CHAPTER XII

COMBUSTION LIMITS AND EFFICIENCY OF TURBOJET ENGINES

By Edmund R. Jonash and Henry C. Barnett

INTRODUCTION

Combustion must be maintained in the turbojet-engine combustor over a wide range of operating conditions resulting from variations in required engine thrust, flight altitude, and flight speed. Furthermore, combustion must be efficient in order to provide the maximum aircraft range. Thus, two major performance criteria of the turbojet-engine combustor are (1) operatable range, or combustion limits, and (2) combustion efficiency.

Several fundamental requirements for efficient, high-speed combustion are evident from the discussions presented in chapters III to V. The fuel-air ratio and pressure in the burning zone must lie within specific limits of flammability (fig. III-16(b)) in order to have the mixture ignite and burn satisfactorily. Increases in mixture temperature will favor the flammability characteristics (ch. III). A second requirement in maintaining a stable flame is that low local flow velocities exist in the combustion zone (ch. VI). Finally, even with these requirements satisfied, a flame needs a certain minimum space in which to release a desired amount of heat, the necessary space increasing with a decrease in pressure (ref. 1). It is apparent, then, that combustor design and operation must provide for (1) proper control of vapor fuel-air ratios in the combustion zone at or near stoichiometric, (2) mixture pressures above the minimum flammability pressures, (3) low flow velocities in the combustion zone, and (4) adequate space for the flame.

It is desirable to consider how the operation and the design of current turbojet combustors match these fundamental combustion requirements. Because of turbine-blade temperature limitations, over-all fuel-air ratios considerably leaner than stoichiometric must be maintained in the turbojet combustor; because of the high propulsive thrust per unit frontal area required, combustion-chamber velocities of 100 feet per second or greater must be tolerated; and because of availability and handling considerations, liquid hydrocarbon fuels that require vaporization and mixing with the air prior to combustion must be used. Combustor design alleviates the first two problems, velocity and fuel-air ratio, by allowing approximately 80 percent of the air to bypass the combustion zone, thus providing for lower velocities and higher fuel-air ratios within the combustion zone. In addition, considerable turbulence, which increases the flame surface area and hence the effective flame velocity (ch. V), is generated in the combustion zone by means of swirling-air entry ports and penetrating air jets. Heating the fuel-air mixture to its ignition temperature is aided by recirculating high-temperature exhaust gases into the fresh charge. Vaporization of the liquid fuel is aided by pressure atomizing nozzles or by any of a number of fuel prevaporization methods that are currently being used.

The design of current turbojet combustors has not completely satisfied the fundamental requirements for complete combustion at all conditions of operation. Moreover, attempts to answer the ever-pressing need for greater heat-release rates from smaller combustors in shorter lengths and over wider ranges of operating conditions result in incomplete combustion or flame blow-out under certain conditions. Performance trends typical of those observed in current turbojet engines are shown in figure 58. Combustion efficiency is plotted against the engine speed corrected to standard sea-level conditions $N/\sqrt{\theta}$, where N is the engine rotational speed and θ is the ratio of engine-inlet total temperature to NACA standard sea-level static temperature. Since the value of $\sqrt{\theta}$ does not vary greatly from unity for the range of conditions shown the abscissa scale is a close representation of the actual engine rotational speed. These data, which were obtained in full-scale engine tests at simulated altitude conditions (ref. 2), show that combustion efficiencies decrease with a decrease in engine rotational speed, with an increase in altitude, and with a decrease in flight Mach number. At high-altitude conditions, efficiencies as low as 50 percent were encountered, representing a very considerable loss in aircraft range.

The problem of combustion limits encountered in some engines at high altitude is illustrated in figure 59 (ref. 3). The curve represents an altitude operational limit imposed on the engine by the inability of the combustor to release sufficient heat to drive the engine at the required conditions. Altitude operation of the engine is severely limited, particularly at low engine speeds.

Two major tasks confronting designers of turbojet combustors are (1) optimizing the design for a particular engine and flight application and (2) predicting the flight performance of the design. The solutions to both problems require an understanding of the effects of the individual operating and design variables on performance. This chapter treats these variables in some detail. The effects of inlet-air conditions, fuel and air admission characteristics, and fundamental combustion characteristics on performance are considered. Although these variables have been recognized for some time, their interrelated effects on performance cannot yet be expressed quantitatively. As a result, combustor design remains, to a large extent, an art. Approximate methods that have been developed to relate effects of operating variables and to estimate the performance characteristics of a given combustor are described in this chapter.

