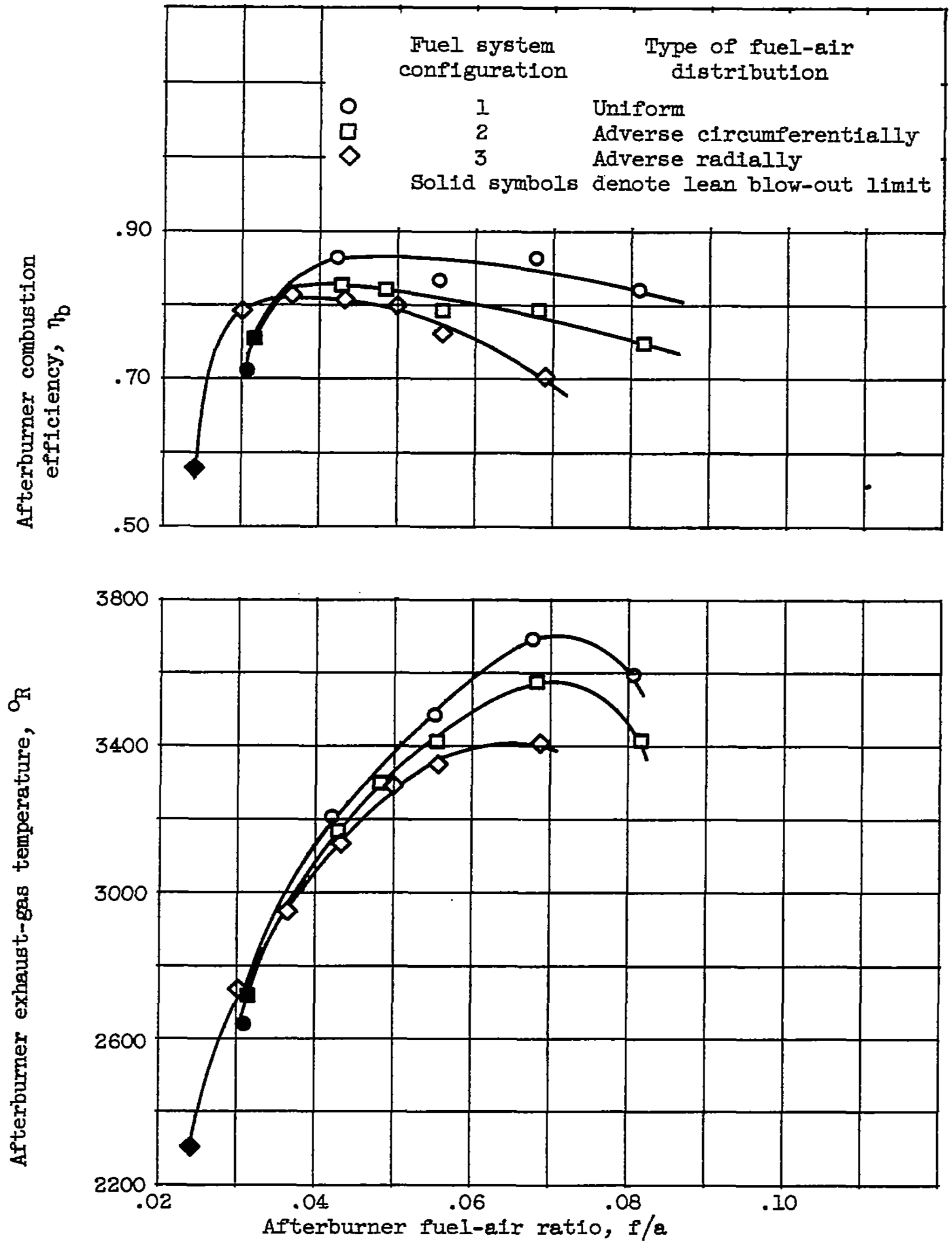

Figure 8. - Effect of fuel-air distribution on afterburner combustion performance. Afterburner configuration A; diffuser-outlet gas velocity, 500 to 600 feet per second; afterburner-inlet total pressure, 800 to 980 pounds per square foot; afterburner-inlet total temperature, 1710° R.

