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CHAPTER XIV

RAM-JET PERFORMANCE

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INTRODUCTION

The ram jet is basically one of the most simple types of aircraft engine. It consists only of an inlet diffuser, a combustion system, and an exit nozzle. A typical ram-jet configuration is shown in figure 128. The engine operates on the Brayton cycle, and ideal cycle efficiency depends only on the ratio of engine to ambient pressure. The increased engine pressures are obtained by ram action alone, and for this reason the ram jet has zero thrust at zero speed. Therefore, ram-jet-powered aircraft must be boosted to flight speeds close to a Mach number of 1.0 before appreciable thrust is generated by the engine.

Since pressure increases are obtained by ram action alone, combustor-inlet pressures and temperatures are controlled by the flight speed, the ambient atmospheric condition, and by the efficiency of the inlet diffuser. These pressures and temperatures, as functions of flight speed and altitude, are shown in figure 129 for the NACA standard atmosphere and for practical values of diffuser efficiency. It can be seen that very wide ranges of combustor-inlet temperatures and pressures may be encountered over the ranges of flight velocity and altitude at which ram jets may be operated. Combustor-inlet temperatures from 500° to 1500° R and inlet pressures from 5 to 100 pounds per square inch absolute represent the approximate ranges of interest in current combustor development work.

Since the ram jet has no moving parts in the combustor outlet, higher exhaust-gas temperatures than those used in current turbojets are permissible. Therefore, fuel-air ratios equivalent to maximum rates of air specific impulse or heat release can be used, and, for hydrocarbon fuels, this weight ratio is about 0.070. Lower fuel-air ratios down to about 0.015 may also be required to permit efficient cruise operation. This fuel-air-ratio range of 0.015 to 0.070 used in ram jets can be compared with the fuel-air ratios up to 0.025 encountered in current turbojets.

Ram-jet combustor-inlet velocities range from 150 to 400 feet per second. These high linear velocities combined with the relatively low pressure ratios obtainable in ram jets require that the pressure drop through the combustor be kept low to avoid excessive losses in cycle efficiency. It has been estimated that, for a long-range ram-jet engine, an increase in pressure loss of one dynamic head would require a compensating 1-percent increase in combustion efficiency. Therefore, combustor pressure-loss coefficients (pressure drop/impact pressure) of the order of 1 to 4 are found in most current engines.

The operating conditions described impose major problems in the design of stable and efficient ram-jet combustion systems. This chapter presents a survey of ram-jet combustor research and, where possible, points out criteria that may be useful in the design of ram-jet combustion systems.

EXPERIMENTAL METHODS

Data Sources

Ram-jet combustor performance data have been obtained in connected-pipe, free-jet, tunnel, and flight tests. A connected-pipe facility (e.g., ref. 1) consists of a subsonic diffuser, a combustion chamber, and an exhaust nozzle connected by suitable ducting to air supply and exhaust pumps. A free-jet test installation (e.g., ref. 2) consists of a ram-jet engine complete with supersonic diffuser installed downstream of a supersonic nozzle. In subsonic or supersonic tunnel tests (e.g., ref. 3), the ram-jet engine has been installed either directly in the main air stream or downstream of a connecting air supply duct. Ram-jet-combustor data have also been obtained with engines attached to subsonic aircraft (ref. 4), with free-falling engines dropped from high-flying aircraft (ref. 5), and with engines launched by rocket power (ref. 6).

Data Reduction Methods

Combustion efficiency, one of the most important performance parameters for evaluating ram-jet combustors, is defined as the ratio of the actual enthalpy rise across the combustor to the theoretical heating value of the fuel. Combustion-efficiency data for a ram-jet engine are difficult to obtain directly from inlet and exhaust-gas temperature measurements because of the high exhaust-gas temperatures. For this reason, indirect methods have been evolved whereby combustion-chamber pressures, engine thrust, or heat-balance measurements are reduced to give combustion efficiency. For applications where thrust measurements are obtained, ram-jet performance is usually expressed in terms of impulse efficiency, which is defined as the ratio of actual to theoretical specific impulse.

Pressure method. - In the pressure method, the increase in momentum of the gases flowing through the combustion chamber is determined by means of total- and static-pressure measurements. These pressures can be related to the temperature rise across the combustor by the following compressible-flow equation (ref. 7):

$$T_4 = \frac{p_5^2 A_5^2 g}{(w_a + w_f)^2} \frac{\gamma_{st,5}(\gamma_{av} + 1)}{2R} \qquad (1)$$

where

A	area
g	acceleration due to gravity
p	static pressure
R	gas constant
T	total temperature
w	weight flow
γ	specific-heat ratio
γ_{av}	average specific-heat ratio between static and total temperature at exhaust-nozzle throat

Subscripts:

a	air
f	fuel

[redacted]

st	static
4	combustor outlet
5	exhaust-nozzle throat

Equation (1) is based on a choked exhaust nozzle where the Mach number M_5 is 1 and the temperatures at the combustor outlet and at the exhaust-nozzle throat are assumed to be equal. This equation is rendered more exact if the nozzle throat area is corrected by a discharge coefficient.

Exhaust total-pressure measurements are also used to determine combustion efficiency directly without calculation of exhaust temperatures by defining combustion efficiency by the relation (ref. 8)

$$\eta_b = \frac{(f/a)'}{f/a} \tag{2}$$

where

f/a	fuel-air ratio
$(f/a)'$	ideal fuel-air ratio that would produce same burner total pressure as actual fuel-air ratio
η_b	combustion efficiency

The calculation of $(f/a)'$ is based on the fact that air flows for burning and nonburning conditions are the same for an engine with a diffuser operating supercritically. Thus, total pressure at the nozzle throat for a choked exhaust nozzle is calculated by compressible-flow equations similar to equation (1). By assuming no change in total pressure and temperature between the combustor outlet and the nozzle throat, the ratio of total pressures for burning and nonburning conditions is obtained (refs. 8 and 9):

$$\frac{P_{4,b}}{P_{4,nb}} = \sqrt{\frac{T_{4,b}}{T_0}}\left(1 + \frac{w_f}{w_a}\right)\sqrt{\frac{\left[\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}\left(\frac{R}{\gamma}\right)\right]_b}{\left[\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}\left(\frac{R}{\gamma}\right)\right]_{nb}}} \tag{3}$$

where

P	total pressure

Subscripts:

b	burning
nb	nonburning
0	free stream

From measured values of $P_{4,b}/P_{4,nb}$, $T_{4,b}$ is calculated; $(f/a)'$ is computed from tables of ideal combustion temperature as a function of fuel-air ratio. Efficiencies are then calculated by means of equation (2).

Thrust-measurements method. - Combustor exhaust total temperatures are also calculated from jet-thrust measurements in wind-tunnel installations where engines are mounted on thrust balances. The exhaust-nozzle total temperature, essentially equal to combustor-exhaust total temperature, is computed by the following energy equation derived in early NACA work:

$$T_4 = T_5 = \frac{p_5A_5F}{gR(w_a + w_f)^2} - \frac{p_5A_5^2(p_5 - p_0)}{gR(w_a + w_f)^2} + \frac{F - A_5(p_5 - p_0)^2}{2gJ(c_p)_5(w_a + w_f)^2} \qquad (4)$$

where

$(c_p)_5$	constant-pressure specific heat at exhaust-nozzle throat
F	jet thrust
J	mechanical equivalent of heat

Combustor efficiency is then calculated from the exhaust-gas temperature in the same way as described for the pressure method.

Heat-balance method. - Combustion efficiencies obtained by the pressure and thrust-measurement methods are only close approximations to true chemical combustion efficiencies if these efficiencies are defined as ratios of actual to ideal temperature rise or as ratios of fuel-air ratio (eq. (2), e.g.). An exact combustion efficiency is defined as a ratio of actual to ideal enthalpy rise. A method of obtaining this true combustion efficiency involves the use of a water quench spray at the nozzle exit. The temperature of the resulting steam-exhaust-gas mixture is measured at a station sufficiently past the spray to allow complete evaporation of the water. From enthalpy values corresponding to this measured temperature, combustion efficiency is determined by the following heat-balance equation (ref. 10):

$$\eta_b = \frac{(\Delta H_w + \Delta H_e + \Delta H_j)}{h(f/a)} \qquad (5)$$

where

h	lower heating value of fuel
ΔH	enthalpy rise

Subscripts:

e	exhaust gases
j	cooling-jacket water
w	quench water for exhaust gases

Equation (5) is used for fuel-air mixtures leaner than stoichiometric. For mixtures richer than stoichiometric, the enthalpy rise of exhaust gases ΔH_e is determined from

$$\Delta H_e = \Delta H_s + \left[(f/a)_{ac} - (f/a)_s\right]\left[(L_v)T_i + (c_p)_m(T_e - T_i)\right] \qquad (6)$$

[redacted]

where

$(c_p)_m$	mean constant-pressure heat capacity of fuel
L_v	latent heat of vaporization of fuel

Subscripts:

ac	actual
i	inlet mixture
s	stoichiometric

FLAMEHOLDER AND COMBUSTION-CHAMBER GEOMETRY

General Considerations

The problem encountered in ram-jet combustors is that of initiating a stable flame in a fuel-air mixture traveling at velocities as high as 800 feet per second. This stabilization can be accomplished by placing a bluff body such as a rod or disk in the gas stream. A flame initiated in the fuel-air mixture attaches itself to the eddy region behind the bluff body, and this stabilized flame serves to ignite the oncoming fuel-air mixtures. The subject of flame stabilization by bodies within the gas stream is covered in chapters IV to VI, and this chapter is concerned only with the direct ram-jet-combustor applications of flame stabilization.

The simplest type of flameholder is a baffle placed at a single plane normal to the gas flow. Baffles may take the form of rods, disks, cones, or combinations of these. More advanced baffle designs consist of U- or V-shaped gutters with the open end facing downstream, arranged singly or in annular, radial, or grid-like planar combinations (fig. 130(a)).

Ram-jet flameholders are also designed in three-dimensional forms in which the axial dimension of the flameholder is appreciable. A gutter-type flameholder may be constructed with axial sloping gutters to form a three-dimensional flameholder (fig. 130(b)). A refined type of three-dimensional flameholder of wide use is the conical can where the flameholder consists of a conical surface perforated to allow the desired open flow area (fig. 130(c)).

Integral piloting systems are often used to assist flameholders in maintaining combustion under adverse conditions. The pilot creates the low-velocity region for stable combustion by channeling a small portion of the combustible mixture into a relatively large flow passage. Pilots are frequently combined with simple-baffle flameholders or with three-dimensional flameholders.

A number of other flameholder designs have also been investigated in ram-jet combustors. Immersed-surface types in which plates or blades have been placed downstream of a gutter flameholder directly in the flame zone have been employed successfully. Some work has been done with types that have the fuel-injection and flameholding systems combined in one unit.

The following section does not aim to select one of those general types of flameholder as being superior to the others. In general, flameholder research has aimed at perfecting each of the various types of flameholder for its own specified purposes rather than in competing one type against another.

Simple-Baffle Types

Stability limits. - Some information concerning flame stability of simple baffles is treated in chapters III and VI. In addition, recent reviews of the subject have been published (refs. 11 and 12). A theoretical analysis of the effect of flameholder dimensions and inlet-gas variables upon stability has been developed by considering the fact that blow-out occurs when the heat supply rate from the eddy region behind the flameholder is infinitesimally less than the heat required to ignite the approaching fresh gases.

If viscosity is regarded as a function of the 0.7 power of temperature, then the following equation for fuel-air-ratio stability limits may be derived (ref. 13):

$$\frac{f}{a} = \Phi\left(\frac{V_{bl}}{p_i^{0.95} D^{0.856} T_i^{1.70}}\right) \tag{7}$$

where

D diameter of disk-type flameholder normal to flow

V velocity

Φ functional notation

Subscript:

bl blow-out

In additional studies of stability limits reported in references 14 to 21, the effects of such variables as fuel type, mixture temperature, stabilizer size and type, temperature, pressure, and turbulence were investigated experimentally.

In actual engines, the most common simple-baffle flameholder system consists of gutters arranged in grids or annular-radial combinations. Some work has been done on a flameholder system as simple as a sudden expansion in cross section from diffuser to combustor (ref. 22).

The blow-out limits obtained in free-flight investigations of ram-jet engines with V-gutter grid flameholders are described in references 4 and 23. Reference 23 reports that increasing the blocked area of the flameholder by increasing the number of gutters in the grid tended to widen the stability limits. The gutters were all 3/4 inch wide; the effect of gutter width was not determined. A comparison of U- and V-gutter grids of approximately the same blocked area in another investigation (ref. 24) showed no difference in stability limits between these types of gutters.

Results of a series of investigations with V-gutters arranged in annular-radial combinations are reported in references 7, 25, and 26. The flameholders consisted of several rings of annular V-gutters of varying widths, staggered longitudinally, and interconnected by radial V-gutters or flat-plate struts similar to the configuration shown in figure 130(a). Changes in blocked area had little effect on stability limits, but the increased gutter widths improved these limits. A correlation representing a simplification of equation (7) applies to the data of these investigations (ref. 25) in the form

$$\left(\frac{f}{a}\right)_{bl} = \Phi\left(\frac{M_3}{n^{0.45}}\right) \tag{8}$$

where

$(f/a)_{bl}$	fuel-air ratio at either lean or rich blow-out
M_3	combustor-inlet Mach number based on entire cross section
n	nominal gutter width

The correlation is shown in figure 131, where the velocity - gutter-width parameter is plotted against blow-out fuel-air ratio. A similar plot (ref. 17) shown in figure 132 correlates fuel-air-ratio limits with a parameter r/V_3, where r is a nominal circular-baffle flameholder radius and V_3 the combustor inlet velocity. In this case, an exponent of unity for the flameholder dimension correlates stability limits as well as the exponent of 0.45 in equation (8).

Some work has also been reported on the use of ceramic or ceramic-filled baffles rather than steel or nickel alloy types. A comparison between a steel flameholder consisting of four radial V-gutters and a similar flameholder of alundum and silicon carbide shows a much wider range of stability limits for the ceramic baffle, especially at the rich limits (refs. 27 and 28). The wider stability range with ceramic flameholders is probably due to the reduction of heat losses by conduction from the flame zone. This is in conformity with the analysis previously presented which shows that blow-out occurs when heat losses exceed the heat supply rate to the flame zone.

Combustion efficiency. - An analysis of the combustion processes must necessarily consider fuel-air preparation and inlet parameters as well as flame stabilization and oxidation. Thus in order to compare flameholders, it is essential to control the fuel-air preparation and inlet variables. The role of the flameholder is discussed in this section, with particular reference to the simple-baffle type.

Preliminary combustion-efficiency investigations were performed on a variety of flameholder configurations (e.g., ref. 29). In early NACA work, screens, solid and perforated strips, flat plates, disks, cones, and V-gutters were used as flameholders in a 20-inch-diameter ram jet. Another investigation (ref. 30) showed that V-gutters in series were very successful for high combustion efficiency. In general, the most widely used simple-baffle type of flameholder is formed of V-gutters, although ram-jet engines have been designed with perforated-gutter flameholders (ref. 31), corrugated gutters (refs. 32 and 33), and the simple sudden-expansion type of flameholder (ref. 22) often with vortex blades at the entrance to the combustor (ref. 34).

The principles underlying the operation of efficient simple-baffle flameholders can be stated briefly. The stagnation region downstream of the baffle is a stable, high-temperature zone which acts as a torch for the adjacent high-velocity mixture. For stability, a wide baffle is desired, but this in turn increases the velocity of the unburned mixture past the flameholder; therefore, a compromise between efficiency and stability must be made (ref. 12). A second principle observed is that a continuous flame path connecting all of the flameholder baffles is desired. Thus, reignition can proceed if flame is locally snuffed out.

These principles are illustrated in the investigation reported in reference 35. The four gutter-grid flameholders used, shown in figure 133, are typical of the simple-baffle type. Their combustion efficiencies were about the same, with a slight advantage for the standard-gutter flameholder. In general, the configurations that gave the highest peak efficiencies had the narrowest fuel-air-ratio range of operation. This compromise of efficiency with stability limits has been noted repeatedly in combustor investigations. As noted previously, this is the case primarily because large-width baffles for wide stability limits increase the velocity of the unburned gases and reduce efficiency. A further explanation may lie in the fact that low-pressure-drop flameholders operated at high temperature ratios favorable for high efficiency tend to amplify pressure disturbances introduced in the diffuser (ref. 36). The intensified pressure fluctuations no doubt decrease stability. Also reported in reference 35 is an investigation of an adjustable gutter-grid flameholder having a gutter angle that could be varied from 0° to 53° during operation to give a variation in the blocked frontal area from 14.2 to 59.5 percent of the combustion-chamber area. The combustion efficiency of the adjustable-gutter flameholder as a function of gutter angle is shown in figure 134, where the data show that variations in gutter angle from 25° to 50° had little effect on combustion efficiency. However, other results of the investigation showed that the stable limits of operation were improved slightly with increased gutter angle.

Gutter-grid flameholders were also used in the free-flight tests reported in reference 23. Three grids of 49, 55, and 60 percent blocked area were constructed of 3/4-inch V-gutters. The maximum combustion efficiencies obtained with the two grids of smaller blocked area were greater than those obtained with the third flameholder of 60 percent blocked area. Perhaps flame blow-out at some portions of the grid for the holder with 60 percent blocked area was responsible for these results.

The staggered annular-radial V-gutter combinations previously cited in the discussion of stability limits (refs. 7, 25, and 26) were also employed in a combustion-efficiency test program to determine the effect of flameholder geometry on performance. Figure 135 (ref. 26) indicates the effects of flameholder blocked area and gutter width upon combustion efficiency. Unlike stability, combustion efficiency is not greatly influenced by gutter width, and the gains afforded by increased area blockage are very slight.

Piloting Systems

A pilot is a portion of the combustor in which a reduced air velocity is maintained by expanding part of the air stream. This low-velocity region provides a stable burning zone from which flame may be propagated to the rest of the combustor. Theories of flame propagation from a low-velocity region to a high-velocity region are discussed in chapters III, IV, and V. A typical pilot configuration is shown in figure 136. Since the pilot contains a low-velocity region, the design principles are different from those used for the main combustor. In the pilot a large pressure-loss coefficient may be tolerated and heat release per unit volume is small. Fuel-air ratios can be maintained at fixed optimum values and special fuels may be used.

Pilot heat release. - A program was conducted (ref. 37) to determine whether the heat release of a pilot or the production of active particles controls flame propagation from the pilot. Experiments were performed in a 2-inch-diameter burner with a pilot zone supplied with hydrogen and oxygen. The burner itself was run under fixed conditions of pentane flow, air velocity, temperature, and pressure. Specific impulse increased almost linearly as the heat release from the pilot was raised by increasing the flow of stoichiometric hydrogen-oxygen mixture. When more hydrogen was added, with the same oxygen flow, the heat release was kept constant while the production of hydrogen atoms dropped more than a hundredfold; nevertheless, the specific impulse remained nearly constant. Reference 37 takes this to be a negative type of evidence in favor of the importance of pilot heat release, as opposed to the production of actual particles in the pilot flame. However, it is by no means conclusive evidence, because the effects of the temperature of the pilot exhaust gas were not considered.

Design and use of pilots. - The physical size of a piloting zone is an important factor in the design of combustors. It has been found experimentally that a circular pilot cross section is better than a rectangular one (ref. 38), and that a length equal to a diameter is adequate before pilot recirculation air is admitted (ref. 39). Reference 40 states that the sum of the diameters of the first row of recirculation air holes should equal 40 percent of the pilot circumference.

A one-dimensional aerodynamic analysis of the required size of a pilot combustor is shown for one set of initial conditions in reference 41. A more extensive treatment of optimum pilot size is given in reference 42. In this report, an ideal piloting system is considered in which all the combustion takes place in a low-velocity stoichiometric pilot zone. Secondary air is mixed with the exhaust products downstream of the pilot combustor to give the desired over-all fuel-air ratio. The study shows that it is possible to maintain a large pilot area for efficient low-velocity combustion without incurring excessive total-pressure losses.