EFFECT OF ENGINE OPERATING VARIABLES ON COMBUSTION

EFFICIENCY AND LIMITS

Among the primary engine operating variables affecting combustion efficiency and stability are combustor inlet-air pressure, inlet-air temperature, inlet-air velocity, and fuel-air ratio. The degree to which these variables influence performance in different turbojet engines may vary, but the trends observed are reasonably uniform for most engines. From the large amount of data accumulated during the past several years, representative results are presented here to illustrate the effects of these variables on combustion efficiency and stability. This section is concerned only with performance data obtained with liquid fuels in atomizing-type annular and tubular combustors. Combustor performance characteristics with vaporized fuel are treated in a later section that considers the effects of fuel variables on engine performance.

Combustor Inlet-Air Pressure

The effect of combustor inlet-air pressure on combustion efficiency is shown in figure 60(a) for data obtained in two different combustors (refs. 3 and 4) at constant values of inlet-air temperature, reference velocity[1], and fuel-air ratio. These and other data show conclusively that decreases in combustor pressure cause significant decreases in efficiency. For different combustors the shape of the curves is reasonably consistent, but the pressure at which significant losses in efficiency occur will vary, as illustrated by the two curves in figure 60(a).

---

[1]Mean combustor air velocity based on density and flow rate of inlet air and maximum combustor cross section.

Also, with more or less favorable conditions of inlet temperature, reference velocity, and fuel-air ratio than those used for the data in the figure, the curves may be displaced to higher or lower values of combustion efficiency and to lower or higher values of pressure. The decrease in efficiency with decreased pressure may be attributed to any of several fundamental factors involved. For example, the volume required for the flame increases (ref. 1) and the flammability mixture limits decrease as pressure is reduced (ch. III). These and other factors are discussed further in a later section of this chapter.

Studies reported in chapter III and cited earlier in this chapter show the existence of pressure flammability limits that define pressures below which combustion cannot be sustained. In turbojet combustors, a decrease in combustor pressure causes decreases in efficiency, as shown in figure 60(a); as lower and lower pressures are imposed, the combustion process passes through a phase of instability, and eventually the flame is completely extinguished. Although the particular range of operating conditions represented by the curves of figure 60(a) did not result in flame blow-out, it can be assumed that blow-out would occur at pressures not far below the lower limits of the curves shown. In any case, the lower pressure limit of a turbojet combustor always occurs at a pressure considerably higher than the flammability pressure limits (about 1.0 lb/sq in. abs) presented in figure III-16. This fact may be attributed to the very great difference between the static, homogeneous fuel-air-mixture conditions represented by the data of figure III-16 and the dynamic, heterogeneous situation existing in a turbojet combustor.

Combustor Inlet-Air Temperature

In general, the effect of a decrease in combustor-inlet temperature on combustion efficiency is similar to the effect of a decrease in pressure. Representative trends are illustrated in figure 60(b) for the same combustors used to obtain the data of figure 60(a). These data, which were obtained at constant values of inlet-air pressure, velocity, and fuel-air ratio, show that combustion efficiency decreases at an increasing rate as the inlet temperature is decreased, particularly in combustor A.

The effect of combustor inlet-air temperature on combustion efficiency is in part associated with the problem of evaporating the fuel in the combustion chamber. Chapter I shows that the rate of evaporation of a liquid fuel spray increases with approximately the fourth power of the air temperature (fig. I-22). In addition, increased temperature favors fundamental combustion reactions, as evidenced by increased flame speed (ch. IV).

Combustor Inlet-Air Velocity

Typical variations of combustion efficiency with reference velocity are illustrated by the data in figure 60(c), which were obtained at constant values of inlet-air pressure, temperature, and fuel-air ratio. Combustion efficiency decreases rapidly with an increase in velocity in combustor A; increases in velocity beyond about 105 feet per second would probably result in flame blow-out. In the range of velocities investigated, combustion efficiency of combustor B was less sensitive to variations in velocity than was that of combustor A. For combustor B, increases in velocity first increased and then decreased combustion efficiency. The decreased combustion efficiency encountered at low velocities in combustor B occurs in many combustors and is attributed, in many cases, to impaired fuel-spray characteristics obtained with some fuel-injection nozzles at the low fuel flows attending low air velocities. Generally, this phenomenon is encountered at "off-design" conditions only, that is, at velocities considerably below those encountered in actual engine operation. The decrease in combustion efficiency at high velocity encountered with combustors A and B may be associated with the decrease in residence time of the fuel-air mixture in the combustion zone. However, other factors can be involved; for example, variations of the fuel-air mixing characteristics with velocity.

