[redacted]

Copy ~~4~~

RM E58A21a

Copy 2

NACA RM E58A21a

UNCLASSIFIED

CLASSIFICATION CHANGED

NACA

RESEARCH MEMORANDUM

COMBUSTION OF GASEOUS HYDROGEN AT LOW PRESSURES IN A 35° SECTOR OF A 28-INCH-DIAMETER RAMJET COMBUSTOR

By William R. Kerslake

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

~~CLASSIFICATION CHANGED~~

To ~~CONFIDENTIAL~~

By authority of NASA PA#7 Date June 4, 1959
effective date May 29, 1959. by JBE

I.N. 58-406

APR 24 1958

CLASSIFIED DOCUMENT

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

April 22, 1958

[redacted]
UNCLASSIFIED
[redacted]

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

COMBUSTION OF GASEOUS HYDROGEN AT LOW PRESSURES IN A 35° SECTOR OF A 28-INCH-DIAMETER RAMJET COMBUSTOR

By William R. Kerslake

4648

SUMMARY

Gaseous hydrogen fuel was burned in a connected-pipe combustor with a cross section equal to 35° sector of a 28-inch diameter. Eleven shrouded fuel-injector configurations were used to obtain combustion data at the following high-altitude ramjet combustor conditions: pressure, 5 to 24 inches of mercury absolute; velocities, 340 to 160 feet per second; and inlet air temperature of 240° F. Combustion efficiencies were measured above 95 percent for wide bands of fuel-air ratios. The combustor configurations reported herein extend the efficient burning range of hydrogen at ramjet conditions to a pressure of 1/6 atmosphere; best configurations previously reported gave high efficiency to only 1/2 atmosphere. Comparable combustion data of a full-size ramjet engine using the shrouded fuel injector are also presented.

CR-1

INTRODUCTION

The theoretical advantages of using hydrogen fuel for a high-altitude high flight Mach number ramjet engine have been shown thoroughly in reference 1 (also NACA unpublished data). These advantages stem from the hydrogen properties of a high flame speed or reactivity, especially at low pressures (ref. 2), a large heat sink or cooling capacity, and a high heating value per pound. In order to realize fully the potential advantages of hydrogen, high combustion efficiency must be achieved in a short, light-weight combustor with small flameholder pressure losses.

At high altitudes where burner pressure fell below 1/2 atmosphere, the simple spray bars of references 3 and 4 no longer gave good combustor performance, particularly at short burner lengths. The objective of the work discussed herein was to establish design principles for a fuel injector capable of good performance at low burner pressures in a short combustor length.

As the program progressed, the importance of certain design variables became evident, such as, (1) amount of air admitted inside the shrouds, (2) location of mixing tabs on the downstream end of the shrouds, (3) length and width between the shrouds, (4) manner and location of injecting fuel inside the shrouds, and (5) spacing between shroud units. Variables (1) and (2) were studied primarily because the knowledge thus gained could be immediately applied in the 28-inch-diameter ramjet engine that was tested in the NACA Lewis 10- by 10-foot supersonic wind tunnel. Design variables (3), (4), and (5) as well as (1) and (2) could be observed more easily in a two-dimensional test section at a later time and were left for possible future study. The starting point or basic design of the fuel injector was similar to the shrouded fuel injector of reference 5. One attempt was made to test a scale effect by doubling the number of radial fuel-injector elements and at the same time reducing the size of the element to one-half. 4548

Testing was conducted in a connected-pipe burner with a cross section equal to a 35° sector of a 28-inch-diameter circle. This cross section was the largest one that could be accommodated in the existing test facility. The test ranges of inlet pressure and velocity were selected to be equivalent to tunnel operation at simulated altitudes of 80,000 to 120,000 feet and flight Mach numbers of 3.0 to 4.0. The inlet air temperature was approximately 240° F, which corresponded to the total temperature in the tunnel at a Mach number of 3.0. (At a flight Mach number of 3.0 in the stratosphere the total temperature is 640° F.)

As the ramjet engine was primarily designed for low-equivalence-ratio operation (up to 0.4 stoichiometric fuel-air ratio), the bulk of experimental data was taken at these low equivalence ratios. Combustion efficiencies are reported for 11 different shroud configurations. Three of these configurations were also tested up to stoichiometric fuel-air ratios for possible future application. The performance of one configuration that was tested in the 28-inch-diameter ramjet in the tunnel is also presented for comparison.

APPARATUS

Connected-Pipe Test Facility

A schematic drawing of the airflow is shown in figure 1. Air was supplied at 40 pounds per square inch gage and heated electrically to provide a combustor-inlet temperature of approximately 240° F. The heated air was metered by a variable-area calibrated orifice, passed through a throttling valve, and entered a plenum chamber. From the plenum chamber it was ducted into a 12-inch-diameter pipe to the combustor section. Gaseous hydrogen fuel flowed directly from a multigas-cylinder trailer through a throttling valve and critical flow-metering orifice to the fuel injectors in the combustor. Air-atomized quench water, metered by rotameters, was introduced at the combustor exit. The resulting gas-water mixture came to an equilibrium temperature in a 15-foot long heat balance or calorimeter section. The equilibrium-mixture temperature was measured by two thermocouple rakes before the gases were exhausted through a throttling valve to the laboratory altitude exhaust system. The calorimeter wall temperature was measured by skin thermocouples to permit calculation of heat losses from the calorimeter. Windows at either end of the rig permitted observation of the burner.

4648

Combustor Section

Details of the 35°-wedge-sector burner are presented in figure 2. The burner simulated a wedge cut from a 28-inch-diameter ramjet combustor. Air entered through an orifice-type flow restriction and passed through a 2-foot long flow-straightening annular section. The fuel injectors were located in the annular sector, just before a step change to a circular sector. This step change simulated a pilot-ended centerbody in the 28-inch-diameter ramjet.

Wall static-pressure taps, probing stations, spark plug, and thermocouple rake were located as shown in figure 2. The burner walls were cooled by forced air convection. The distance was 14 inches from the point of fuel injection to the thermocouple rake with 10 additional inches to the quench-water spray. As the rake was in the hot core of gases the readings could not be used to calculate directly the combustion efficiency. The rake gave relative values of combustion efficiency and temperature profile between the various fuel injectors. The cold-flow velocity profile in the burner is shown for two stations (2 and 3) in figure 3. The probe traveled at right angles to the burner wall.

Fuel-Injector-Flameholder Configurations

Figures 4(a) to (k) present details of the fuel injectors. Each flattened injector tube had 13 pairs of drilled holes located on the centers of equal areas of the simulated annulus. The injector tubes of configurations J and K had holes one-half the size of those used for configurations A to I.

Configuration A (fig. 4(a)) was similar to that used in reference 5 and was a starting point for design departure to improve low-pressure combustion efficiency and burner stability.

Configuration B, with a reduced air supply inside the shrouds, was expected to provide a more stable flameholding zone by both reducing the local velocity and increasing the local fuel-air ratio. The flamespeed of hydrogen is a maximum at an equivalence ratio of 2 (ref. 2). (Equivalence ratio is the fraction of stoichiometric fuel-air ratio.) Configurations C to F, in which progressively more air was admitted between the shrouds, were studied to see if part of the air might not improve the combustion efficiencies but not seriously decrease stability. In configuration F, the blockage between the shrouds was radially nonuniform, attempting to shelter the region where the flame first blew off the spray bar.

The problem of mixing the hot fuel-rich gases issuing from the flameholder with the remaining air would probably be the most difficult when all the air was bypassed around the shrouds, as in configuration B. A completely blocked-shroud configuration was therefore chosen to examine 4648 the effect of mixing tabs on the downstream end of the shrouds. Configuration G had the tabs bent straight in line with the shrouds and was a basis for comparison. Configuration H with tabs bent outward was an attempt to introduce more turbulence with a V-gutter-type blockage. With configuration I (tabs bent inward) it was hoped that, in addition to a lower friction pressure drop, the air would flow around the shrouds with an inward component. This inward-air component would impinge on both sides of the issuing fuel creating a favorable zone for mixing and spreading. Configuration B was designed to create uniform antisymmetrical zones of mixing (as opposed to the symmetrical tabs of configuration A).

Configurations A to I were fabricated from the same flattened fuel spray bars and shrouds. Modifications between the configurations were made by changing the upstream end of the shrouds or by bending the mixing tabs. Configurations J and K were of similar shape to configurations B to I, but four injector units were tested in the same cross section that previously held two units. The four injector units had the same radial dimensions, but their cross section was one-half of the two-unit size. Increasing the number of fuel injectors was expected to improve the outlet-temperature profile and perhaps to reduce the combustor length.

PROCEDURE

Operating Conditions

For all the configurations except A, data were taken at constant airflow levels of 4.0, 1.5, and 0.7 pounds per second. A run was defined as a series of data points at constant airflow with stepwise changes in the fuel flow. The pressure of the burner (unless otherwise noted) was the lowest pressure available in the particular apparatus used. The 1.5-pound-per-second airflow condition was picked because it most closely simulated velocities in the 28-inch-diameter ramjet. The 4.0-pound-per-second airflow represented operation at higher burner pressures with somewhat higher velocities. At the 0.7-pound-per-second airflow the flameholder could be tested to near stoichiometric combustion, but the air velocity was about one-half that of the realistic ramjet combustor. The following table presents typical operating ranges at the three airflows:

Airflow, lb/sec	Approximate Inlet Air Conditions			
	Pressure range, in. Hg abs	Velocity range, ft/sec	Temperature, °F	Maximum fuel equivalence ratio
0.7	5-12	190-70	240	1.00
1.5	7-12	280-160	240	.49
4.0	16-25	320-220	240	.18

The maximum equivalence ratio was limited by the fuel supply system.

The burner was ignited by a sparkplug conveniently located in the burner wall 5 inches downstream of the fuel injectors. Since this location was not optimum, the airflow had to be reduced below 100 feet per second, and the pressure raised to more than 10 inches of mercury absolute before the burner would start. A more favorable location for the sparkplug would be near or in the path of a fuel jet.

Combustion Efficiency

Combustion was assumed to be terminated by the quench-water spray. Reference 5 presents combustion data taken with a heat balance and quench-water spray in which the quench-water flow rate was varied while the burner fuel and airflows remained constant. Since the combustion efficiency remained almost constant over the range of quench-water flows, it was concluded in reference 5 that the combustion reaction was definitely terminated by the quench water. The combustion reaction in this program should be even more quickly quenched because the water was more finely injected (more injection points per cross-sectional area) in addition to being air atomized.

Combustion efficiency was defined as the ratio of the measured enthalpy rise in the burner divided by the theoretical lower heating value of the fuel. The enthalpy rise in the burner was calculated from a heat balance around the calorimeter section. To eliminate the heat capacity of the products, the combustion reaction was theoretically assumed to occur at a calorimeter-outlet temperature of approximately 400° F. The theoretical heating value of the fuel would then be the weight flow of fuel times its heat of combustion at 400° F, 51,970 Btu per pound. The following table shows the relative importance of the various constituents in the heat balance for a typical data point with a 240° F inlet air temperature and 0.0078 pound per second of fuel at 60° F.

Constituent	Temperature change, °F	Enthalpy rise, Btu/sec
Air	240 to 400	49
Fuel	60 to 400	9
Quench water	50 to 400	301
Jacket water	50 to 60	12
Losses of calorimeter to room air, calculated from ref. 7		20
Total		391

4648

$$\text{Combustion efficiency} = \frac{\text{Enthalpy rise}}{\text{Fuel heating value}} = \frac{391}{(0.0078)(51,970)} = 98 \text{ percent}$$

RESULTS

Shroud Air Blockage

Figure 5(a) and table I present combustion efficiencies for the original configuration A with 100-percent open area between shrouds. A rapid fall-off of efficiency was evident at lean fuel flows. At the lower burner pressure of runs 1 and 2, blowout of the outer half of both fuel injectors occurred at about a 0.3 equivalence ratio.

Airflow to configuration B was completely blocked off between the shrouds or zero-percent open area. Configurations C, D, E, and F had progressively more air admitted between the shrouds. Combustion efficiency data for these configurations are shown in figures 5(b) to (f), and figure 5(g) is a summary plot for the 1.5-pound-per-second airflow condition of the faired curves of figures 5(a) to (f).

Mixing Tabs

The results of varying mixing tabs on the downstream edge of the shrouds are shown in figure 6. There was little or no effect on combustion efficiency. The predominant effects were noted in the cold-flow pressure losses and outlet-temperature profiles. Cold-flow pressure losses $\Delta p/q$, where Δp is the wall static-pressure drop across the fuel-injector flameholder and q is the velocity head, were a moderate 2.0 for configuration H to a low 0.7 for configuration I. Configuration A with no blockage on the upstream end of the shrouds had a very low cold flow $\Delta p/q$ of 0.2. The static-pressure drop corresponds approximately to a total-pressure drop at the test velocities.

For comparing the temperature profiles, a profile factor was defined as the maximum minus the minimum measured temperature divided by the average temperature rise $\frac{T_{max} - T_{min}}{\Delta T}$. Configuration B with antisymmetrical tabs had the best mean profile factor, and configuration G with no tabs had the worst profile factor of figure 6. Individual profile factors are presented in table I.

