N73 28919

NASA TECHNICAL MEMORANDUM

NASA TM X-2855

NASA TM X-2855

CASE FILE COPY

AFTERBURNER PERFORMANCE OF FILM-VAPORIZING V-GUTTERS FOR INLET TEMPERATURES UP TO 1255 K

by J. Robert Branstetter and Gregory M. Reck

Lewis Research Center

Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1973

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-2855		

4. Title and Subtitle	5. Report Date
AFTERBURNER PERFORMANCE OF FILM-VAPORIZING V-GUTTERS FOR INLET TEMPERATURES UP TO 1255 K	August 1973
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
J. Robert Branstetter and Gregory M. Reck	E-7435
	10. Work Unit No.
	501-24
9. Performing Organization Name and Address	11. Contract or Grant No.
Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D. C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Combustion tests of five variations of an integral, spray-bar - flameholder combination were conducted in a 0.49-m-diameter duct. Emphasis was on low levels of augmentation. Fuel impinged on guide plates, mixed with a controlled amount of inlet air, vaporized, and was guided into the V-gutter wake. Combustor length was 0.92 m. Good performance was demonstrated at fuel-air ratios less than 0.025 for inlet temperatures of 920 to 1255 K. Maximum combustion efficiency occurred in the vicinity of fuel-air ratios of 0.02 and was 92 to 100 percent, depending on the inlet temperature. Lean blowout fuel-air ratios were in the vicinity of 0.005. Improvements in rich-limit blowout resulted from enlarging the guide-flow passageway areas. Other means of extending the operating range are suggested. A simplified afterburner concept for application to advanced engines is described.

17. Key Words (Suggested by Author(s))		18. Distribution Statement
Afterburner	Thrust augmentation	Unclassified - unlimited
Flameholder	Combustion	
V-gutter		

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	26	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

Page Intentionally Left Blank

AFTERBURNER PERFORMANCE OF FILM-VAPORIZING V-GUTTERS FOR INLET TEMPERATURES UP TO 1255 K

by J. Robert Branstetter and Gregory M. Reck

Lewis Research Center

SUMMARY

Combustion tests were conducted in a 49-centimeter-diameter duct to evaluate the performance of five variations of a film-vaporizing V-gutter design. Emphasis was placed on low levels of augmentation. ASTM A-1 fuel was injected normal to the airflow from spray bars located 12.7 centimeters upstream of the gutters. The fuel impinged on guide plates and was vaporized by mixing with a portion of the inlet flow which was guided by the plates into the V-gutter wake. Combustor length was established at 92 centimeters by a set of flame-quench water sprays which were part of a calorimeter for measuring combustion efficiency. Vitiated air entered the combustor at temperatures of 920, 1090, or 1255 K. Inlet pressure and velocity were maintained at 1 atmosphere and 150 meters per second, respectively. A fuel-air ratio span from 0.005 to rich-limit blowout was investigated.

Good performance was demonstrated at fuel-air ratios less than 0.025. Maximum combustion efficiency occurred in the vicinity of fuel-air ratios of 0.02 and rose from a 92 percent value to 100 percent as the inlet temperature was increased from 920 to 1255 K. Lean blowout fuel-air ratios were in the vicinity of 0.005. Improvements in rich-limit blowout resulted from enlarging the vaporizer passageways, increasing the inlet temperature, or increasing gutter width. However, widening the gutters reduced combustion efficiency at fuel-air ratios less than 0.01. A performance comparison of the present configuration and a configuration without vaporizer plates suggests simple fuel-staging techniques for operation over a very wide range of afterburner fuel-air ratio.

Spontaneous ignition and fuel spray-bar clogging were experienced at the 1255 K inlet condition.

INTRODUCTION

This study describes the lean mixture afterburning performance of a series of film-vaporizing V-gutters applicable to advanced jet engines intended for a wide range of augmentation and turbine discharge temperature.

Modern augmented turbojet and turbofan engines are called upon to light softly and to operate efficiently over a wide range of thrust. Applications often require intermediate to large augmentation for takeoff and transonic acceleration and a cutback to a much smaller value for cruise. In order to avoid fan stall, turbofan augmentors must provide soft lighting, which requires stable combustion at very small values of augmentor temperature rise. As many as five interrelated stages of fuel injection have been used to meet all these requirements. Even so, sizable pressure pulses and large decreases in combustion efficiency have been encountered when staging has occurred. In addition, the sheltered flame behind the gutter, plus the trend towards higher turbine discharge temperature, transmits heat to the flameholder, which may become overheated. High temperatures can result in spontaneous ignition initiated ahead of the flameholder and flameholder destruction.

The several problems that have been cited prompted a series of investigations (refs. 1 and 2) at the Lewis Research Center. A preliminary study of several afterburner flameholder concepts (ref. 1) at an inlet temperature of 920 K showed film-vaporizing V-gutters to have merit, particularly at small to intermediate values of fuel-air ratio. The basic design consisted of an in-line spray-bar - V-gutter arrangement and a connecting passageway formed by guide plates. In the passageway the fuel spray mixed with a controlled amount of inlet flow, vaporized, and traveled to the V-gutter. The design incorporated features for (1) good lean-mixture performance, (2) flameholder cooling, and (3) avoidance of spontaneous ignition in the passageway. Although unpublished test results have shown this design to be unsuited for fan stream conditions (below 500 K) because of poor fuel atomization at the low inlet temperatures, these tests did indicate that the gutters, when located in the core and attached to flame spreaders extending into a fan stream, could provide pilot flame for the fan stream region.

In the study of reference 2, performance of several conventional V-gutter combustors was evaluated at inlet temperatures of 920 to 1255 K. These designs were similar to the film-vaporizing burners but were without guide plates. One design provided very good combustion performance over a fairly wide range of fuel-air ratio. However, combustion efficiency fell off sharply at the lower fuel-air ratios. Also, raising the inlet temperature made no improvements in lean blowout limit. Neither spontaneous combustion nor flameholder overheating occurred, and thus some of the concern associated with high inlet temperatures was removed.

In the present study, various film-vaporizing V-gutters were built and tested. These burners incorporated the best features of the five film-vaporizing designs of reference 1. Emphasis was placed on good lean-mixture performance and a reduction in combustor pressure losses. A comparison of the present results and those of reference 2 has been included. This comparison provides the basis for a proposed afterburner design having short combustor length and capable of operating over a wide range of fuel-air ratios and inlet temperatures.

Five different film-vaporizing designs were investigated at inlet temperatures of 920, 1090, and 1255 K. Afterburner fuel-air ratio ranged from 0.005 to 0.05. The tests were conducted in a 49-centimeter-diameter duct. A relatively short combustion chamber, 92 centimeters in length, was chosen to provide a spread in the combustion efficiencies for the several inlet conditions examined. Combustion was terminated by a set of water sprays which were part of a calorimeter for measuring combustion efficiency. Vitiated air entered the afterburner at an inlet pressure of 1 atmosphere and a velocity of 150 meters per second. Fuel flow staging, as a means of improving combustion performance, was not attempted.

FACILITY

A diagram of the test facility is presented in figure 1. The combustion air was first heated to a temperature of 450 K in a tube-type heat exchanger and metered with an orifice. A choked butterfly valve located downstream regulated the flow, and a perforated cylinder dispersed the air into the inlet plenum. After passing through the vitiating preheater and the test section, the afterburner exhaust was quenched and calorimetrically measured. Finally, the gases were further quenched and exited through an exhaust butterfly valve into the altitude exhaust system.

ASTM A-1 kerosene was supplied to the afterburner through a conventional system containing flowmeters, a throttle valve, and a positive shutoff valve. Another fuel system provided gasoline to the vitiating preheater.

Pertinent details of the afterburner test section are shown in figure 2. The flame-quench water sprays were directed normal to the gas flow. Each of the two sets of water sprays was supplied with its own flow system containing flowmeters and a throttle valve. The combustion chamber length, defined as the distance from the downstream face of the V-gutters to the flame-quench plane, was set at 92 centimeters. Chamber diameter was 49.0 centimeters. The resulting inlet reference area was 1878 square centimeters. Further details of the hardware can be found in figures 1 and 2 and reference 2.

Thermocouple rakes were located at the exit of the enthalpy-balance section (fig. 1). These instruments and other fixed-position sensors are described in reference 2. Dynamic-pressure transducers were flush mounted on the duct walls with diaphragms exposed to the gas flow in order to detect the presence of pressure oscillations. Data from the steady-state instrumentation were recorded by the laboratory automatic data recording and processing system. A portion of the instrumentation was connected to an analog computer in the control room which provided a continuous display of airflow rate and fuel-air ratio.