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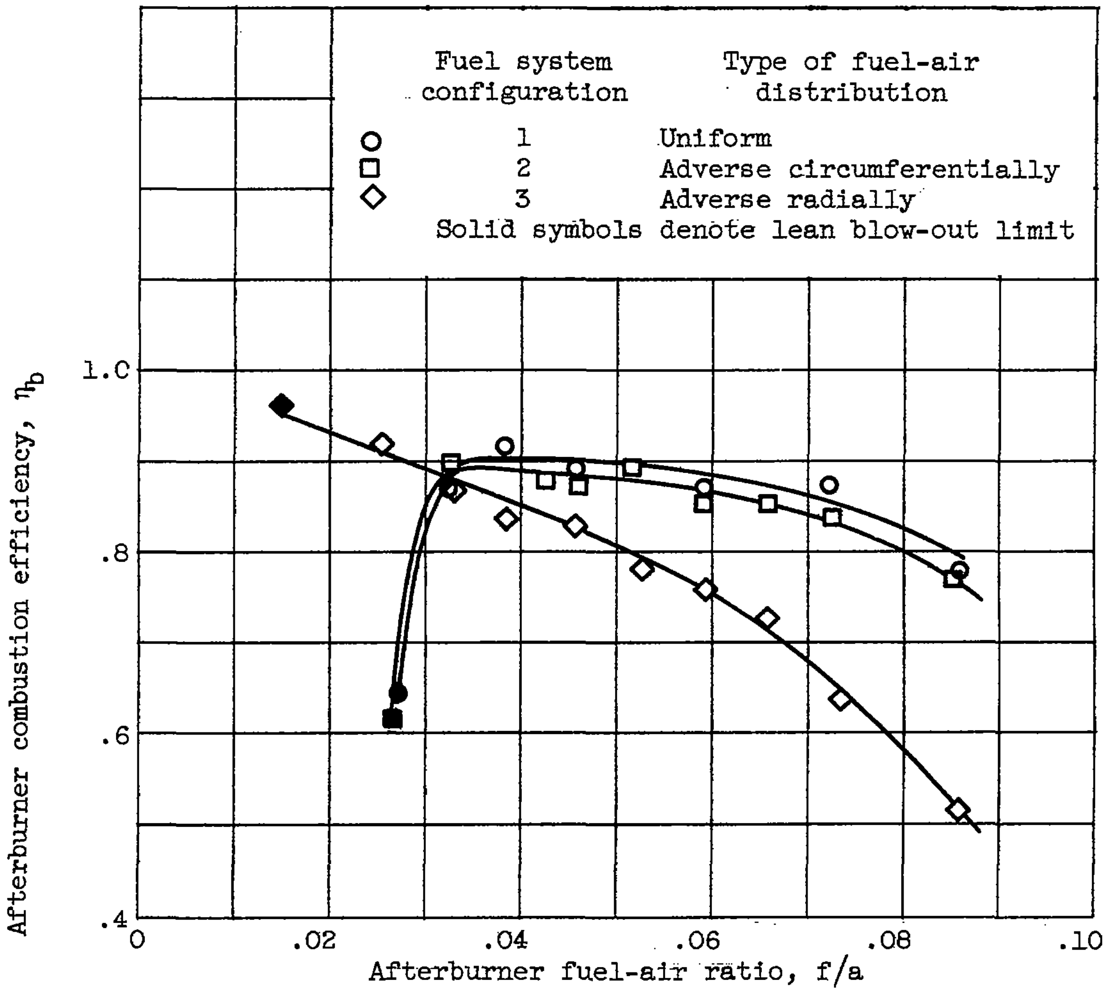

Figure 9. - Effect of fuel-air distribution on afterburner combustion efficiency. Afterburner configuration A; diffuser-outlet gas velocity, 380 to 480 feet per second; afterburner-inlet total pressure, 600 to 800 pounds per square foot; afterburner-inlet total temperature, 1710° R.

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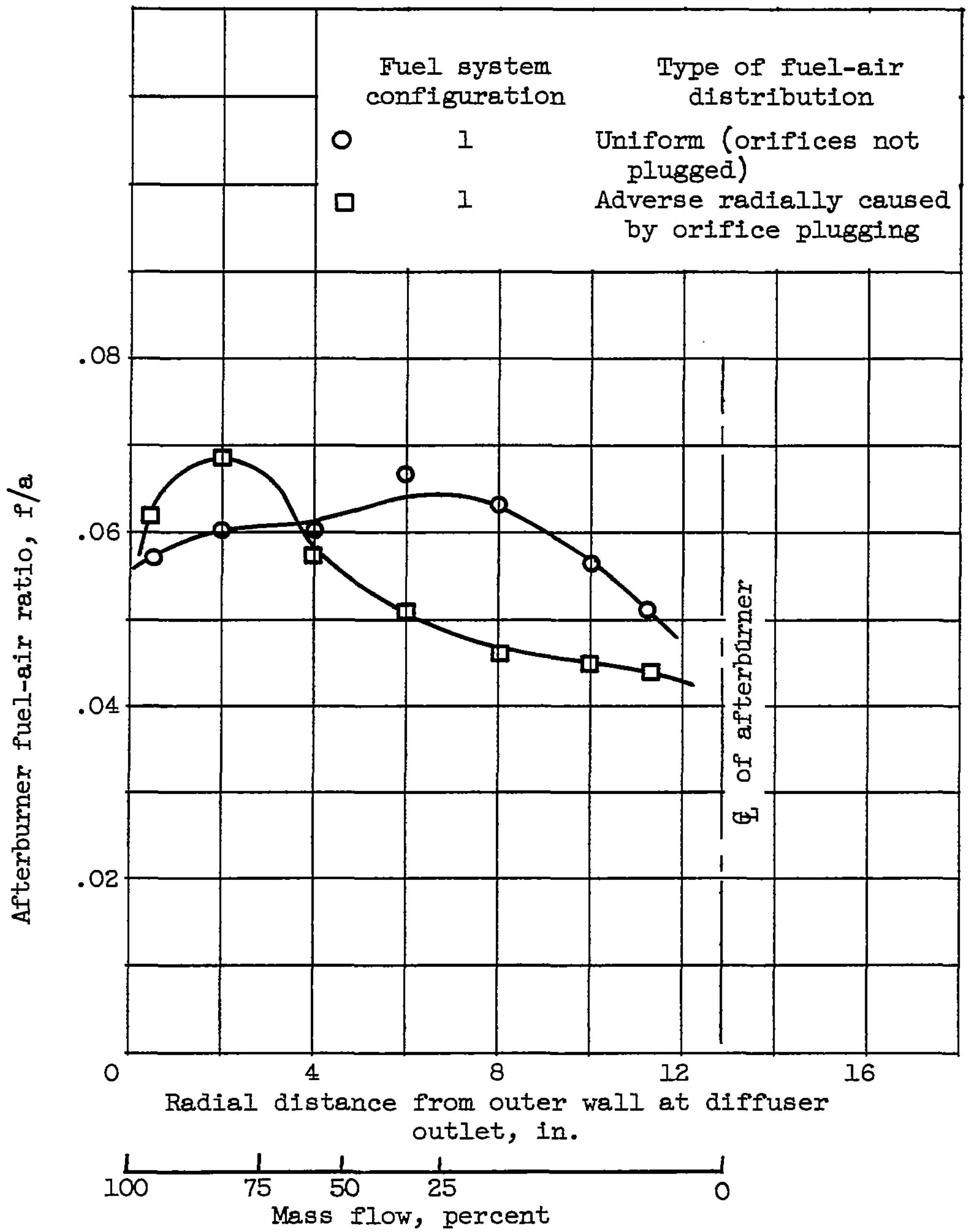

Figure 10. - Effect of fuel-injection-bar orifice plugging on fuel-air ratio profile. Afterburner configuration B; diffuser-outlet gas velocity, 400 feet per second; afterburner-inlet total pressure, 1350 pounds per square foot; afterburner-inlet total temperature, 1710° R.