4648 The temperature-profile-factor data are not completely reliable because they were computed from only one temperature rake with five thermocouples. This rake was across the wake of the fuel injectors and measured flame spreading between injectors, but not radially along each individual injector. Visual observation of the flame indicated approximately uniform radial temperatures, except for an intentionally designed cold-air zone next to the outer wall. The profile data could only be taken up to medium fuel flows, and blanks in the data table were due to thermocouple rake burnout.

Higher Equivalence-Ratio Burning

Figure 7 presents combustion data at equivalence ratios up to 1.00. These data must be qualified, because to enable the limited fuel system to produce high equivalence ratios, the weight flow of air was reduced. Consequently, the air velocity was lower than would be realistic. These tests, however, did produce interesting data. The combustion efficiency remained high (above 87 or 92 percent) up to a 1.00 equivalence ratio at a very low burner pressure (5 to 8 in. Hg abs for run 21). Runs 22 and 23, configurations D and E, were less stable, blowing out at 5 inches of mercury absolute (condition of run 21). The data were subsequently taken at a higher pressure level where combustion was found stable.

Injector Size

Figures 5, 6, and 7 were all run with the same number of fuel injectors (2) and the same distance between shrouds (about $1\frac{1}{2}$ in.). For figure 8 the size of the fuel injector was reduced one-half but the number of injectors was increased to 4. The four fuel injectors were only run at the 0.7-pound-per-second airflow condition for two different shroud open areas. The combustion efficiency as seen in figure 8 was still good (about 90 percent from 0.3 to 0.8 equivalence ratio), but the burner stability was slightly less. The low pressure for stable burning was 6 or 8 inches of mercury absolute for runs 25 and 26, respectively, as compared with 5 inches of mercury absolute for run 21 (fig. 7).

The greatest advantage realized was the improvement of the outlet-temperature profile.

Flameholder Durability

All of the tests of this program were run at subatmospheric pressures because it was believed that the subatmospheric region was where combustion problems would arise. It was assumed that the combustion efficiency would remain as high or rise even higher when hydrogen burned at high pressures. The durability of the flameholder parts would probably be the chief worry with high-pressure burning. The flameholders used in this investigation warped slightly at times but never burned out.

4648

Burner Length

The burner length used in this program was constant, 24 inches from fuel injection to quench-water spray. Since it was desirable to know if this length were optimum and also was inconvenient to move either the fuel injectors or quench-water spray bars, other attempts were made to measure heat release along the burner length. Figure 9 presents data from two methods. In the first method, shown in figure 9(a), the gas temperatures at 4, 7, and 13 inches from the fuel injector were calculated from measured wall static pressures and momentum pressure-drop relations. The final temperature at 24 inches was calculated from the fuel-air ratio and the heat-balance combustion efficiency. It appears from the curves of figure 9(a) that for low equivalence ratios heat addition was completed in a shorter length, and for a high equivalence ratio the full 24 inches was needed. It must be pointed out, however, that small errors in the wall static-pressure measurement would produce large errors in the calculated gas temperature and so the results of figure 9(a) might be fortuitous.

Figure 9(b) presents gas temperature measured by a traversing (at right angles to the airflow) thermocouple probe at four different axial stations. With the data of figure 9(b) it was possible to follow the wake of the flame behind configuration D as it spread out. No quantitative heat-addition rates were possible with the data, because the single traverse of the probe at each axial station was not representative enough to give a true average temperature of the total burner cross section.

DISCUSSION

Combustion Efficiency

A few broad observations can be made on the combustion of hydrogen in this wedge burner. (1) If burning took place, it was usually very efficient (above 90 percent) and remained high over a wide fuel-air-ratio range. When fall-off occurred, it was very rapid. (2) Combustion efficiencies at pressures greater than 1/2 atmosphere were not influenced by the fuel-injector design. Every data point taken in the medium pressure range of 1/2 to 1 atmosphere fell on a single curve of approximately 100-percent combustion efficiency with a rapid fall-off occurring at the extremely low equivalence ratio of 0.05. For this reason, the summary plot of figure 5(g) included only the low-pressure-operation region where effects in performance were found. (3) Dropping the combustion pressure from the medium range to the low range (16 to 25 and 7 to 12 in. Hg abs), shifted the lean end efficiency dropoff to a richer value. This shift can readily be seen in figures 5(b), (c), and (d), or in figure 6.

4648

Shroud Air Blockage

One variable given particular attention was the amount of air admitted inside the fuel-injector shrouds. By varying the percentage of open area between the shrouds, the lean end fall-off could be controlled and, to a lesser extent, the level of the combustion efficiency. For the optimum shroud design a compromise was necessary as the design with the better combustion efficiency had the lesser range of operation. From figure 5(g) it appears that either the 9- or 21-percent design (configurations C or D) would be the best choice.

CR-2

The 63-percent design (configuration F) appears inconsistent with the other curves of figure 5(g). This lack of order of the 63-percent curve is perhaps explained by the manner in which the air was admitted inside the shrouds. Configuration F had blockage that was radially nonuniform and much closer to the fuel spray bar. Thus, the airflow turbulence in the vicinity of the fuel spray bar would be noticeably different than with the further upstream uniform, U-shaped blockage of configurations B to E.

Combustion Inefficiencies

Combustion inefficiencies when using hydrogen fuel should be less than for hydrocarbon fuels. In addition to the greater reactivity and flame speed of hydrogen, there are no unreactive intermediate products formed as is possible in the case of hydrocarbon fuels. Combustion inefficiencies, then, with hydrogen fuel are probably due to two sources. (1) There is insufficient time or burner length for complete mixing of the unburned fuel and air. A distorted air or fuel-flow profile would, of course, increase the time required for sufficient mixing. (2) At severe operating conditions there can be local blowoff of individual areas of the fuel-injector - flameholder system. This blowoff results in fuel-rich zones that pass unburned out of the burner, which is normally long enough for complete mixing. This blowoff could be intermittent or continuous for part of the injector as in the case of configuration A.

Flameholder Size

When the scale of the fuel-injector flameholder was reduced one-half (increasing the number of fuel-injector flameholders to 4), the combustion efficiency began to decline at high equivalence ratios. A possible explanation for the rich end drop is that the smaller injectors create a smaller scale of turbulence which decays more rapidly, thus creating a shorter mixing zone. This short mixing zone could be adequate at medium, but not at high equivalence ratios. The rapid drop in combustion efficiency at low equivalence ratios is similar in behavior to the larger flameholder. Presumably the same effect now occurs at a somewhat higher equivalence ratio. 4648

Data Accuracy

The maximum probable error in combustion efficiency from measurements of fuel, air, and quench-water flows was ±7 percent at the lowest fuel flows and ±2 percent at the highest fuel flows. The calorimeter heat loss of 10 to 20 Btu per second was about 1 to 20 percent of the total heat release depending on the fuel flow. The errors in the measurement of the calorimeter heat losses would result in a combustion efficiency error of ±5 percent at the lowest fuel flow to ±0.5 percent at the highest fuel flow. For example, run 23 of figure 7 reaches 104-percent combustion efficiency at an equivalence ratio of 0.20. If at a 0.20 equivalence ratio a 4-percent error were caused by a fixed calorimeter error, this fixed error would amount to less than 1 percent at a 1.0 equivalence ratio.

Burner Stability

The main contribution of the work reported herein was development of a stable flameholder fuel injector for use with hydrogen fuel at low burner pressures. The injection schemes of references 4, 5, and 6 all begin to suffer combustion efficiency or stability losses below 1/2-atmosphere pressure. By injecting fuel inside a sheltered zone, essentially a U-gutter, stable burning was possible to extremely low equivalence ratios of 0.05 and pressures of 5 inches of mercury absolute. The 5 inches of mercury absolute was a facility and not a stability limit. The scheme of injecting fuel into a sheltered zone not only increased burning stability, but also resulted in good combustion efficiency in a short length. Adding increasing amounts of air directly into the sheltered region raised the combustion efficiency even higher (92 to 99 percent, fig. 5(g)) with only a small decrease in stability. For another example, figure 7 shows that configuration B, a fully sheltered design, burned at 5 inches of mercury absolute, whereas configurations D and E with small amounts of air admitted to the sheltered region blew out at 5 inches of mercury absolute and only burned at pressures higher than 8 inches of mercury absolute.

Additional information about the optimum size or shape of this sheltered zone or where the fuel should be injected into it is still unknown. The wider of the two sizes of shrouds tried gave the better stability. This fact may be related to the hydrogen-air-flame quenching distance which increases rapidly at low pressures (ref. 3). Future designs might attempt to maintain a more desirable or constant fuel-air ratio inside the sheltered zone by using the fuel momentum to draw in additional air as the fuel flow is increased.

A moderate intensity buzz or resonance was occasionally heard with all configurations except A, F, and I. The buzz usually occurred as a function of pressure or fuel flow. If buzzing occurred, it would become audible at about a 0.3 equivalence ratio, increase in amplitude to about 0.5 equivalence ratio, and then die out at richer fuel flows. Buzz did not cause any increase in the temperature of the burner walls. The buzz was not screech in the burner itself, but presumably a resonance of the inlet or exhaust ducting of the burner.

Temperature Profile

The temperature profiles of all the injector configurations were satisfactory for ramjet uses where large exhaust temperature differences can be tolerated with small propulsive losses. Temperature profiles were improved so that: (1) Future use of turbojet primary fuel injectors may be possible, and (2) since a uniform temperature profile implies a complete reaction, if mixing is controlling, a shortened burner length may be possible. Increasing injector blockage does not always improve the temperature profile (fig. 6); the blockage must be added to improve mixing. Increasing the number of fuel injectors and keeping the same percent blockage, however, did almost halve the temperature profile factor as shown in figure 8. The amount of air admitted inside the shrouds seemed to have little effect on the temperature profile factor for those configurations with the rounded leading edge (zero- to 33-percent open area, fig. 5(g)).

The magnitudes of the $\Delta p/q$ flameholder pressure losses across the flameholders agree closely to the theoretical sudden expansion losses for the equivalent blocked areas. The only deviation from theoretical $\Delta p/q$ was between configurations G and B (fig. 6). Configuration B had slightly less $\Delta p/q$ than G even though their normal blocked areas at any axial station were equal. A possible explanation was that the tabs bent inward acted to diffuse the air around the shrouds, and the tabs bent outward acted as vortex generators, increasing the boundary-layer air energy and resulting in the air flowing around the tab rather than separating.

Full-Scale Engine Comparison

Figure 10 shows data taken with fuel-injector configurations A and D in both the connected-pipe burner and a full-size ramjet engine tested in the 10- by 10-foot supersonic wind tunnel. Configuration A was run in a 16-inch-diameter ramjet engine (ref. 6), and configuration D was run in a 28-inch-diameter ramjet engine. The agreement was excellent in the overlapping portions of the curves. The question raised by figure 10 was that of the fall-off of the 28-inch-diameter-engine lean-combustion efficiency data compared with the connected-pipe data, both using the same fuel-injector configuration D. 4648

SUMMARY OF RESULTS

Gaseous hydrogen fuel was burned in a connected-pipe combustor of cross section equal to a 35° sector of a 28-inch-diameter ramjet-engine combustor.

1. A shrouded fuel injector operated stably and efficiently at burner pressures (5 to 15 in. Hg abs) that were too low for a simple spray-bar fuel injector.

2. Combustion efficiencies above 95 percent were achieved from equivalence ratios of 0.1 to 0.46 at a pressure range of 7 to 12 inches of mercury absolute and a velocity range of 300 to 100 feet per second for the best shrouded configuration.

3. The most stable combustion was achieved with a configuration in which the upstream end of the shroud was completely blocked off.

4. Admitting air to the upstream end of the shroud increased the combustion efficiency level but caused the lean end of the efficiency curve to fall off at a higher equivalence ratio.

5. The completely shrouded fuel injector gave combustion efficiencies above 87 percent at equivalence ratios from 0.1 to 1.00 with a pressure range of 5 to 8 inches of mercury absolute but, due to a facility limit, at a lower velocity range of 190 to 110 feet per second.

6. Mixing tabs on the downstream end of the shrouds had no effect on combustion efficiency but improved the outlet-temperature profile.

7. Reducing the scale of the fuel injectors by one-half resulted in a marked improvement of the outlet-temperature profile, but the minimum burner pressure for stable combustion was increased from 5 to 8 inches of mercury absolute.

CONCLUDING REMARKS ON COMBUSTOR DESIGN

For burners operating over 1-atmosphere pressure a simple direct-spray system is usually adequate. The size of the fuel jets must be coarse enough to prevent blowoff and fine enough to insure proper mixing. References 4 and 5 give details of several types of direct spray-bar systems. For the intermediate pressure range of 1/2 to 1 atmosphere, the simple spray bar might work, but the sheltered-zone type would probably be preferred because durability should not be a severe problem. A 4648 shroud similar to the one used in this report will add about a 3-percent pressure loss due to the blockage but should increase the combustion efficiency nearly to 100 percent.

For burners operating at 1/2- to 1/6-atmosphere pressure, burner stability can be insured by injecting the fuel in a sheltered region and partially burning it there at an over-rich equivalence ratio. (Hydrogen has a maximum flame speed at an equivalence ratio of 2.0). Then the hot fuel-rich stream is mixed with the additional air downstream of the sheltered region to complete combustion and to reach the desired over-all equivalence ratio or temperature. The size of this sheltered region can not be too small, or the burner stability will be impaired; the width should probably be no smaller than about 1 inch. For high combustion efficiencies at extremely low equivalence ratios, a completely shrouded fuel injector should be used. For better combustion efficiency at medium and high equivalence ratios, up to 1/6 of the total air is admitted directly inside the shroud. Mixing tabs on the shroud will provide a better temperature profile and possibly a shorter burner length. It is not known if the manner of injecting fuel inside the shroud is important.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 27, 1957

REFERENCES

1. Silverstein, Abe, and Hall, Eldon, W.: Liquid Hydrogen as a Jet Fuel for High-Altitude Aircraft. NACA RM E55C28a, 1955.