The effect of velocity on combustion efficiency may be assumed to be generally represented by the curve of combustor B. Thus, there is an optimum value of velocity for all combustors. The normal operating ranges of different combustors may, however, be limited to different parts of this general curve, depending upon combustor design and other operating parameters.

Fuel-Air Ratio

The effects of fuel-air ratio on combustion efficiencies obtained in combustors A and B are shown in figure 60(d). Each combustor was operated at conditions of constant combustor inlet-air pressure, temperature, and velocity. Combustion efficiency in combustor A first increased and then decreased with increased fuel-air ratio. Combustion efficiency in combustor B increased with fuel-air ratio throughout the range of fuel-air ratio investigated. The fuel-air-ratio curves of figure 60(d) eventually terminate in the "lean" and "rich" blow-out limits of the combustor. Additional examples of the effects of fuel-air ratio on combustion efficiency may be found in references 5 and 6.

The decrease in combustion efficiency at low fuel-air ratios (fig. 60(d)) is normally associated with insufficient fuel vaporization resulting from poor fuel atomization at low flow rates; thus, liquid fuel might be permitted to flow through the combustor without burning. Actual observation and sampling of exhaust gases from combustors has, in fact, indicated the presence of liquid fuel droplets. In addition, of course, low over-all fuel-air ratios may result in pockets of fuel-air mixtures in the primary zone that are too lean to burn. The decrease in efficiency at high fuel-air ratios is frequently associated with overenrichment of the combustion zone resulting from high fuel-flow rates and improved atomization and vaporization of the fuel. Depending on the combustor and, particularly, on injector design characteristics and operating conditions, combustion efficiency may be more or less sensitive to fuel-air ratio than the curves of figure 60(d) indicate. Furthermore, in operating a particular combustor in a particular engine, only certain parts of the more general curve (combustor A) may apply.

Analysis of Engine Performance Characteristics

It was noted in connection with figure 58 that combustion efficiency in a full-scale turbojet engine decreases with (1) an increase in altitude, (2) a decrease in engine speed, and (3) a decrease in flight Mach number. The variations in combustor-inlet parameters (pressure, temperature, and velocity) that occur with these changes in engine conditions are discussed in chapter X. Figures 3(a), 3(b), 6, and 7(a) indicate that both combustor inlet-air pressure and temperature always decrease with the variations in engine operating conditions noted previously that cause a decrease in combustion efficiency. These trends are consistent with the data presented in figures 60(a) and (b). Further examination of the data of figures 3(c) and 7(c) indicates that the variations in combustor velocity (1) are relatively small and (2) do not exhibit any well-defined trends with the observed combustion efficiency (fig. 58). Figure 60(c) shows that combustion efficiency can either decrease or increase with an increase in velocity. These comparisons do, of course, neglect what can be very important effects of fuel-air ratio on combustion efficiency. Particularly large variations in fuel-air ratio occur with variations in engine speed.

As altitude is increased, a turbojet engine may approach an altitude operational limit (fig. 59). At any engine operating condition, the combustor must furnish a certain required temperature rise (ch. X). The ability of a combustor to supply high values of temperature rise is limited either by rapidly decreasing combustion efficiencies at high fuel-air ratios (fig. 60(d)) or by flame blow-out. As might be expected, then, the maximum temperature rise obtainable with a combustor usually varies in much the same manner as does combustion efficiency. The data of reference 3 show a decrease in maximum temperature rise with a decrease in temperature or pressure and, generally, with an increase in velocity. Figure 61 shows the relation between the maximum temperature rise and that required for operation over a range of altitude at a constant engine rotational speed. Although the temperature rise required does not vary appreciably with altitude for this particular engine, the available temperature rise decreased rapidly with an increase in altitude. The altitude at which the two curves cross (about 32,000 ft) represents the operational limit of the engine.