Percent pilot is defined as the percent of total fuel sent to the pilot zone. This percentage may vary from 0 to 100, the latter value corresponding to the idealized pilot of reference 42. An example of an experimental investigation of a ram-jet combustor operated at varying percent pilot is found in reference 43, where percent pilot ranged from 12 to 100 percent. In some cases, where low-drag flameholders are employed (refs. 9 and 44), piloting of 1 percent or less is sufficient for large gains in stability limits. Figure 137 illustrates the increase in efficiency with small percent pilot for a single V-gutter flameholder described in reference 45.

Pilot operation is not required where inlet conditions are very favorable for combustion and over-all fuel-air ratios near stoichiometric are employed. In the investigation of reference 26, for lean over-all fuel-air ratios, where the fuel was concentrated locally, pilot operation was beneficial, but at rich fuel-air ratios where uniform fuel distribution was required, pilot operation was of little help.

Piloted flameholders. - Integral piloting systems have been combined with such well-known simple-baffle systems as V-gutter grids (ref. 46), radial gutters (ref. 47), annular-radial gutter combinations (ref. 48), and staggered annular-radial gutter combinations (refs. 8, 26, and 49). In general, the effects of flameholder geometry on combustion performance of the piloted flameholders were not different from those of nonpiloted flameholders. Reference 47, for example, reports no appreciable effect of varied area blockage on combustion efficiency. Comparisons between otherwise similar piloted and nonpiloted configurations are given in references 26, 44, and 49. The piloted designs offered no improvement in peak combustion efficiency, but they did tend to widen the fuel-air-ratio range of operation. A comparison is made in reference 50 of three types of piloted configurations intended for use in a ram-jet combustor at low pressures and rich fuel-air ratios. The configurations consisted of a can that acted as a 100-percent pilot and two gutter combinations, one with five can-type pilots (fig. 138) and the other with a sloping-gutter pilot. The third type was the most satisfactory design. This configuration (also described in ref. 51) consisted of a perforated conical flow divider enclosing a sloping V-gutter basket (fig. 139). The sloping V-gutter and flow divider served first to confine the mainstream fuel to a portion of the air and then to promote good mixing of the pilot combustion products with the mainstream combustibles. Another example of this type of design is given in reference 52.

Three-Dimensional Flameholders

Three-dimensional baffle. - In contrast to the planar, simple-baffle flameholder, the three-dimensional baffle has appreciable axial depth. The advantage of this design is that the volume of the primary zone can be large, and a means for controlling the introduction of dilution air is provided. The pilot configurations of references 50 and 51 (fig. 139) are an approach to the three-dimensional type.

Flameholder designs have been evolved (refs. 43 and 53) in which the radial gutters slope at a comparatively small angle to the combustor axis and provide a conical flame-holding surface. The sloping-baffle configuration investigated in a 16-inch connected-pipe facility described in reference 53 consisted of two sets of U-shaped baffles separated by a conical section (fig. 130(b)). The 6 baffles in the primary zone and the 12 baffles in the secondary zone were inclined at 30° angles to the combustor axis. The fuel-mixing control sleeve, which extended from the fuel injectors to the flameholder, intercepted approximately 20 percent of the total engine air mass flow and ducted this air into the primary combustion zone. Combustion originated in the wake of the upstream set of baffles and was substantially complete in the sheltered region downstream of these baffles. The use of a sloping baffle and conical shielded zone provided an expanding volume for the combustion region, thereby maintaining a low flow velocity which permitted combustion to be completed in a relatively short length.

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The combustion performance of this configuration as a function of fuel-air ratio is compared in figure 140 with that of a baffle-pilot configuration investigated in the same facility and at the same test conditions. The advantage of providing fuel-air mixing control downstream of the point of initiation of combustion is an increase in combustion efficiency at low fuel-air ratios.

Another type of three-dimensional flameholder is the rake type, which consists of a pilot body with petal-like fins extending downstream and radially from the pilot (fig. 141). Usually several of these flameholder combinations are positioned at an axial station in the combustor. Multiple-rake flameholders were used in free-flight investigations reported in references 5 and 54 to 57, where these configurations were found to be superior to piloted gutter flameholders in stability limits and efficiency. Another comparison of a rake-type flameholder with a piloted serrated baffle flameholder also showed improved results with the former type (ref. 58). Further gains would have been possible with improved fuel injection systems. An investigation of more complex rake designs (ref. 59) showed that best performance was obtained with a rake-type flameholder which had alternate rakes connected to the pilot burner outlet by V-gutters. The three rakes that were connected in this manner appeared to be more effective as flameholders than the other three rakes because of the continuous flame path from pilot to baffle.

Can flameholder. - The principle of an expanding combustion zone is inherent in the design of a conical can-type flameholder. Can combustors fall into two general types of designs: simple cans and annular cans. A typical simple can is shown in figure 142(a). The flameholder consists of a continuous or segmented conical surface, expanding in a downstream direction with a pilot assembly usually situated at the upstream end of the cone. An annular can (ref. 60), shown in figure 142(b), consists of two conical cans, the vertex of inner can facing downstream, and the vertex of the outer can facing upstream. Can flameholders may differ in cone angle, distribution of holes and hole sizes, arrangement of holes, and shape of holes. Cans are usually specified in terms of open area and pitch alinement. Open area is the ratio of the area of the perforations to the cross-sectional area of the combustion chamber; the pitch alinement is the number of rows of perforations that spiral around the conical surface counted along the intersection of an axial plane on the surface.

The effect of cone angle on combustion performance has not been systematically investigated in the literature, the standard half angles being from 5° to 15°. However, the effect of pitch alinement on combustion efficiency and stability limits

[redacted]

has been investigated (ref. 61). A slight improvement in efficiency was found through the use of a two-pitch-alinement can rather than a zero-pitch-alinement can, but stability limits were unaffected by the alinement.

In an investigation of can combustors intended mainly for piloting applications (ref. 38), stability limits were unaffected by hole size, total open area, or pitch alinement. Reference 41, on the other hand, reports that for a single-rowed can flameholder, increasing hole size increases the rich limits but does not affect the lean limits.

The effect of open area and hole type on combustor performance is described in reference 62 for a 10-inch-diameter quarter-segment combustor in a free-jet installation. Figure 143 compares the combustion efficiency of four can configurations, three having open areas of 100, 145, and 177 percent with round holes the same size in each case, and one having an open area of 100 percent with transverse rectangular slotted holes. The flameholder with 100 percent open area yielded a maximum efficiency of 94 percent, a value slightly higher than the maximum combustion efficiency obtained with the cans of greater open area. The transverse-slotted can exhibited a maximum efficiency close to that of the corresponding round-hole can, but efficiencies at low fuel-air ratios were much less for the slotted can, probably because the increased frontal area of the slots admitted too much air to the primary portion of the can.

Immersed-Surface Flameholders

The use of surfaces in the flame zone of a combustor stems from the observed catalytic effects of certain materials in the ignition of quiescent combustibles. The employment of similar materials in a high-velocity combustor was a logical extension of this principle. In addition to the thermal effect, a beneficial increase in mixing rate was envisioned. Some of the effects of immersed surfaces on combustion efficiency and stability are described in the following paragraphs.

A systematic program of investigations of immersed surface combustors was conducted and is reported in references 10, 44, 63, and 64. In reference 63, the flameholder employed was a wedge-shaped block of graphite that had been spray-coated with aluminum. Two such wedges placed parallel across the cross section of the combustor represented a conventional type flameholder. Additional rows of similar wedges were introduced downstream of the original row to evaluate the effect of surfaces immersed in the flame zone. The flameholder configurations used in this program are shown schematically in figure 144. The effect of the immersed surfaces on pressure loss and combustion efficiency was slight, but the additional surfaces did widen the combustion stability limits.

In reference 64, Inconel surfaces were employed because carbon blocks have inadequate shock resistance. The results indicated that, within the requirements of providing a low-velocity path for flame propagation, the number of surfaces and their geometry were unimportant. A conventional V-gutter configuration is compared in reference 10 with another in which 12 Inconel blades were positioned in the flame zone. Variation of the immersed-surface temperatures confirmed that the performance gains were due to aerodynamic rather than thermal influences. Both stability limits and combustion efficiency were improved by the immersed surfaces. The combustion-efficiency effect is illustrated in figure 145, where efficiency is plotted against equivalence ratio. The difference between efficiency of cooled and uncooled blades is small in comparison with the difference between efficiencies of the configurations with and without immersed surfaces.

A systematic investigation of simplified immersed-surface configurations in reference 44 concluded that the greatest gains in combustion efficiency could be effected by the use of a single blade in the flame zone close to the flameholder. Optimum efficiency results were obtained with a blade across the combustor perpendicular to and 4 inches downstream of the single V-gutter flameholder (figs. 146 and 147). Apparently the flame-immersed blade is best positioned close to the flameholder, but not close enough to disturb the normal wake region behind the flameholder (less than 4 in. in this case). At a slight compromise in efficiency and pressure drop, a considerable improvement in stability limits was obtained by combining this single perpendicular blade with three parallel blades farther downstream. A further widening of stability limits was possible by removal of all of the flame-immersed surfaces.

In studies described in reference 65, the effect on combustion of a grill of heated, coated molybdenum strips submerged in the combustion zone of a 6-inch-diameter combustor was determined. The anticipated acceleration of combustion was not realized because the strips did not act as surface combustion aids, but instead conducted heat from the flame zone to the combustor walls.

The advisability of employing immersed surfaces in the combustion zone appears controversial, even though the aerodynamic influence of these surfaces was shown to be important (ref. 10). Mixing can possibly be controlled in a simpler manner, for example, by proper spacing and sizing of holes in a can-type flameholder. However, these tests very dramatically emphasized the fact that the rate of mixing of unburned and burned gases can be the controlling step in the combustion process.

IGNITION

The basic principles of ignition discussed in chapter III apply to ram-jet combustors. The techniques generally used in starting ram-jet combustors incorporate either pyrotechnic flares or spark plugs located within the pilot zone. The spark system is more desirable for ground tests since repeated starts can be obtained. However, under certain operating conditions, chronic failures of the spark system have been experienced, and ignition with a hypergolic fuel such as aluminum borohydride is advantageous. Flight-test data reported in reference 4 show that up to pressure altitudes of 14,000 feet spark systems are satisfactory, but above that altitude flare systems are necessary. However, in recent tests with a 48-inch ram jet (ref. 66), reliable spark ignition was obtained at 1/8 atmospheric pressure. A further aid to spark ignition at low pressure is the addition of small amounts of hydrogen in the region of the spark (ref. 12). A magnesium-flare ignition system that has proved to be very satisfactory is described in reference 6. Additional ease in starting flight models is afforded by the use of magnesium flares in conjunction with rake-type flameholders (refs. 6 and 67).

FUELS AND FUEL SYSTEMS

Combustion proceeds most favorably in a near stoichiometric fuel-air mixture, where flame speed and temperature are at a maximum. Thus, the principles underlying the design of a fuel system are the achievement of a near stoichiometric mixture and complete vaporization of fuel in the precombustion zone.

Fuel Injection

Fuel-injection types. - In ram-jet combustors, the energy of the high-velocity air stream is used to atomize the fuel, thus allowing simple fuel-injector designs and low fuel pressures to be used. Air-blast atomization is discussed in chapter I, where it is shown that drop size can be predicted from certain fuel properties and the relative air and fuel velocities and volumes by the following equation:

$$d_{32} = \frac{585\sqrt{\sigma_f}}{U_r\sqrt{\rho_f}} + 597\left(\frac{\mu_f}{\sqrt{\sigma_f\rho_f}}\right)^{0.45}\left(1000\,\frac{Q_f}{Q_a}\right)^{1.5} \tag{9}$$

where

d_{32}	Sauter mean diameter, microns
Q_f/Q_a	fuel-air volume ratio
U_r	relative air-fuel velocity, meters/sec
μ	viscosity, poises
σ	surface tension, dynes/cm
ρ	density

Subscripts:

a	air
f	fuel

For a typical ram-jet combustor-inlet velocity of 300 feet per second and with JP-4 fuel, the drop-size calculation can be approximated by $d_{32} = \frac{585\sqrt{\sigma_f}}{U_r\sqrt{\rho_f}}$, since Q_f/Q_a is small. The value of d_{32} at this condition is about 35 microns. This drop-size diameter is roughly one-third that predicted for a 17.5-gallon-per-hour Monarch spray nozzle in still air by the following equation from chapter I:

$$d_{32} = 251\Delta P^{-0.17} \text{ microns} \tag{10}$$

where

ΔP pressure drop across nozzle

For a pressure differential of 100 pounds per square inch, d_{32} is 115 microns.

These drop-size estimates show that the air flow past the fuel injector provides remarkably good atomization and that further mechanical improvements are unnecessary. Thus it is not surprising that injector types of a wide variety have proved satisfactory. At low fuel-air ratios it is reported (ref. 41) that simple fixed-orifice nozzles give the highest efficiencies because less dilution of the fuel-air mixture occurs. However, fewer injection points are required with the Monarch nozzle because the radial component of the fuel-droplet velocity distributes the fuel over a greater area than the simple-orifice type. At higher fuel-air ratios, air-atomizing types of nozzles provide a more homogeneous mixture and are more satisfactory. Variable-area spring-loaded nozzles appear promising for ram-jet applications, but difficulty has been encountered in providing equal flow through each nozzle in multinozzle installations.

A program was conducted (ref. 68) to determine the effect of nozzle size in a configuration of six fixed-area nozzles evenly spaced at an axial station. The results showed that there is an optimum size of nozzle for maximum efficiency. With overly large nozzles, distribution is poor; similarly, with undersized nozzles, fuel pressure is so high that fuel particles strike and flow along the chamber wall and do not mix with air properly, decreasing efficiency.

Other methods of fuel injection include impinging jets and spray bars. Excellent efficiencies are reported (refs. 69 and 70) for fuel-injection systems consisting of multiple impinging jets of compressed air and fuel. Spray bars, usually perforated tubes, are also widely used since they have the advantage of low area blockage.

Location and direction of fuel sprays. - The location and direction of fuel sprays are determined by the combustor-inlet conditions and the type of fuel injector. Since it is desired that a vaporized, locally stoichiometric mixture be produced at the flameholder, the direction of fuel spray is of some importance, particularly for fuel injectors just upstream of the flameholder. Injection of fuel in a contrastream direction allows a greater path of travel of the fuel droplets and produces a more homogeneous mixture than injection in the costream direction. Thus reference 51 reports excellent combustion efficiencies at rich fuel-air ratios by contrastream injection, but recommends costream or cross-stream injection, which produce a more concentrated fuel mixture, at lean fuel-air ratios.

The significance of fuel-injector location is best illustrated by some examples from reference 71. Combinations of upstream fuel injection, flameholder injection, and split injection between the two positions were employed, as shown in figure 148. The combustion efficiencies of the four injector configurations are shown in figure 149 as a function of fuel-air ratio. The broadest range of operation was obtained with flameholder injection, where operation was possible from fuel-air ratios of 0.012 to 0.047. The upstream-injection case gave only a narrow range of operation near stoichiometric fuel-air ratio and peak efficiencies of less than 80 percent. This range was broadened by the use of split injection, and the peak efficiency increased slightly by the use of flameholder split injection. Thus the results indicate that upstream or split injection, which gives a nearly homogeneous mixture, produces the best performance at rich fuel-air ratios, and localized flameholder injection produces the best performance at lean fuel-air ratios.

These findings have been widely confirmed. Results from reference 72 plotted in figure 150(a) show that for a can-type combustor peak efficiencies at low fuel-air ratios are obtained with internal (flameholder) injection; peak efficiencies at high fuel-air ratios are obtained with upstream injection. For operation over a wide range of fuel-air ratios, a combination of internal and upstream operation was most satisfactory.

The principle of fuel-mixture stratification to obtain efficient combustion at lean fuel-air ratios also applies to the radial positioning of the fuel injector. Figure 150(b) (ref. 72) shows that for upstream fuel injection, efficiency is better at low fuel-air ratios for injector positions near the centerbody but the reverse is true at high fuel-air ratios. Figure 151(a) shows the effect of injector-ring diameter on combustion efficiency (ref. 73). The fuel-air ratio for peak efficiency increases with increasing fuel-ring diameter as seen in the cross plot (fig. 151(b)). The solid line in figure 151(a) illustrates the fact that injector rings of two different diameters may be combined to broaden the range of operation.

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Staged fuel injection. - For operation over a wide range of fuel-air ratio, the principle of fuel-injection staging is used. A set of injectors, denoted as primary fuel injectors, supply fuel for low-fuel-air-ratio operation. For operation at richer fuel-air ratios, additional fuel is injected through secondary sets of injectors, which are positioned for the most efficient combustion.

The performance of a combustor operated with careful proportioning of primary and secondary fuel flows is shown in figure 152 (ref. 72). High efficiencies were achieved by operating with primary fuel up to fuel-air ratios of 0.034 and then by maintaining the primary fuel-air ratio constant at 0.014 and increasing the secondary fuel flow. A mixture control sleeve of the type described in the following section separated the primary and secondary fuel-air mixtures.

Such combinations of primary and secondary fuel injection are very common in all types of ram-jet combustors. A three-stage fuel-injection system for a can flameholder is described in reference 62, one stage located at the can entrance and the other two downstream of the first stage. Best results were obtained when the first stage was used for very lean fuel-air ratios, the first and second stages for ratios up to 0.045, and all three stages for ratios above 0.045. It is important to reduce the primary fuel flow to a low value at rich fuel-air ratios, as is illustrated in figure 152 and further shown in a plot from reference 73 (fig. 153), where the rich limits of combustion narrow as primary fuel flow is increased from 18 to 34 percent of the total fuel flow.

Mixture control sleeves. - Good combustion efficiency at lean fuel-air ratios can be obtained with upstream injection as well as with flameholder injection if excessive mixture dilution upstream of the flameholder is prevented by a control sleeve. The combustor configurations shown in figures 130(b) and (c) and 152 illustrate the placement of such a control sleeve. Although primary and secondary fuel injection are from the same axial station upstream of the flameholder, the primary fuel-air mixture within the control sleeve is channeled directly to the upstream portion of flameholder where it maintains a rich concentration. The control sleeve produces the same effect as does the near-stoichiometric pilot zone of reference 42, described in the section on piloting.

An early type of mixture control sleeve is described in reference 74, but the device had not been fully exploited until recently (refs. 1, 9, 34, 43, 53, 75, and 76). An increase in combustion efficiency from 30 to 75 percent at a fuel-air ratio of 0.025 with no increase in combustor pressure loss is reported in reference 75. The advantages of a sleeve system are reviewed in reference 34. Besides the improvement of combustion efficiency at low fuel-air ratios provided by rich local mixtures, the control sleeve produces more consistent fuel distribution and sharp-edged fuel-air profiles and allows the use of simple fuel orifices rather than atomizing nozzles.

Effect of Fuel Variables

Fuel type. - The effect of fuel type on combustion performance in a ram jet would depend on the controlling step in the combustion process. The combustion process may be considered as successive steps of fuel vaporization, mixing, and chemical oxidation. If the vaporization step were controlling, then the physical properties of the fuel would be of great importance; if oxidation were controlling, the chemical properties would determine the performance of the fuel. Small-scale tests of efficiencies of several fuels bear out these hypotheses. (Fundamental combustion properties are discussed in chapters I to VI.) Investigations of gaseous fuel-air mixtures (ref. 45) where fuel volatility is eliminated as a factor show that fuels of low ignition energy, or short ignition lags, such as hydrogen, acetylene, carbon disulfide, or propylene oxide, produce the best efficiencies.

Although large-scale engine tests cannot be as easily analyzed, the same conclusion may be reached regarding the effect of fuel properties. In reference 77, the use of gasoline rather than JP-3 fuels increased combustion efficiency 10 percent at an inlet-air temperature of 920° R. These results indicate that a 53-inch length for a 20-inch-diameter combustor was insufficient for complete vaporization of the less-volatile fuels. Similarly, in other investigations where low inlet temperatures and short combustor lengths caused the vaporization of liquid fuels to govern the over-all combustion efficiency, gasoline was superior to the less-volatile kerosene (refs. 32 and 45). Other studies have found n-heptane to be superior to the less-volatile Diesel oil (refs. 26 and 78) and propylene oxide superior to kerosene (refs. 3, 32, 58, 59, 79, and 80), but this effect with the latter pair of fuels may be attributed to flame speed as well as to increased volatility.