2. Drell, Isadore L., and Belles, Frank E.: Survey of Hydrogen Combustion Properties. NACA RM E57D24, 1957.

3. Dangle, E. E., and Kerslake, William R.: Experimental Evaluation of Gaseous Hydrogen Fuel in a 16-Inch-Diameter Ram-Jet Engine. NACA RM E55J18, 1955.

4. Krull, H. George, and Burley, Richard R.: Effect of Burner Design Variables on Performance of a 16-Inch-Diameter Ram-Jet Combustor Using Gaseous-Hydrogen Fuel. NACA RM E56J08, 1957.

5. Kerslake, W. R., and Dangle, E. E.: Tests with Hydrogen Fuel in a Simulated Afterburner. NACA RM E56D13a, 1956.

6. Bailey, A., and Lyell, N. C.: Loss of Heat from External Surface of Hot Pipe in Air. Engineering, vol. 147, no. 3810, June 20, 1939, pp. 60-62. 4648

7. Wasserbauer, Joseph F., and Wilcox, Fred A.: Combustor Performance of a 16-Inch-Ram-Jet Using Gaseous Hydrogen as Fuel at Mach Number 3.0. NACA RM E56K28a, 1957.

TABLE I. - PERFORMANCE DATA OF HYDROGEN FUEL IN 35° WEDGE SECTION OF A 28-INCH DIAMETER RAMJET

Run	Configu-ration	Equiva-lence ratio	Combustion efficiency, percent	Burner inlet				Profile factor, $\frac{T_{max} - T_{min}}{\Delta T}$
				Airflow, lb/sec	Pressure, in. Hg abs	Temper-ature, °F	Velocity, ft/sec	
1	A	0.197	33.1	1.69	8.7	256	260	0.92
		.206	57.5	1.71	8.45	253	270	1.03
		.233	37.3	1.69	9.0	259	251	1.11
		.256	38.7	1.69	9.3	260	245	1.10
		.287	39.0	1.69	9.6	261	237	1.00
		.315	89.5	1.69	11.75	247	191	.17
		.328	81.7	1.70	12.2	262	186	.19
		.332	87.6	1.74	12.9	248	179	.32
		.350	94.5	1.72	12.75	247	179	.25
		.364	89.2	1.74	13.4	242	170	.26
		.403	93.5	1.74	14.1	241	162	.22
2	A	0.158	30.3	2.08	9.40	243	282	0.89
		.182	33.2	2.45	11.1	224	282	1.07
		.264	55.2	2.47	13.3	224	237	1.03
		.303	88.3	2.09	14.65	232	185	.39
3	A	0.193	50.8	2.02	11.80	248	227	1.00
		.230	54.6	2.04	14.15	245	190	.31
		.235	56.3	1.91	13.3	259	187	.26
		.254	74.3	2.05	14.85	246	181	.25
		.257	67.2	1.98	14.1	235	183	.15
		.276	68.5	2.02	15.0	230	174	.33
		.256	91.0	2.02	16.05	246	167	.38
		.331	84.0	1.92	15.2	233	164	.24
		.347	90.3	2.03	16.75	245	161	.27
4	A	0.195	47.5	1.74	13.8	239	165	0.23
		.250	61.4	1.74	14.1	257	162	.20
		.254	76.3	1.74	13.6	259	165	.31
		.315	91.0	1.74	13.9	258	164	.36
		.357	95.5	1.74	13.8	236	165	.23
5	A	0.227	67.3	2.31	23.7	237	127	0.21
		.227	70.8	2.31	25.0	236	146	.20
		.229	63.6	2.33	17.0	236	176	.31
6	B	0.046	85.6	1.50	7.26	251	274	0.07
		.046	87.9	1.50	7.16	250	270	.07
		.051	76.7	1.50	7.17	249	277	.09
		.053	83.4	1.50	7.32	250	272	.09
		.054	86.9	1.50	7.26	250	274	.11
		.062	90.1	1.50	7.36	250	270	.10
		.074	87.0	1.50	7.46	250	260	.15
		.074	88.8	1.50	7.45	249	280	.28
		.088	89.3	1.50	7.51	250	252	.17
		.102	88.4	1.49	8.33	250	238	.40
		.111	88.5	1.50	8.31	250	240	.25
		.140	92.2	1.50	8.81	250	226	.26
		.161	93.6	1.49	9.09	252	218	.45
		.178	90.5	1.50	9.26	251	215	.27
		.210	94.0	1.48	9.79	252	201	.52
		.227	90.1	1.50	9.86	251	203	.34
		.231	89.4	1.50	10.02	253	199	.31
		.264	90.7	1.50	10.52	253	190	.23
		.291	92.5	1.50	10.82	250	184	.19
		.302	93.7	1.50	10.77	247	185	.25
		.327	91.1	1.50	11.07	253	180	.16
		.350	92.0	1.50	11.42	250	175	.12
		.376	94.8	1.50	11.46	247	173	.18
		.385	90.0	1.50	11.47	252	174	.12
		.421	88.7	1.50	11.82	251	169	.14
		.441	91.7	1.50	11.97	252	187	.15
		.460	89.4	1.50	12.02	252	166	.15
		.460	92.6	1.50	12.08	247	165	.15
7	B	0.019	79.2	4.0	16.23	233	320	0.06
		.027	83.7	4.0	16.93	234	306	.03
		.040	92.1	4.0	17.91	236	290	.07
		.080	97.1	4.01	19.99	237	261	.36
		.116	93.5	4.0	21.87	232	237	.65
		.171	94.2	4.0	24.07	231	215	.71
8	C	0.050	40.9	1.46	6.66	257	295	0.32
		.055	48.6	1.45	6.55	251	295	.22
		.076	81.7	1.45	7.40	251	281	.24
		.078	82.4	1.46	7.62	260	259	.19
		.079	88.9	1.45	7.62	258	256	.19
		.103	87.6	1.45	7.90	254	243	.36
		.103	91.5	1.45	7.90	252	244	.34
		.120	95.0	1.45	8.37	260	233	.36
		.135	91.7	1.45	8.45	255	226	.42
		.171	97.7	1.46	9.08	255	214	.38
		.177	96.3	1.43	9.02	262	214	.32
		.186	94.5	1.44	9.15	257	208	.47
		.230	99.8	1.46	9.86	255	197	.40
		.240	95.6	1.43	9.73	259	196	.33
		.307	94.4	1.46	10.67	255	183	.35
		.367	94.8	1.46	11.38	255	171	.32
		.476	93.0	1.46	12.03	255	183	.27
9	C	0.019	47.6	4.06	16.20	242	328	0.20
		.024	69.2	4.06	17.47	322	340	.21
		.024	76.5	4.04	17.47	329	341	.21
		.031	84.5	4.06	17.47	239	304	.13
		.046	94.1	4.06	18.66	261	289	.15
		.046	94.8	4.06	18.67	237	283	.054
		.049	93.0	4.02	19.25	338	312	.21
		.074	101.8	4.06	20.31	235	260	.27
		.083	97.9	4.06	21.30	314	276	.35
		.084	98.6	4.00	21.25	349	264	.31
		.102	101.0	4.06	21.63	254	241	.42
		.115	97.9	4.06	22.85	312	256	.51
		.130	97.7	4.06	23.10	233	226	.49
		.153	97.4	4.06	24.60	310	236	.59
		.164	98.0	4.06	24.40	233	216	.52
		.175	95.0	4.06	25.12	308	232	.62
10	D	0.102	69.0	1.49	7.4	255	270	0.64
		.112	65.5	1.45	7.46	247	257	.31
		.113	61.9	1.45	7.41	247	259	.30
		.134	88.4	1.46	8.5	256	232	.66
		.163	96.2	1.47	9.0	257	219	.65
		.172	92.6	1.45	8.89	247	216	.39
		.194	97.7	1.49	9.5	258	211	.63
		.227	98.0	1.47	9.9	260	200	.56
		.228	99.7	1.48	9.9	254	200	.58
		.234	100.0	1.45	9.96	247	193	.38
		.279	95.5	1.49	10.45	254	190	.51
		.300	96.0	1.45	10.40	247	185	.33
		.322	98.5	1.49	11.05	264	181	.45
		.368	93.3	1.45	11.08	247	173	.26
		.386	94.6	1.49	11.6	254	172	.37
		.439	92.7	1.45	11.71	247	163	.24
		.439	94.0	1.49	12.1	255	165	.36
		.472	92.9	1.49	12.4	255	160	.35
		.493	91.6	1.45	12.06	247	158	.23

TABLE I. Concluded. PERFORMANCE DATA OF HYDROGEN FUEL IN 35° WEDGE SECTION OF A 28-INCH-DIAMETER RAMJET

Run	Configuration	Equivalence ratio	Combustion efficiency, percent	Burner inlet				Profile factor, $\frac{T_{max} - T_{min}}{\Delta T}$
				Airflow, lb/sec	Pressure, in. Hg abs	Temperature, °F	Velocity, ft/sec	
11	D	0.018	87.6	4.07	15.78	228	331	0.20
		.034	76.5	4.07	17.19	228	306	.09
		.056	90.0	4.07	18.84	232	290	.21
		.067	88.4	4.07	18.88	226	277	.20
		.085	98.9	4.05	20.64	234	265	.28
		.118	97.5	4.04	22.11	257	258	.44
		.145	96.0	4.07	23.63	226	221	.49
		.147	96.4	4.07	23.75	226	220	.48
		.176	94.6	4.07	24.88	226	211	.48
12	E	0.204	93.6	1.48	9.88	255	191	0.33
		.214	96.9	1.52	10.26	255	191	.40
		.265	99.0	1.43	10.27	256	181	.41
		.324	97.0	1.42	10.94	257	189	.39
		.396	96.4	1.42	11.66	259	180	.27
		.485	95.2	1.42	12.29	259	180	.20
13	F	0.133	58.0	1.50	7.88	245	262	0.72
		.197	96.7	1.50	9.38	245	211	.75
		.254	96.5	1.50	10.13	245	195	.72
		.320	99.2	1.50	10.66	246	186	.69
		.389	92.4	1.50	11.11	246	178	.74
		.470	97.3	1.50	11.59	245	171	.75
14	F	0.048	96.4	3.91	18.06	258	326	1.15
		.078	96.0	3.99	19.96	252	278	1.45
		.109	94.6	4.00	20.88	245	252	1.64
		.142	92.2	3.90	21.84	246	285	1.49
		.179	92.1	3.93	23.28	245	223	1.32
15	G	0.061	78.5	1.48	7.11	250	276	0.68
		.079	86.0	1.48	7.61	248	257	.91
		.118	91.1	1.48	8.16	247	240	1.12
		.182	90.7	1.48	8.71	247	226	1.13
		.226	95.6	1.48	9.41	247	208	1.07
		.308	90.3	1.48	9.98	248	197	.88
		.396	84.6	1.48	10.48	246	187	.76
		.487	88.3	1.48	10.96	248	179	.83
16	G	0.019	72.0	4.04	16.81	232	317	0.24
		.044	91.8	4.15	18.36	224	290	.72
		.064	93.5	4.15	20.41	223	268	1.27
		.127	88.0	4.06	22.36	224	233	1.59
		.181	88.7	4.08	23.98	225	217	1.24
17	H	0.055	96.1	1.48	7.58	242	255	0.20
		.081	87.2	1.48	7.87	242	244	.50
		.081	89.6	1.48	7.89	242	243	.50
		.114	94.3	1.48	8.34	243	229	.62
		.170	96.2	1.46	8.64	241	222	.82
		.235	94.2	1.48	9.14	241	209	.81
		.304	90.3	1.49	10.19	210	184	.76
		.364	89.6	1.48	10.46	212	178	----
		.432	98.3	1.48	10.70	214	175	----
		.484	87.6	1.48	11.00	215	169	----
18	H	0.019	78.5	4.27	17.78	210	303	0.17
		.030	87.3	4.28	18.81	214	288	.20
		.044	90.6	4.29	19.96	214	271	.34
		.045	95.6	4.16	19.81	222	269	.28
		.080	96.6	4.24	21.77	210	245	.80
		.106	95.9	4.25	22.87	208	232	1.04
		.144	93.6	4.24	23.87	208	220	1.12
		.170	91.1	4.24	24.57	204	216	1.12
19	I	0.051	68.2	1.49	7.01	239	278	0.39
		.065	72.5	1.49	7.28	239	268	.40
		.080	79.0	1.47	7.48	242	258	.38
		.080	86.7	1.47	7.58	240	254	.38
		.107	85.8	1.47	8.05	242	240	.38
		.137	88.9	1.47	8.45	245	230	.36
		.163	93.3	1.49	9.15	239	215	.38
		.184	89.8	1.47	9.08	245	215	.40
		.230	94.7	1.49	9.60	250	205	.42
		.280	93.0	1.49	10.13	259	192	.49
		.365	95.7	1.49	10.83	239	160	.49
		.429	90.8	1.49	11.25	240	175	.55
		.490	87.5	1.48	11.68	240	168	.63
20	I	0.016	78.2	4.00	15.98	245	329	0.31
		.028	80.0	3.98	16.58	244	315	.13
		.042	85.0	4.02	17.85	246	308	.38
		.046	88.1	4.00	17.75	244	296	.36
		.074	87.3	4.02	19.48	247	273	.38
		.101	87.8	4.00	20.78	249	255	.39
		.144	95.1	3.98	22.09	242	238	1.64
		.185	89.7	3.99	23.53	242	222	1.61
21	B	0.099	59.0	0.695	4.75	251	188	0.46
		.156	80.0	.690	5.07	231	176	.42
		.290	94.0	.690	5.64	231	156	.39
		.419	90.7	.692	6.05	231	146	.27
		.554	87.8	.690	6.59	252	140	.22
		.718	90.9	.680	7.53	254	117	----
		.853	86.0	.680	7.78	254	113	----
		.995	86.1	.680	8.00	238	110	----
22	D	0.152	98.6	0.707	8.34	228	109	0.59
		.334	101.2	.720	9.72	238	98	.42
		.478	97.5	.707	10.47	228	86	.29
		.690	95.1	.707	11.70	229	78	.26
		.769	97.8	.704	12.82	250	71	----
23	D	0.789	93.2	0.697	7.32	230	123	----
		.956	90.8	.695	7.42	252	108	----
		1.003	86.5	.695	7.67	233	104	----
24	H	0.108	78.0	0.700	8.07	251	112	0.44
		.159	104.9	.700	8.61	251	102	.43
		.292	104.0	.700	9.79	251	94	.38
		.394	99.4	.690	10.57	252	84	.38
		.529	99.6	.690	11.79	252	78	.32
		.696	95.3	.690	13.31	253	67	----
		.842	90.8	.690	14.36	253	62	----
		.969	96.8	.690	15.39	254	58	----
25	J	0.100	80.9	0.690	5.76	256	161	0.26
		.161	87.8	.690	6.06	256	153	.21
		.214	92.0	.690	6.22	257	150	.24
		.336	97.9	.690	6.65	255	140	.11
		.463	96.5	.686	6.75	253	137	.10
		.633	94.6	.685	7.00	255	132	.10
		.727	89.7	.686	7.20	255	129	.10
		.862	78.5	.686	7.25	256	126	.10
26	K	0.222	92.9	0.680	8.43	249	106	0.22
		.380	90.3	.680	8.31	248	107	.19
		.482	91.0	.680	8.38	247	106	.18
		.631	91.5	.680	8.38	248	106	----
		.789	88.2	.678	8.56	246	108	----
		.909	88.6	.676	8.13	248	110	----
		.919	89.8	.675	8.35	246	107	----
		1.011	86.6	.670	8.43	248	106	----