As the operating altitude of a turbojet combustor is increased, the character of the flame changes noticeably. At low-altitude, high-pressure operating conditions, most turbojet combustor flames are a brilliant orange-yellow. This luminosity is due to incandescent carbon particles suspended in the hot gas stream. The emissivity of such a flame can be of the order of 0.8 (ref. 7). As the operating altitude is increased, a gradual transition to a relatively nonluminous blue flame occurs. Finally, at conditions near the operational limits of the combustor, varying degrees and types of flame instability appear, frequently in the form of low-frequency pulsations. These pulsations are often accompanied by movement of the flame-seating zone along the length of the combustor. Flame fluctuations are discussed further in a later section.

EFFECT OF FUEL AND AIR ADMISSION CHARACTERISTICS ON COMBUSTION EFFICIENCY AND LIMITS

The foregoing discussion, indicating the general effects of operational variables on the limits and efficiency of combustion in turbojet combustors using liquid fuels, suggested that the effects of some of these variables are due, in part, to the influence of the variables on preparation of flammable fuel-air mixtures. A number of fuel and combustor design variables that influence the preparation of this mixture are considered in this section.

In a liquid-atomizing combustor the flammable mixture is prepared by atomizing the liquid fuel, vaporizing the resulting fuel droplets, and admitting the proper quantity of air. Although these individual processes are discussed separately, they are by no means independent of one another, nor does each occur in a distinct zone of the combustor.

Fuel-Atomization Factors

The fuel-atomization characteristics that would be expected to influence mixture preparation in the turbojet combustor are drop size and spray pattern. The data of chapter I show that the rate of evaporation of a liquid drop is directly proportional to its diameter. Since the number of drops in a given mass of spray is inversely proportional to the cube of the average drop diameter, the evaporation rate of the spray is inversely proportional to the square of the average drop diameter. More direct evidence of the importance of drop size is shown in figure 62 (ref. 8). The time required to burn a single drop of kerosene fuel increased by a factor of 13 when drop size was increased three-fold. The second atomization factor, spray pattern, will influence the distribution of the drops and, hence, local fuel-air ratios in the combustion zone.

Atomization characteristics. - Atomization characteristics are not only influenced by design of the nozzle and by properties of the fuel (viscosity, surface tension), but also vary with operating condition. Figure 63 shows the variation in flow rate, drop diameter, and cone angle with nozzle pressure differential for two simple swirl-type nozzles. The mean drop diameter (Sauter mean diameter) was calculated from equation (34) of chapter I. Mean drop diameter decreases with an increase in pressure and, hence, with an increase in flow rate. For a given pressure differential, the use of the smaller nozzle also results in somewhat smaller drops. For a given flow rate, it is apparent that considerably smaller drops will be obtained with nozzles of smaller size. Comparison of the data of figures 62 and 63 indicates that the mean drop sizes obtained from these nozzles would have a burning time of less than 0.01 second for the conditions represented.

3080

The cone angle of the spray (fig. 63) first increases and then decreases as the flow rate is increased. At values of flow rate (and pressure) below those shown, the cone angle decreases very rapidly until a "bulb" type spray results. Since the operation of a turbojet engine requires a very wide range of flow rate, it is evident that, with a simple pressure-atomizing nozzle, atomization characteristics will vary considerably with operating conditions.

Effects of atomization. - A typical example of the effect of fuel atomization on the combustion efficiency of a full-scale turbojet engine (ref. 9) is presented in figure 64. At the high-altitude cruising conditions investigated, combustion efficiency was reduced as much as 25 percent as a result of increasing the fuel-nozzle capacity from 3 to 7 gallons per hour (nominal ratings of 100 lb/sq in.). This marked decrease in combustion efficiency may be attributed to the poorer atomization resulting from the decrease in nozzle pressure drop encountered with the use of larger fuel nozzles.

More detailed studies of the effects of fuel atomization characteristics on combustion performance have been conducted in direct-connect-duct investigations with tubular and annular combustors. Results of one of these studies (ref. 10) are illustrated in figure 65. The variation of combustion efficiency with combustor temperature rise for aviation gasoline is shown in figure 65(a) for three fuel-nozzle sizes and at fixed inlet-air conditions. At low values of temperature rise corresponding to low fuel-flow rates, the smallest nozzle gave the highest efficiency; at high values of temperature rise, the largest nozzle gave the highest combustion efficiency. With all three nozzles, maximum-temperature-rise conditions were encountered, indicating conditions of overrich fuel-air mixtures. The values of maximum temperature rise increased with increase in fuel-nozzle size.