AFTERBURNER DESIGNS

Basically, a film-vaporizing V-gutter is a modification of an in-line flameholder - spray-bar geometry (ref. 1) to which guide plates are attached (see fig. 2). Fuel impinges on the guide plates, mixes with a controlled amount of inlet air, undergoes vaporization, and is guided into the V-gutter wake.

For the present study, the gutters were arranged in a set of three, straight, parallel units (fig. 2). Lateral spacing was 12.7 centimeters. This geometry was used in both references 1 and 2. For purposes of afterburner development studies in small ducts, parallel V-gutters were judged to provide a satisfactory arrangement. (A parallel flameholder array may be viewed as a sector of a much larger burner containing a circular flameholder array (ref. 2).)

Results for the reference 1 film-vaporizer designs strongly influenced the selection of the five designs investigated in this study. For best lean mixture performance the guide plates should neither be too short nor extend out over the V-gutter. Combustion efficiency showed improvement when the distance from the spray bar to the V-gutter lip was increased from a value of 6.7 centimeters to a value of 10.5 centimeters. Gutter width of reference 1 was 5.7 centimeters for most cases and 7.6 centimeters for one case. In conjunction with a lateral spacing of only 12.7 centimeters, both widths were judged to be larger than necessary. The inlet scoop formed by flaring upstream surfaces of the vaporizer plates (ref. 1) appeared to be an encumbrance and was not used in this study. Finally, the rate of airflow through the vaporizer passageway had not been varied in any systemmatic manner as it was in this investigation. All of the foregoing facts were given consideration in the investigation described in this report.

Photographs of a typical burner assembly used in the present investigation are shown in figure 3. A sketch and the dimensions of the five geometric variations are presented in figure 4. The spray bars, detailed in figure 5, passed through slots in the end caps of the vaporizer. Each integral vaporizer and V-gutter assembly was supported from two straps which were pinned to the H-frame (fig. 3(b)). The straps and the two pins on the leading edge of each vaporizer (fig. 3(b)) prevented the vaporizer from buckling when subjected to metal temperature gradients. The spray bar, by having a snug lateral fit in the end caps of the vaporizer, minimized lateral movement of the vaporizer and V-gutter assembly. Figure 6 shows lateral spacing and gutter length dimensions. The spray bars were connected to a common manifold and were supported on the opposite (capped-off) ends by loose-fitting sleeves welded to the chamber wall.

The spray bars were made from nickel-base alloy, and the remainder of the burner assembly was fabricated from Hastelloy sheet.

Table I presents flameholder blockage areas and vaporizer passageway areas in the form of ratios. The values of projected blocked area ratio of the V-gutters are shown on two bases - the actual ratio and a corrected ratio which assumes the array to be a section of a much larger afterburner.

TEST PROCEDURE

The three afterburner-inlet test conditions are presented in table II. For test conditions A and B, afterburner ignition was accomplished by momentarily increasing the fuel flow to the vitiating preheater and torching to the V-gutters. Performance data were taken over as wide a range of fuel-air ratios as was possible. Rich (or lean) blowout points were determined by slowly increasing (or decreasing) afterburner fuel flow until flameout occurred. Blowout was detected by a decrease in either combustor pressure or temperature at the enthalpy-balance exit plane. A borescope and gutter-mounted thermocouples assisted blowout detection. The blowout point defined the highest (or lowest) value of fuel-air ratio that could sustain a flame in the shelter of the flameholders. The first gutter to blow out defined the blowout fuel-air ratio.

Condition C required a special procedure since fuel decomposition and subsequent spray-bar clogging were encountered at low rates of fuel flow. Afterburner ignition was accomplished at condition A or B prior to shifting to condition C. Testing was the same as for conditions A and B except that fuel-air ratios less than 0.010 were not attempted.

Combustion efficiency was obtained by using an enthalpy-balance technique which required that no liquid water be present at the enthalpy-balance plane. To ensure that none was present, the average gas temperature at the enthalpy-balance plane was maintained at 700 K or greater by controlling the quench-water flow rate. Data used for computation of combustion efficiency were obtained only after the system reached thermal equilibrium. Operating characteristics of the calorimeter are described in reference 2.

CALCULATIONS

The U. S. customary system of units was used for primary measurements and calculations. Conversion to SI units (Systeme International d'Unites) was done for reporting purposes only. In making the conversion, consideration was given to implied accuracy and may have resulted in rounding off the value expressed in SI units.

Afterburner Fuel-Air Ratio (Unburned)

To include the effects of vitiation of the inlet air and incomplete combustion in the preheater, the afterburner fuel-air ratio (unburned) was computed by dividing the total fuel flow available to the afterburner by the available flow of unburned air. All data are presented in terms of this fuel-air ratio.

Inlet Velocity

Inlet velocity was calculated from the measured airflow rate, the inlet reference area of the afterburner test section, the average inlet total temperature, and the inlet static pressure. Flameholder lip velocity was calculated as the product of inlet velocity and the term $1/[1 - \text{(projected blocked area of V-gutters)}/\text{(inlet reference area)}]$.

Combustion Efficiency

Combustion efficiency was defined as the ratio of the heat released in the afterburner to the chemical energy of all fuel entering the afterburner. Heat-transfer losses from the duct components and the vitiating effect of the directly fired preheater were included in the calculations. The combustion efficiency equation and its derivation are shown in reference 2.

Accuracy of Combustion Efficiency Data

An error analysis is presented in reference 2 along with a discussion of the influence that slow oxidation of chilled carbon monoxide (in the enthalpy-balance section (fig. 1)) has on the computed value of combustion efficiency. Because of this dissociation effect, the efficiency values are very likely too low at fuel-air ratios larger than 0.04.

RESULTS AND DISCUSSION

For all configurations investigated, the afterburner inlet flow had a nearly flat temperature profile and a lobed velocity profile. Typical data taken from reference 2 showing the temperature and velocity profiles are presented in figure 7. Performance data from reference 2 showed that combustion efficiency and blowout limits were unaffected by exchanging the lobed velocity profile for a flat profile.

Data Presentation

Performance results for the five burner configurations investigated are presented in figure 8, where the variation of combustion efficiency with fuel-air ratio for three burner inlet temperatures is shown. In addition, periodic pressure oscillations, when present, and blowout limits, when obtained, are identified. No data are presented for configuration C-6 at 1090 and 1255 K or for configuration C-9 at 1255 K because of spray-bar clogging.

General Discussion

The basic variation of combustion efficiency with fuel-air ratio can be observed by inspection of the data in figure 8. The general nature of this variation is a peak efficiency at some intermediate fuel-air ratio with a reduction in efficiency as fuel-air ratio is increased or decreased from its peak efficiency value. The fuel-air ratios at which peak efficiencies were obtained varied from 0.010 to 0.028 depending on the configuration and burner inlet temperature. For all configurations and burner inlet temperatures investigated a fuel-air ratio in the vicinity of 0.017 produced an efficiency at or near the peak values.

Burner blowout fuel-air ratios are identified for the burner configurations and inlet temperatures at which they were acquired. The only lean blowout limit obtained was for configuration C-6 (fig. 8(a)) and occurred at a fuel-air ratio of 0.005. For most of the other cases a fuel-air ratio of 0.008 was reached without obtaining lean blowout. As a fuel-air ratio of 0.008 was being approached, the combustion efficiencies showed a substantial decrease from their peak values.

Rich blowouts were encountered for most combinations of burner configuration and inlet temperature investigated. The fuel-air ratios at rich blowout ranged from 0.020 to 0.050 depending on the burner configuration and inlet temperature. In some instances the rich blowout occurred before a rapid decay in combustion efficiency level, for example, at an inlet temperature of 920 K with configurations C-6, C-8, and C-9, and at an inlet temperature of 1090 K with configuration C-8. In certain other instances, a rapid decay in combustion efficiency occurred prior to blowout, for example, configurations C-7 and C-10 at 920 K, C-8 at 1090 K, and C-9 at 1255 K. A mechanism for blowout that satisfies both observations is suggested. A vigorous flame was present immediately downstream of the flameholder when a stoichiometric mixture existed in this local region. An increase in fuel flow caused the flame to weaken. However, combustion efficiency was not necessarily lowered because the excess fuel was consumed by air which entered the aft portion of the wake region. Nevertheless, flame stability suffered, and blowout was imminent. A further increase in fuel flow produced rough combustion. In some cases blowout occurred immediately. In other cases, the rough combustion triggered periodic pressure oscillations of approximately 200 hertz (fig. 8). A pressure pulse would travel upstream and modulate the rate of fuel flow either at the fuel injector or in the vicinity of the guide plates. The modulated fuel-air mixture traveled downstream at stream velocity, arrived at the flame zone, caused a change in pressure at the combustion chamber, and sent a corresponding pressure pulse upstream to repeat the cycle. Combustion efficiency suffered. Blowout resulted from perturbation of the weakened flame. The frequency for this mechanism (ref. 3) is in reasonably good agreement with the observed frequencies.