Where nearly complete vaporization is ensured, fuels that differ from one another mainly in volatility give nearly the same performance in ram-jet combustors. Reference 81 reports little difference in combustion efficiencies between 80-octane gasoline, JP-3 fuel, and special low-vapor-pressure fuels. Similarly, almost identical results with gasoline and JP-4 fuel were found in the work of reference 82, and samples taken in this investigation at an inlet-air temperature of 1060° R confirmed that vaporization was substantially complete in 17 inches of mixing length.

In ram-jet combustors where vaporization does not control the over-all efficiency, appreciable gains in efficiency result from the use of high-flame-speed fuels. For premixed and prevaporized fuel mixtures, reference 83 states that combustion efficiency increases with the 1.1 power of flame speed.

Octane rating of gasoline-type fuels is of little consequence in ram-jet combustors. Reference 84 shows that 62-octane gasoline performed as well as 100-octane gasoline.

Fuel preheating. - For combustor operating conditions where fuel vaporization is an important factor, increased preheating of fuel aids combustion efficiency. Reference 85 reports a 10-percent increase in combustion efficiency with preheating of 62-octane gasoline from 40° to 200° F. In combustors where vaporization of the fuel is complete for cold injection, such as the combustor discussed in reference 82, preheating the fuel is of no consequence.

OPERATING VARIABLES

Pressure

Effect on combustion efficiency. - Because pressure affects all of the fundamental processes in the combustor, finding occasional contradictory results from pressure investigations is not too surprising. Evaporation of liquid fuels is retarded by increased combustor pressures (ch. I), whereas this pressure increase aids the oxidation reaction (ch. III). Thus, in general, at low and moderate pressures where fuel vaporization is rapid, efficiency increases with pressure. Conversely, where vaporization is the controlling step, as at high pressures or with low-volatility fuels, efficiency may remain independent of pressure or even decrease slightly with pressure.

Results for a 2-inch-diameter gaseous-propane - air burner (fig. 154) show a continuous increase in combustion efficiency with pressure increases from 5 to 85 inches of mercury absolute (ref. 45). Similar plots of combustion efficiency as a function of inlet pressure have been established from larger-scale tests of combustors with simple-baffle flameholders (ref. 86), rake-type flameholders (ref. 55)

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and can flameholders (ref. 87) over pressure ranges as great as from 8 to 85 inches of mercury absolute. The more usual findings, however, are that efficiency increases with pressure up to a certain value and then remains independent of pressure. Figure 155 illustrates this trend from results given in reference 77, where at a fuel-air ratio of 0.06, combustion efficiency increases with pressures from 7 to 55 inches of mercury absolute and remains constant at higher pressures.

In combustors where fuel vaporization is more critical, the pressure effects shown in figures 154 and 155 may not apply. In reference 60, for example, data are presented for can combustors where efficiency increases with pressure only up to a pressure of 20 inches of mercury absolute, above which efficiency decreases slightly. References 3 and 71 state that efficiency was virtually independent of pressure at pressures as low as 17 to 28 inches of mercury absolute. That these results are due to an increased importance of fuel vaporization is confirmed by the work of reference 88, where over a pressure range of 30 to 65 inches of mercury absolute, combustion efficiency decreased with pressure when radial simple-orifice fuel injectors were used and increased with pressure when hollow-cone spray nozzles were used. The spray nozzles had better vaporization characteristics than the fixed-orifice injectors.

Effect on stability limits. - Increased inlet pressure usually tends to widen both the lean and rich limits of combustion, especially at very low pressures (refs. 55, 56, 73, 77, and 86). As in the case of combustion efficiency, where fuel vaporization is a critical factor, pressure may have an adverse effect upon limits. In figure 156, the effect of pressure on stability limits is shown for three inlet temperatures (ref. 73). At the two higher temperatures, the expected widening of the limits with increased pressures is seen; but at 810° R, where vaporization may control, the limits are independent of pressure above 18 inches of mercury absolute. A fundamental treatment of the effect of pressure on flame stabilization is given in chapter VI.

Temperature

Effect on combustion efficiency. - The two important combustion steps of vaporization and oxidation are both accelerated by increased temperatures (chs. I and III); hence, combustion efficiency would be improved appreciably by increased inlet temperatures. This effect of temperature has been confirmed by many combustion studies, although the results of some of these reports are of doubtful significance because of lack of control of other variables, principally pressure. Investigations where inlet temperature was the only variable have shown that combustion efficiency increases almost linearly with increasing inlet temperature (e.g., refs. 34, 59, 62, 77, 78, and 88). Since the temperature contribution to combustion efficiency is not the result of two competing effects, efficiencies increase asymptotically with temperature to limiting values of 100 percent. Studies of ram-jet combustors are presented in which increased inlet temperature improved combustion efficiency greatly under conditions of low inlet pressure (ref. 60) and off-stoichiometric fuel-air ratios (ref. 76). However, at atmospheric pressure and near-stoichiometric fuel-air ratios, where efficiencies were normally near 100 percent, increasing inlet temperatures could not improve combustion efficiency.

Effect on stability limits. - The stability curves for three inlet temperatures shown in figure 156 indicate that increased inlet temperatures widen stability limits, especially the rich limits. These findings of the effect of temperature on stability limits are in agreement with those of other investigations (refs. 27, 78, 81, 89, and 90). A discussion of the effect of temperature on stability is also given in chapter VI.

Velocity

Effect on combustion efficiency. - Increased inlet velocity improves fuel atomization (ch. I); but, for a given chamber length, increased velocities allow shorter reaction times for the evaporation and oxidation steps in the combustor. Thus, as with inlet pressure, competing contributions to combustion efficiency are influenced by inlet velocity. Experimental information has been presented wherein combustion efficiencies may increase up to maximum and then decrease with increasing velocity (ref. 61), decrease with increasing velocity (refs. 78 and 88), or be unaffected by velocity changes (ref. 3). These contradictory findings are apparently due to different relative importances of the atomization, vaporization, and oxidation steps in the combustor. This has been borne out by the work of reference 71, where combustion efficiency reached a maximum with velocity for upstream or split fuel injection runs and decreased with increasing velocity for flameholder fuel injection. The most usual findings, however, are that combustion efficiency decreases with increasing air velocity.

Effect on stability limits. - Increased velocity has been found to both widen (ref. 74) and narrow (refs. 4 and 78) lean limits. With a homogeneous fuel-air mixture, increased velocity would normally result in poorer lean limits of combustion. However, under certain conditions of stratified fuel-air-mixture distribution, the increased mixing rates associated with increased velocity would tend to improve the local combustible concentration. The only available literature on rich limits (ref. 73) shows that the limits are decreased by increased inlet velocities.

Angle of Attack

Angle-of-attack operation distorts the velocity profile at the combustor, and therefore would be expected to be detrimental to combustion efficiency. Investigations of 16-inch can-type combustors at several angles of attack (refs. 91 and 92) showed that efficiency decreased about 10 percent with an increase in angle of attack from 0° to 10°, but stability limits were unaffected.

Correlations of Operating Variables

It is obvious from the experimental literature that the same change in an inlet variable may affect combustor performance in opposite directions, depending on which step in the over-all process predominates. Semitheoretical correlations must of necessity assume a controlling step in the combustor. Most combustor investigations are conducted under conditions to which an oxidation-controlled mechanism would be most closely analogous. For this particular case, the usual correlation of combustion efficiency takes the form

$$\eta_b = \Phi\left(\frac{pTl\,\frac{f}{a}}{V}\right) \tag{11}$$

where

l combustion length

as proposed in reference 14. A function of this type was successful (ref. 93) in correlating the performance of turbojet combustors under conditions of constant combustor length and limited fuel-air-ratio ranges. With these limitations, the simplified parameter pT/V will suffice for correlation.

A correlation similar to the preceding was derived for application to ram-jet combustors (ref. 94). The theoretical basis for the correlation was the assumption that the mixing of burned and unburned gases and their movement through the flame front controlled the over-all combustion rate. Thus, combustion efficiency was defined as the ratio of the mass flow of gases through the flame front to the over-all mass flow of unburned gases through the combustor

$$\eta_b = \frac{\rho_u A_{ff} u}{\rho_u A_c V} \qquad (12)$$

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where

u fundamental flame speed

Subscripts:

c combustor cross section

ff flame front

u unburned gases

Flame-front area and flame speed were evaluated in terms of inlet variables to give a function of inlet pressure, temperature, and velocity. Empirical data from runs with a 5-inch ram-jet combustor with V-gutter flameholders could be correlated by the expression

$$\eta_b = \Phi\left(\frac{P^{0.3}\ T}{V^{0.8}}\right) \qquad (13)$$

This expression could be applied to data of many different fuels by multiplying the correlation parameter by the term $(u_f/u_{ref})^{1.1}$, where u_f is the flame speed of the fuel employed and u_{ref} is the flame speed of a reference fuel (ref. 83). The reference fuel used in references 83 and 94 was gasoline with a flame speed of 1.4 feet per second. The correlation is shown in figure 157, where combustion efficiency is plotted against the correlating parameter. Reasonable agreement between the results with different fuels is shown with the exception of carbon disulfide, a compound with a very low ignition energy. A linear relation between combustion efficiency and the correlation parameter is exhibited up to efficiencies of 80 percent, above which the effect of the parameter on efficiency is slight. At high values of the inlet variable parameter, therefore, combustion efficiency would be high and would be unaffected by moderate changes in inlet variables. This conclusion has also been shown in tests in a 16-inch combustor reported in reference 76.

SUMMARY OF RAM-JET COMBUSTION PRINCIPLES

Ram-jet combustion work has been conducted mainly along experimental lines. Because the field is comparatively new, considerable effort was expended in exploratory programs, and only a few of the many variables affecting ram-jet combustor performance have been investigated systematically. Some of the ram-jet design principles which have been evolved are briefly reviewed in the following discussion.

Flameholder Geometry

The single-plane, simple-baffle flameholder can be applied satisfactorily at favorable inlet-air conditions and at rich fuel-air ratios. Its simplicity, low weight and drag, and structural reliability are very desirable. However, at less-favorable inlet conditions (particularly at inlet pressures below one-half atmosphere and at lean fuel-air ratios), the three-dimensional flameholder, as exemplified by the can type, has more desirable performance characteristics. The most satisfactory simple-baffle shape was a V-gutter arranged to form an annular-, radial-, or grid-type flameholder. Combustion performance is insensitive, within certain limits, to variations in baffle width, spacing, angle, and area blockage. Baffle widths of 1 to 2 inches and angles from 30° to 60° have been most generally used.

The three-dimensional flameholder type most widely investigated is the conical can. It is believed that the superior performance of this type at lean fuel-air ratios and at low pressures is due to fuel-air mixing control downstream of the point of initiation of combustion, which is absent in the simple-baffle flameholder. Within the range investigated for the can flameholder, geometric variables of hole number, size, shape, pitch, and open area do not influence combustion efficiency appreciably, and most of the geometric investigations were directed toward reduction of flameholder pressure loss. The flameholders investigated had open areas ranging from 75 to 175 percent.

The sloping-baffle flameholder, a combination of the simple-baffle and the can-type flameholders, appears to have the desirable performance characteristics of the can type. However, the many variables involved in this design have not as yet been investigated.

In reference 95 a comparison is made of five configurations tested in the same 20-inch ram-jet engine. From these tests of can, sloping-baffle, annular-piloted, and piloted V-gutter flameholder designs, it was found that all types gave combustion efficiencies of 80 to 90 percent. A comparison on the basis of specific impulse, where the effect of friction loss is included, showed the same high level of performance for all designs.

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Piloting

The use of a large-size pilot in conjunction with either the simple-baffle or the can flameholder is a desirable design principle for improved combustion performance, particularly at lean-fuel-air-ratio conditions. It has been shown analytically and experimentally that a shielded, low-velocity pilot zone can occupy a relatively large percentage of the combustor area without causing or producing excessive pressure losses (ref. 42).

Both high combustion efficiency and wide stability limits are desired in pilots; but it has been found experimentally that a pilot which has wide stability limits usually has poor combustion efficiency. The importance of pilot burning efficiency on over-all combustion performance has not been definitely established, except to the extent that, where the pilot heat release represents a large portion of the total heat release, the pilot combustion efficiency should be high. A circular pilot cross section gave better efficiency than a rectangular cross section, and a pilot length equal to its diameter was adequate. Pilot performance was insensitive to hole size, number, and spacing within the limits investigated. For large-size combustors, an annular-shaped pilot is believed to have an advantage over the centerbody pilot, since for a given pilot cross-sectional area, the radial distance from pilot to outer wall can be reduced.

Fuel Injection

Location of injectors. - The location of the fuel injector with respect to the flameholder is one of the most significant variables influencing ram-jet combustor performance. In general, for efficient combustion at lean fuel-air ratios it is desirable to stratify the fuel-air mixture, thereby producing a locally stoichiometric region. For near-stoichiometric operation, a homogeneous mixture gives best results. Information on mixture distribution downstream of fuel injectors is given in chapter I. A stratified mixture can be obtained with some degree of effectiveness by radial and axial location of the fuel injector so that the fuel mixes with only a portion of the combustion air. A more effective technique for obtaining stratification is mechanical control of fuel-air mixing by means of a mixing control sleeve (refs. 1 and 75).

For efficient combustion at lean as well as rich operation, the use of dual fuel-injection systems is necessary. For best combustion efficiency, the primary injector supplies the fuel at lean fuel-air ratios, and both primary and secondary injectors are used for rich mixtures. At increasingly rich operation, a smaller fraction of the fuel is supplied by the primary and the remainder by the secondary injector.

Locating the fuel injector upstream of the flameholder is a generally accepted practice. However, care must be exercised to prevent flame from seating upstream of the flameholder, especially with the can-type flameholder. It is possible to inject the fuel within the flameholder, and combustion efficiency, though not impaired at lean fuel-air ratios by this method of injection, is poor at rich conditions.

Types of injectors. - Simple-orifice, solid, and hollow-cone sprays have been used with equal success. The spray bar with multiple orifices provides a large number of injection points with little area blockage; this is desirable for rich operation. However, spray nozzles do not plug as easily, and changes in nozzle tip size can be readily made. Variable-area fuel nozzles also seem suited for ram-jet application.

Fuel Type

The majority of the investigators have concluded that for inlet-air temperatures corresponding to flight Mach numbers of 2.0 or greater, combustion is satisfactory with either gasoline or JP fuels. High-volatility and high-flame-speed fuels such as propylene oxide show some gains at severe operating conditions such as at low inlet-air temperatures or with short combustor lengths.

Inlet-Air Conditions

The combustion efficiency of ram-jet combustors follows well known trends with inlet-air conditions. Efficiency under usual conditions increases with pressure and temperature and decreases with velocity. These effects have been correlated for an idealized combustor in which the vaporization and mixing steps have been eliminated as possible rate-controlling mechanisms (ref. 94). For these reasons, and because the effects of other variables such as combustor length and operating fuel-air ratio have not been definitely established, these correlations can be applied specifically only in certain cases.

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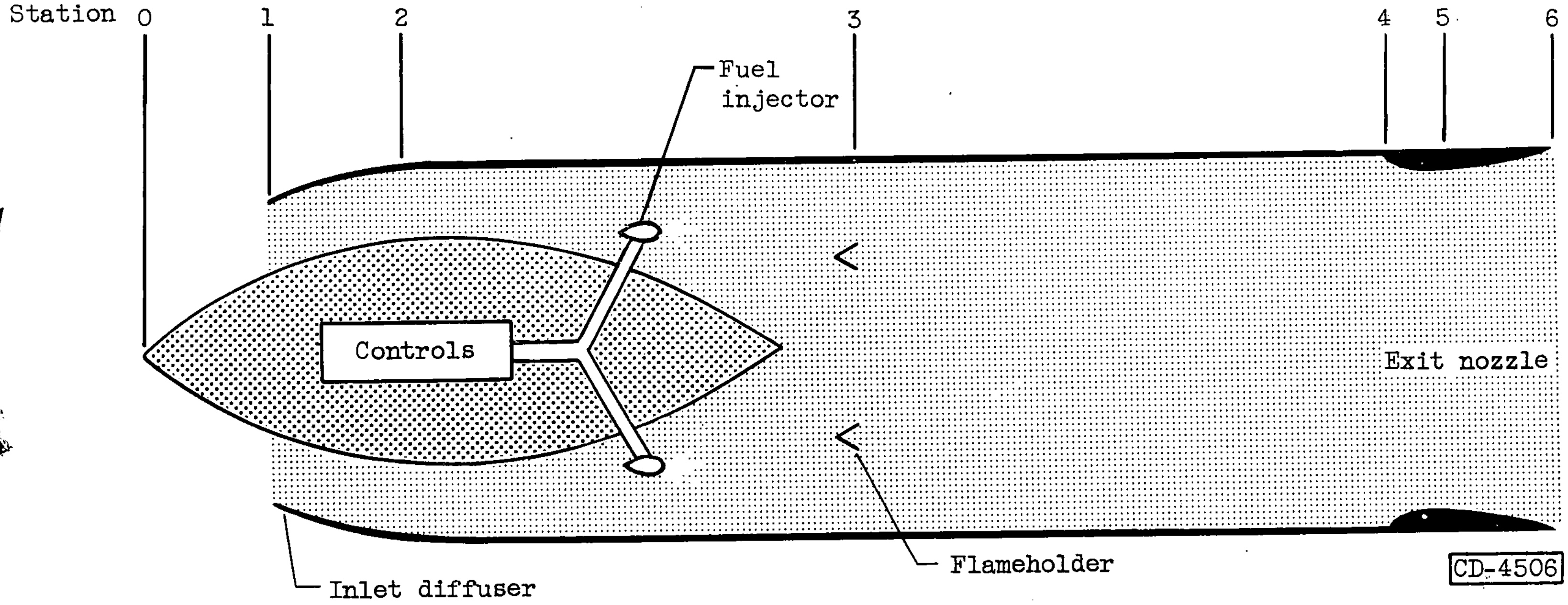


Figure 128. - Typical ram-jet configuration.