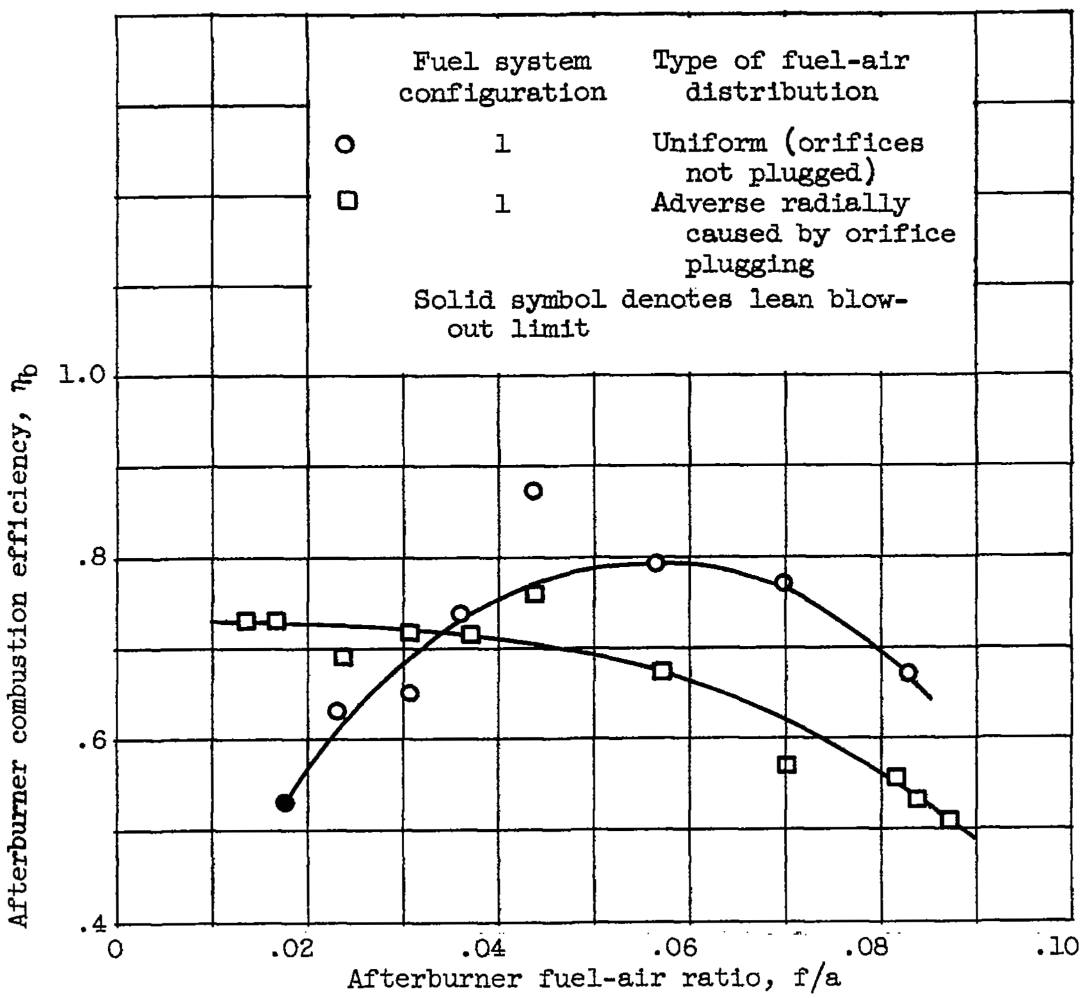

Figure 11. - Effect of fuel-injection-bar orifice plugging on afterburner combustion efficiency. Afterburner configuration B; diffuser-outlet gas velocity, 380 to 500 feet per second; afterburner-inlet total pressure, 1060 to 1400 pounds per square foot; afterburner-inlet total temperature, 1710° R.