Effect of Inlet Temperature

Combustion efficiency. - Combustion efficiency results of figure 8 have been replotted in figures 9(a) and (b) for fuel-air ratios of 0.012 and 0.017, respectively. A value of 0.012 is the smallest fuel-air ratio providing reasonably accurate combustion efficiency data, and a value of 0.017 is in the vicinity of peak combustion efficiency. An inspection of figure 9 shows combustion efficiency increased as inlet temperature increased. In the vicinity of 1255 K, the efficiency was near 100 percent and was insensitive to changes in inlet temperature. Figure 9(a) shows efficiencies of 88, 96, and 100 percent for inlet temperatures of 920, 1090, and 1255 K, respectively. Figure 9(b) shows efficiencies of 92, 98, and 100 percent for these temperature values.

Blowout. - Rich-limit blowout results of figure 8 have been replotted in figure 10 for the three inlet temperatures investigated. An increase in inlet temperature produced an increase in rich-limit fuel-air ratio. The improvement was progressive with inlet temperature rise. For example, the blowout fuel-air ratios for configuration C-8 were 0.023, 0.030, and 0.035 for inlet temperatures of 920, 1090, and 1255 K, respectively.

Effect of Configuration Change

Combustion efficiency. - In order to make a direct comparison of the five film-vaporizing configurations, the data curves of figure 8 are shown in figure 11 in three groups corresponding to the three inlet temperatures. Except in the vicinity of blowout the four narrow gutter designs yielded nearly identical combustion efficiency performance; however, configuration C-9 exhibited a slightly wider plateau on the efficiency curves of figure 11 than did the other narrow gutter designs. But in general, an increase in either discharge passageway or guide plate spacing did not affect combustion efficiency.

The wide gutter design, configuration C-10, produced good combustion efficiencies over a wide range of fuel-air ratio (fig. 11). Within the fuel-air-ratio span of stable combustion, the data curves of configurations C-10 and C-9 were in close proximity.

Blowout. - Rich-limit blowouts occurred at relatively low values of fuel-air ratio. Selective changes in burner geometry were of some benefit. Small improvements were observed when the discharge passageway of the vaporizer was increased (compare configurations C-6, C-7, and C-8 in fig. 10). Also, an increase in distance separating the two guide plates was beneficial and may be observed by comparing the rich limits of configurations C-7 and C-9 (fig. 10). An increase in gutter width combined with an increase in guide-plate spacing produced a pronounced improvement in rich-limit blowout (fig. 10). A comparison of configurations C-9 and C-10 shows that the combined geometry increases (fig. 4) raised the rich-blowout fuel-air ratio by 0.014 at 920 K and by 0.018 at 1090 K. These improvements are so much greater than the improvements obtained for guide-plate spacing alone (configurations C-7 and C-9) that gutter width is judged to be the governing dimension affecting blowout.

Lean-limit blowout characteristics are difficult to judge because of the lack of lean blowout data; however, several observations are noteworthy. With the possible exception of configuration C-8, an increase in either discharge passageway or guide-plate spacing did not affect lean combustion efficiency performance as the blowout limit was approached (fig. 11). Compared to all four narrow gutter designs the wide gutter design (configuration C-10) is shown in figure 11(a) to have a lower efficiency in the very lean region for an inlet temperature of 920 K. At higher inlet temperatures (figs. 11(b) and (c)), configuration C-10 has lean mixture efficiency values compared to those of the narrow gutter designs. Unfortunately, data error in this region of operation is at a maximum and is of similar magnitude to the data spread.

Rich-limit improvement and possible lean-limit deterioration resulting from an increase in gutter width can be explained with the aid of reference 4. Therein, a method is described for obtaining the amount of flow entering the burning zone in the shelter of a bluff body. Applying this technique to the present geometries indicates that the flame zone captures a considerably larger portion of air when the gutter is widened. Since the bulk of the fuel enters the sheltered flame zone, gutter widening reduces the local fuel-air ratio of the sheltered flame. The flame is quenched when either the lean or the rich flammability limit (fuel-air ratio) is reached.

In summary of the blowout results, the merit of the wide gutter design (configuration C-10) is in extension of rich-limit blowout. This extension is sizable. On the debit side, configuration C-10 has a projected blocked-area ratio of 0.450 (table I) and, therefore, produces a sizable friction loss. Also, this design exhibited lower combustion efficiency than the narrow gutters for fuel-air ratios less than 0.01.

Operational Experiences

Spontaneous ignition. - At an inlet temperature of 1255 K, danger from spontaneous ignition exists when the mixture is within the flammability fuel-air limits while passing through the vaporizer. A locally very rich mixture, short residence time, and vaporization cooling reduce the likelihood of spontaneous ignition. However, these methods of suppression were not always sufficient at very small rates of fuel flow. Configuration C-6, which had the smallest passage discharge area, exhibited spontaneous ignition when the fuel-flow rate was inadvertently reduced to a fuel-air ratio near 0.005. The subsequent flame cut holes in V-gutters.

Spray-bar clogging. - At the 1255 K condition, fuel coking within the spray bars occurred at low fuel-flow rates and would progress, over a period of minutes, until the offending spray bar became completely clogged with solids. Clogging was a much more common occurrence than during the reference 2 studies. In the present tests, the vaporizer guide plates radiated heat to the spray bars, whereas the reference 2 spray bars dissipated radiant energy to the cold chamber walls. The net result was a spray-bar temperature difference amounting to an estimated 100 K.

Flameholder durability. - Other than for spontaneous ignition, the only damage sustained by the vaporizing V-gutters was a modest amount of warpage resulting from the lack of provisions for the thermal expansion difference between the guide plates and the V-gutter. Figure 12 shows a typical set of thermocouple data for the V-gutter surfaces. Temperature decreased as fuel-air ratio increased. This was counter to the behavior experienced for conventional burners (ref. 2). The sizable cooling effect obtained by guiding the fuel past the V-gutter is illustrated with the aid of the lower curve of figure 12. Cooling, provided by a fuel-air ratio of 0.012, lowered the gutter temperature by 150 K.

High-frequency instability. - Configuration C-10, the wide (5.7-cm) gutter design which permitted operation at relatively high fuel-air ratios, was the only configuration to exhibit high-frequency combustor pressure oscillations (1000 and 2000 Hz). The instability occurred at a fuel-air ratio of 0.045 and an inlet temperature of 1255 K. The wave mode is not known. The 1000-hertz frequency is in good agreement with a first transverse mode of chamber resonance (ref. 3). Also, this frequency satisfies a disturbance associated with a nonacoustic, unstable flow attributed to flame anchored in a duct (ref. 3). This latter disturbance, by being in tune with the resonant frequency, could have contributed energy to the observed oscillation. In reference 1, the very wide (7.6-cm) film-vaporizing gutters exhibited 900-hertz instability at fuel-air ratios above

0.03. (Inlet temperature was 920 K.) The referenced report showed that 5.7-centimeter-wide gutters did not exhibit high-frequency oscillations, although they were tested to fuel-air ratios in excess of 0.05. These observations indicate that high-frequency instability may be associated with a widening of the gutters and with elevated inlet temperature.

Comparison of Guide-Plate Burner and Reference Burner

The presence of film-vaporizing guide plates, as opposed to their absence, had a pronounced effect on afterburner combustion performance. The comparison that follows utilizes reference 2 data obtained without guide plates. Otherwise, the reference configuration is identical to configurations C-6, C-7, C-8, and C-9. The apparatus, test procedure, and test conditions were the same as those of the present study. Figure 13 shows the reference 2 results and the data for configuration C-9. (For configuration C-9, data at the 1255 K condition were not obtained but can be inferred with the aid of fig. 11(c).) Meaningfulness of the comparison is improved by the observation that the reference 2 data, in their own right, provided generally good performance (see the INTRODUCTION).

At a fuel-air ratio of 0.025, figure 13 shows both configurations to provide combustion efficiencies near 90 and 97 percent at inlet temperatures of 920 and 1090 K, respectively. At 1255 K, a combustion efficiency of 98 to 100 percent is projected for configuration C-9. The referenced configuration also yielded near 100 percent efficiency. At fuel-air ratios leaner than 0.025 the film-vaporizing design provided improved performance relative to the conventional design. For instance, the combustion efficiency improvements at a fuel-air ratio of 0.017 are 10 and 2 percentage points at inlet temperatures of 920 and 1090 K, respectively. At a fuel-air ratio of 0.012, the corresponding improvements are 20 and 4 percentage points. No efficiency difference could be expected at 1255 K.