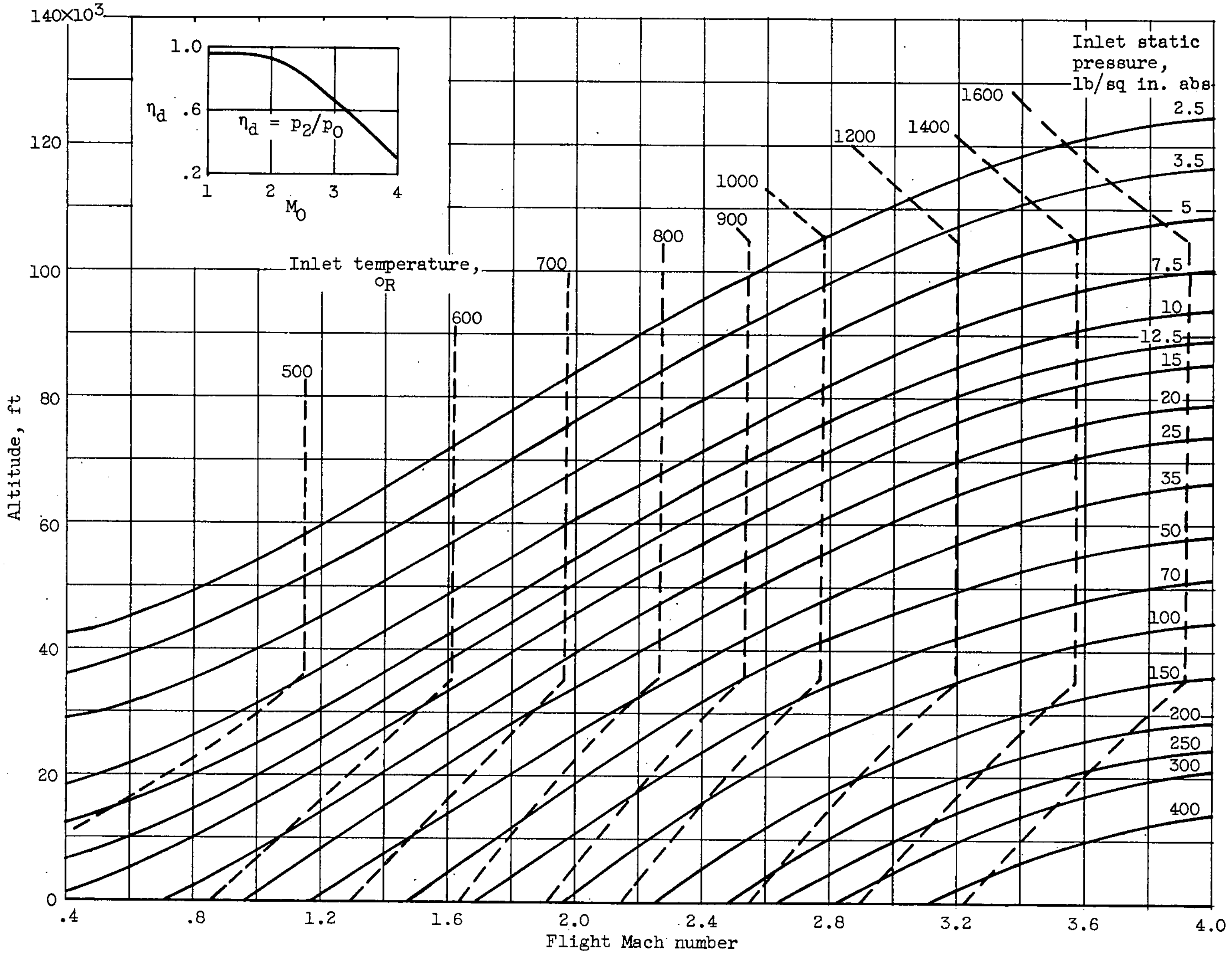
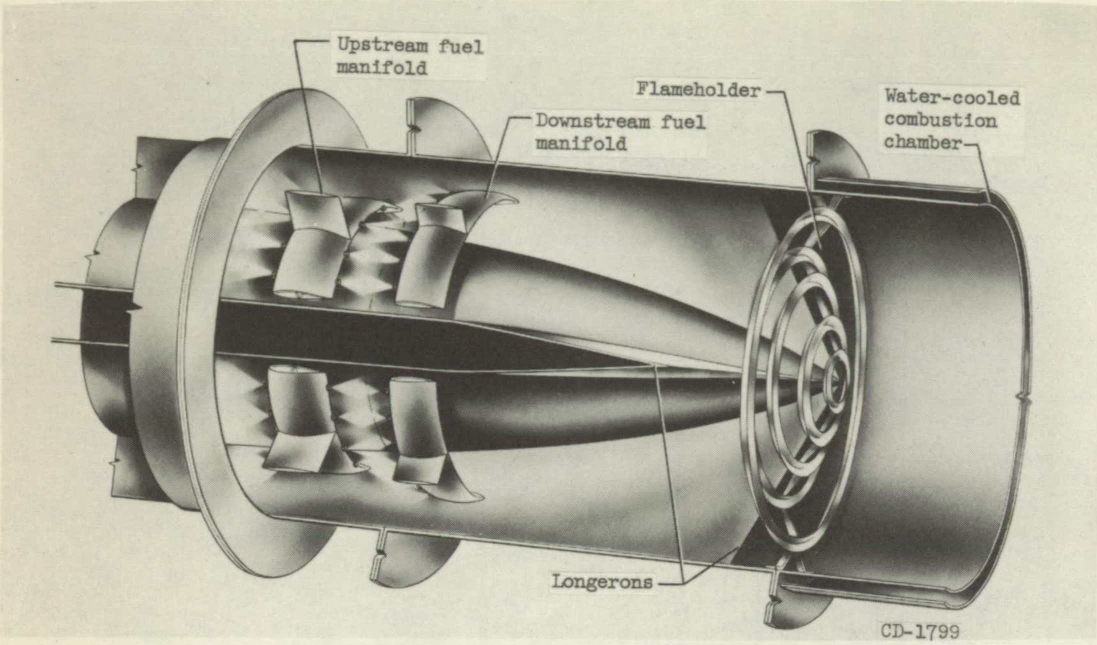
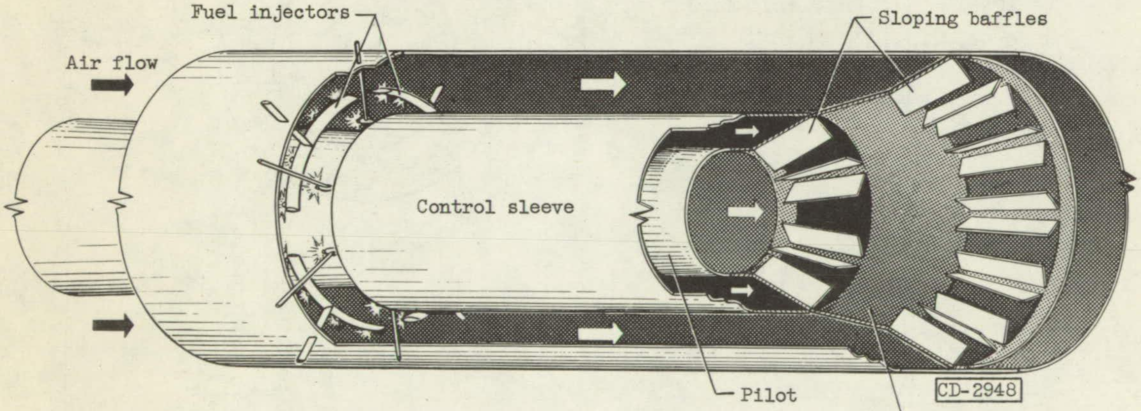


Figure 129. - Ram-jet inlet conditions for various flight speeds and altitudes. Inlet-air velocity, 200 feet per second; assumed diffuser recovery η_d ranges from 0.95 at Mach 1 to 0.30 at Mach 4.

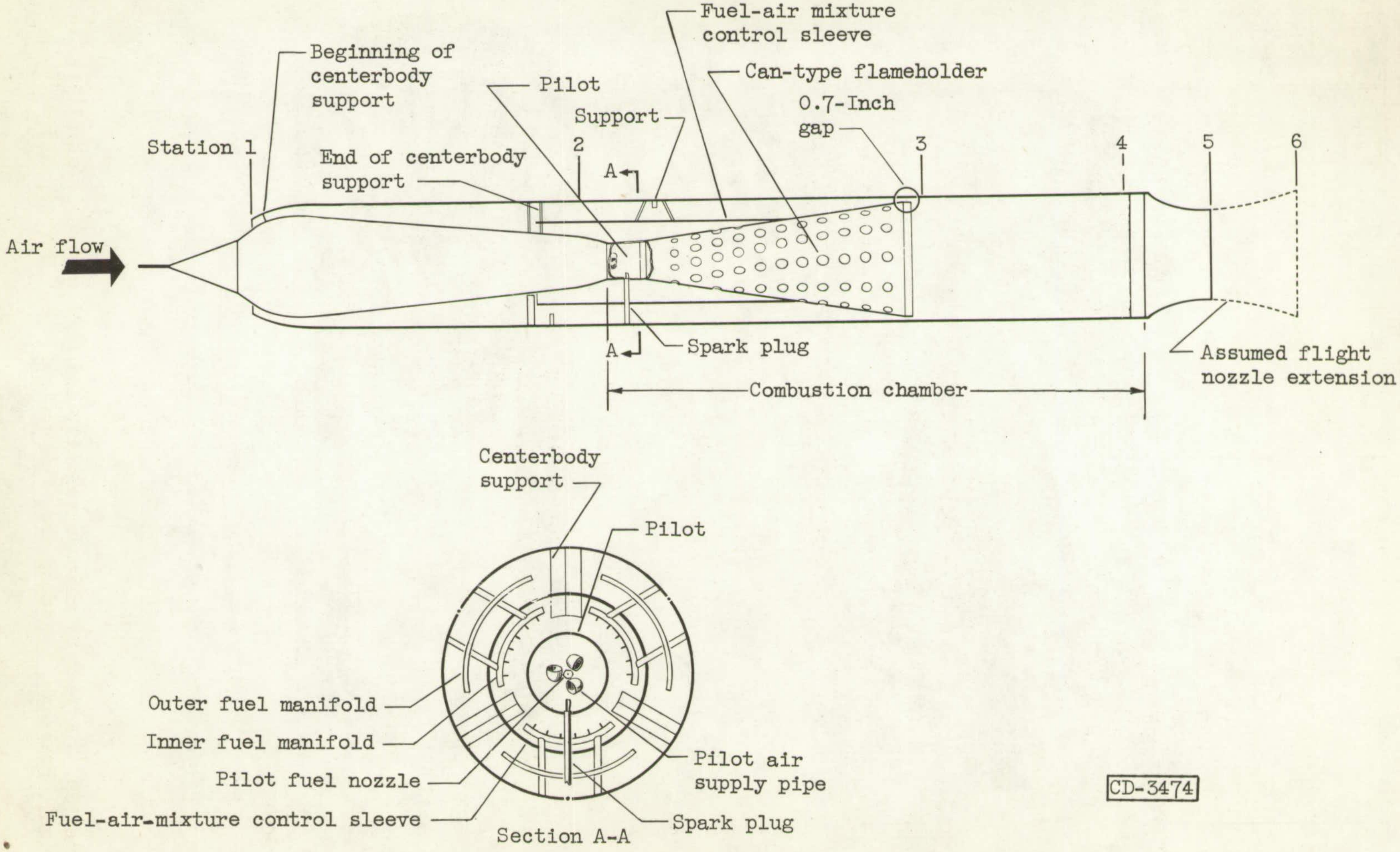


(a) V-gutter flameholder.



(b) Sloping-baffle flameholder (ref. 53).

Figure 130. - Typical ram-jet flameholder configurations.



(c) Can-type flameholder.

Figure 130. - Concluded. Typical ram-jet flameholder configurations.

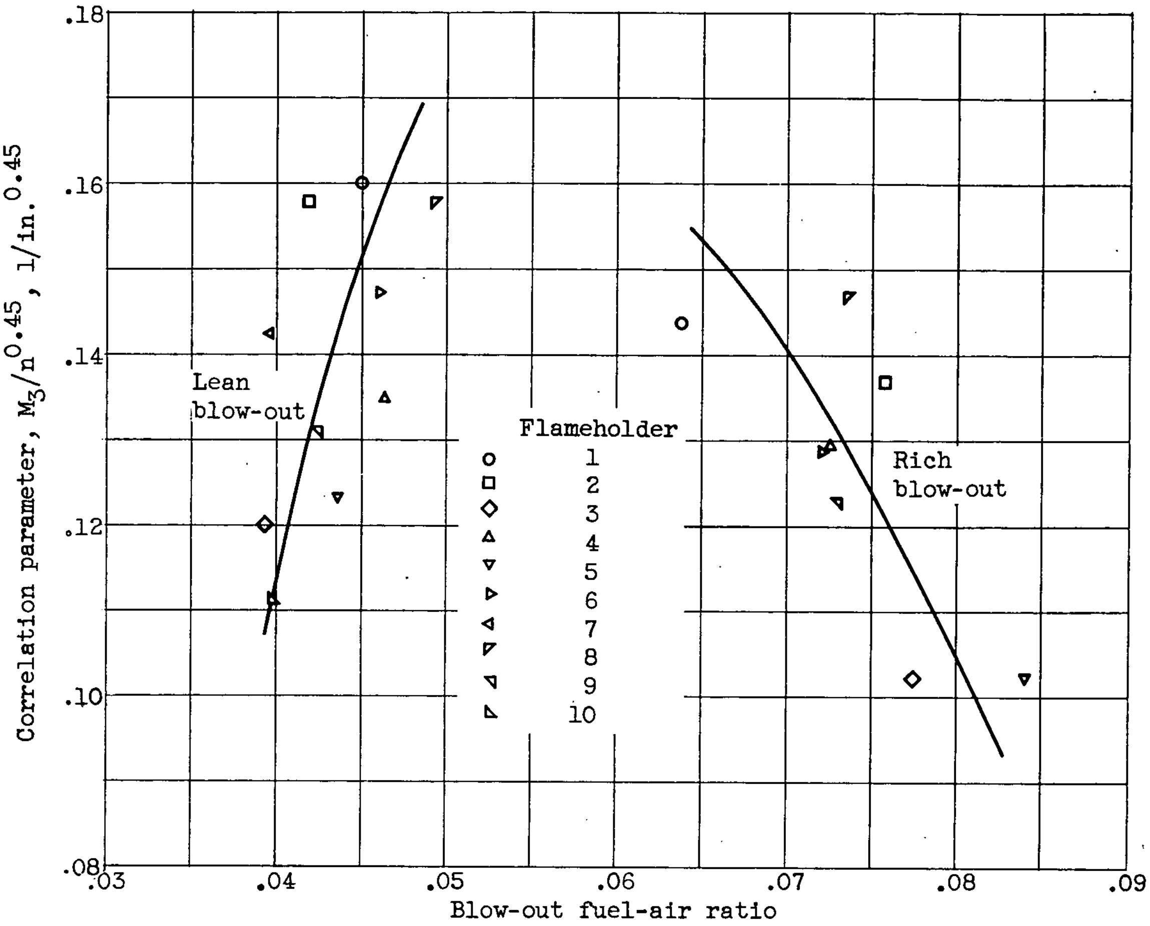


Figure 131. - Correlation of blow-out data with gutter size. Combustion-chamber-outlet total pressure, 2000 pounds per square foot absolute.

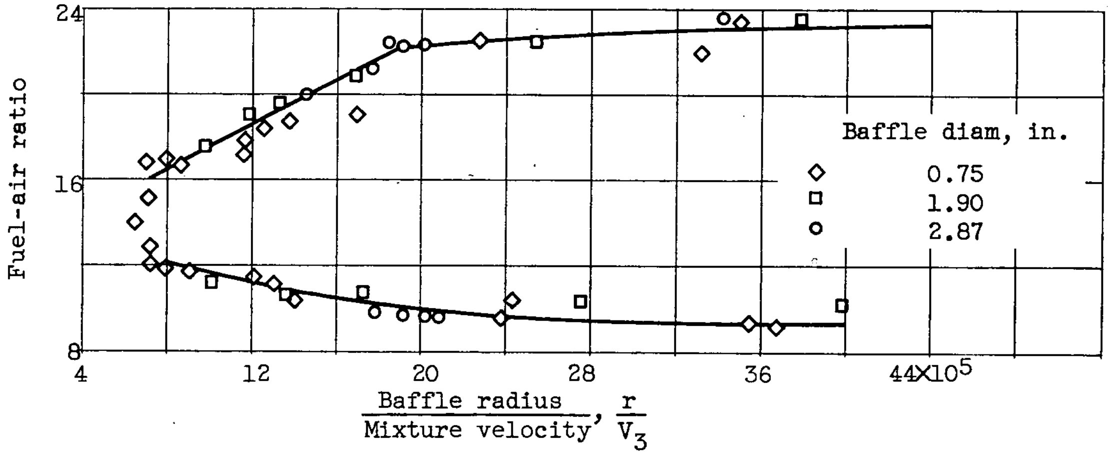
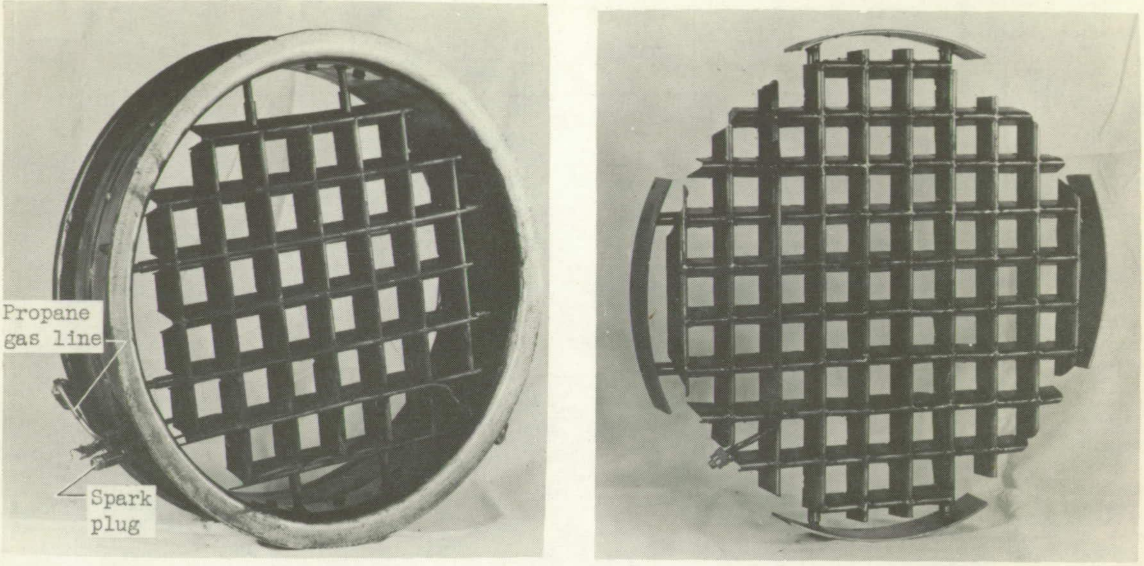
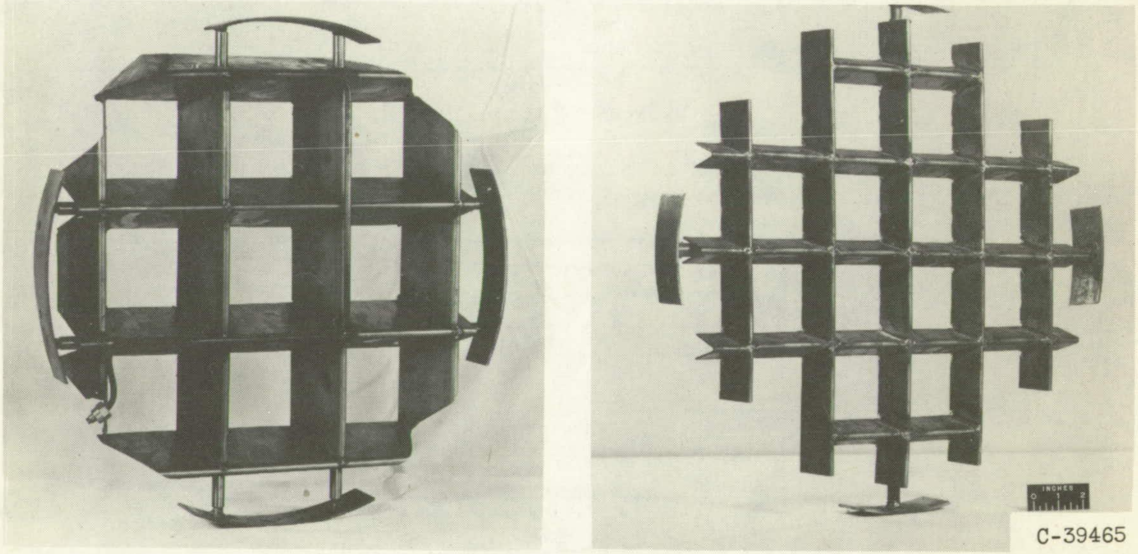


Figure 132. - Effect of mixture velocity and baffle size on stability range. Pressure, 1 atmosphere; temperature, 300° F (ref. 17).



(a) Standard flameholder mounted in flameholder section.

(b) Three-quarter-scale flameholder.



(c) Double-scale flameholder.

(d) 1.4 Spaced flameholder.

Figure 133. - Gutter-grid flameholders used in 20-inch ram jet (ref. 35).