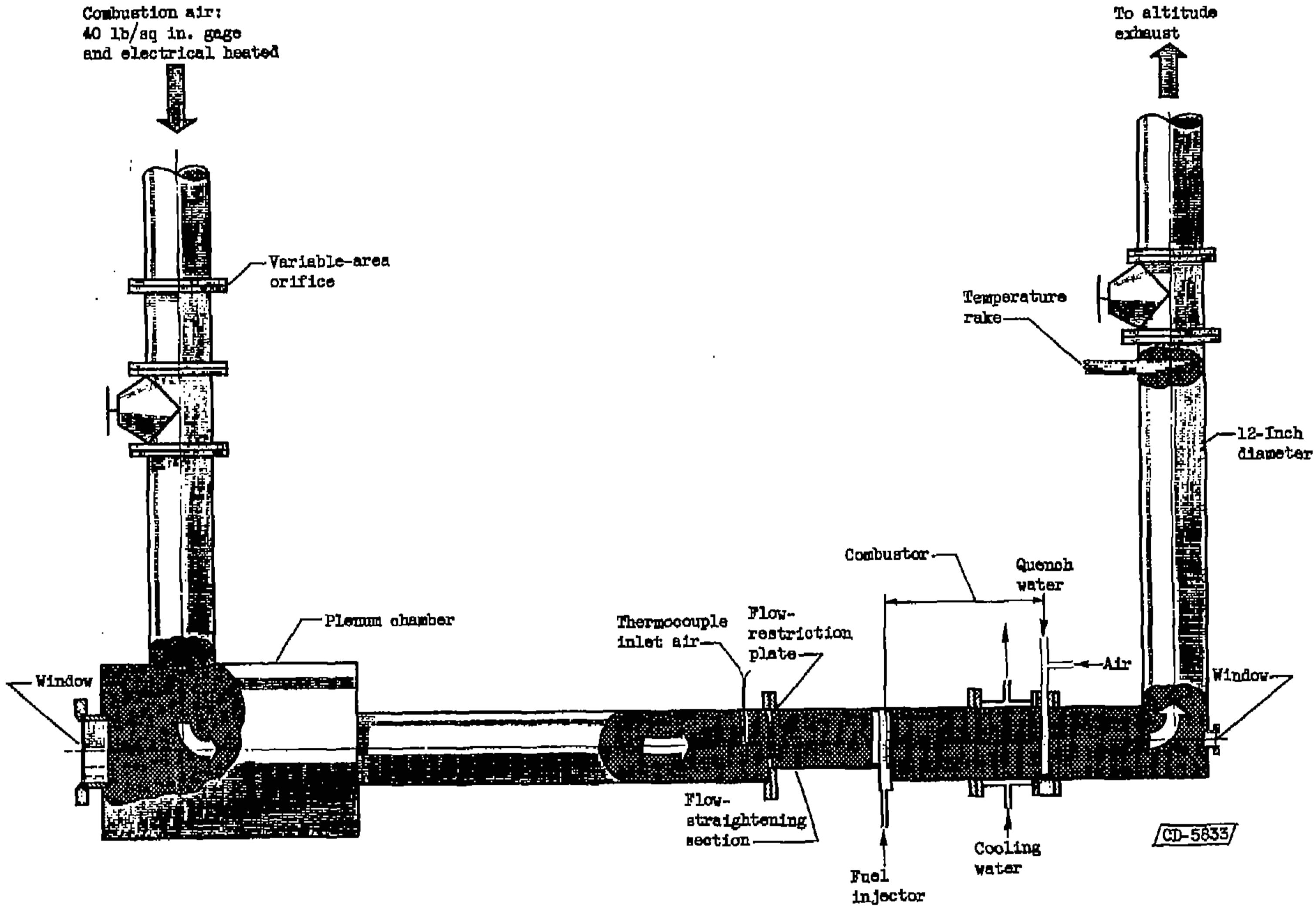


Figure 1. - Schematic diagram of the installation of a connected-pipe ramjet combustor.

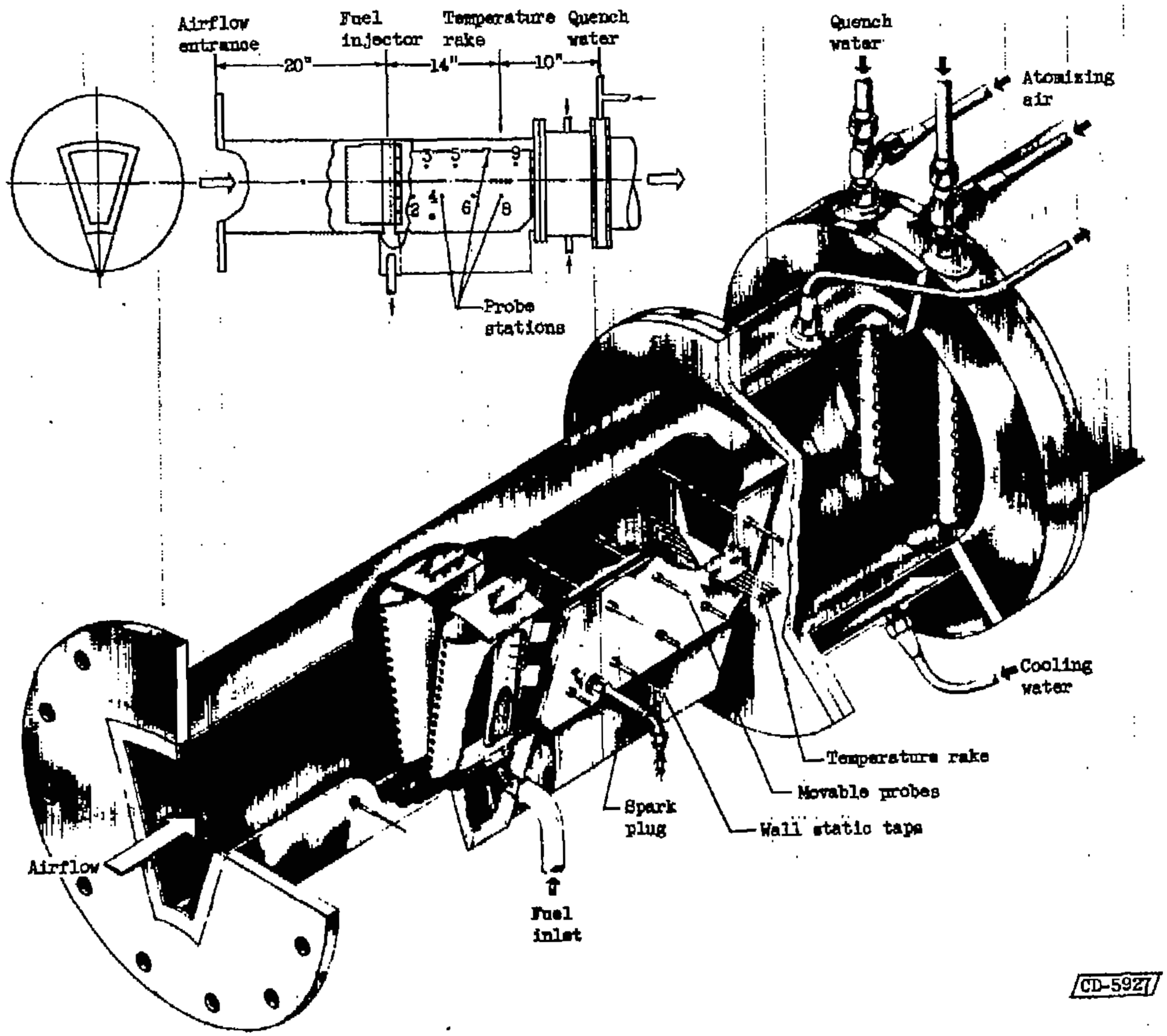


Figure 2. - Detail view of the 35°-wedge section of a 28-inch-diameter ramjet combustor.