An examination of performance at fuel-air ratios greater than 0.025 shows up the serious shortcomings of the current film-vaporizing V-gutter designs (fig. 13). The C-9 configuration encounters premature rich-limit blowout, whereas the conventional design continues to provide good combustion performance as the fuel-air ratio is increased.

One method at our disposal for improving rich-mixture performance of the film-vaporizing designs is fuel staging. Before the onset of low-frequency pressure oscillations associated with the proximity of rich-limit blowout, the film-vaporizer fuel flow must be limited. A further increase in overall fuel-air ratio must come from sources that do not enrich the sheltered recirculating flame. Suggestions for the local distribution of this added fuel are provided in reference 2. The reference 2 design of figure 13 provided better performance than a design having a more uniform fuel distribution obtained by locating the fuel injectors farther upstream. Supplemental information on fuel staging in conjunction with film-vaporizing burners is given in reference 1; however, the 41-centimeter distance between the second-stage spray bars and the V-gutters may be excessive, based on reference 2 results. Also, long distances could trigger spontaneous ignition at the 1255 K inlet condition. These observations (refs. 1 and 2) provide useful guidelines for the addition of a second fuel-injection stage to the film-vaporizing gutters.

A possible method of extending rich-limit fuel-air ratio without resorting to staging would be to move the spray bars of figure 4 to a new location immediately in front of the vaporizer plates. Then, at the higher fuel flow rates, fuel mist would escape into the main stream and arrive at a more favorable location on the flame front envelope.

The consistent blowout performance improvements at intermediate fuel-air ratios for the several geometry changes (configurations C-6 to C-9) are encouraging because the improvements were in general noted to occur without any observed detrimental effects. Hence, further improvement in rich-limit blowout may be possible provided the proper geometric changes are made. For instance, additional increases in vaporizer passageway areas may be beneficial. For the present set of operating conditions, a reduction in gutter width does not appear advisable, and fuel staging would be preferred to any widening of the gutters.

Let us return now to a discussion of the very low end of the fuel-air ratio scale. Film-vaporizing systems appear capable of providing stable combustion at good combustion efficiency levels for overall fuel-air ratios as small as 0.004. This belief is based on the good performance obtained with three gutters at a fuel-air ratio of 0.012 and the physical restriction imposed on fuel spreading. The fuel to each gutter is consumed in the local wake of the gutter. Hence, injection of fuel to only one gutter should achieve the desired result. Also, this manner of staging would lessen the danger of spontaneous ignition in the vaporizer passageway when the inlet temperature is high.

Overheating of uncooled, uninsulated spray bars at the 1255 K inlet temperature condition is unavoidable at low fuel-flow rates. While radiation shielding provided by the guide plates accentuates the spray-bar clogging problem, the results of both the present and reference 2 investigations show the need for some form of protection from fuel overheating. Test durations were too short to ascertain the need for cooling once a sizable flow had been obtained in the spray bar. However, inadvertent reduction in fuel flow could lead to rapid clogging at the 1255 K inlet temperature condition.

Potential Application to Afterburner Design

The preceding discussion provides suggestions for the design of a short-length burner capable of operating over a wide range of inlet temperatures and fuel-air ratios.

One such scheme that appears to provide reliable performance without blowout, spontaneous ignition, spray-bar overheating, and gutter overheating utilizes two stages of fuel injection. The basic design would consist of the C-9 configuration plus a modification to the fuel system (fig. 14). Performance estimates are shown in figure 15(a). Only the film-vaporizing spray bars are supplied with fuel at fuel-air ratios less than 0.024. At larger fuel-air ratios, the fuel is routed jointly to manifolds A and B (fig. 14) to reproduce the fuel distribution characteristics of reference 2. This manifolding scheme should provide good cooling of the flameholders since film vaporization is used for all gutters. The lean termini of the curves at the two lower inlet temperatures are prior to blowout (fig. 15(a)). The lean terminus of the 1255 K inlet temperature curve was chosen to avoid the region of spontaneous ignition and spray-bar clogging. However, afterburner ignition would not be advisable at inlet temperatures much above 1100 K for risk of coking that would result from repeated introduction of fuel into a hot spray bar.

At fuel-air ratios above 0.04, the data curves of figure 15(a) have been adjusted upwards from those of the reference 2 data (fig. 13) in order to compensate for combustion efficiency losses attributed to carbon monoxide (see the section CALCULATIONS). The figure 15(a) results at the 1090 K inlet condition show the combustion efficiency to be above 95 percent for fuel-air ratios from 0.012 to 0.045. Stable combustion at this test condition is indicated for fuel-air ratios from 0.0075 to 0.060.

Performance for a scheme of three fuel injection stages is shown in figure 15(b). For this arrangement, the center spray bar of manifold A (fig. 14) is valved off for fuel-air ratios less than 0.015. Lean mixture performance is improved. For example, combustion efficiency at the 1090 K inlet condition is above 95 percent for fuel-air ratios as small as 0.0075. Stable combustion is extended to a fuel-air ratio of 0.004.

SUMMARY OF RESULTS

Performance of five variations of a film-vaporizing V-gutter design was measured at inlet temperatures of 920, 1090, and 1255 K. Vaporizer passageway areas and gutter width were varied. Spacing between the fuel spray bar and the flameholder was 12.7 centimeters, and combustion length was 92 centimeters. Inlet velocity and pressure were 150 meters per second and 1 atmosphere, respectively. The following results were obtained:

1. Good performance was demonstrated at fuel-air ratios less than 0.025. Maximum combustion efficiencies occurred in the vicinity of fuel-air ratios of 0.015 to 0.025 and were 92, 98, and 100 percent for inlet temperatures of 920, 1090, and 1255 K, respectively. At a fuel-air ratio of 0.012, efficiencies were 88, 96, and 100 percent for the respective inlet temperature values. Lean blowout fuel-air ratios were in the vicinity of 0.005.

2. The overall best configuration had rich blowouts at fuel-air ratios of 0.026 and 0.032 for inlet temperatures of 920 and 1090 K, respectively.

3. Rich-limit blowout was improved by enlarging the vaporizer discharge passageway and by enlarging the distance between the guide plates.

4. Rich-limit blowout improved when the gutter width was increased. However, the wide (5.7-cm) gutters, besides having a large frontal area, exhibited lower combustion efficiency than the narrower gutters for fuel-air ratios less than 0.01.

5. The 1255 K inlet temperature condition produced several problems. The vaporization plates acted as radiation shields and thereby caused the spray bars to run hotter and to clog more readily than was observed for exposed spray bars that radiated freely to the cold chamber walls. There was one occurrence of spontaneous ignition in the vaporizer passageways. Otherwise, no serious overheating problems were encountered.

6. The film-vaporizer burner results, when compared to the results for a burner without the guide plates, showed that the plates provided lower lean blowout limits and better combustion efficiencies up to fuel-air ratios of 0.025. At fuel-air ratios near 0.025 both designs produced good performance. However, a further increase in fuel-air ratio resulted in blowout for the film-vaporizing burner and a continuation of good performance for the conventional design.

7. The foregoing comparison suggested fuel injection staging techniques that could be employed to extend the fuel-air ratio range of film-vaporizing burners. The expected performance of two such schemes utilizing two and three stages of fuel injection are presented. For the two-stage system, at an inlet temperature of 1090 K the combustion efficiency was above 95 percent for fuel-air ratios from 0.012 to 0.045. Stable combustion was expected for fuel-air ratios from 0.0075 to 0.060.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 17, 1973,
501-24.

REFERENCES

1. Reck, Gregory M.; Branstetter, J. Robert; and Diehl, Larry A.: Preliminary Sector Tests at 920 K (1200° F) of Three Afterburner Concepts Applicable for Higher Inlet Temperatures. NASA TN D-6437, 1971.
2. Branstetter, J. Robert; and Reck, Gregory M.: Afterburner Performance of Circular V-gutters and a Sector of Parallel V-gutters for a Range of Inlet Temperatures to 1255 K (1800° F). NASA TN D-7212, 1973.

3. Blackshear, Perry L., Jr.; and Rayle, Warren D.: Oscillations in Combustors. Basic Considerations in the Combustion of Hydrocarbon Fuels with Air. Henry C. Barnett and Robert R. Hibbard, eds. NACA Rept. 1300, 1959, ch. 8.

4. Lefebvre, A. H.; Ibrahim, A. R. A. F.; and Benson, N. C.: Factors Affecting Fresh Mixture Entrainment in Bluff-Body Stabilized Flames. Combustion and Flame, Vol. 10, Sept. 1966, pp. 231-239.