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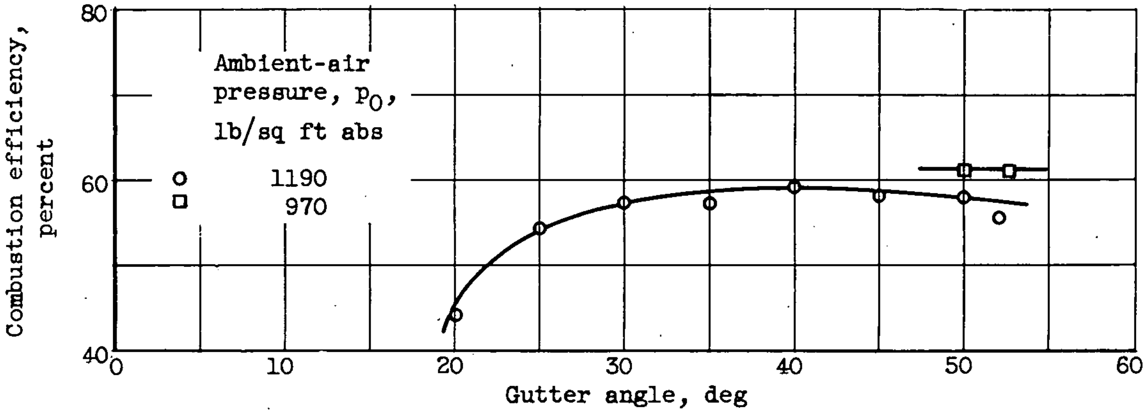

Figure 134. - Effect on combustion efficiency of gutter angle of adjustable three-gutter flameholder. 20-Inch ram jet with 5-foot combustion chamber; fuel-air ratio, 0.072 to 0.078; combustion-chamber-inlet static pressure, 1500 pounds per square foot absolute (ref. 35).

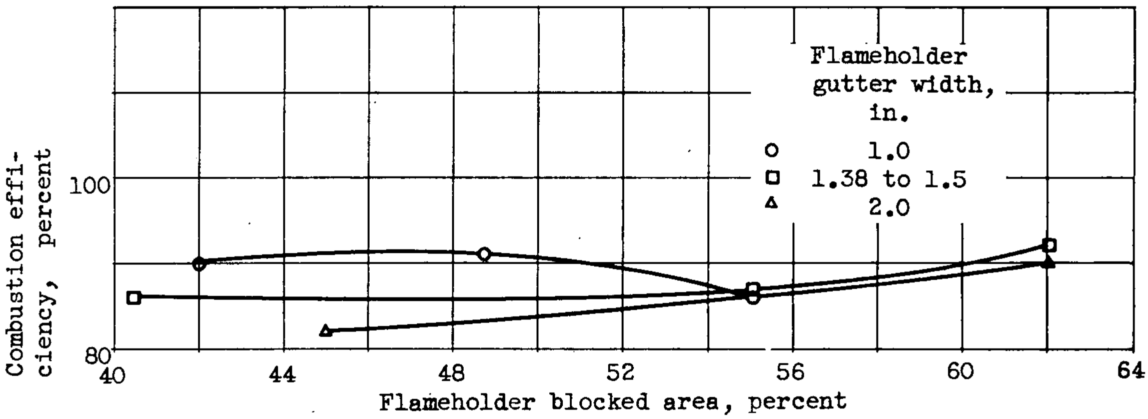

Figure 135. - Effect of flameholder blocked area on combustion efficiency. Fuel-air ratio, 0.050; combustion-chamber-exit pressure, 1800 pounds per square foot absolute (ref. 26).

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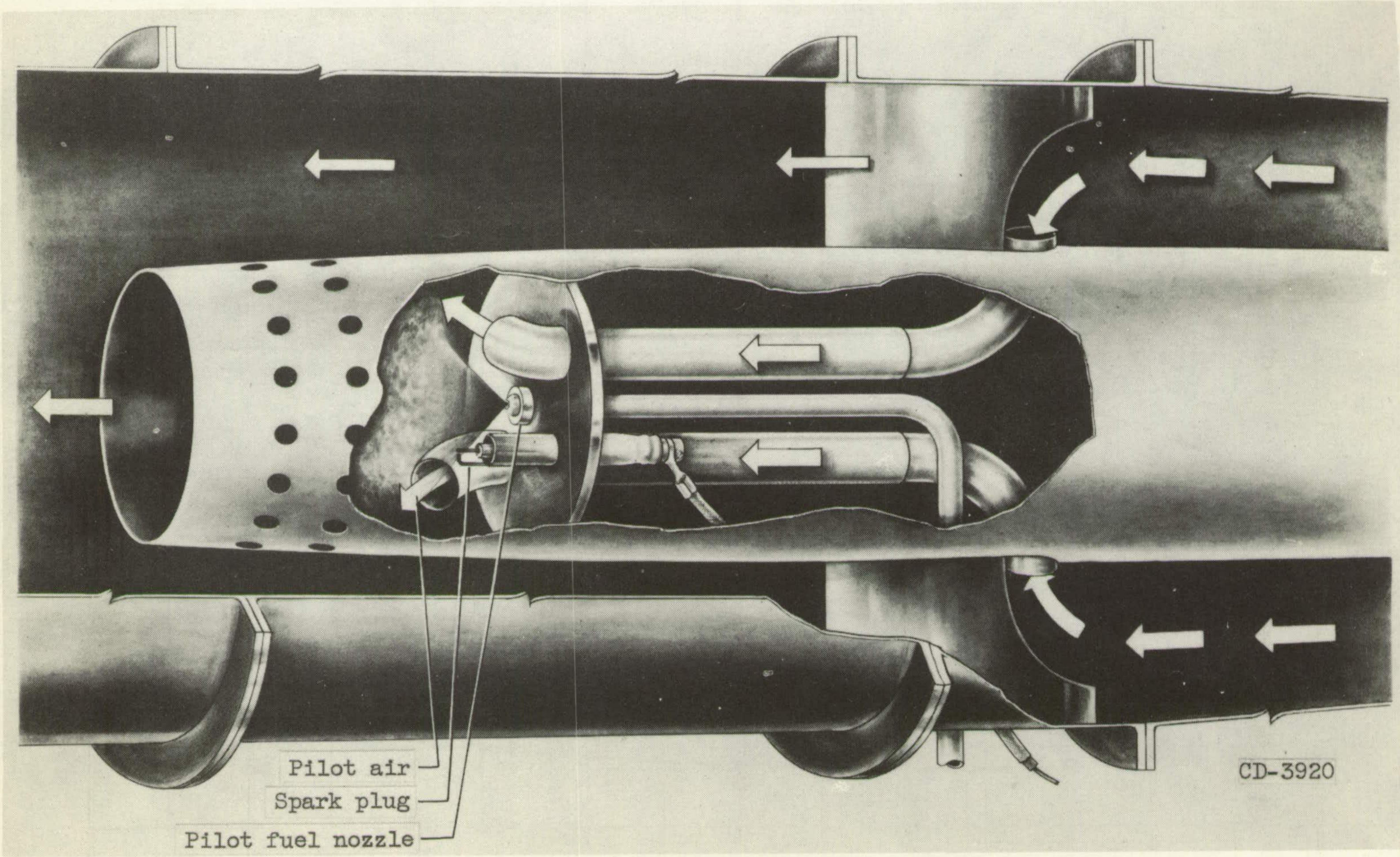

Figure 136. - Typical pilot configuration.

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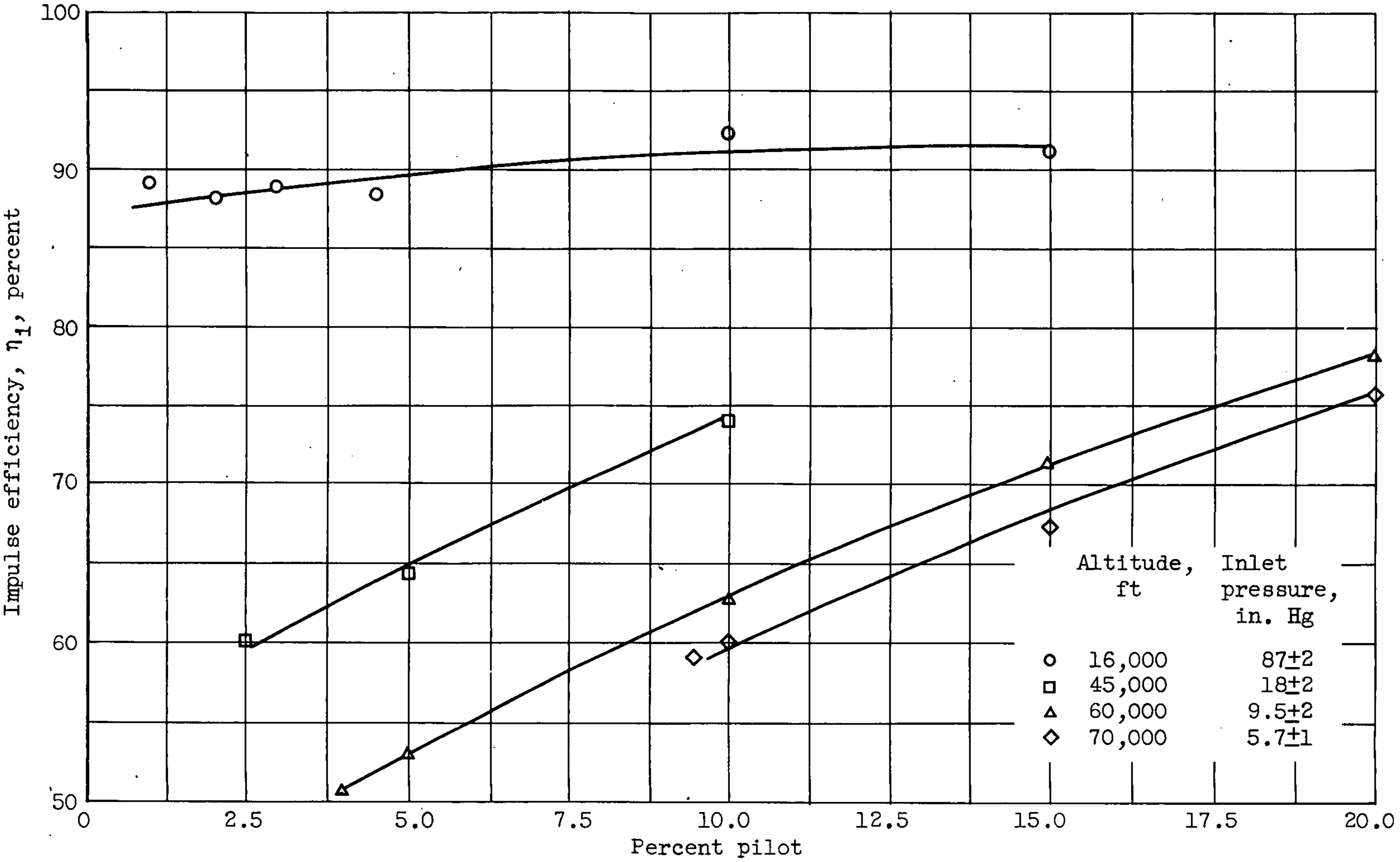

Figure 137. - Effect of pilot heat on burner efficiency. Burner length, 14 inches; fuel, pentane; stoichiometric conditions (ref. 45).

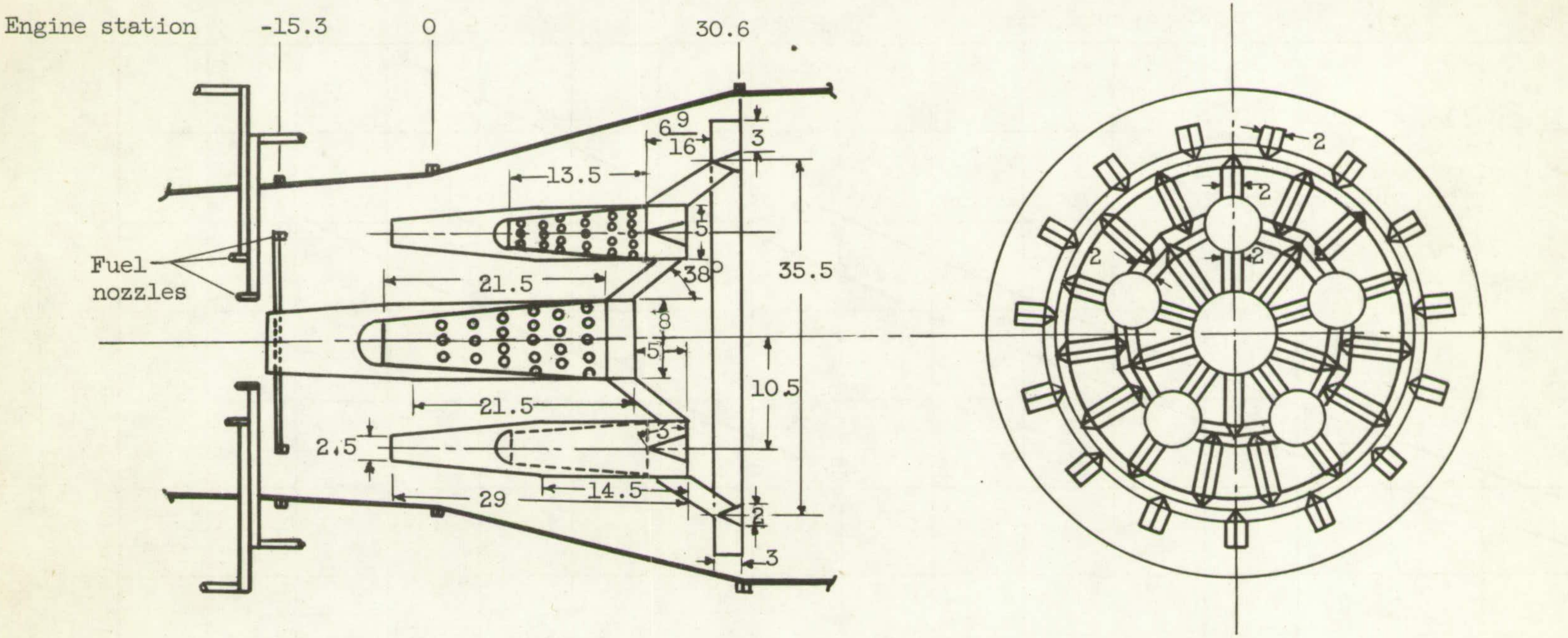

Figure 138. - Flameholder configuration employing five pilot zones (ref. 50). (Dimensions in inches.)

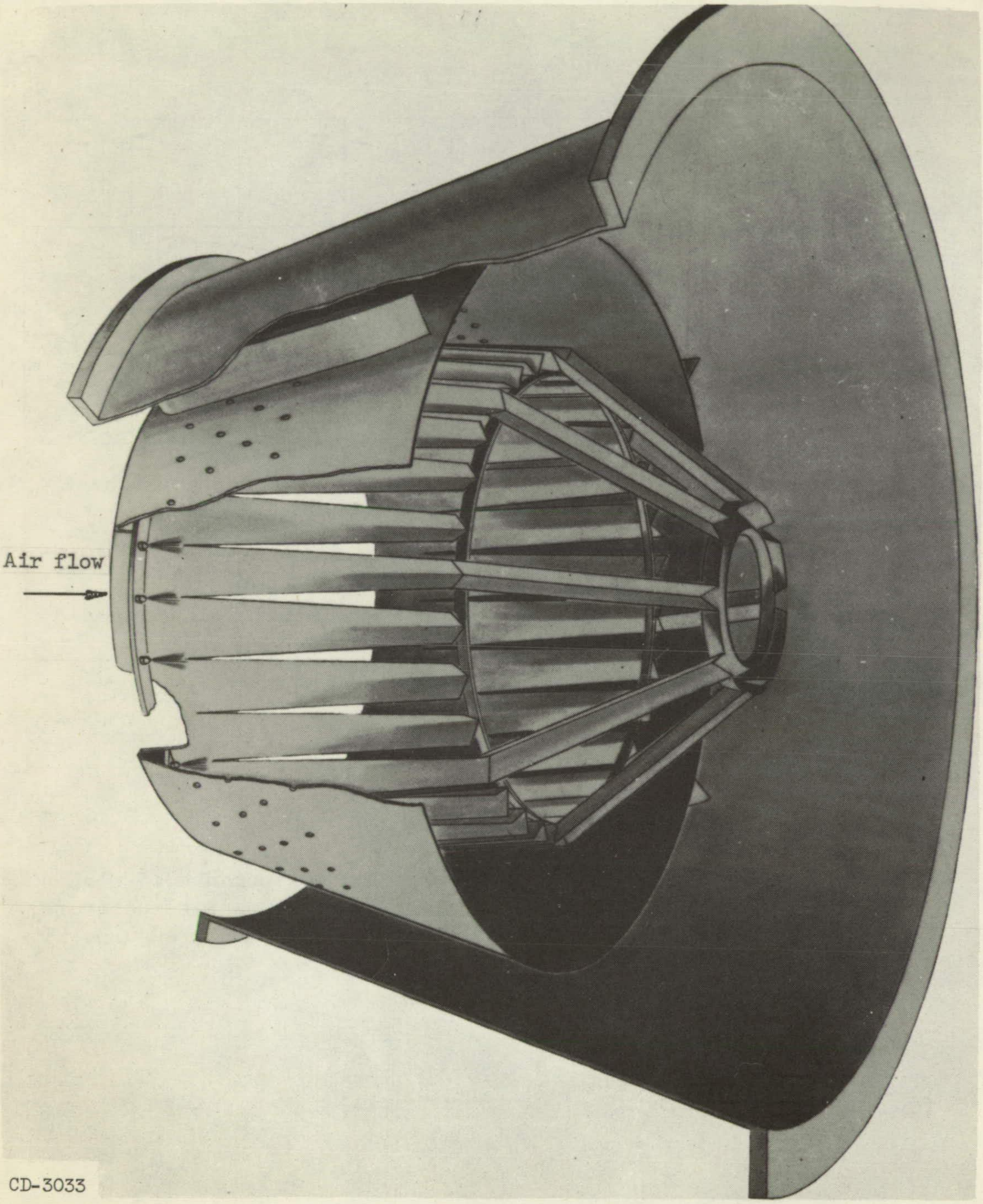

Figure 139. - Annular-piloted combustor configuration (refs. 50 and 51).

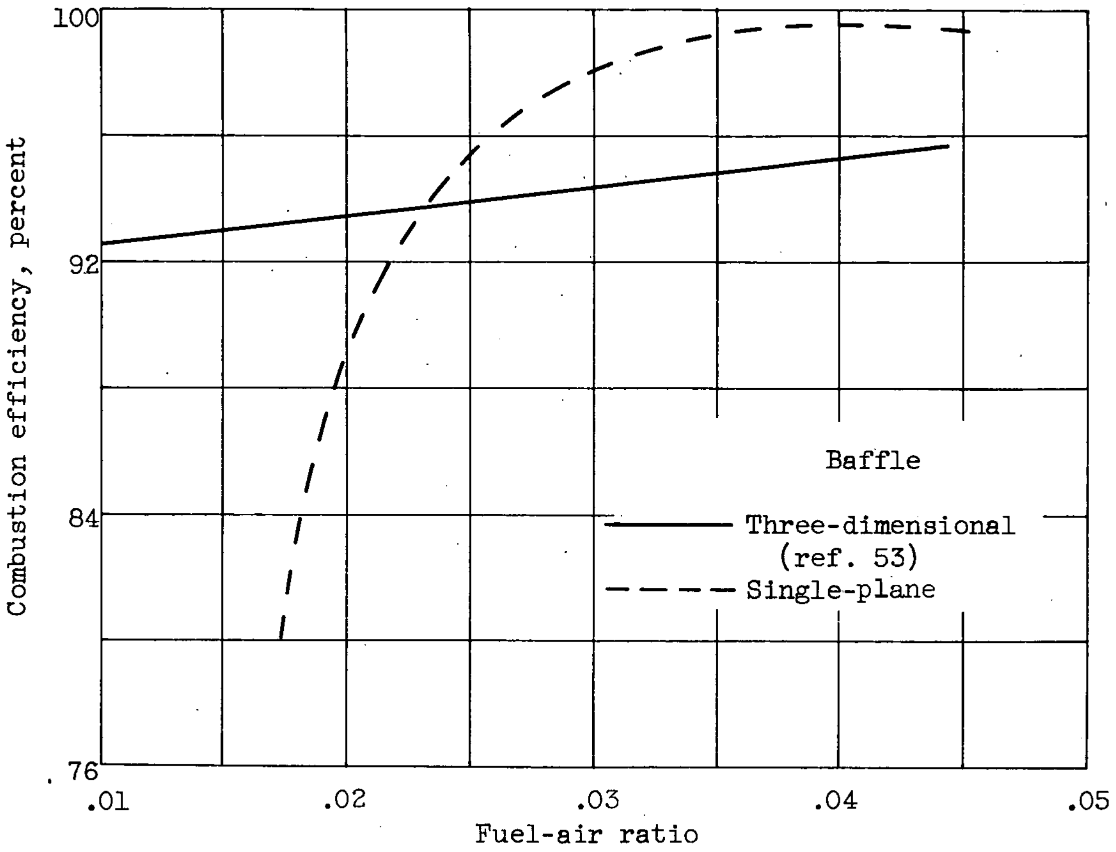

Figure 140. - Comparison of combustion performance of planar and three-dimensional flameholders. Inlet-air temperature, 600° F; velocity, 230 to 260 feet per second; pressure, 31 to 35 inches of mercury absolute.