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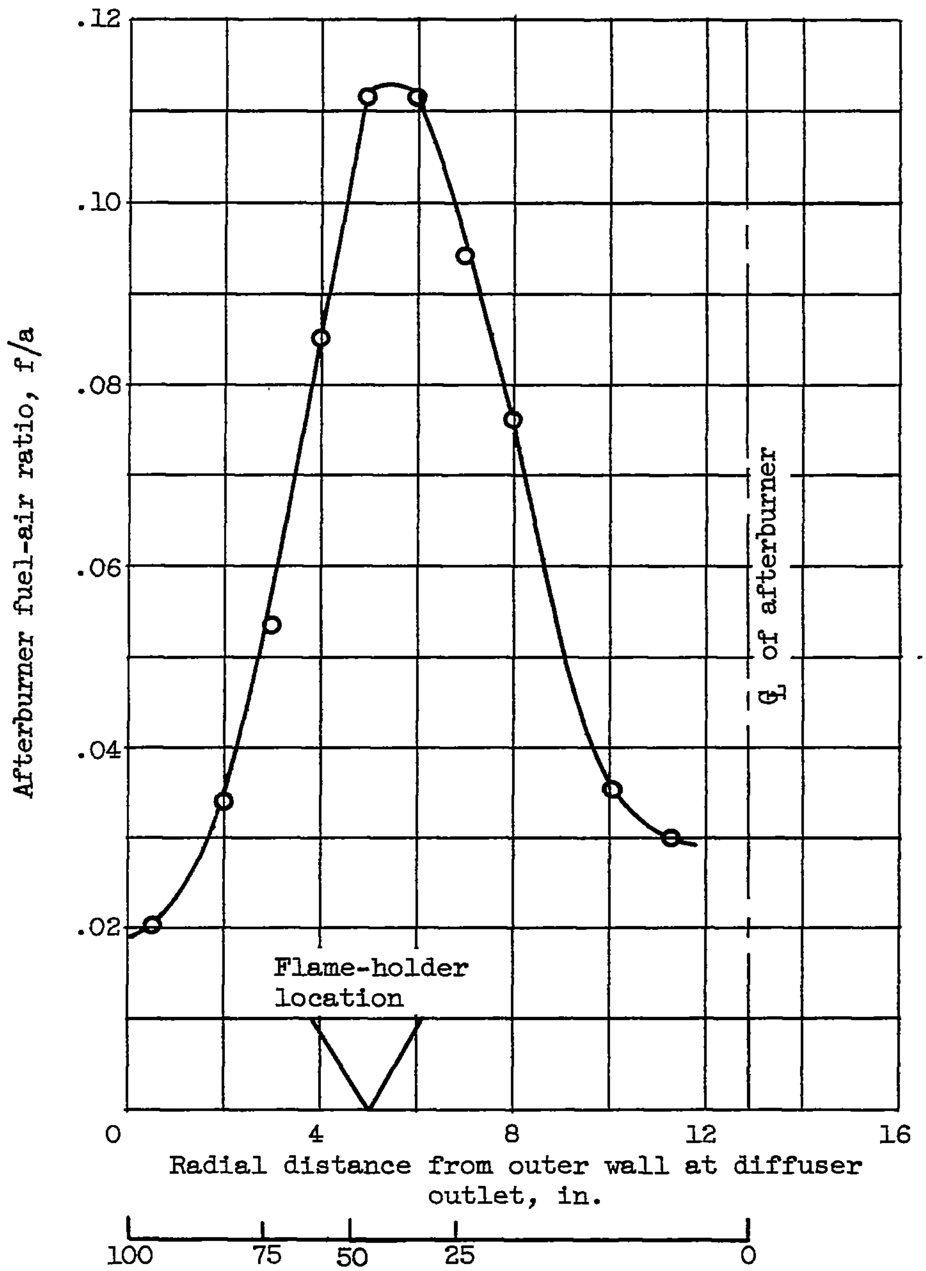

Figure 12. - Fuel-air ratio profile for locally rich fuel-air distribution. Fuel system 4; afterburner configuration C; diffuser-outlet gas velocity, 450 feet per second; afterburner-inlet total pressure, 1170 pounds per square foot; afterburner-inlet total temperature, 1710° R.

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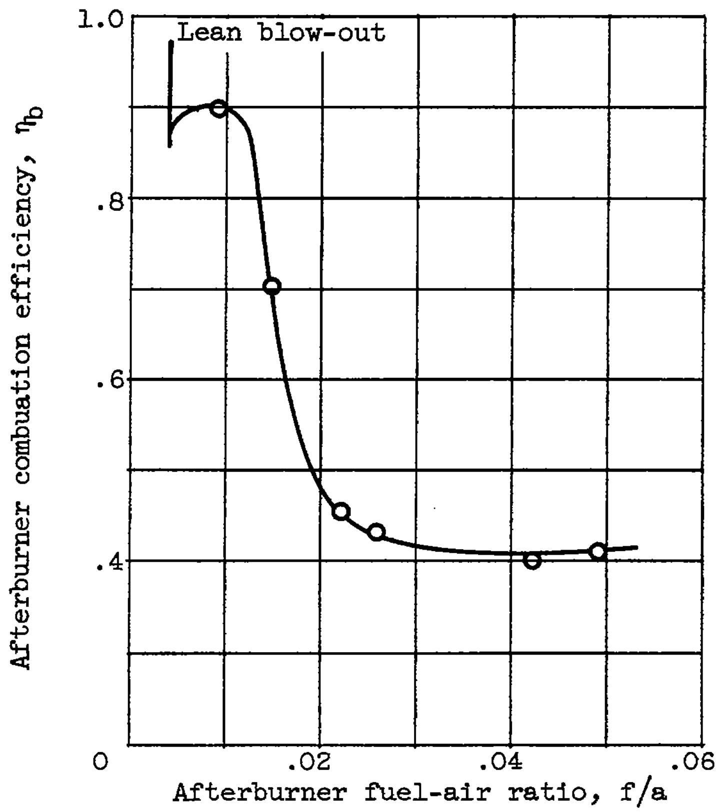

Figure 13. - Effect of locally rich fuel-air ratio distribution on afterburner combustion efficiency. Fuel system 4; afterburner configuration C; diffuser-outlet gas velocity, 480 to 540 feet per second; afterburner-inlet total pressure, 1060 to 1200 pounds per square foot; afterburner-inlet total temperature, 1710° R.