TABLE I. - FLAMEHOLDER BLOCKAGE AND VAPORIZER

FLOW PASSAGE AREA

Configuration	Actual projected blocked area of V-gutters[a]	Projected blocked area of V-gutters assuming array to be a section of a larger afterburner[b]	Vaporizer passageway area at inlet[a]	Vaporizer passageway area at fuel spray-bar plane[a]	Vaporizer passageway area at discharge[a]
	Fraction of reference				
C-6	0.216	0.300	0.108	0.054	0.072
C-7	.216	.300	.108	.054	.108
C-8	.216	.300	.108	.054	.144
C-9	.216	.300	.144	.090	.108
C-10	.324	.450	.216	.162	.108

[a]Reference inlet area is 1878 cm^2 (291 $in.^2$).
[b]Fractional blockage is (gutter width/lateral spacing).

TABLE II. - AFTERBURNER-INLET TEST CONDITIONS

	Test condition		
	A	B	C
Total temperature, K (°F)	920 (1200)	1090 (1500)	1255 (1800)
Static pressure, N/cm^2 (psia)	10.0 (14.5)	10.0 (14.5)	10.0 (14.5)
Velocity, m/sec (ft/sec)	150 (500)	150 (500)	150 (500)
Preheater-inlet total temperature, K (°F)	450 (350)	450 (350)	450 (350)
Nominal airflow rate, kg/sec (lb/sec)	11 (25)	9 (20)	8 (18)
Nominal preheater fuel-air ratio	0.012	0.017	0.022
Preheater combustion efficiency, percent	97.0	98.0	98.5

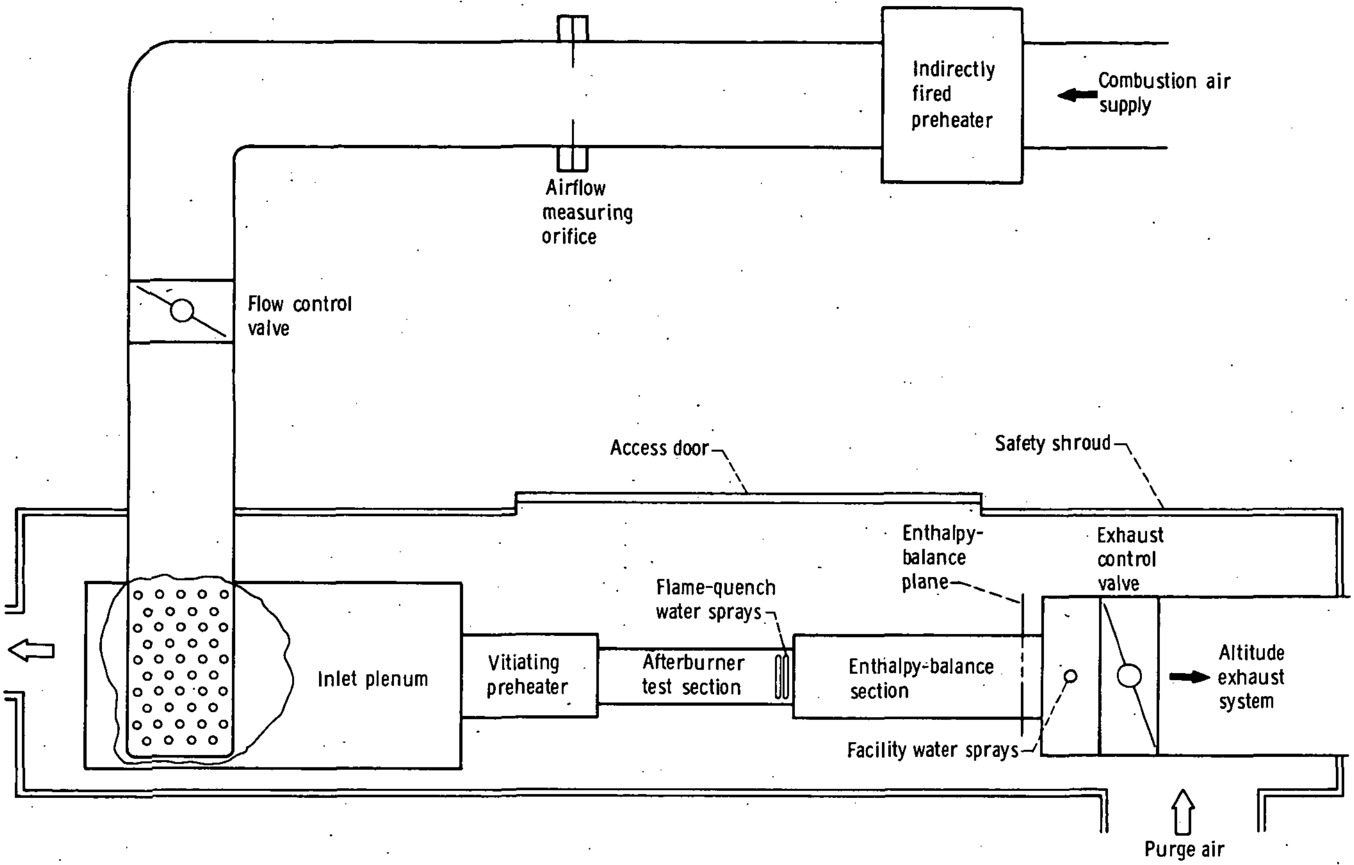


Figure 1. - Schematic diagram of afterburner test facility.

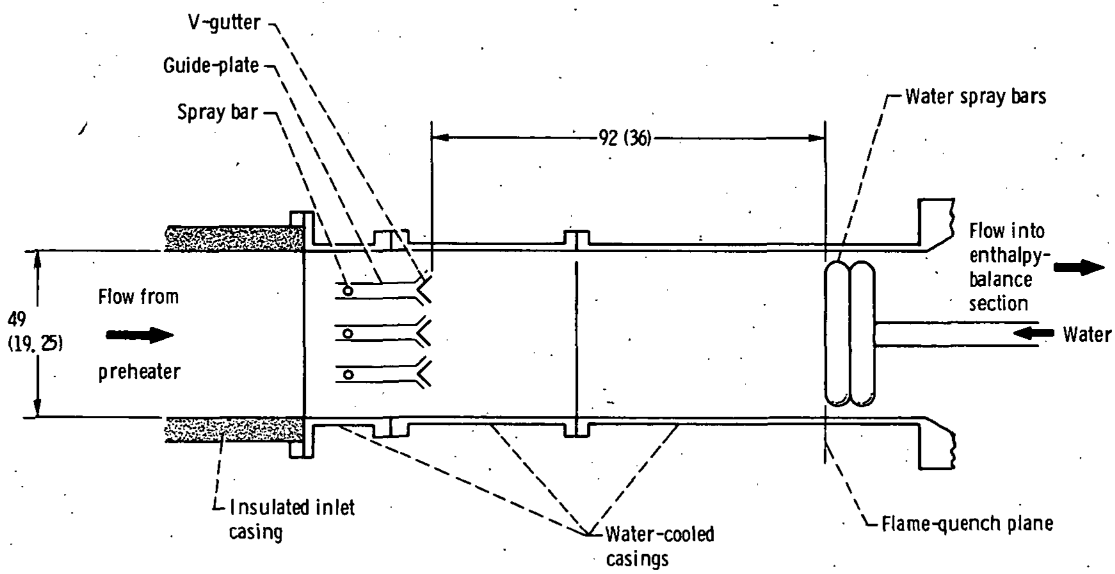
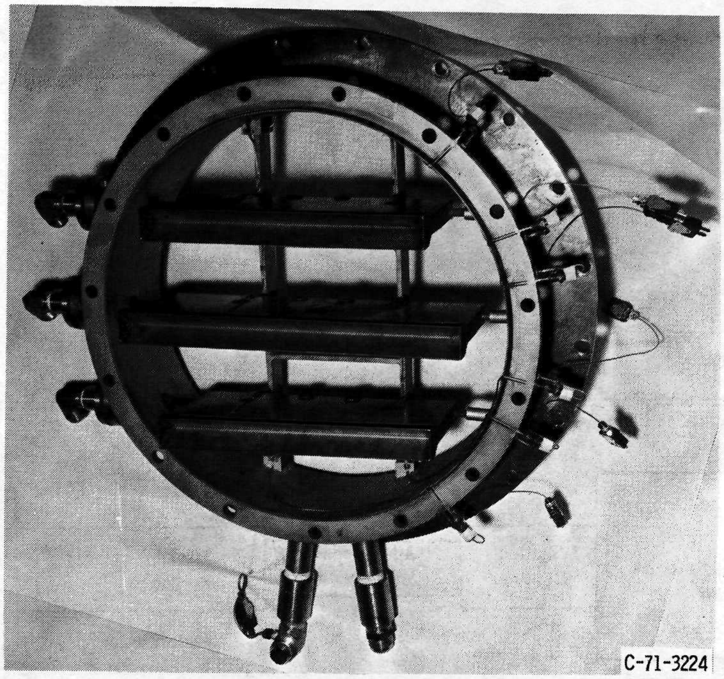
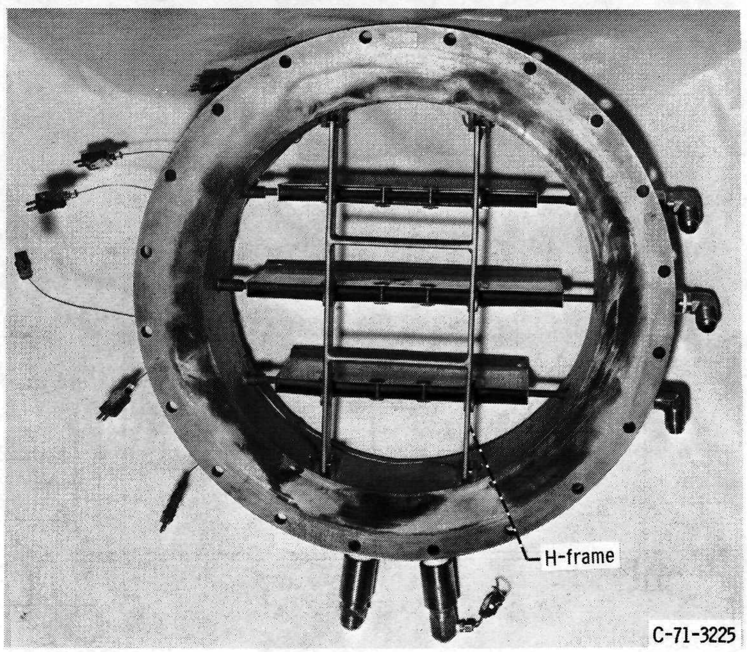