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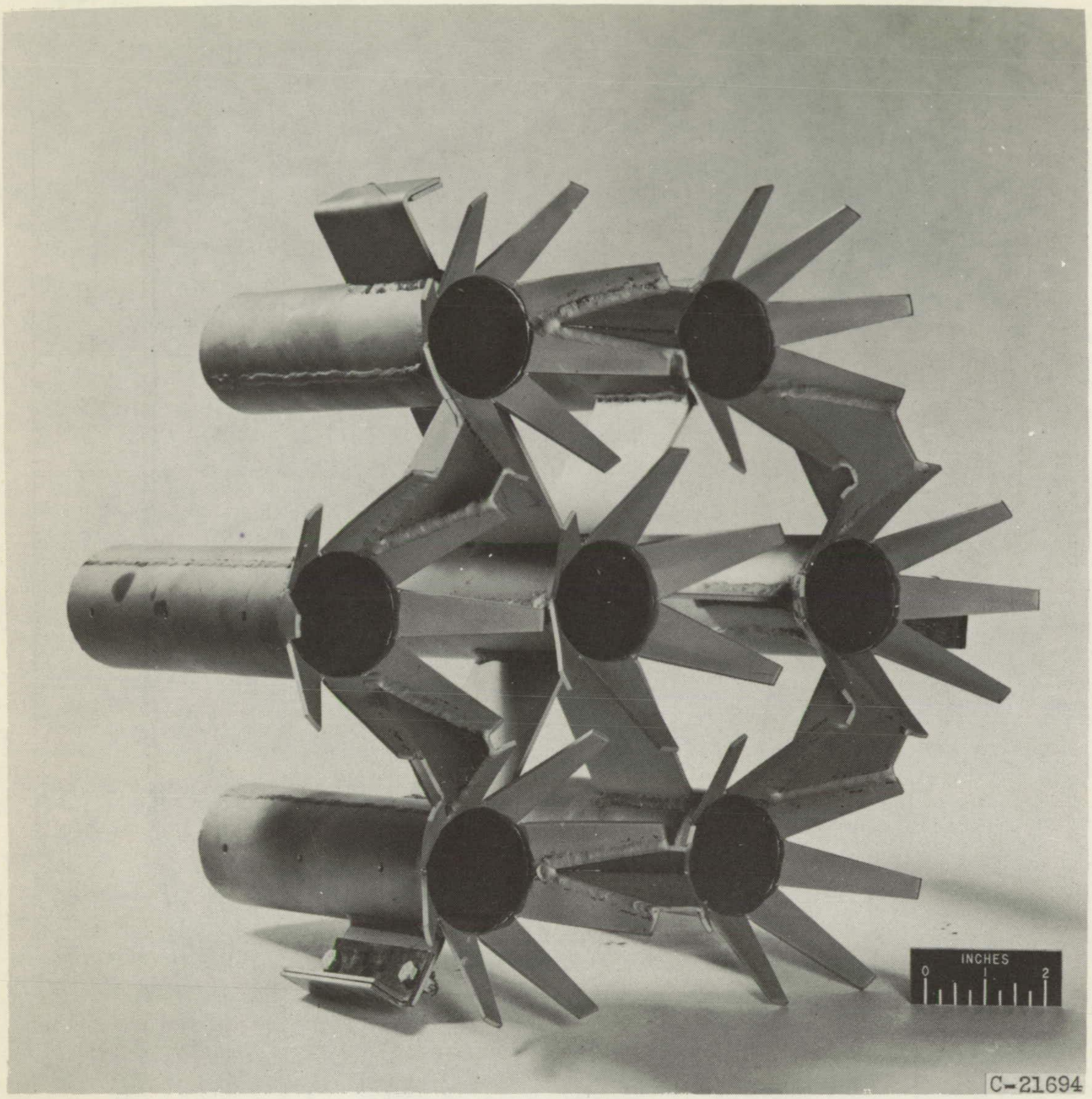
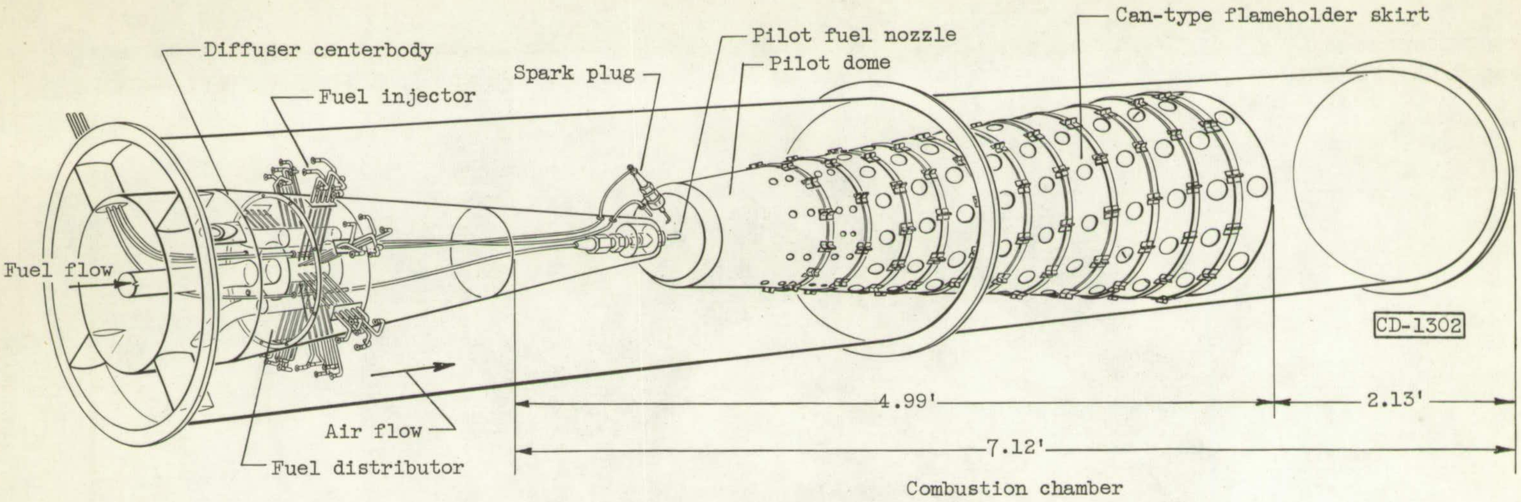
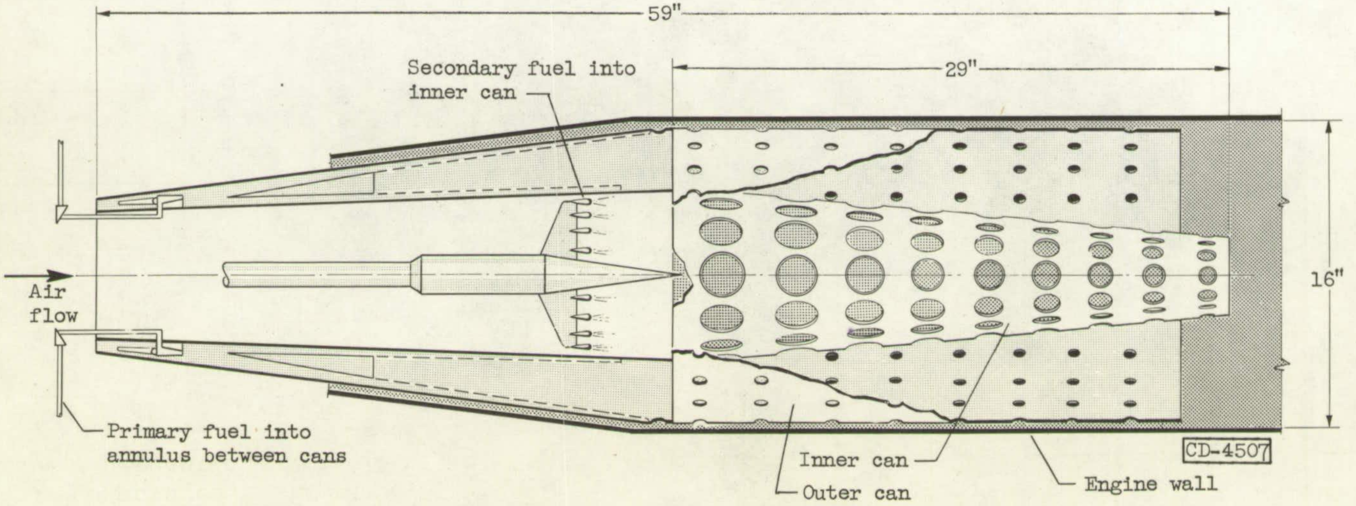


Figure 141. - Rake-type flameholder with flare pilots.



(a) Simple can flameholder installed in ram-jet engine.



(b) Annular can flameholder (ref. 60).

Figure 142. - Typical can flameholder.

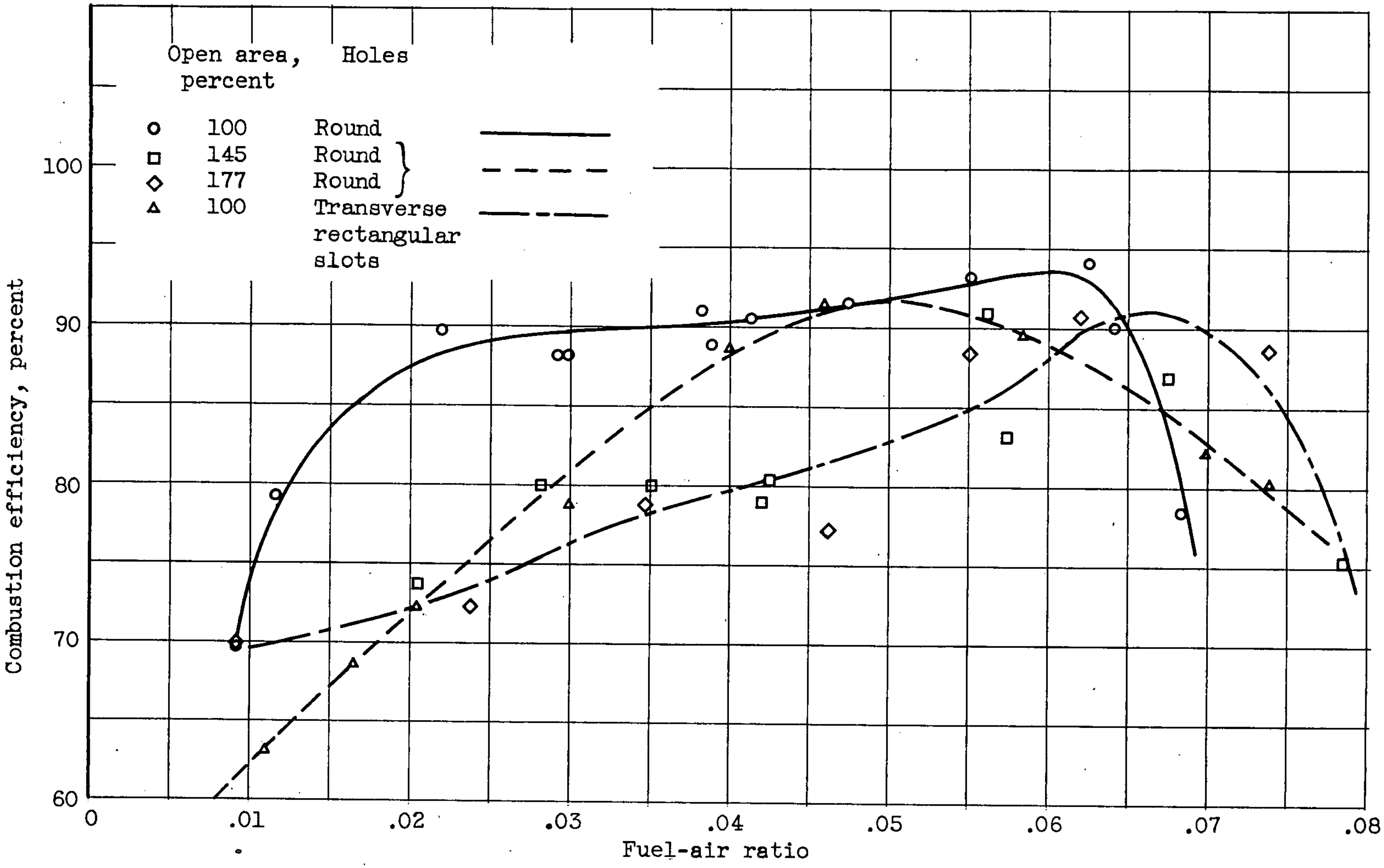


Figure 143. - Effect of can open area upon combustion efficiency of 10-inch-diameter, quarter-segment combustor during free-jet tests. Inlet-air temperature, 180°±10° F; atmospheric exhaust (ref. 62).

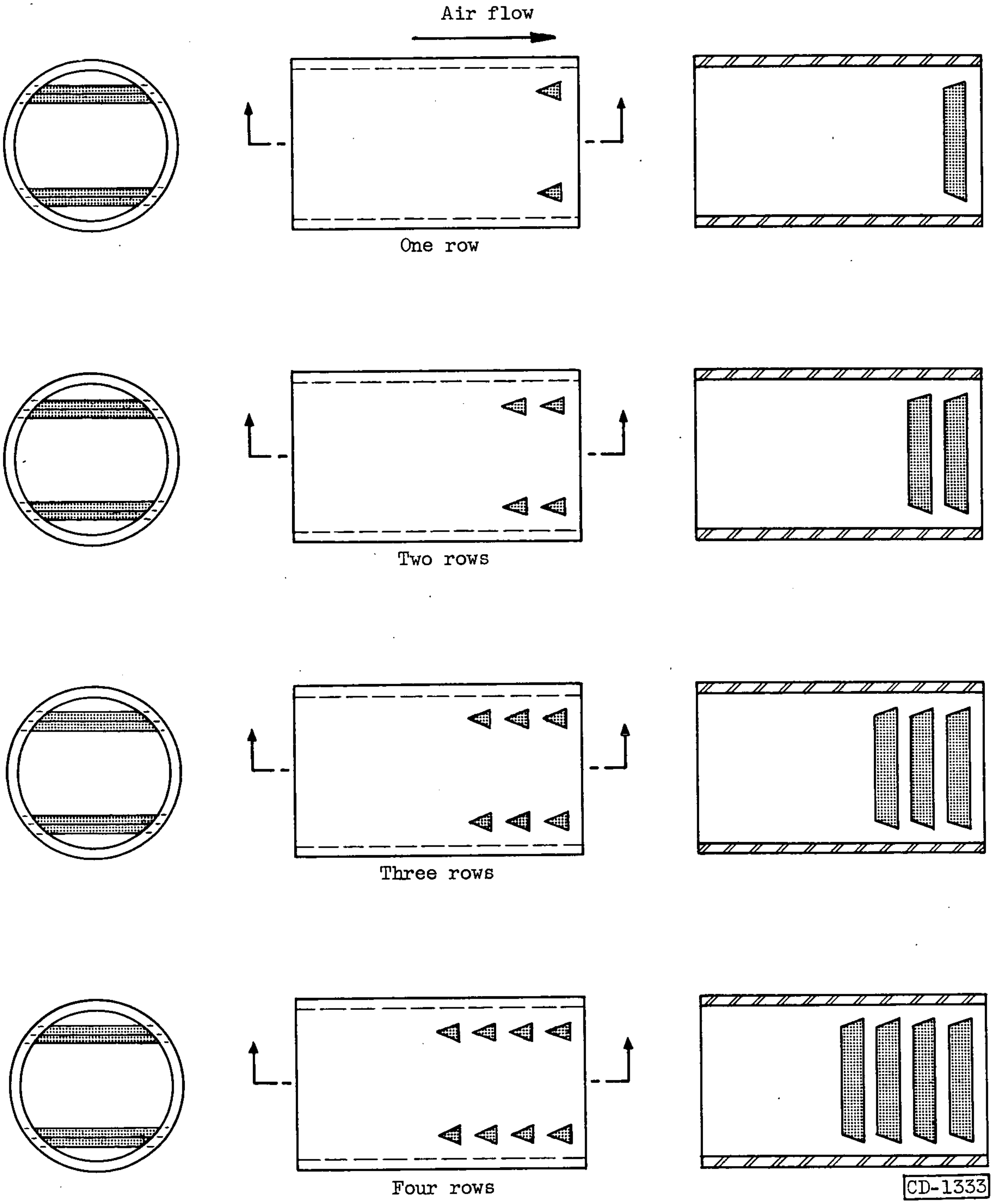


Figure 144. - Flameholder configuration employing immersed surfaces (ref. 63).