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CN-5 back

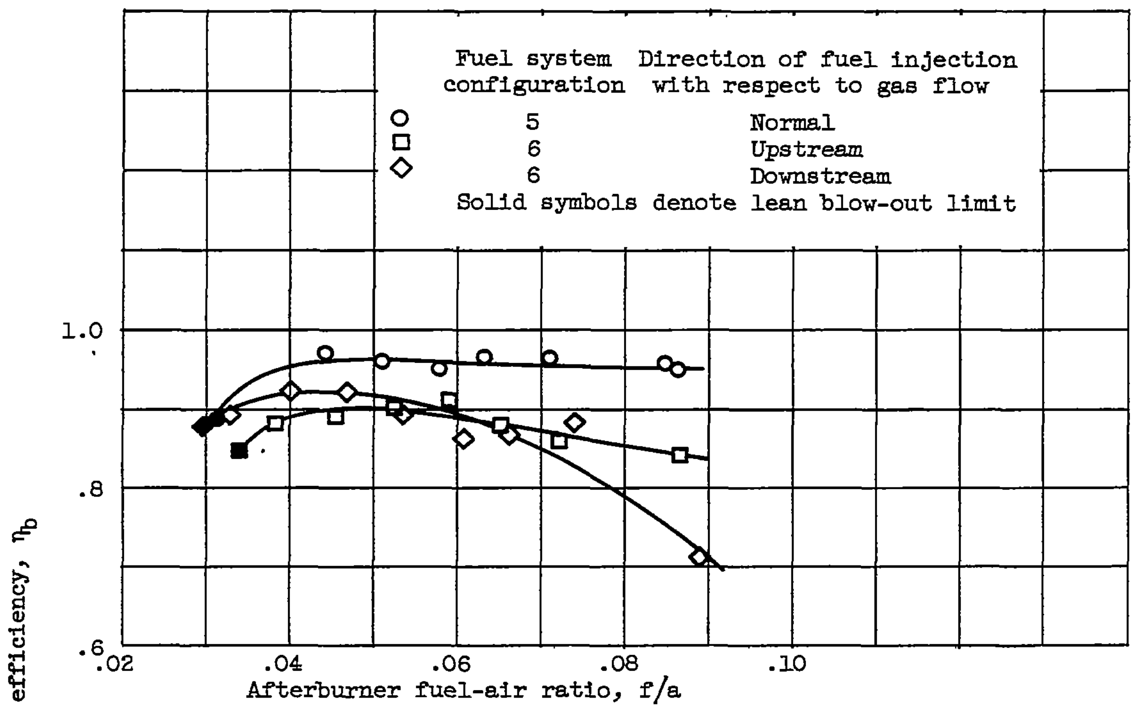

Figure 14. - Effect of fuel-injection direction on afterburner combustion efficiency. Afterburner configuration D; diffuser-outlet gas velocity, 460 to 540 feet per second; afterburner-inlet total pressure, 1060 to 1350 pounds per square foot; afterburner-inlet total temperature, 1710° R.

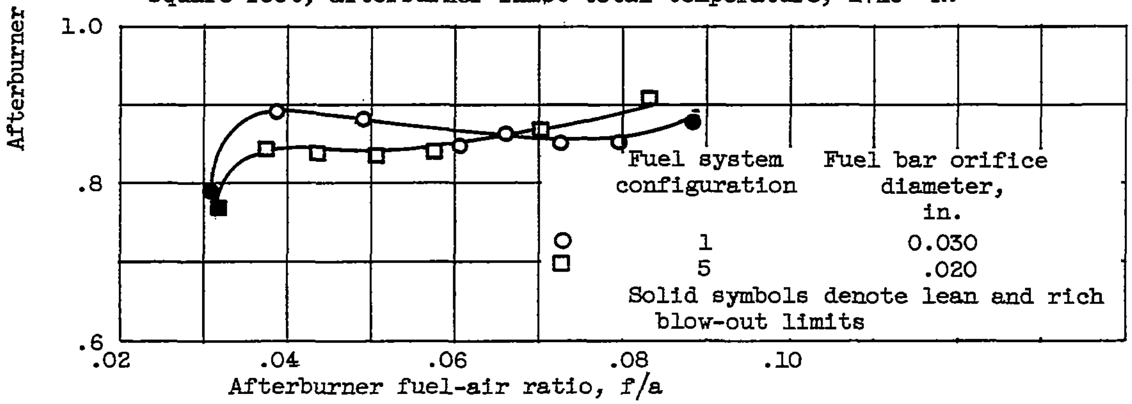

Figure 15. - Effect of fuel-injection-bar orifice diameter on afterburner combustion efficiency. Afterburner configuration E; diffuser-outlet gas velocity, 500 to 600 feet per second; afterburner-inlet total pressure, 1100 to 1300 pounds per square foot; afterburner-inlet total temperature, 1710° R.