Figure 2. - Cross-sectional sketch of afterburner test section. (Dimensions are in centimeters (in.).)

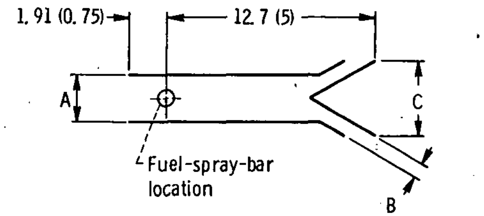


(a) View looking upstream.



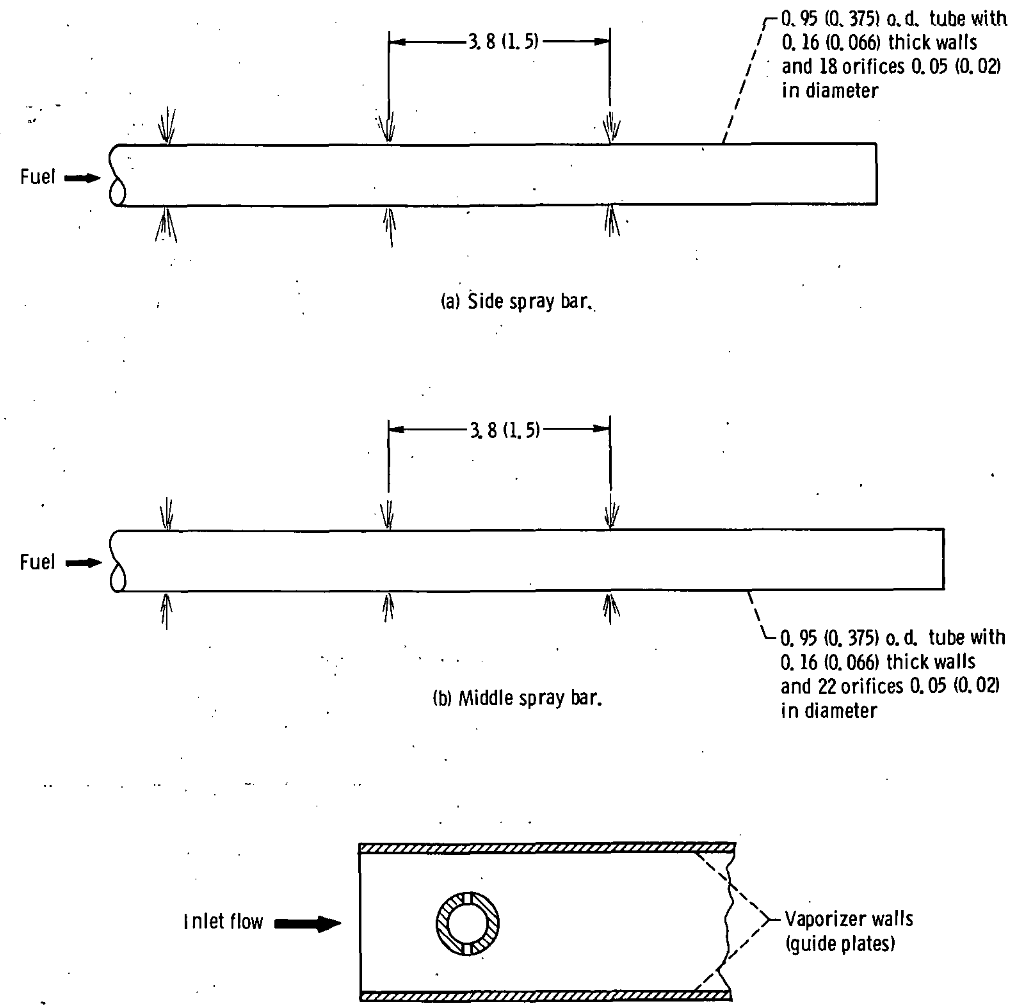
(b) View looking downstream.

Figure 3. - Typical flameholder assembly.



Configuration	Guide-plate spacing, A	Vaporizer discharge width, B	Gutter width, C
C-6	1.91 (0.75)	0.63 (0.25)	3.8 (1.5)
C-7	1.91 (.75)	.95 (.375)	3.8 (1.5)
C-8	1.91 (.75)	1.27 (.5)	3.8 (1.5)
C-9	2.5 (1)	.95 (.375)	3.8 (1.5)
C-10	3.8 (1.5)	.95 (.375)	5.7 (2.25)

Figure 4. - Cross-sectional sketch and dimensions of film-vaporizing designs. Included angle of gutter is 60°. (Dimensions are in centimeters (in.).)



(a) Side spray bar.

(b) Middle spray bar.

(c) Cross section of spray bar mounted in vaporizer.

Figure 5. - Fuel spray bars. (Dimensions are in centimeters (in.).)

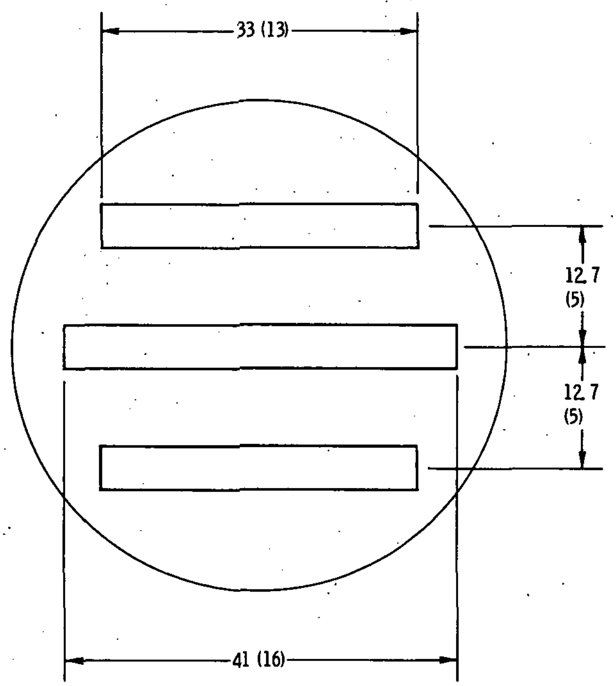
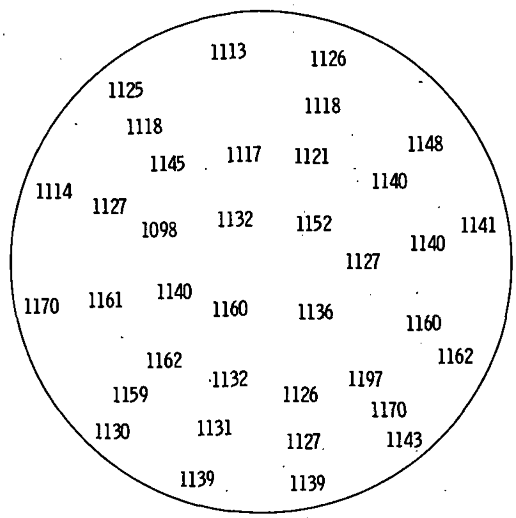
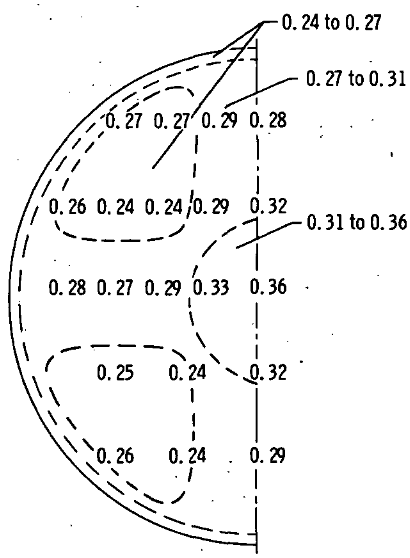


Figure 6. - Sketch of projected blockage of film-vaporizing V-gutters. (Dimensions are in centimeters (in.).)