These data, in addition to data obtained with other nozzle sizes, are further analyzed in figure 65(b) to indicate the fuel-nozzle pressure differential required at the various operating conditions. At low values of temperature rise, high pressure differentials gave the best performance. As temperature rise was increased, however, use of the higher pressure differential resulted in maximum-temperature-rise conditions and in rapid decreases in combustion efficiency; whereas, with the lower pressure differential, temperature rise continued to increase with increased combustion efficiency. Thus, a certain minimum quality of atomization, or a maximum drop size, is required at all conditions of operation, but it is possible to atomize a fuel too well and thereby produce primary-zone mixtures that are too rich to burn. The use of larger nozzles at high fuel flows increases drop size (fig. 63), the increase in turn reducing the rate of evaporation and extending the zone of evaporation farther downstream where additional air is being introduced. These results cannot be assumed to apply to all combustor designs, operating conditions, and fuels. With a particular combination of these variables, only a part of the over-all trends may be observed.

The thrust range required of a turbojet engine results in a wide range of fuel-flow rate (about 12 to 1 in current engines). The use of a single pressure-atomizing nozzle of the type used in the studies described necessitates large variations in fuel pressure and in spray characteristics, as shown in figure 63. The data of figure 65 show that these variations in spray characteristics can markedly affect the combustor performance. A single fuel nozzle may provide insufficient atomization at low flow rates and excessive atomization at high flow rates. It appears desirable, then, to consider the use of multiple nozzles, of different sizes, in the combustor to ensure more nearly constant atomization characteristics and to avoid excessive fuel-system pressures.

Duplex nozzles, combining the principal components of two individual nozzles of different size, have been developed for use in many current turbojet engines. A further development of the duplex nozzle is the variable-area nozzle (ref. 11), which produces a finely atomized spray over a flow range from about 30 to 500 pounds per hour with a corresponding range of pressure differential from about 50 to 70 pounds per square inch. The nozzle was tested in a full-scale engine at sea-level conditions (ref. 11) and at high-altitude conditions (ref. 12). Figure 66 presents combustion-efficiency data obtained with a conventional fixed-area nozzle and with a variable-area nozzle in a full-scale engine operating at an altitude of 40,000 feet and a ram pressure ratio of 1.00. Use of the variable-area nozzle resulted in an increase in combustion efficiency of approximately 5 percent at this particular operating condition. By combining the data obtained over a range of altitudes from sea level to 40,000 feet and a range of ram pressure ratios, the curve shown in figure 67 was obtained. These data show that reductions in fuel consumption as large as 16 percent were obtained with the variable-area fuel nozzle, the largest reductions occurring at low fuel-flow rates where the fixed-area nozzle did not provide sufficient fuel atomization.

<u>Effects of spray pattern</u>. - Combustion efficiencies for a 40-gallon-per-hour, 80°-cone-angle nozzle are compared in figure 68 with those for a 15.3-gallon-per-hour, 30°-cone-angle nozzle in a tubular combustor operating at severe conditions. The combustion efficiencies for the smaller, narrow-cone-angle nozzle decreased more rapidly with a decrease in fuel-air ratio than did those obtained with the larger, wide-cone-angle nozzle. This trend indicates that leaner fuel-air ratios were present in the combustion zone with a narrow-cone-angle nozzle in spite of the finer atomization resulting from the higher attendant pressure differentials. Reducing the angle of the spray cone and increasing the pressure differential increased spray penetration through the center of the combustor without effecting sufficient spreading in the upstream, primary-combustion region. The accompanying reduction in fuel residence time and the poor mixing served to reduce combustion efficiency.

The data of figure 68 indicate that wide-cone-angle nozzles should be used to attain high combustion efficiency. The investigation reported in reference 13 shows, however, that wide-angle fuel sprays, such as those produced by the 80°-cone-nozzle, can result in appreciable wetting of combustion-chamber walls with fuel. Illustrative data in figure 69 indicate that installation of fuel "dams" to collect and return fuel films from the wall of the combustor to the combustion zone improved combustion efficiencies significantly. The most pronounced effects were noted at low fuel-air ratios, probably because the power atomization at these conditions induced greater wall wetting. This evidence indicates that fuel depositing on the walls of the combustion chambers may pass through the combustor without entering into the combustion process and cause a loss in efficiency. In addition, wetting of the wall with fuel has been found to be conducive to another deleterious combustor characteristic, carbon deposition (ch. XIII). A certain amount of wall-wetting occurs in most combustors. Depending upon the design of the combustor, varying quantities of the liquid fuel deposited may be reatomized by the incoming jets of air.