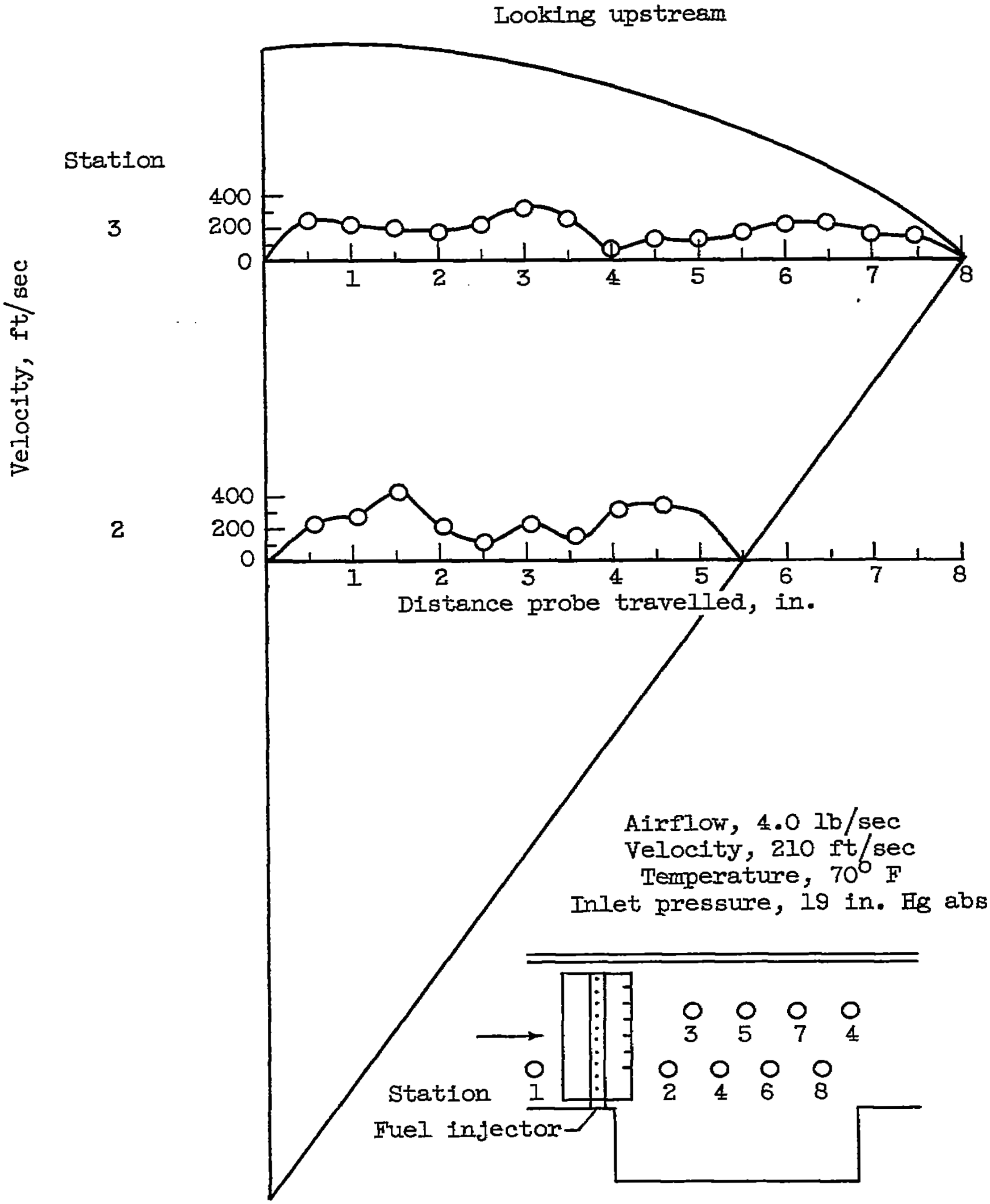
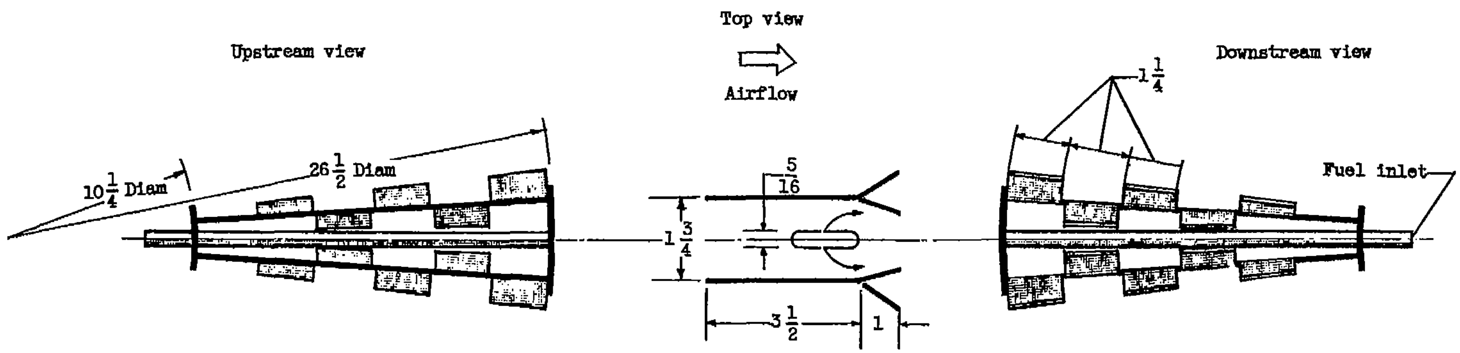
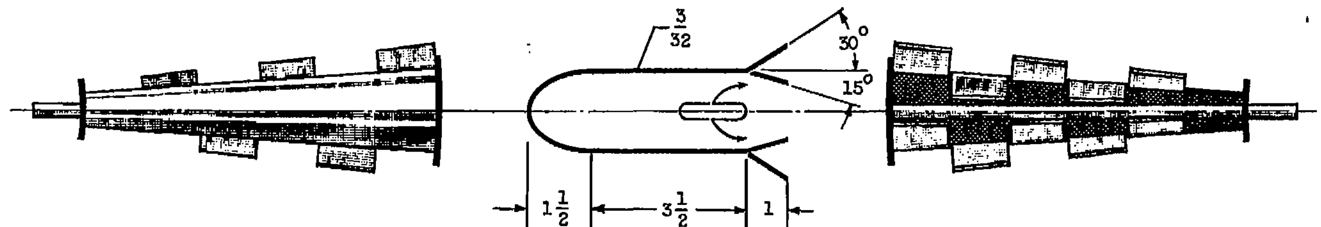


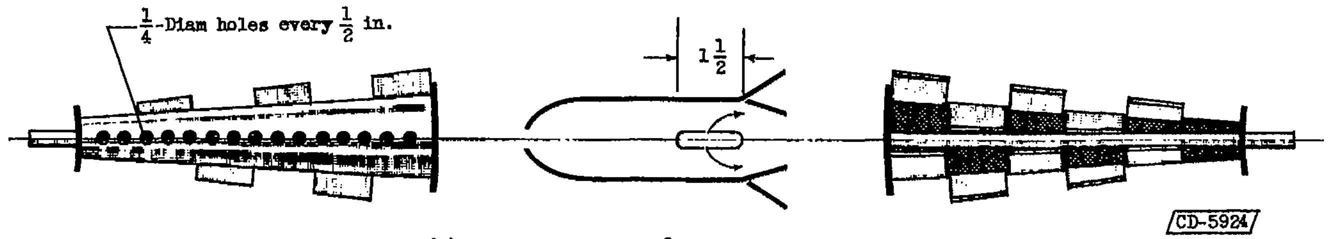
Figure 3. - Air velocity profiles downstream of flameholders (no heat addition). Flameholder configuration E.



(a) Configuration A, 35° two-injector flameholders.

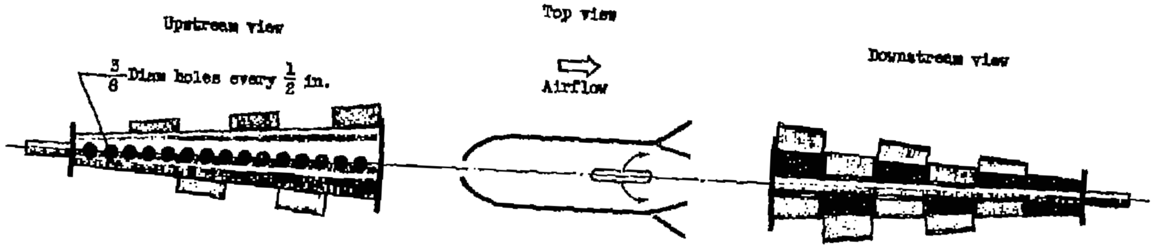


(b) Configuration B, 35° two-injector flameholders.

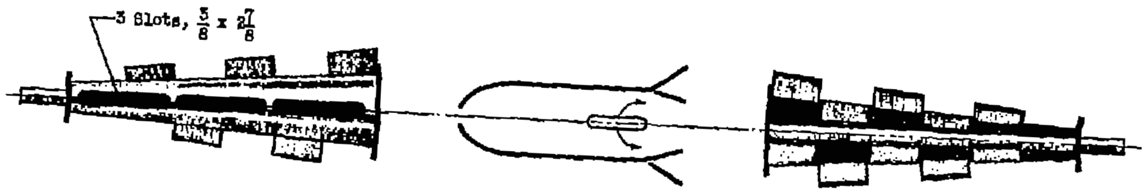


(c) Configuration C, 35° two-injector flameholders.

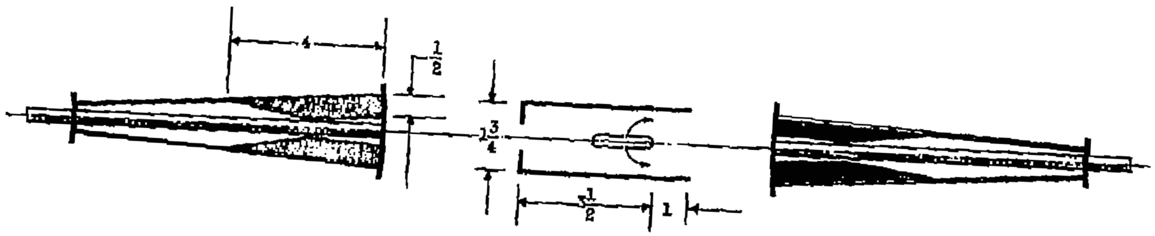
Figure 4. - Details of fuel-injector flameholders used in a 35° sector of a 28-inch-diameter ramjet combustor. (All dimensions in inches.)



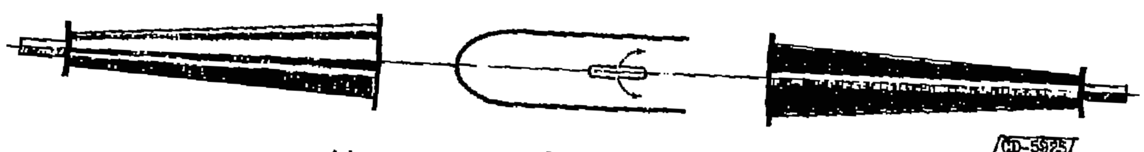
(d) Configuration D, 35° two-injector flameholders.



(e) Configuration E, 35° two-injector flameholders.

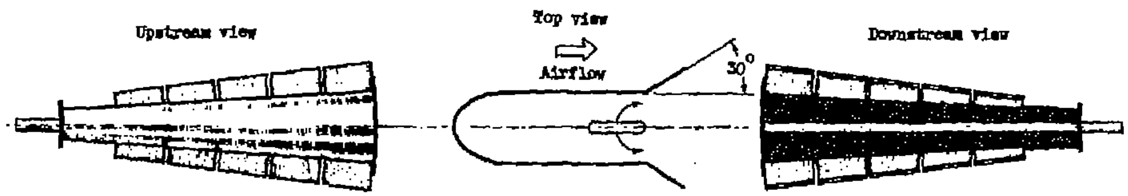


(f) Configuration F, 35° two-injector flameholders.

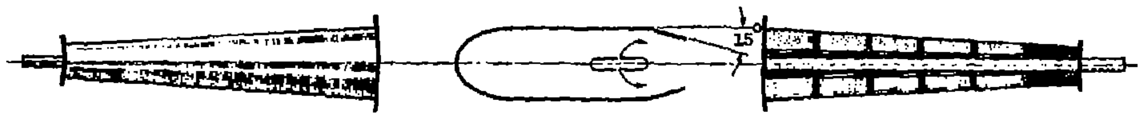


(g) Configuration G, 35° two-injector flameholders.

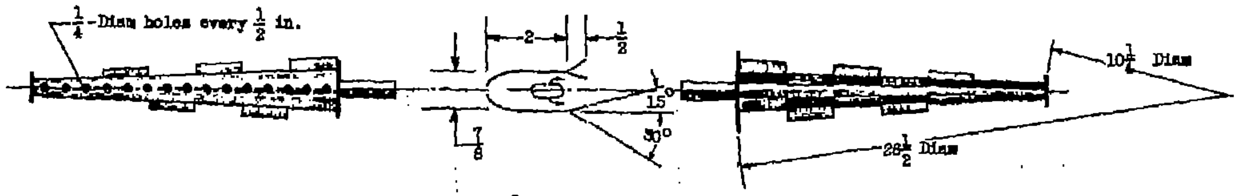
Figure 4. - Continued. Details of fuel-injector flameholders used in the 35° sector of a 28-inch-diameter ramjet combustor. (All dimensions in inches.)



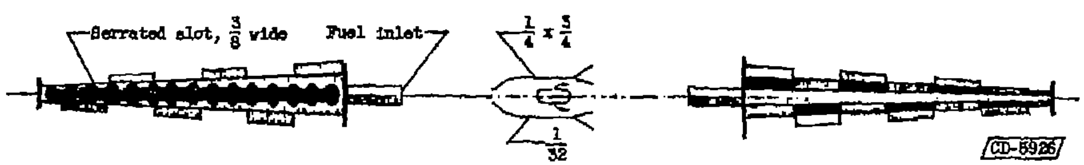
(h) Configuration H, 35° two-injector flameholders.



(i) Configuration I, 35° two-injector flameholders.



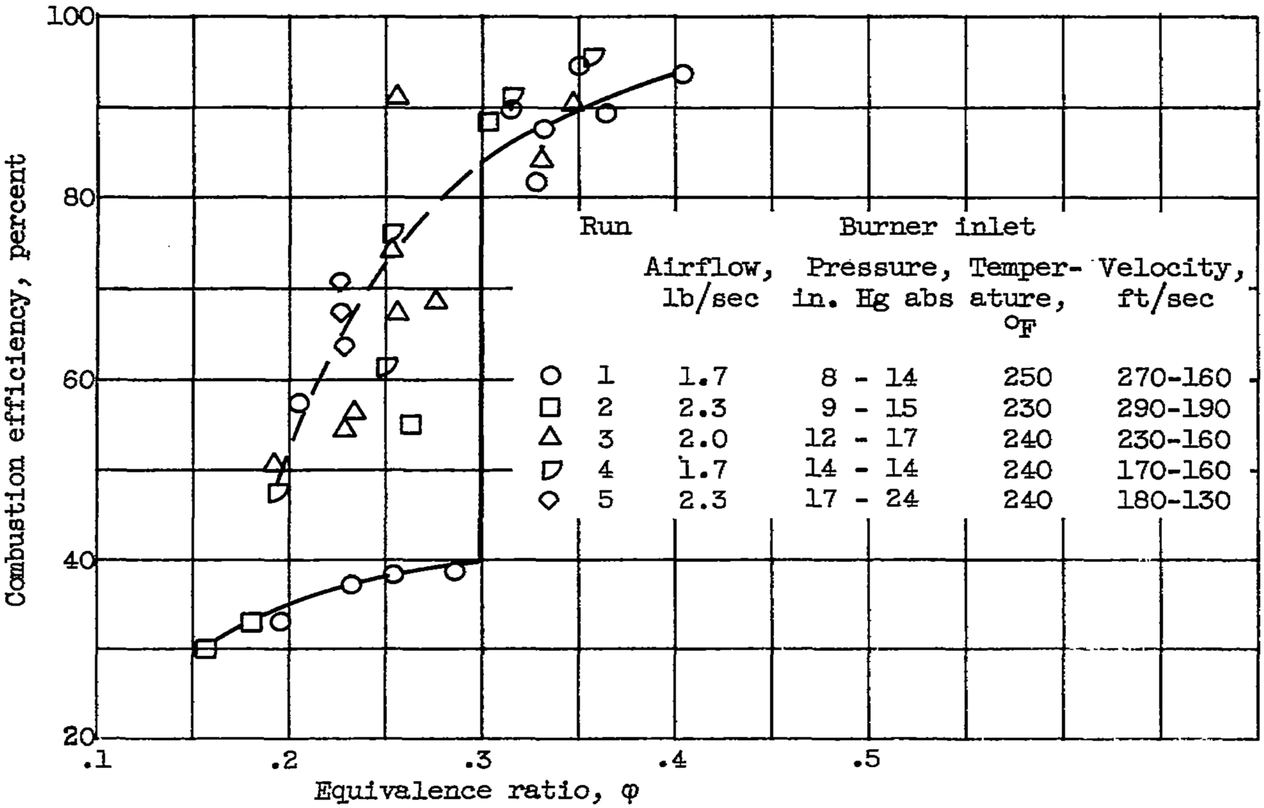
(j) Configuration J, 35° four-injector flameholders.