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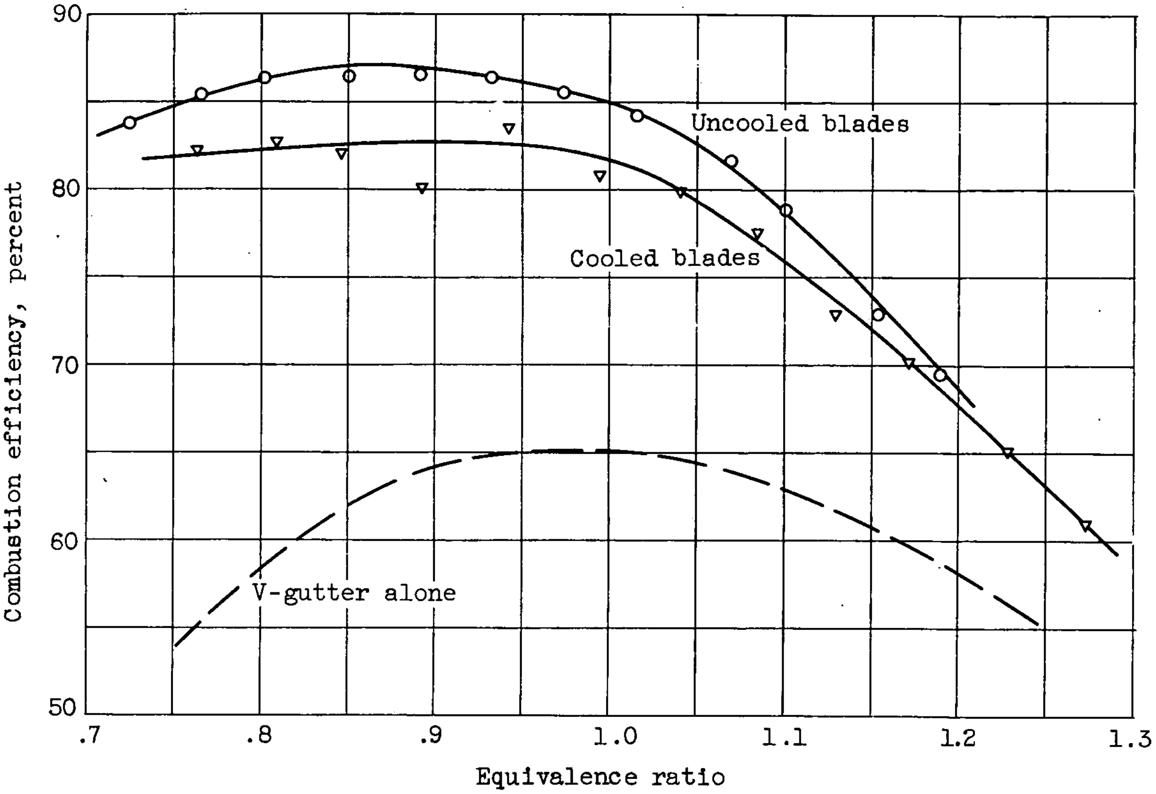
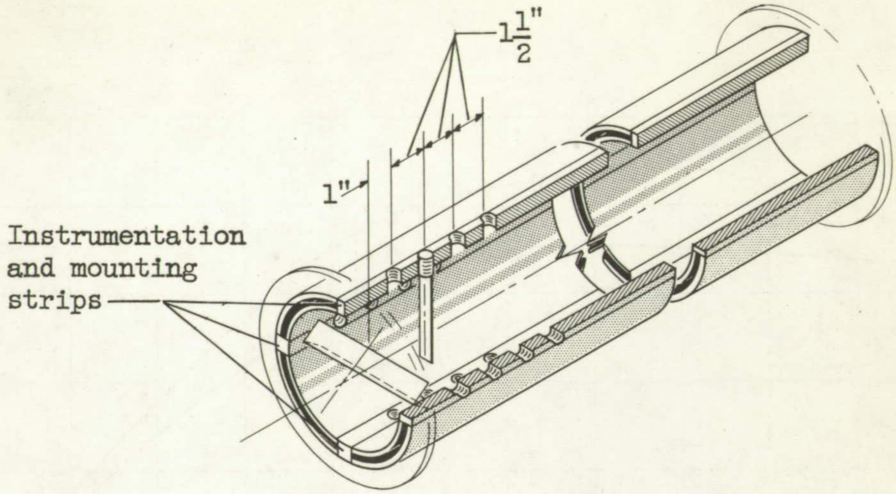
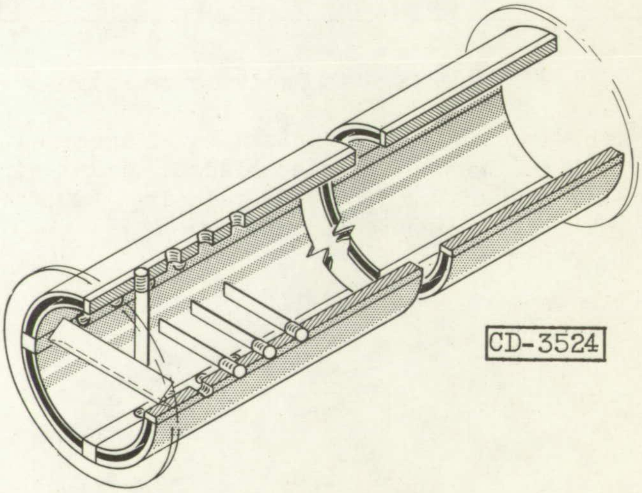


Figure 145. - Combustion efficiencies of immersed-surface configurations with both cooled and uncooled blades. Inlet-air pressure, 1 atmosphere; inlet-air temperature, 660° R; velocity, 200 feet per second; fuel, gasoline with high-pressure injection.

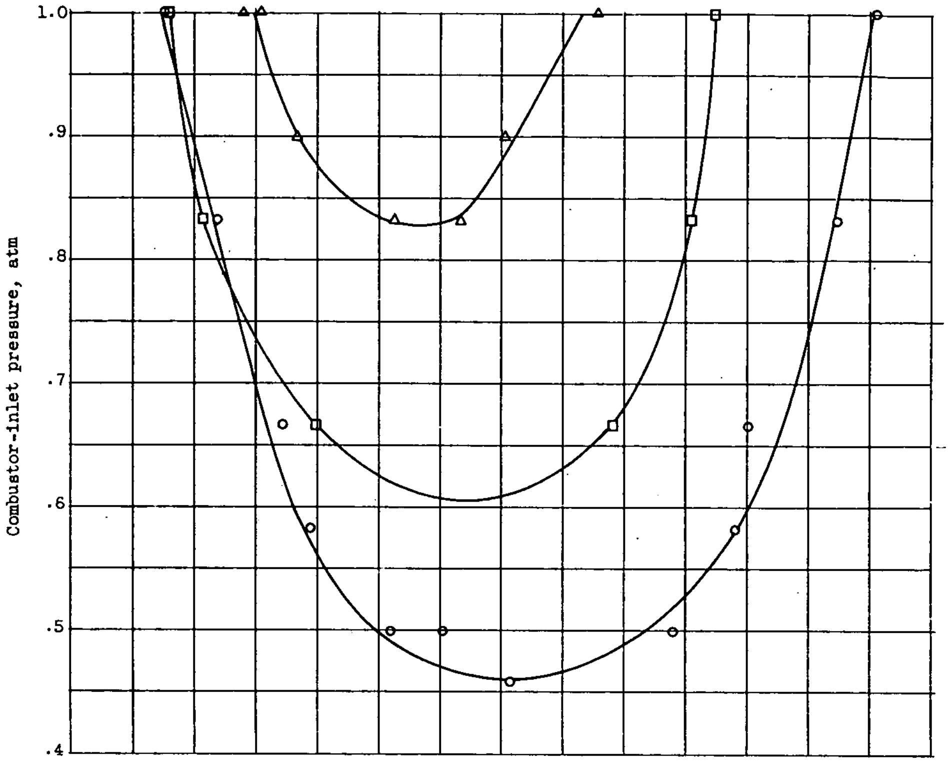


(a) Single-perpendicular-blade configuration.

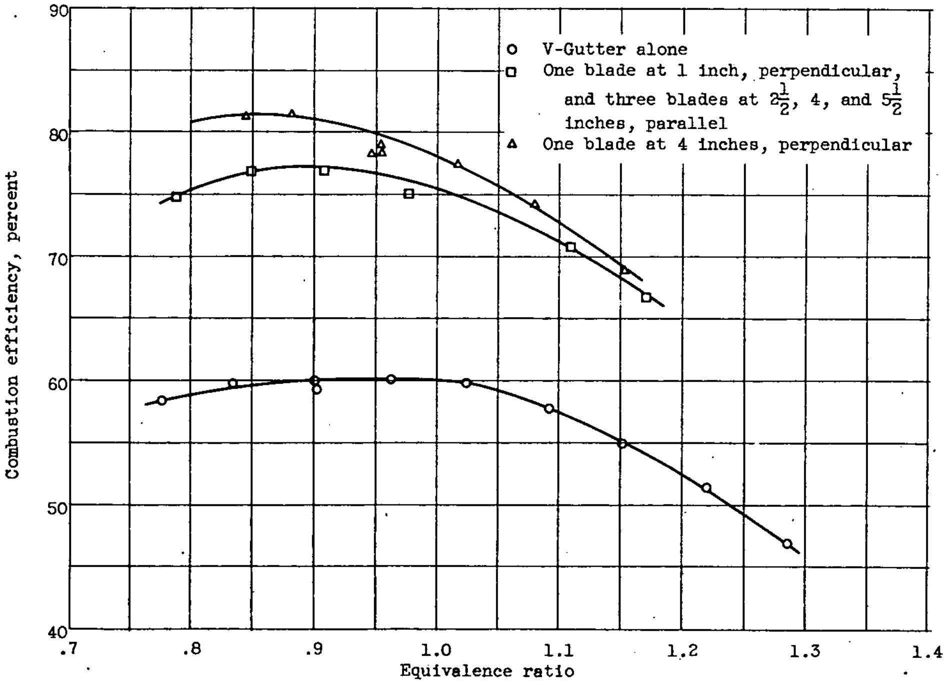


(b) Four-blade configuration.

Figure 146. - Typical arrangements of blades (immersed surfaces).



(a) Comparison of stability limits.



(b) Comparison of combustion efficiency.

Figure 147. - Effect of location of immersed surfaces on combustion efficiency and stability limits of 5-inch-diameter combustor. Inlet-air temperature, 660° R; inlet-air velocity, 220 feet per second.

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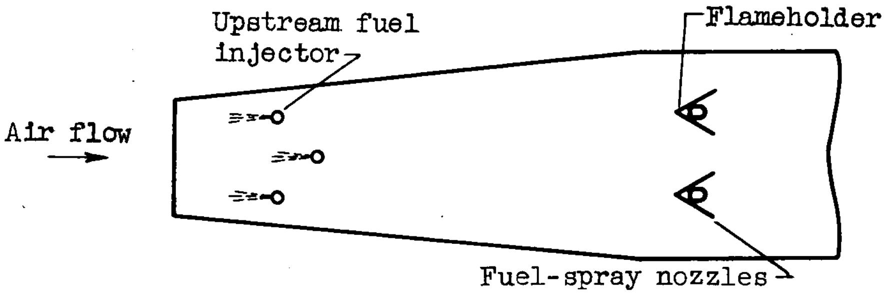
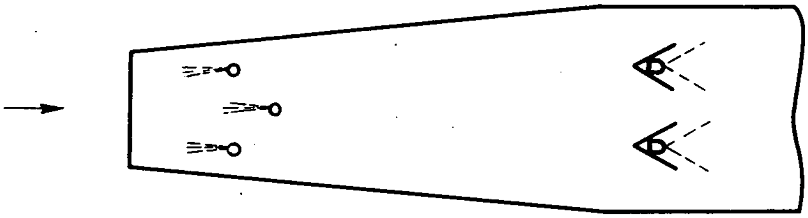
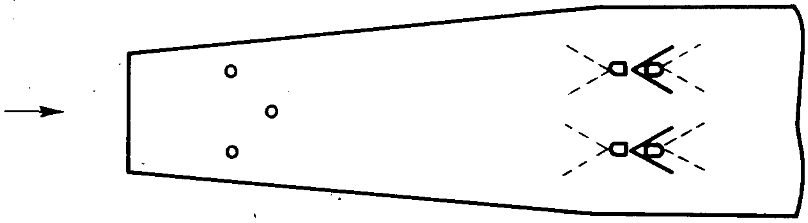


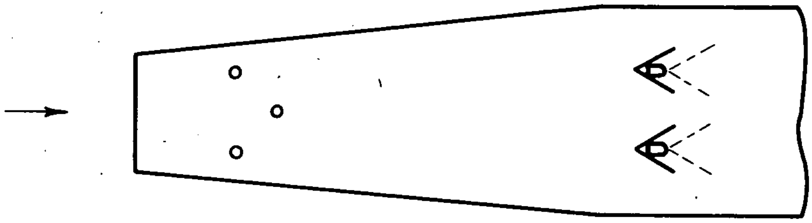
(a) Upstream-injection burner.



(b) Split-injection burner.

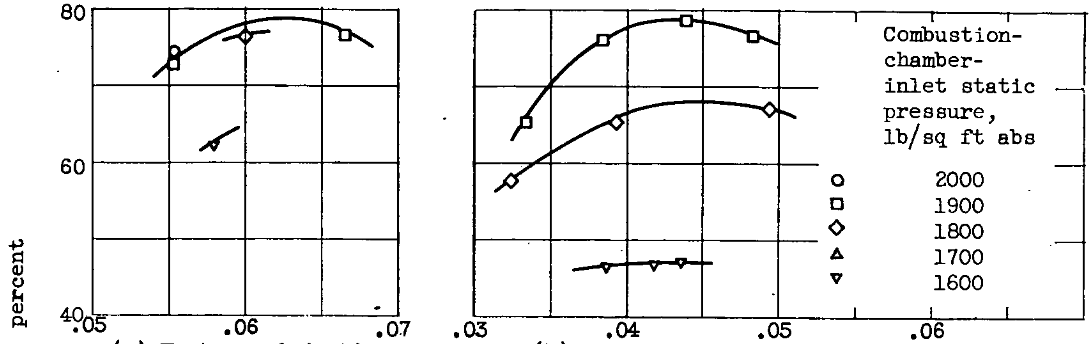


(c) Flameholder split-injection burner.



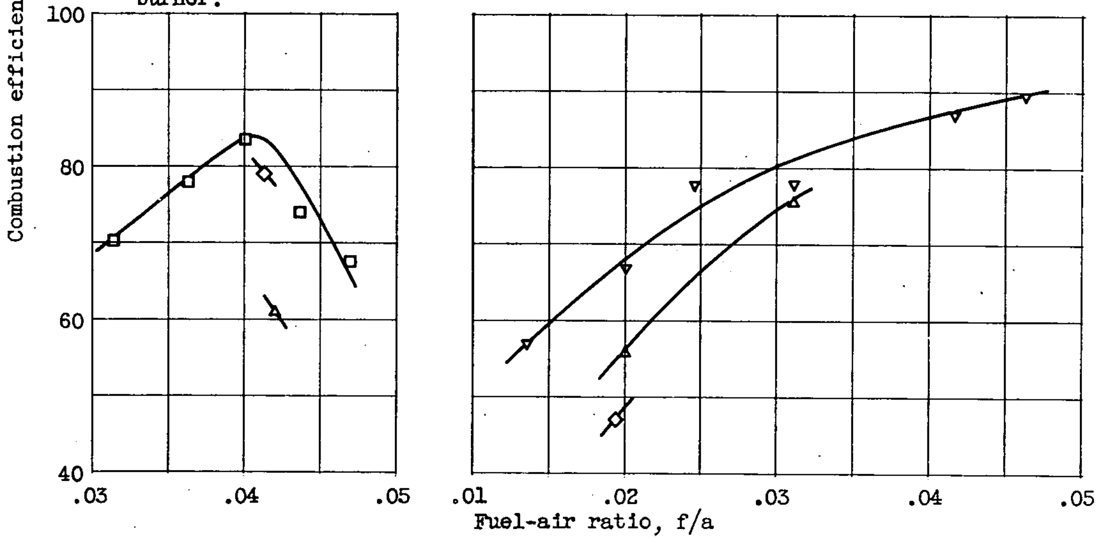
(d) Flameholder injection burner.

Figure 148. - Fuel-injection arrangements used in operational performance investigation of 20-inch ram jet (ref. 71).



(a) Upstream-injection burner.

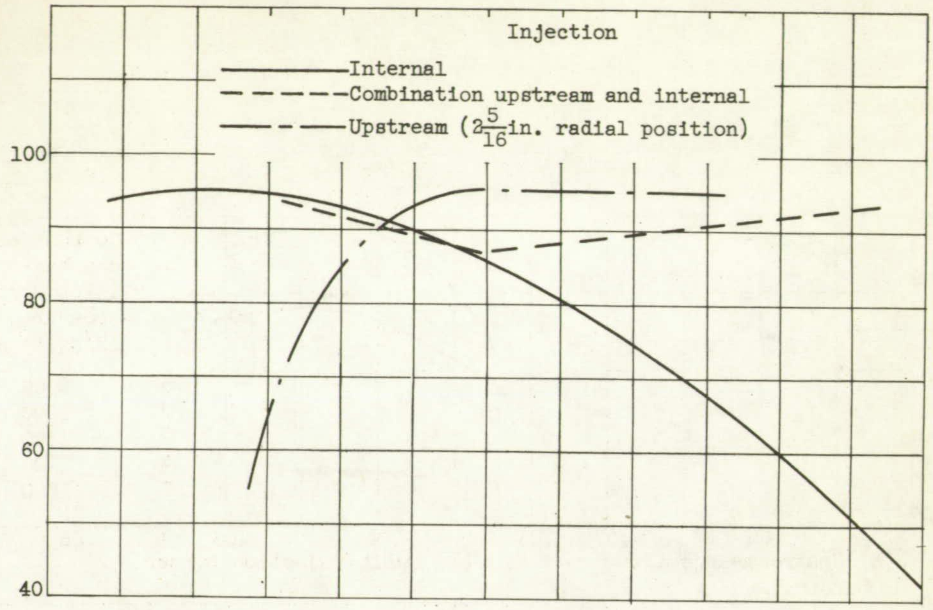
(b) Split-injection burner.



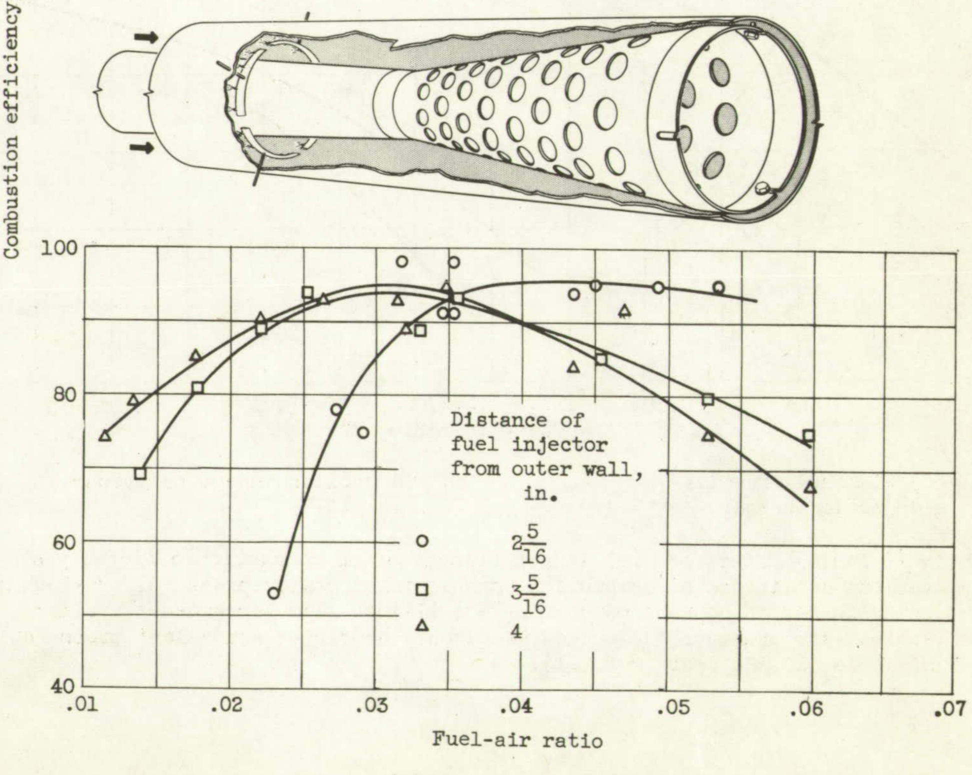
(c) Flameholder split-injection burner.

(d) Flameholder injection burner.

Figure 149. - Effect of fuel-injector location on combustion efficiency at various conditions of combustion-chamber-inlet static pressure. 20-Inch ram jet with 8-foot combustion chamber and 17-inch-diameter exhaust nozzle; ambient-air pressure, 20 inches of mercury absolute; equivalent pressure altitude, 10,100 feet (ref. 71).