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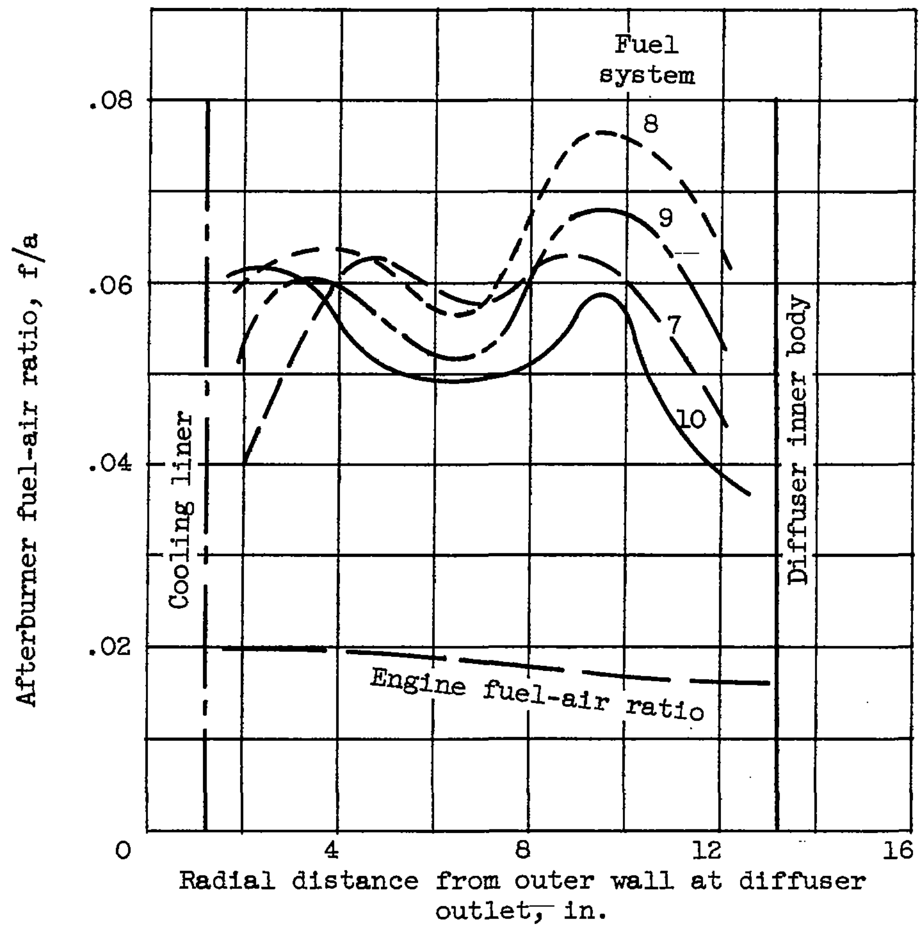

Figure 16. - Effect of varying fuel-injection-bar orifice diameter on fuel-air ratio distribution at flame holder. Afterburner configuration F.

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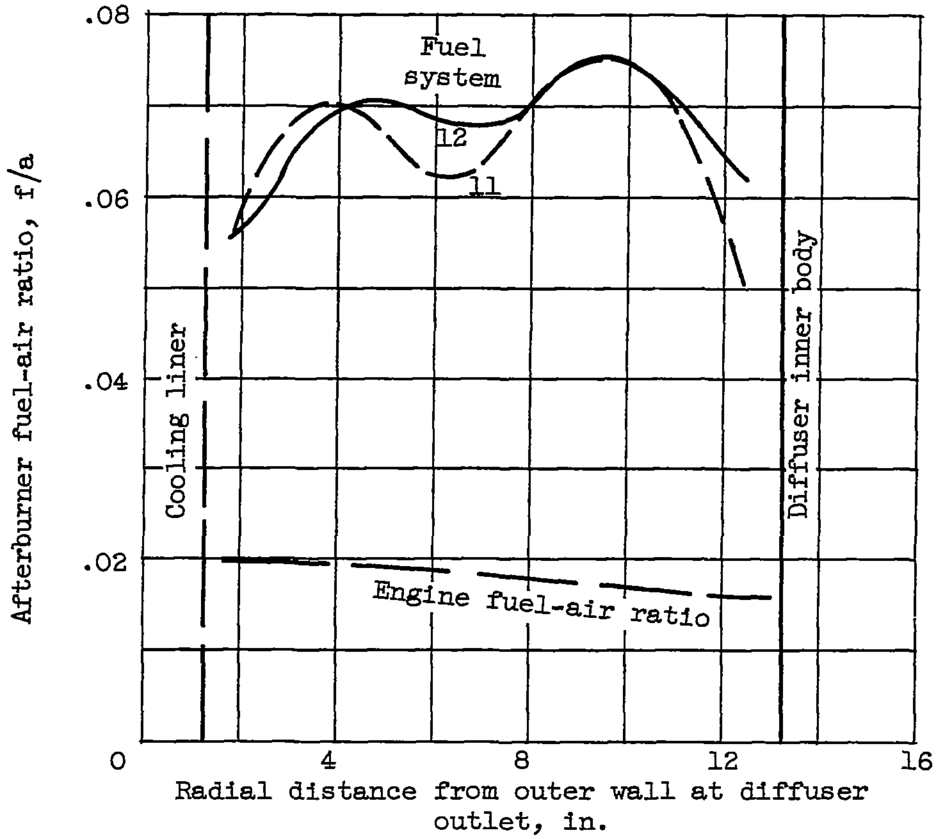

Figure 17. - Effect of varying fuel-injection-bar orifice locations on fuel-air ratio distribution at flame holder. Afterburner configuration G.

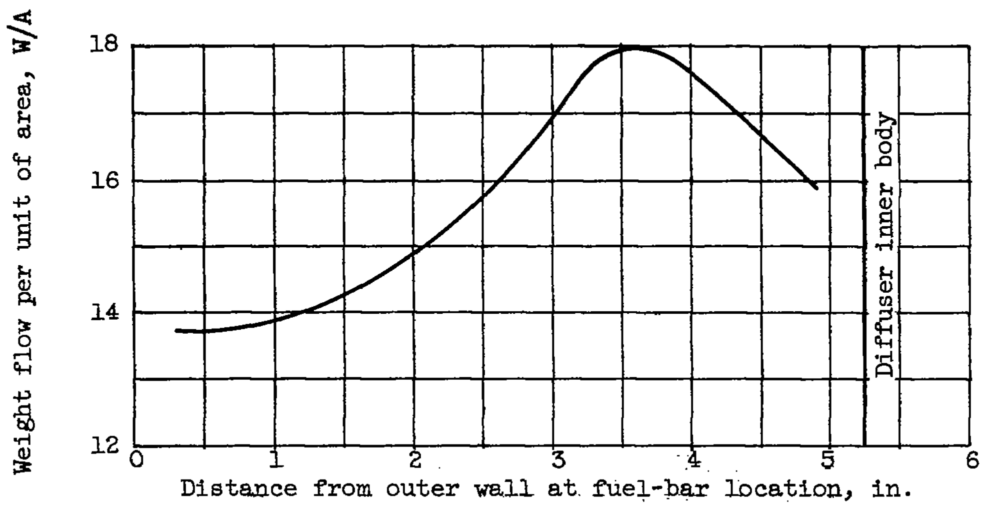

Figure 18. - Typical weight-flow profile at fuel-injection-bar location for engine-afterburner II.