(k) Configuration K, 35° four-injector flameholders.

Figure 4. - Concluded. Details of fuel-injector flameholders used in a 35° sector of a 28-inch-diameter ramjet combustor. (All dimensions in inches.)

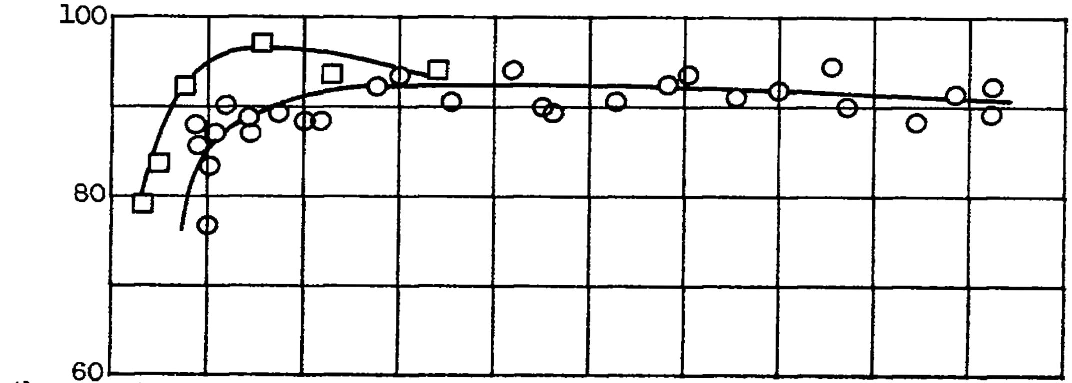
4648



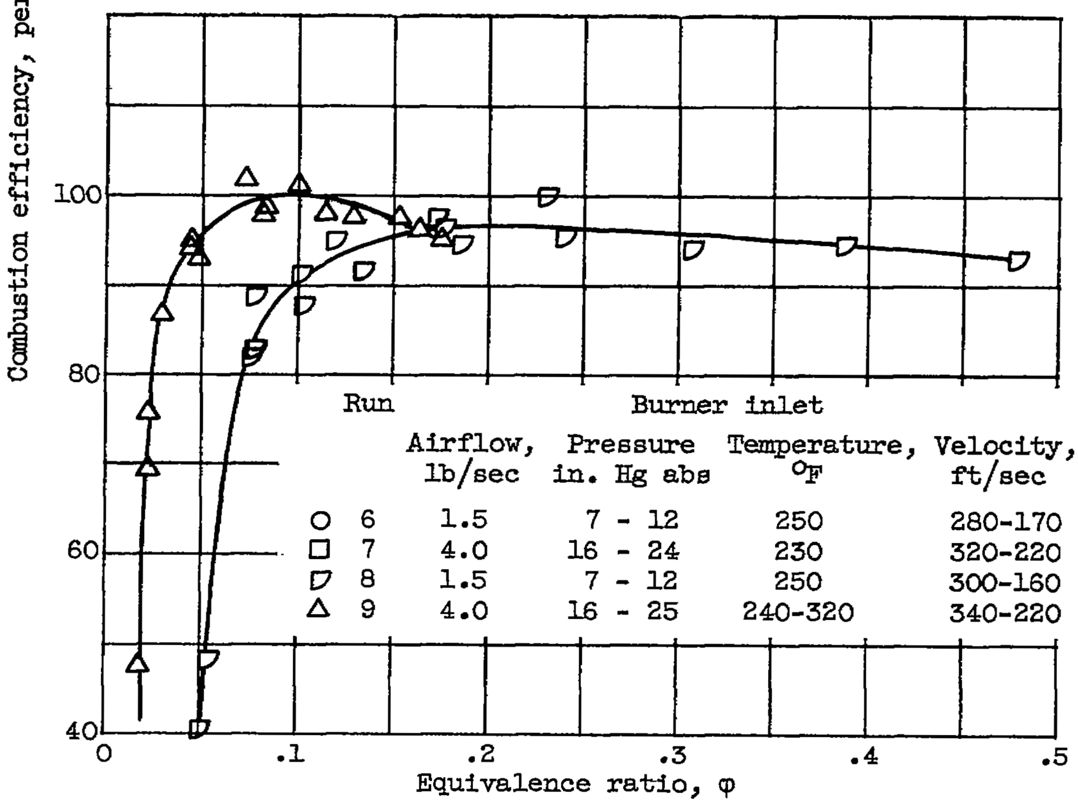
(a) Configuration A; 100-percent open area between shrouds; cold flow, 0.15; 35° two-flameholder units. (Original configuration, similar to ref. 7).

Figure 5. - Combustion efficiency of various flameholder - fuel-injector configurations in a 35°-wedge section of a 28-inch-diameter ramjet combustor. Variations of open area in the leading edge of the flameholder.

[redacted]



(b) Configuration B; zero percent open area between shrouds; cold flow, 1.2; 35° two-flameholder units.

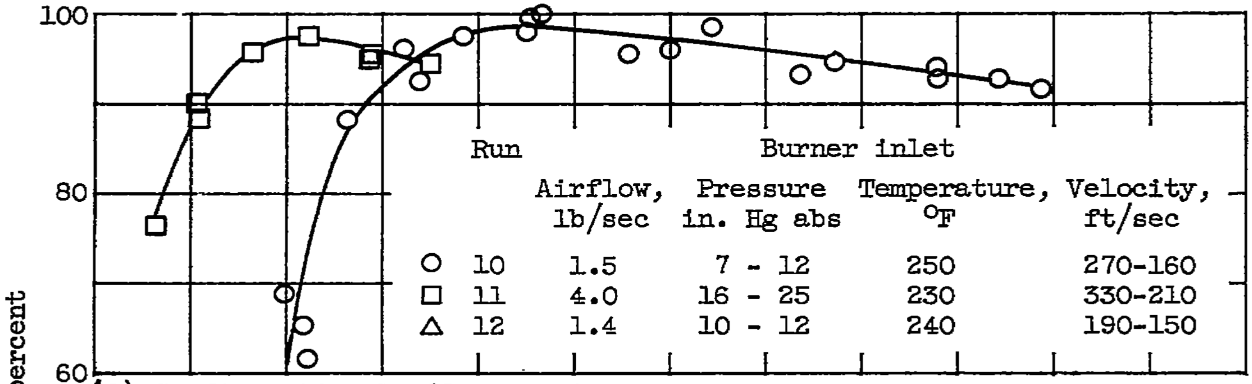


(c) Configuration C; 9-percent open area between shrouds; cold flow, 0.9; 35° two-flameholder units.

Figure 5. - Continued. Combustion efficiency of various flameholder - fuel-injector configurations in a 35°-wedge section of a 28-inch-diameter ramjet combustor. Variations of open area in the leading edge of the flameholder.

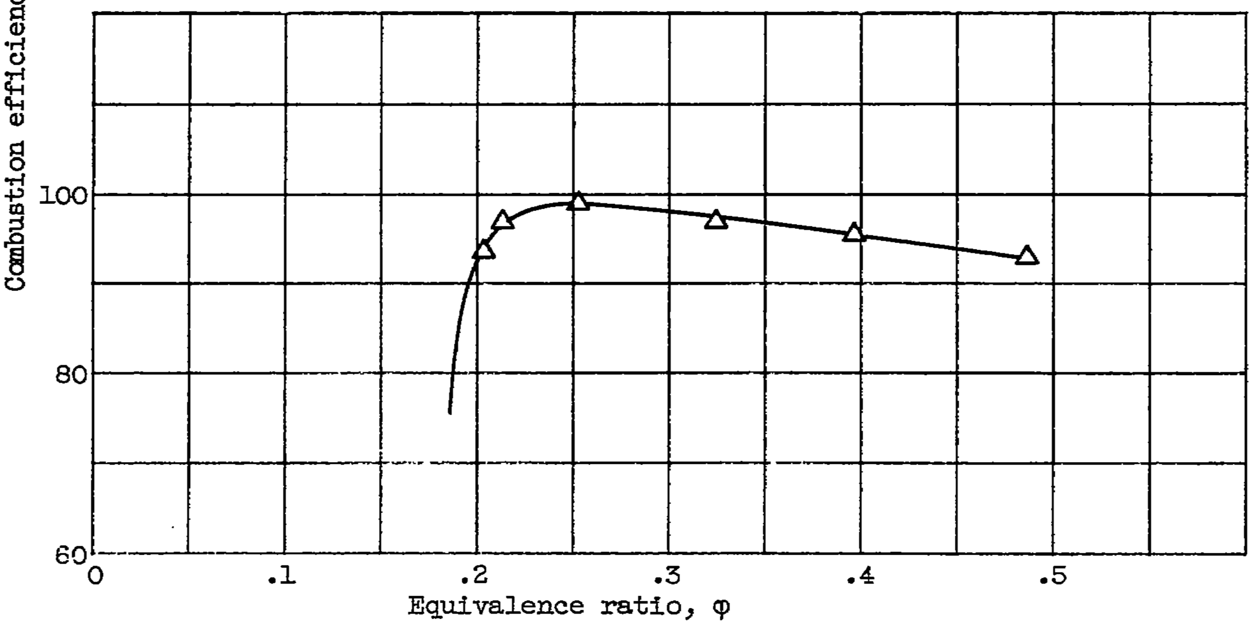
4648

4648



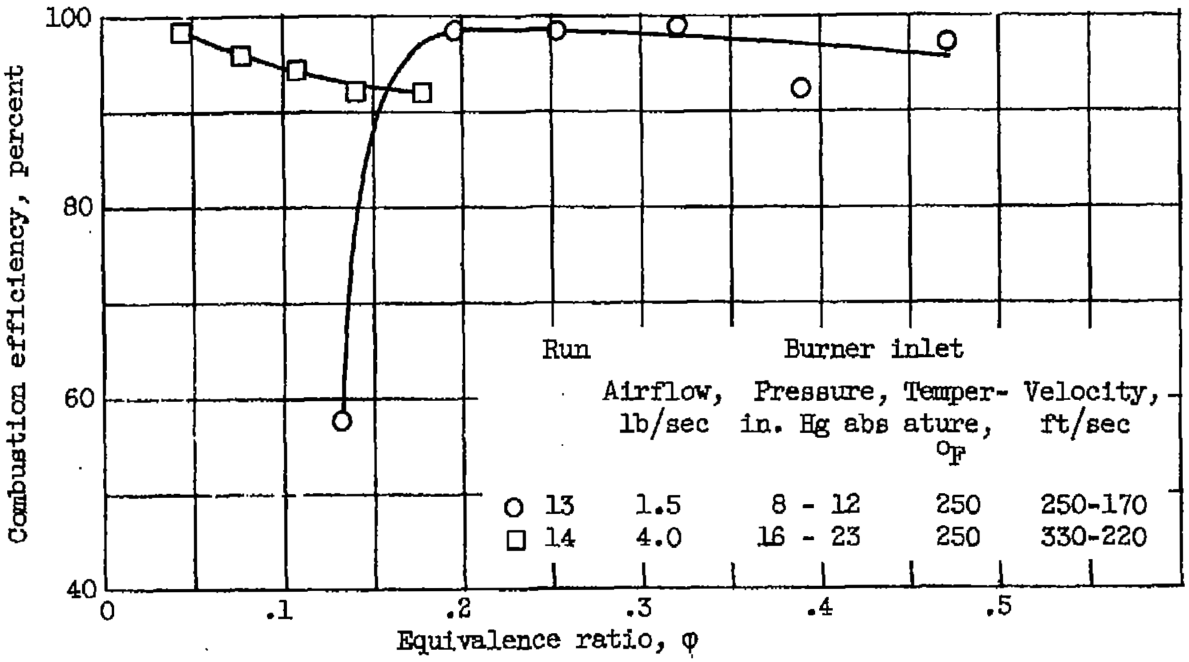
(d) Configuration D; 21-percent open area between shrouds; cold flow, 0.7; 35° two-flameholder units.