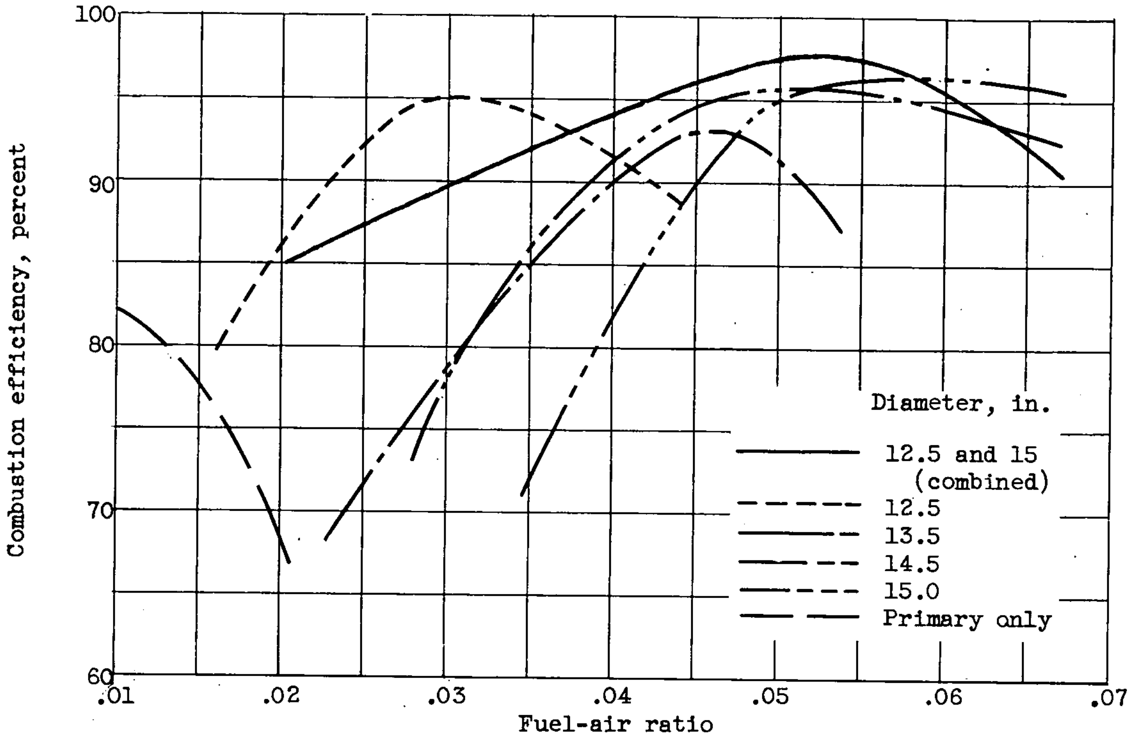


(a) Linear location.

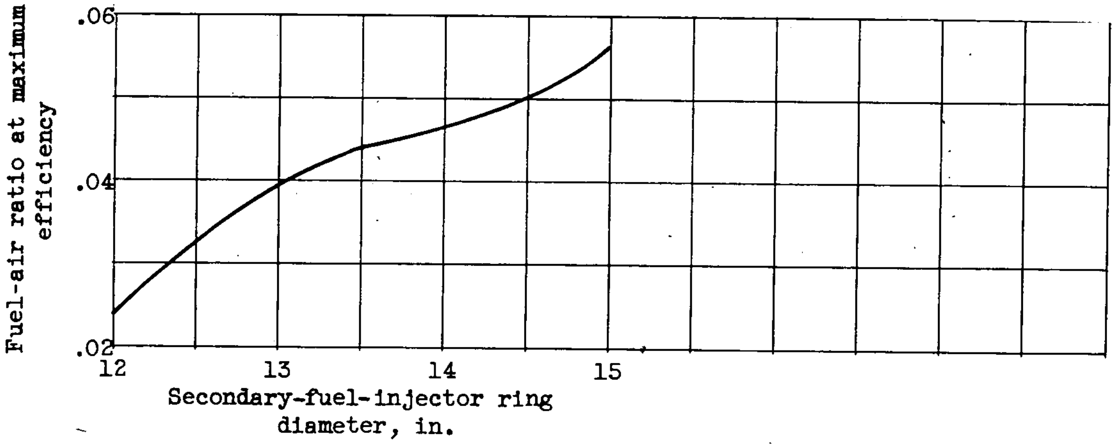


(b) Radial location.

Figure 150. - Effect of fuel-injector location on performance of can-type combustor. Inlet-air pressure, 32 to 36 inches of mercury absolute; inlet-air temperature, 1050° to 1070° R; velocity, 230 to 260 feet per second; fuel, MIL-F-5624A grade JP-4 (ref. 72).



(a) Combustion efficiencies.



(b) Fuel-air ratio at maximum efficiency.

Figure 151. - Effect of secondary-fuel-injector ring diameter on combustion. Inlet-air pressure, 15 inches of mercury absolute; inlet-air temperature, 580° R; fuel, ANF-48; 20-inch-diameter combustor; 20-percent primary flow (ref. 73).

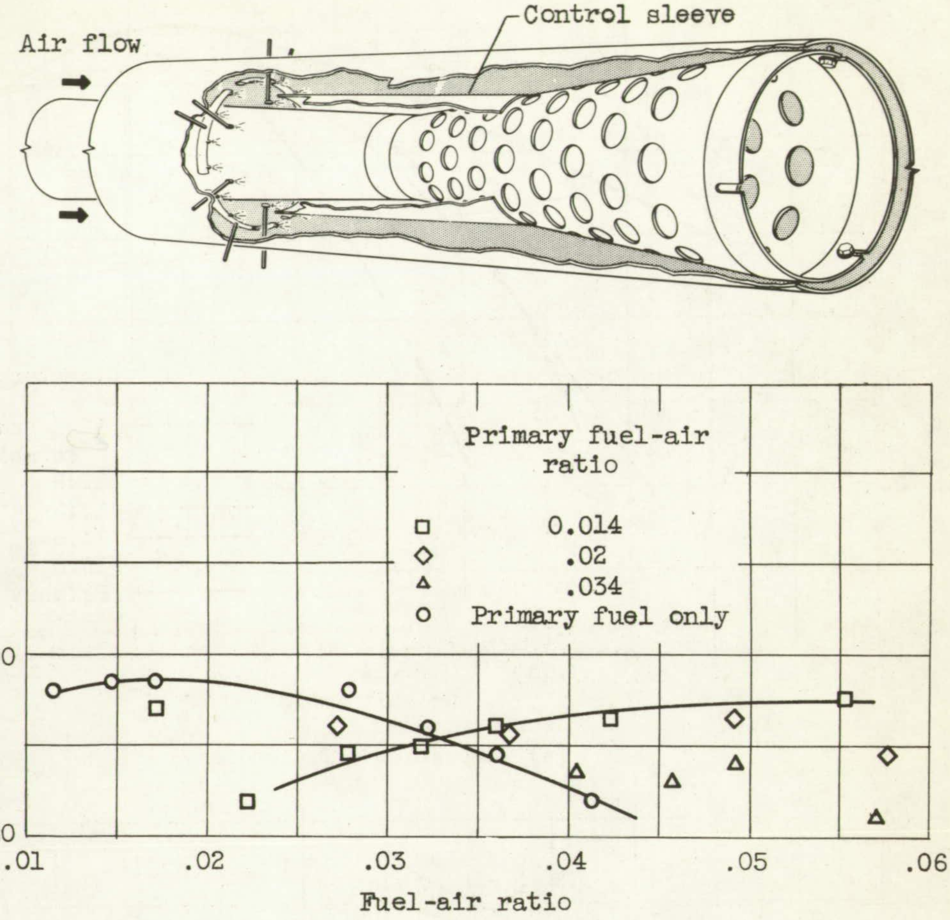


Figure 152. - Effect of fuel staging on combustor performance. Inlet-air pressure, 32 to 36 inches of mercury absolute; inlet-air temperature, 1050° to 1070° R; velocity, 230 to 260 feet per second; fuel, MIL-F-5624A (ref. 72).

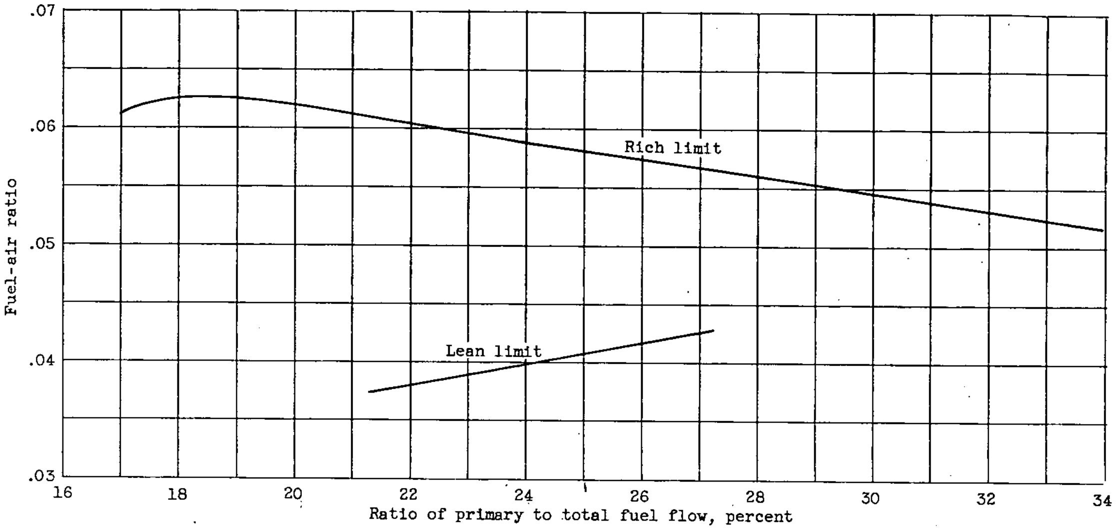


Figure 153. - Effect of primary fuel flow on combustor operating limits of 20-inch-diameter can combustor. Inlet-air pressure, 15 inches of mercury absolute; temperature, 910° R; velocity, 280±40 feet per second; fuel, ANF-48 (ref. 73).

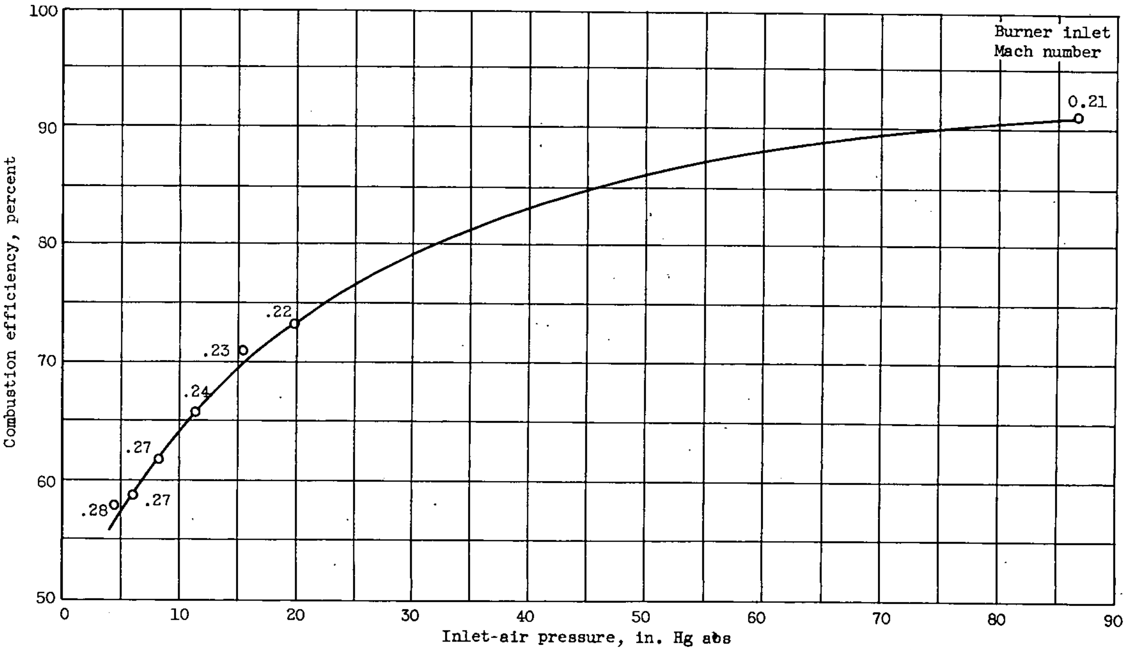


Figure 154. - Effect of inlet-air pressure on burner efficiency. Burner length, 14 inches; fuel, pentane; stoichiometric conditions; pilot heat, 10 percent (ref. 45).

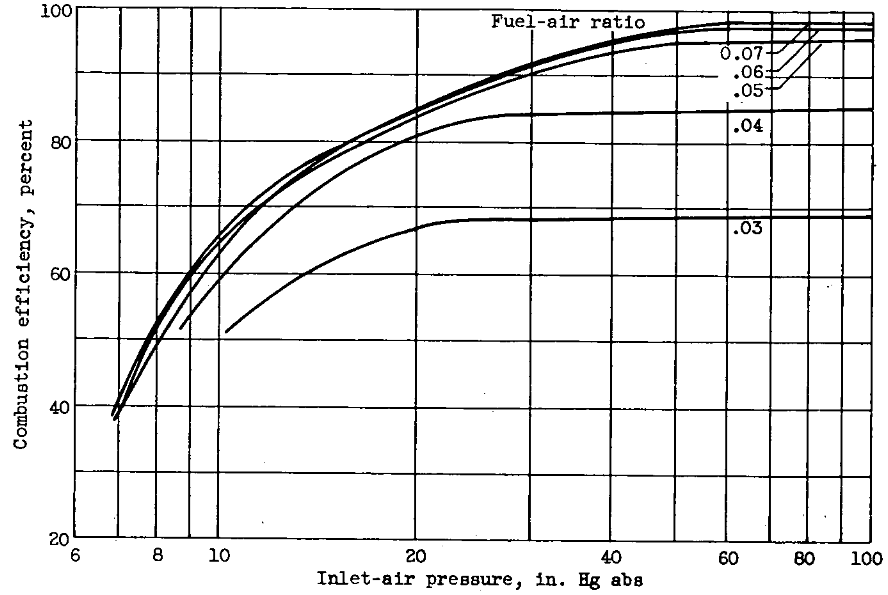


Figure 155. - Combustion efficiency of 20-inch-diameter ram-jet combustor as function of fuel-air ratio and burner inlet pressure. Inlet-air temperature, 920° R; fuel, ANF-58; exit nozzle, 55 percent (ref. 77).

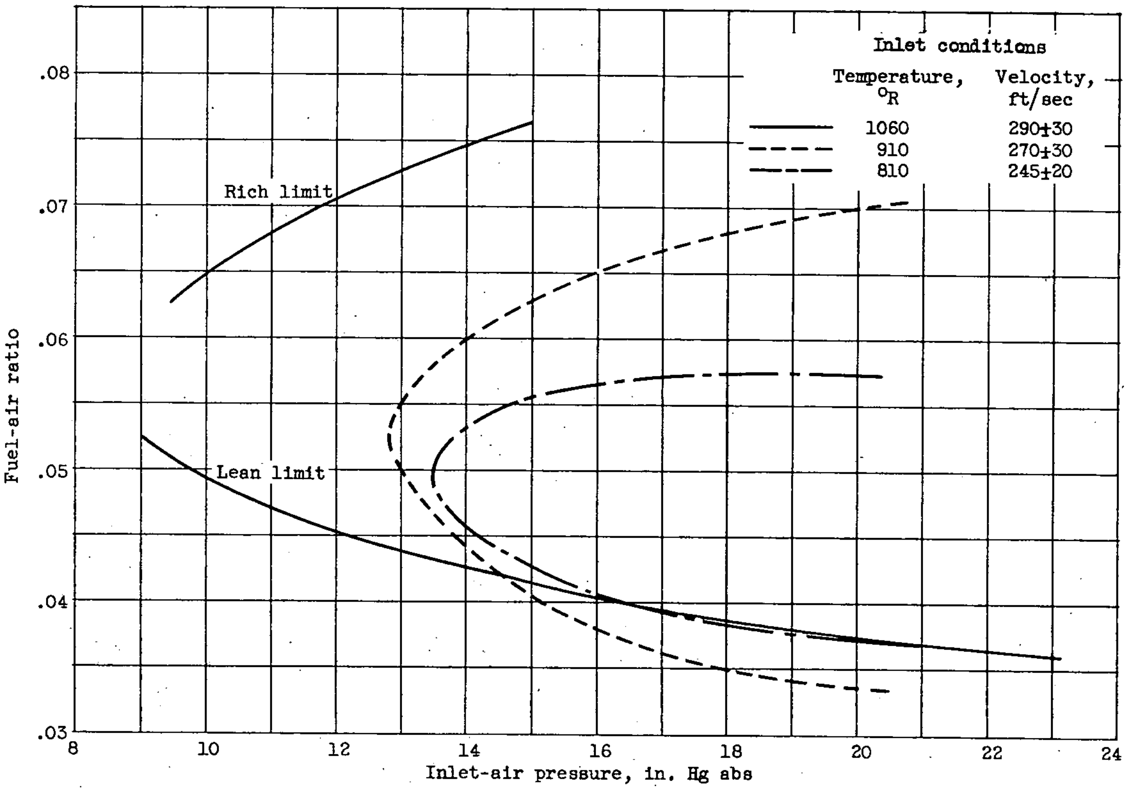


Figure 156. - Effect of inlet-air pressure on combustion limits for three inlet temperatures in 20-inch-diameter ram jet with can-type flameholder. Fuel, ANF-48 (ref. 73).

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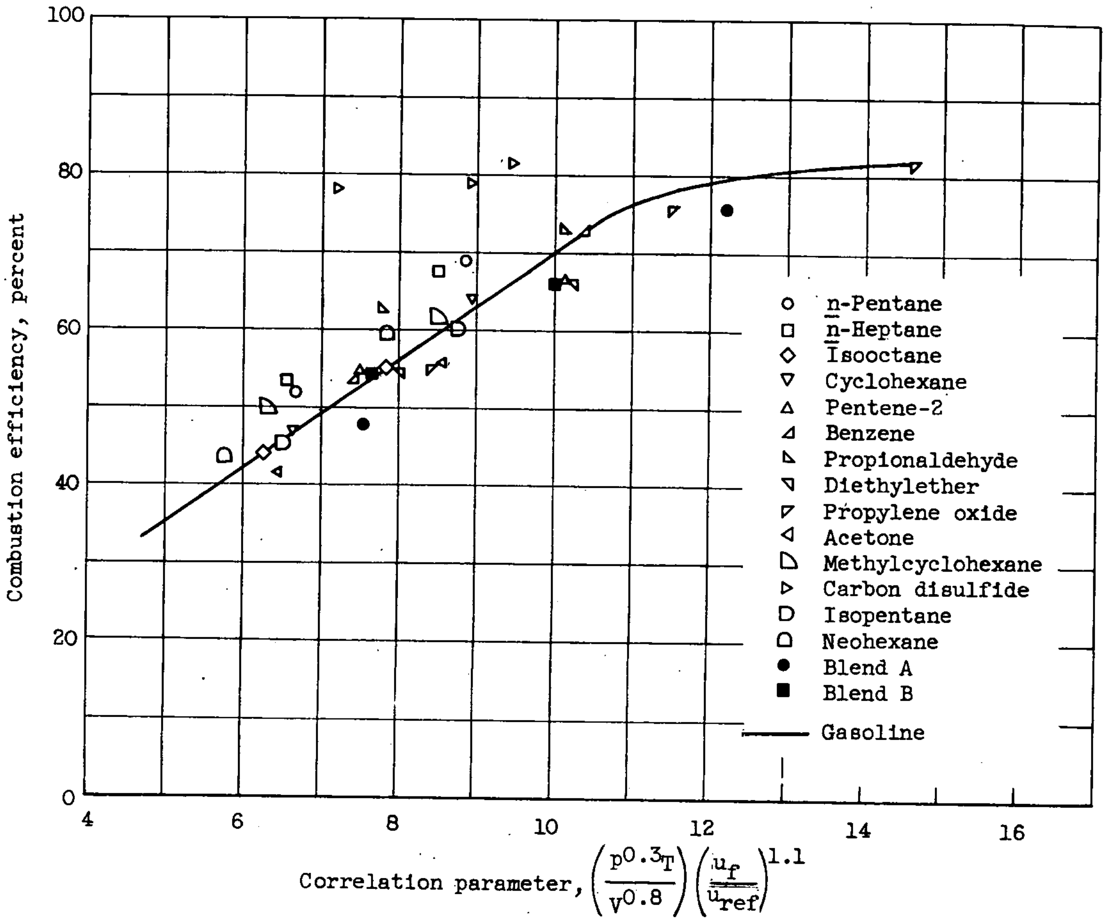

Figure 157. - Correlation of combustion efficiency for V-gutter flameholder in 5-inch ram-jet combustor for 14 pure fuels, a gasoline, and 2 fuel blends. (Blend A contains 2/3 propylene oxide plus 1/3 isopentane by weight; blend B, 1/3 propylene oxide plus 2/3 isopentane by weight.)