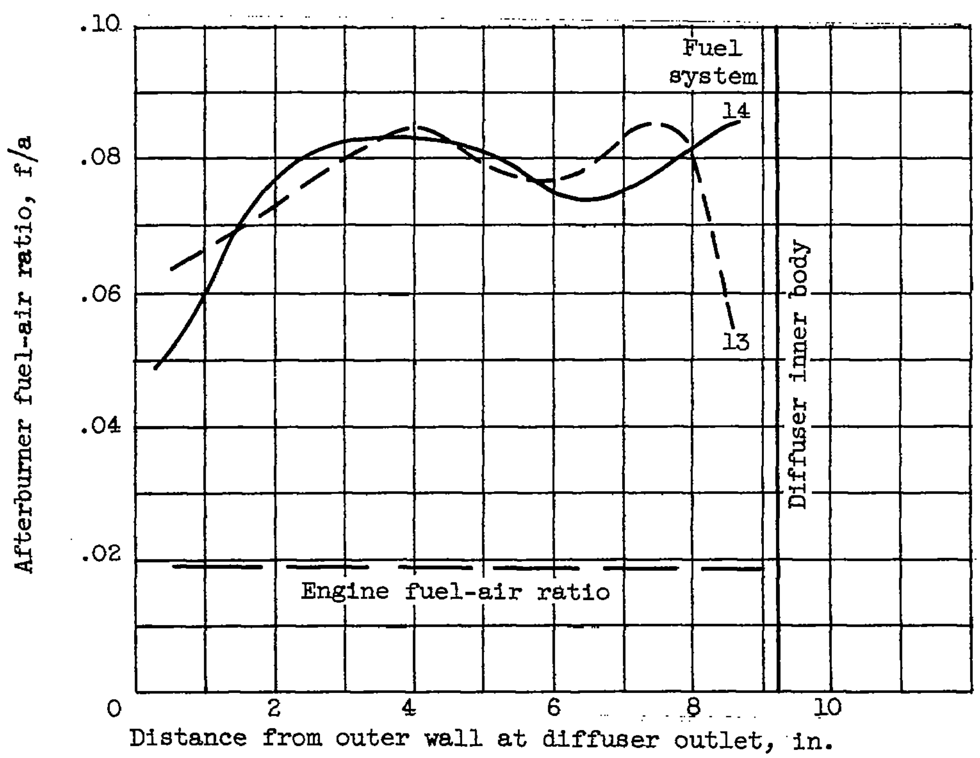

Figure 19. - Fuel-air ratio distribution for two fuel systems designed to give uniform fuel-air ratio distribution. Afterburner configuration H.

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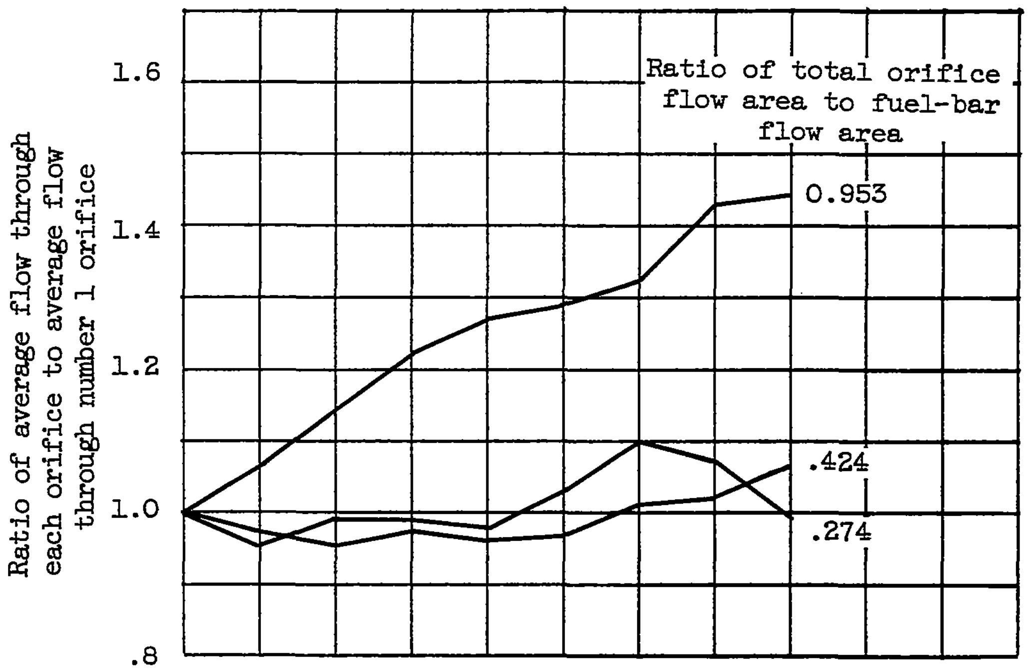
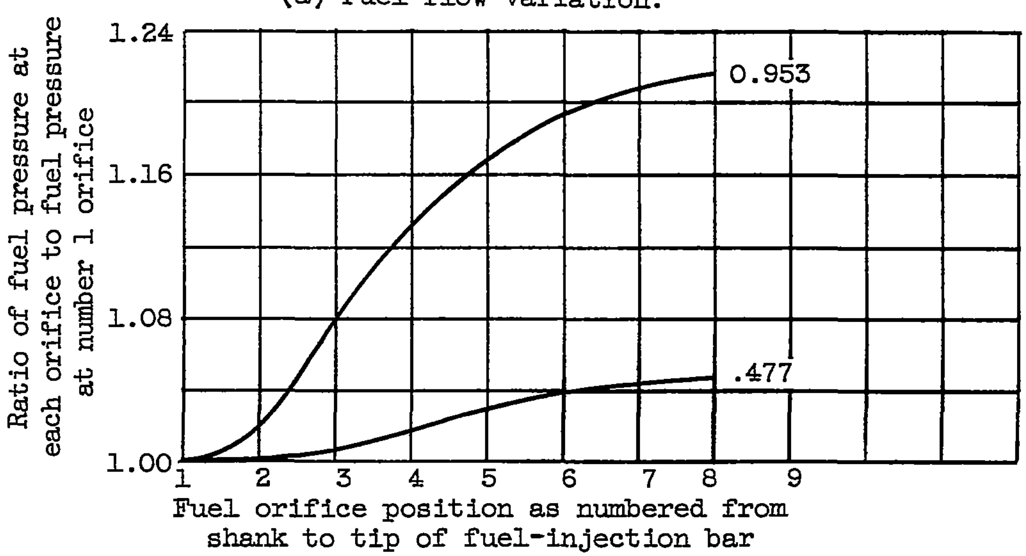