CR-4



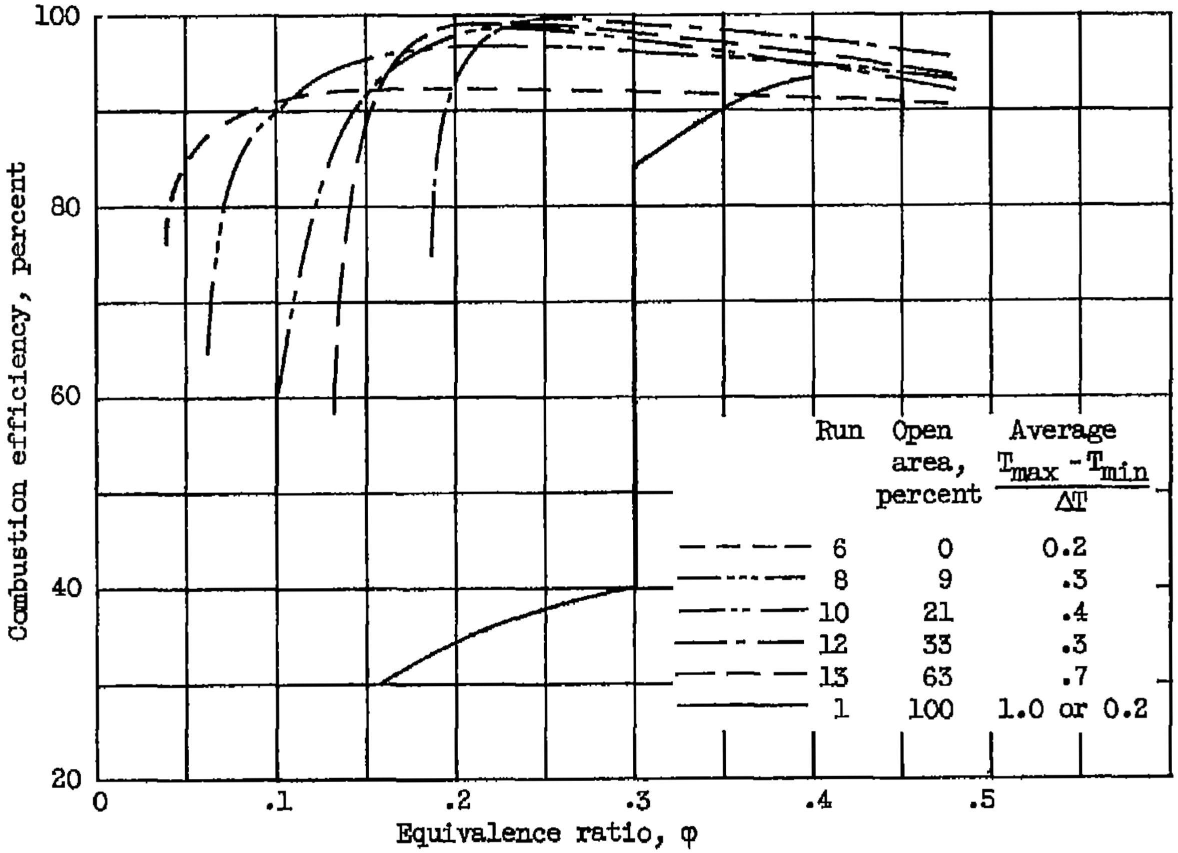
(e) Configuration E; 33-percent open area between shrouds; cold flow, 0.7; 35° two-flameholder units.

Figure 5. - Continued. Combustion efficiency of various flameholder - fuel-injector configurations in a 35°-wedge section of a 28-inch-diameter ramjet combustor. <u>Variations of open area in the leading edge of the flameholder</u>.



(f) Configuration F; 63-percent open area between shrouds; cold flow, 0.2; 35° two-flameholder units.

Figure 5. - Continued. Combustion efficiency of various flameholder - fuel-injector configurations in a 35°-wedge section of a 28-inch-diameter ramjet combustor. Variations of open area in the leading edge of the flameholder.



(g) Comparison of configurations A to F at the same test conditions; airflow, 1.5 pounds per second; pressure, 7 to 12 inches of mercury absolute; velocity, 330 to 160 feet per second; and temperature, 250° F.

Figure 5. - Concluded. Combustion efficiency of various flameholder - fuel-injector configurations in a 35°-wedge section of a 28-inch-diameter ramjet combustor. Variations of open area in the leading edge of the flameholder.

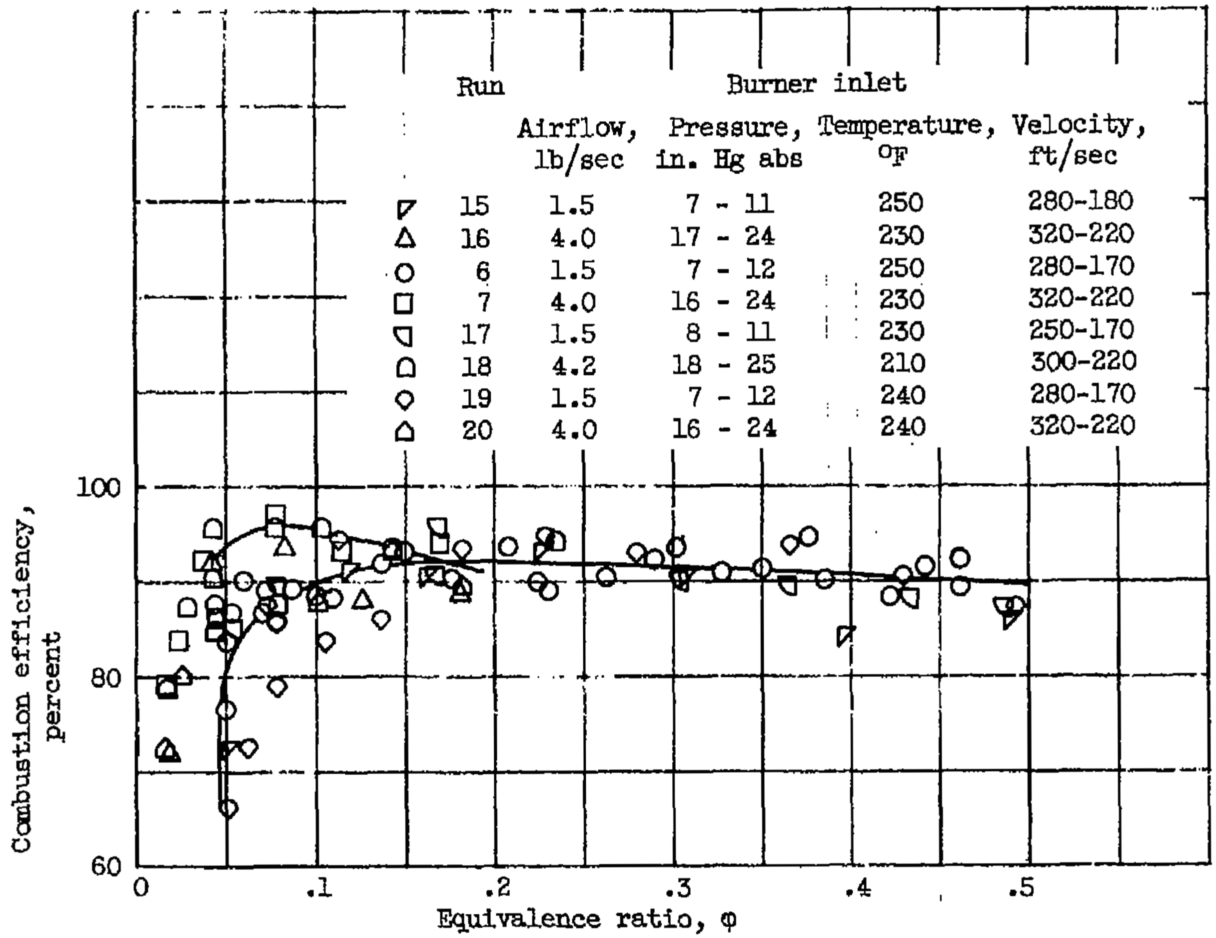


Figure 6. - Combustion efficiency of various flameholder - fuel-injector configurations in a 35°-wedge section of a 28-inch-diameter ramjet combustor. Effect of mixing tabs; 35° two-flameholder units; zero-percent open area between shrouds.

4648

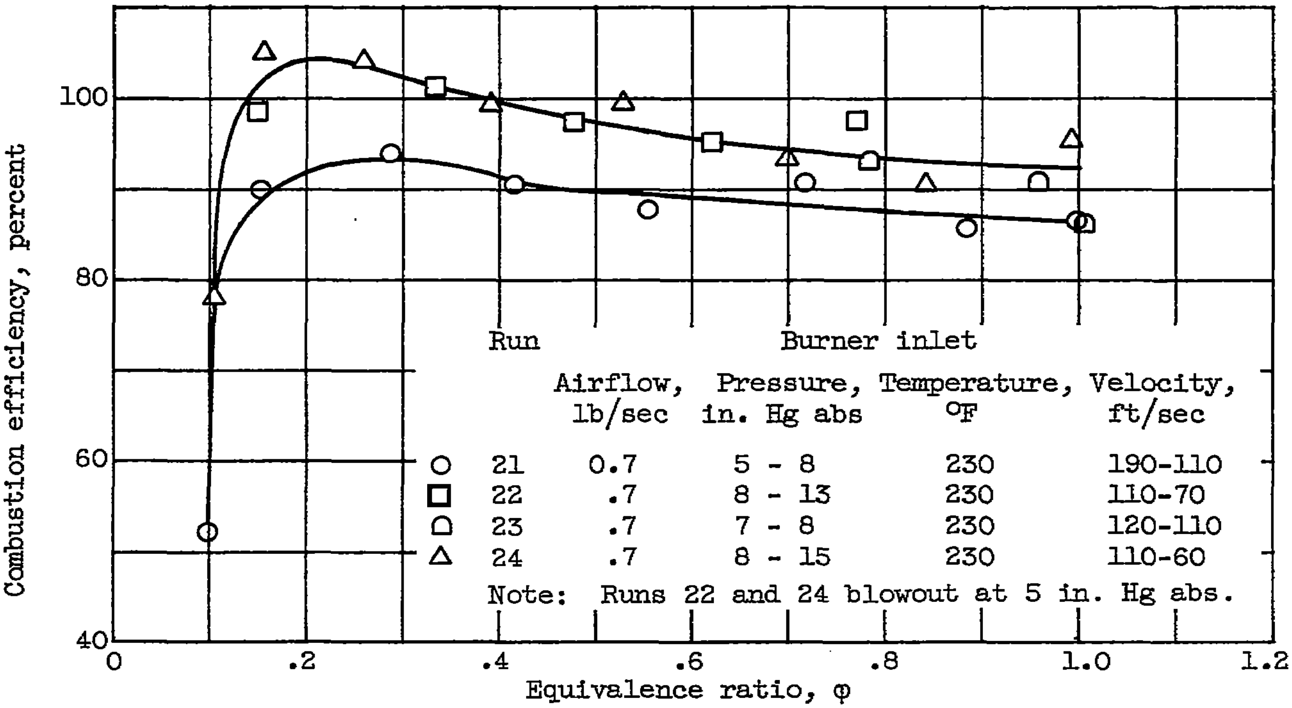


Figure 7. - Combustion efficiency of various flameholder - fuel-injector configurations in a 35°-wedge section of a 28-inch-diameter ramjet combustor. Performance at high equivalence ratios; 35° two-flameholder units. (Note compressed equivalence-ratio scale.)