(a) Total temperature, K; average, 1140 K.



(b) Mach numbers; average, 0.275.

Figure 7. - Typical inlet flow profiles.

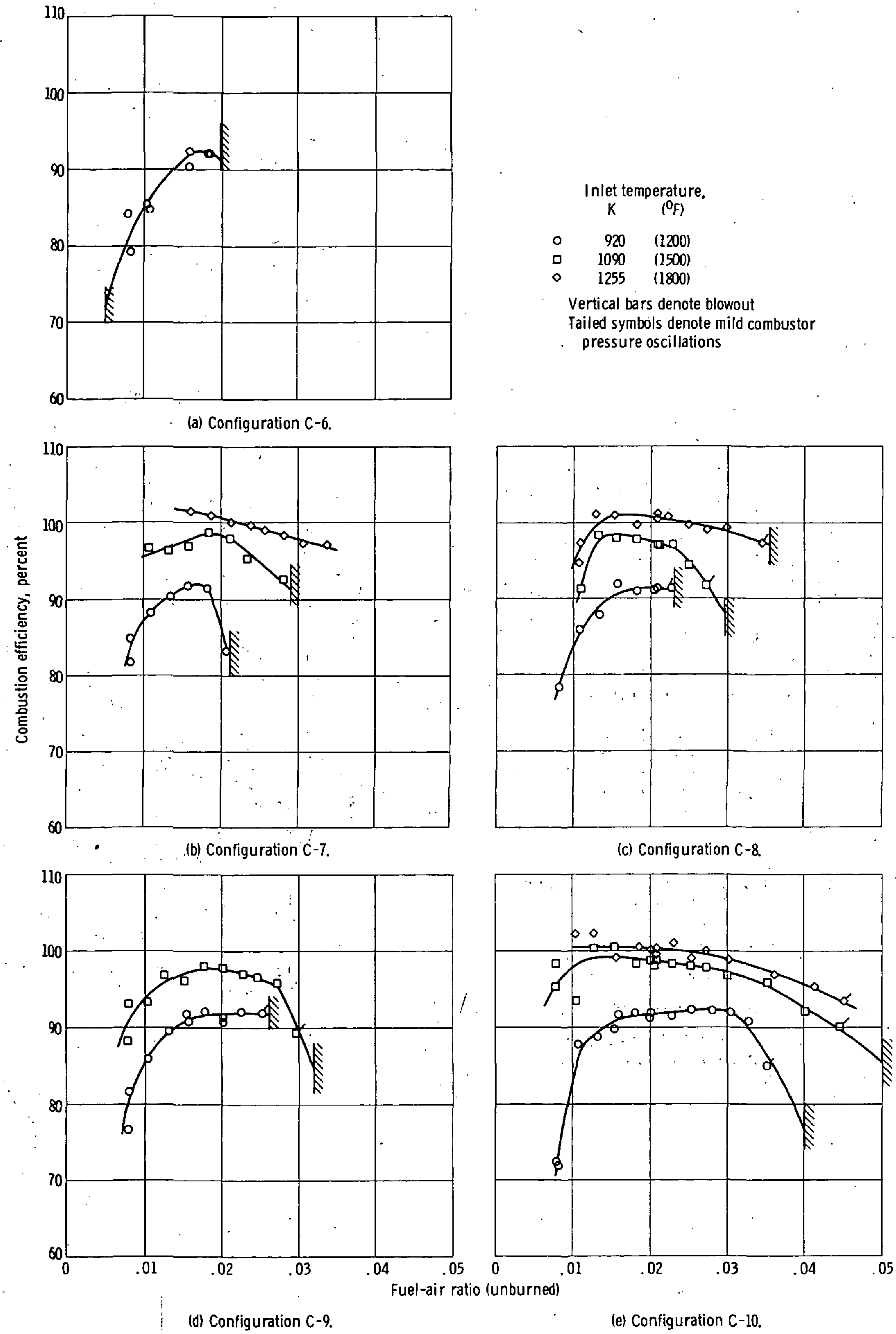
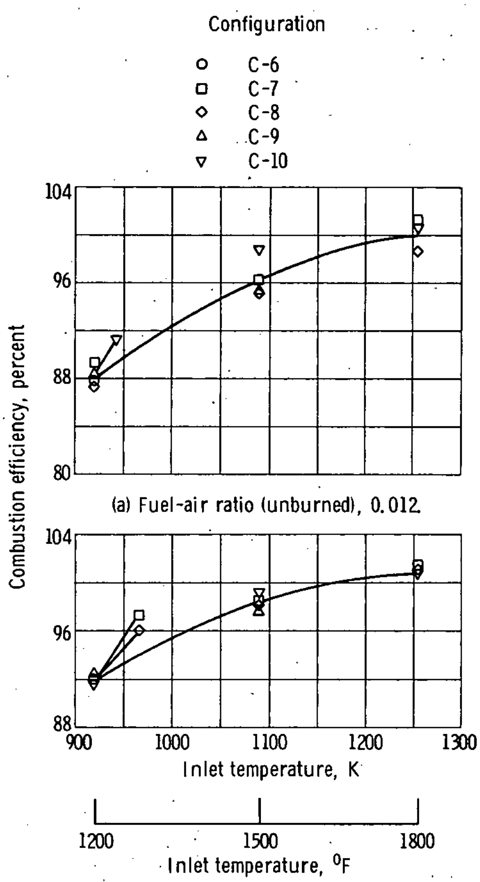


Figure 8. - Combustion performance of film-vaporizing V-gutter afterburner. Inlet conditions: pressure, 1 atmosphere; velocity, 150 meters per second (500 ft/sec).



(b) Fuel-air ratio (unburned), 0.017.

Figure 9. - Effect of inlet temperature on combustion efficiency. Data are from figure 8.

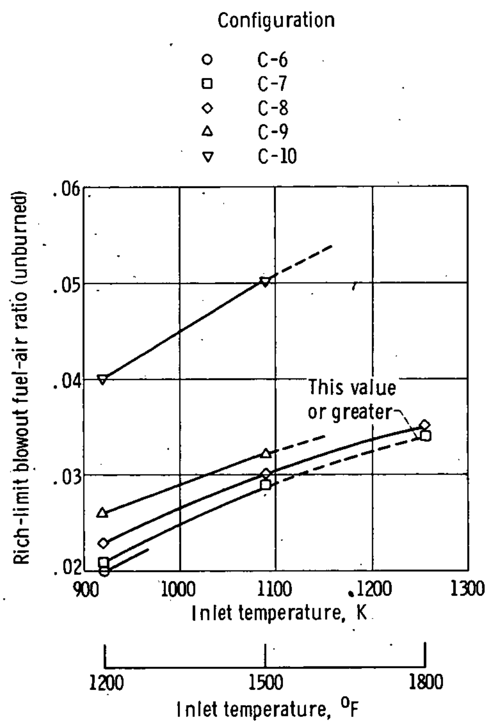
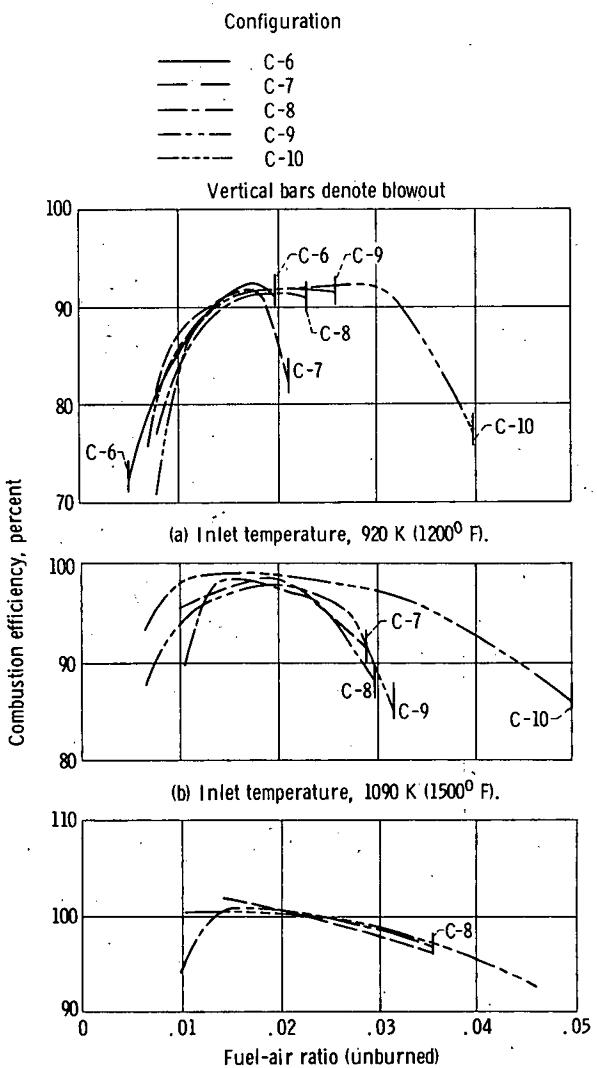


Figure 10. - Effect of inlet temperature on rich blowout. Data are from figure 8.