(a) Fuel flow variation.



(b) Fuel pressure variation.

Figure 20. - Flow characteristics of fuel-injection bars having various ratios of total orifice flow area to fuel-bar flow area. Each curve represents average flow from six fuel bars (12 orifices at each position).

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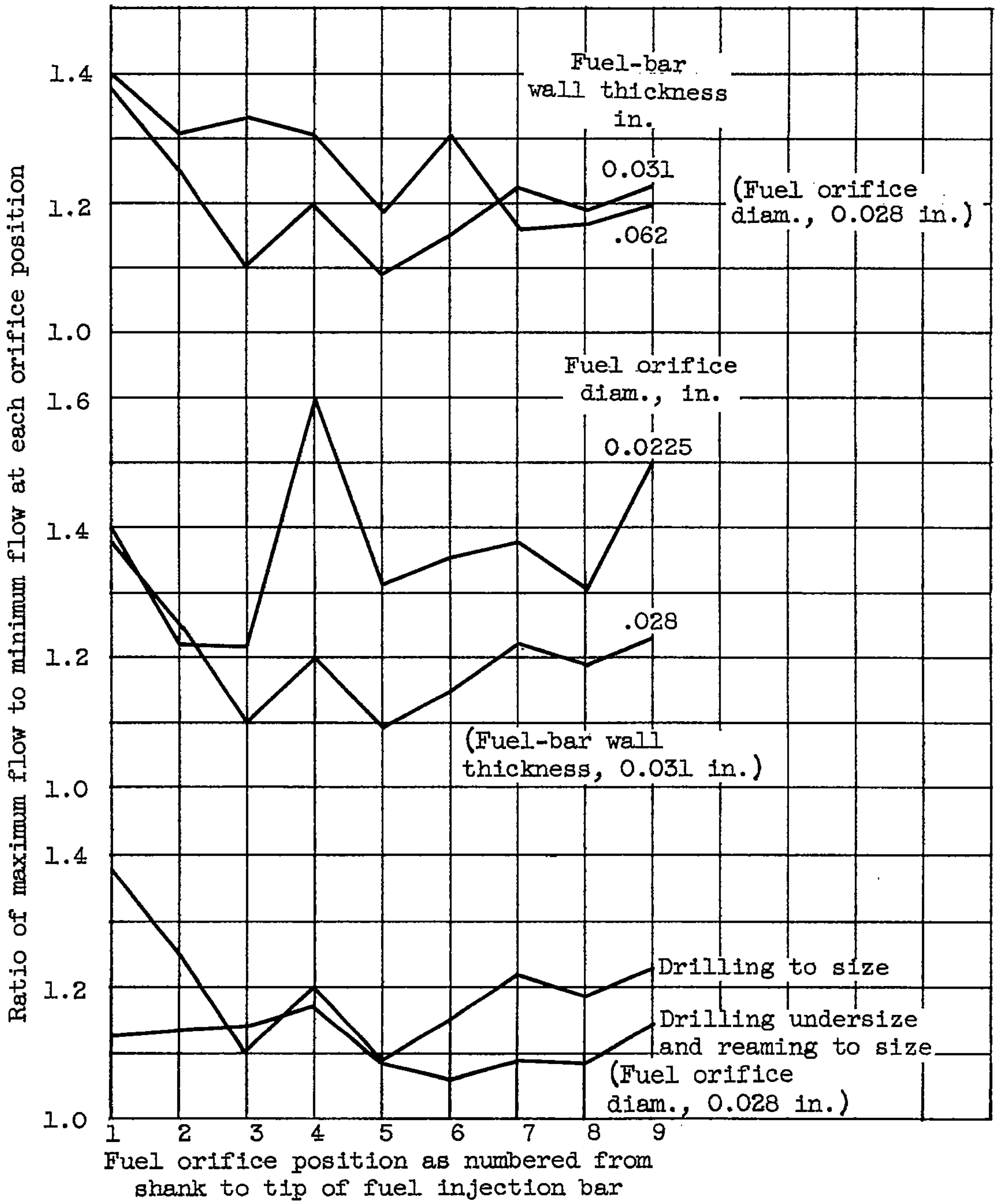

Figure 21. - Effect of fuel-injection-bar dimensional changes and manufacturing technique on variation of fuel flow. Each curve based on measurements from six fuel bars (12 orifices at each position).

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