4648

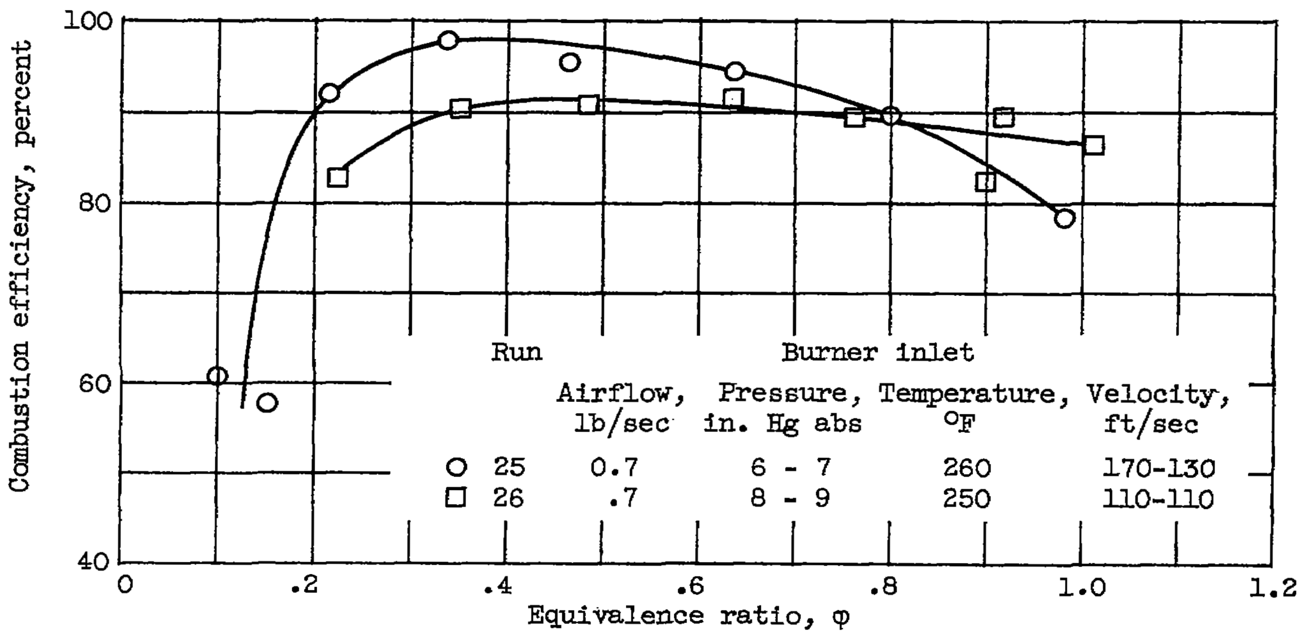
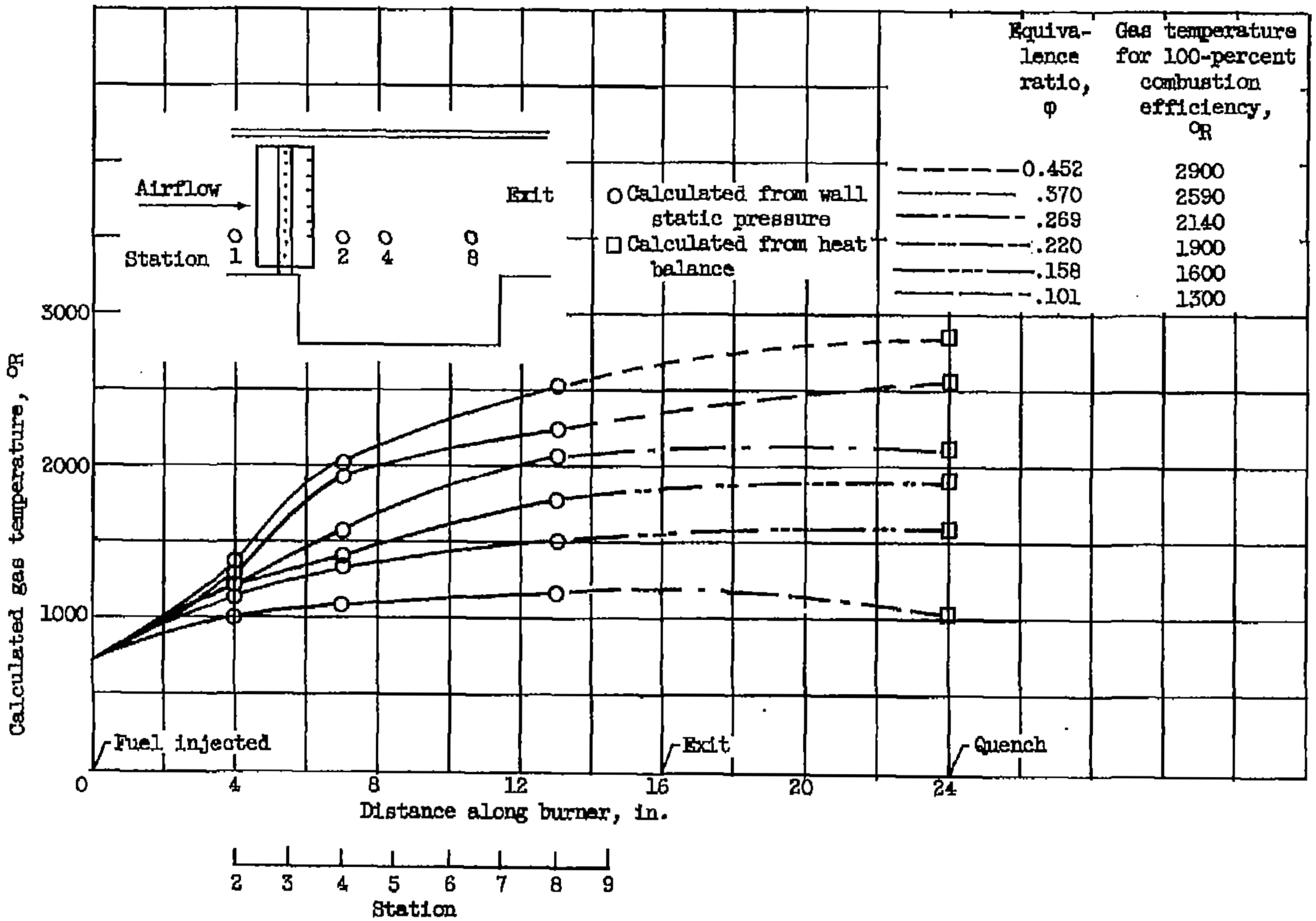
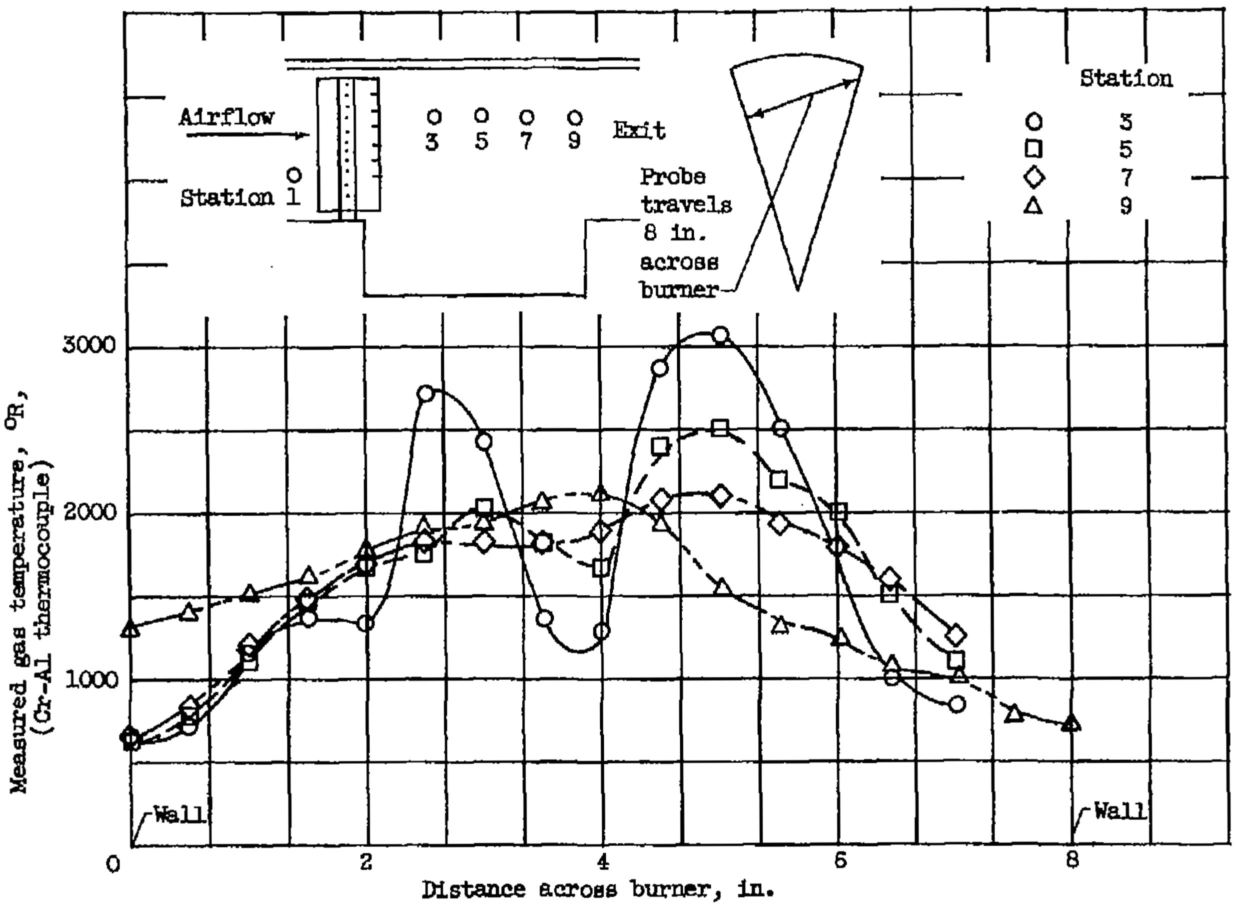


Figure 8. - Combustion efficiency of <u>four</u> flameholder - fuel-injector units in a 35°-wedge section of a 28-inch-diameter ramjet combustor; <u>35° four flameholder units</u>.



(a) Gas temperatures calculated from measured wall static pressures. Burner-inlet conditions for run 10: airflow, 1.5 pounds per second; pressure, 7 to 12 inches of mercury absolute; temperature, 250° F; velocity, 270 to 160 feet per second.

Figure 9. - Heat addition along burner length. Fuel-injector configuration D in the 35°-wedge section of a 28-inch ramjet combustor.



(b) Gas temperature measured by thermocouple probe. Burner-inlet conditions: airflow, 1.5 pounds per second; pressure, 8.8 inches of mercury absolute; velocity, 222 feet per second; temperature, 248° F; combustion efficiency, 91.0 percent. Probe corrected for radiation.

Figure 9. - Concluded. Heat addition along burner length. Fuel-injector configuration D in the 35°-wedge section of a 28-inch ramjet combustor.

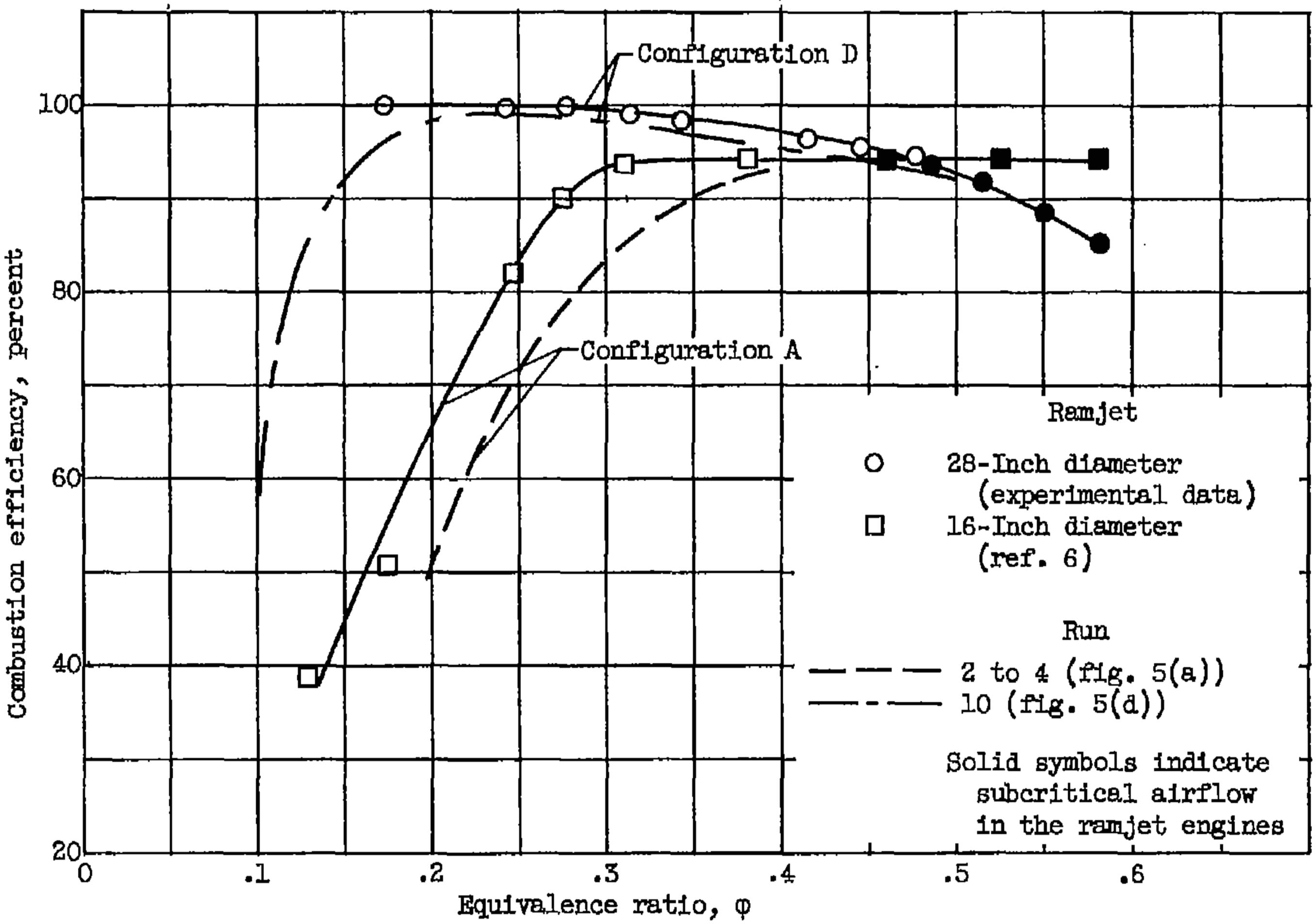


Figure 10. - Combustion efficiency of fuel-injector configurations A and D in both the 35°-wedge burner and full-size ramjet engines. Inlet conditions were approximately the same for all curves. Temperature, 250° F; pressure, 7 to 17 inches of mercury; velocity, 270 to 160 feet per second.

~~SECRET~~

UNCLASSIFIED

UNCLASSIFIED

[redacted]

~~CONFIDENTIAL~~