(a) Inlet temperature, 920 K (1200° F).

(b) Inlet temperature, 1090 K (1500° F).

(c) Inlet temperature, 1255 K (1800° F).

Figure 11. - Effect of burner geometry on performance. Data are from figure 8.

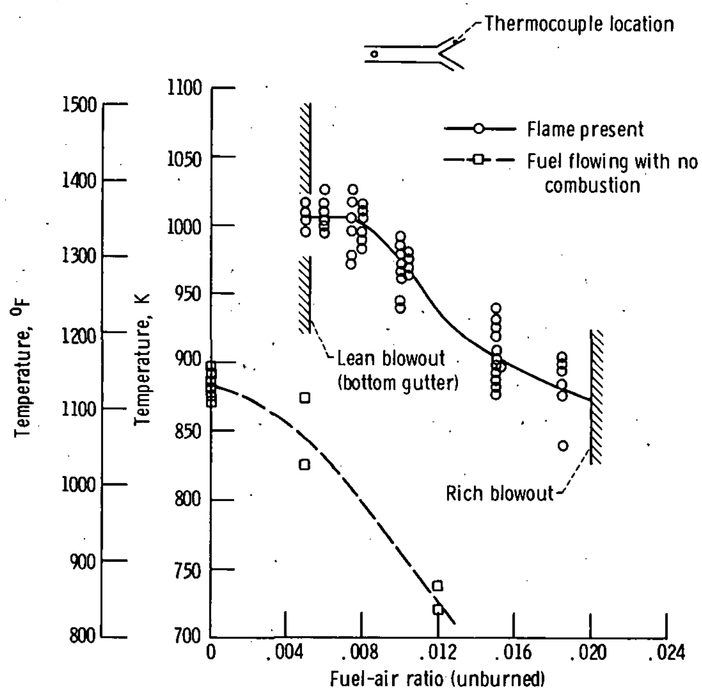


Figure 12. - V-gutter metal temperatures measured by individual thermocouples. Two thermocouples located on each gutter; configuration C-6; inlet temperature, 920 K (1200° F).

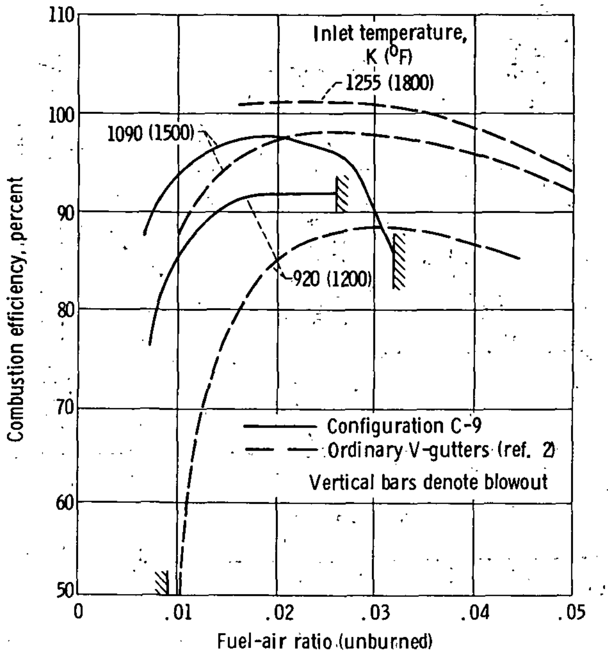


Figure 13. - Performance comparison of configuration C-9 and reference 2 design. Inlet conditions: pressure, 1 atmosphere; velocity, 150 meters per second (500 ft/sec).

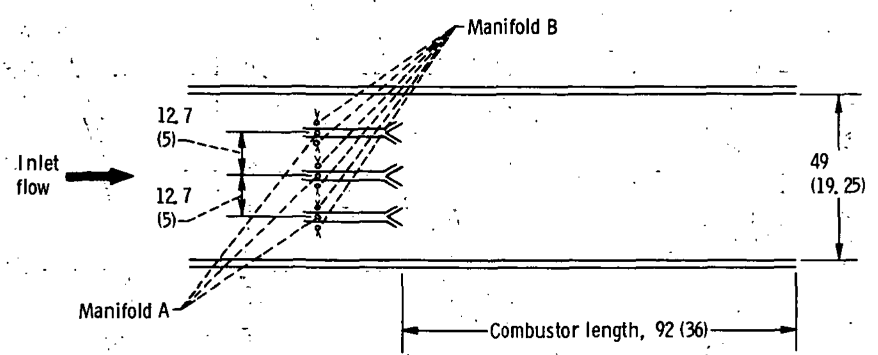


Figure 14. - Scheme providing two stages of fuel injection. Scheme consists of configuration C-9 plus a set of spray bars (manifold B) for extending operating range to higher fuel-air ratios. (Dimensions are in centimeters (in.).)

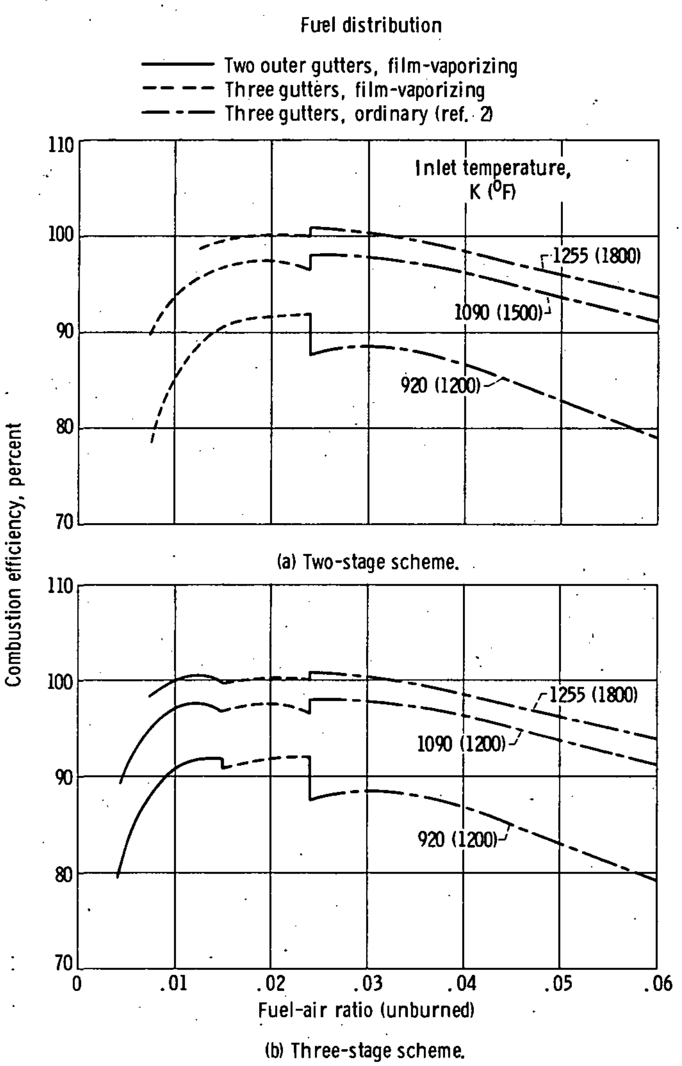


Figure 15. - Performance for suggested arrangements of fuel staging. Three 3.8-centimeter- (1.5-in.-) wide V-gutters; in-line fuel injectors located 12 centimeters (5 in.) upstream of gutters; inlet conditions: pressure, 1 atmosphere; velocity, 150 meters per second (500 ft/sec).

Page Intentionally Left Blank

Page Intentionally Left Blank