The effect of distribution of atomized fuel in the primary zone of a tubular combustor on combustion performance was investigated in reference 4. Figure 70 presents data of reference 4 obtained with several liquid injectors using liquid MIL-F-5624A, grade JP-3 fuel. Comparison of the two atomizing nozzles (simplex and duplex) shows that the duplex nozzle gave considerably higher combustion efficiencies at low values of temperature rise and somewhat lower combustion efficiencies at high values of temperature rise. From preceding discussions of fuel atomization effects, it may be concluded that the simplex nozzle did not provide sufficient atomization at the low fuel-air ratios, while the duplex nozzle provided excessive atomization at high fuel-air ratios and resulted in fuel-rich mixture conditions. 3080

The other four injectors shown in figure 70 are considered "solid-stream" injectors, since no provisions for fuel swirl are incorporated; all use simple orifices. Among the solid-stream injectors, the highest combustion efficiencies were obtained with a tube injector (tube B) that distributed fuel along the length of the combustor. From a comparison of the performance of the three different tube injectors, a noticeable effect of the distribution of injection holes along the axis may also be observed. An explanation for the poor performance of the radial injector with liquid fuel may be the fact that with this injector solid streams of unatomized fuel were injected in the downstream direction with too much penetration and too short a residence time for the fuel drops.

The preceding discussion shows the important effects of fuel-spray characteristics on the combustion performance of liquid fuels. Fuel-spray characteristics are affected not only by injector design but also by properties of the fuel and by the design of the combustor. Mean drop size is proportional to surface tension of the fuel to powers from 0.6 to 0.7 or less, and to viscosity of the fuel to the 0.25 power (ch. I). Very substantial effects of the air-flow currents on liquid fuel sprays also were observed in investigations reported in reference 14. Figure 71 (from ref. 14) indicates that air flow in a tubular combustor increased fuel atomization considerably over that observed with the spray in quiescent air. Other photographic evidence presented in reference 14 shows that increased air velocity resulted in increased fuel atomization and distribution. Thus, it is generally not possible to predict, from photographs or measurements made in quiescent atmospheres, the spray characteristics that will be obtained with a particular injector installed in a combustor. Furthermore, satisfactory methods of measurement of fuel-spray characteristics, drop size and distribution, are generally too complex to be readily adaptable to the actual turbojet combustor.

Because the end result of fuel atomization, distribution, and evaporation is the formation of flammable fuel-air mixtures in the combustion zone, the fuel-spray characteristics required for optimum performance depend on operating conditions and combustor design. Some combustor designs have been evolved that minimize, to a large extent, the effects of fuel-spray variables on combustor performance. An example of data obtained with such a design is shown in figure 72 (ref. 9). In an experimental annular combustor, two fuel nozzles (capacities, 10.5 and 6 gal/hr) were tested at a simulated flight altitude of 30,000 feet, and three fuel nozzles (capacities, 10.5, 6.0, and 3.0 gal/hr) were tested at 40,000 feet. The data indicate only minor effects of fuel-injector size on combustion efficiency. Near the rated speed of the engine, the larger nozzles gave slightly higher combustion efficiencies. This trend is in agreement with data presented in preceding sections; that is, at the high fuel-air ratios required at rated speed, the finer atomization produced by the smaller nozzles resulted in over-rich mixtures in the combustion zone. The experimental combustor represented by these data was of the same general over-all dimensions and was tested in the same engine as the combustor represented by the data of figure 64, which shows very significant effects of fuel-nozzle size on the performance of that combustor.

Fuel Vaporization Factors

The rate of vaporization of a fuel spray is a function of the degree of atomization and of the volatility characteristics of the fuel. It is also a function of operating conditions - temperature, pressure, and velocity of the fluid surrounding the fuel drops (ch. I). Effects of atomization characteristics on combustion performance are discussed in the preceding section of this chapter. Data show that there is an optimum degree of atomization associated with a particular combustor and particular operating conditions. Fuel sprays that are either finer or coarser than this optimum can result in too-rich or too-lean fuel-air-ratio conditions and, hence, in decreased combustion performance. Fuel volatility characteristics would be expected to influence combustion performance in a similar manner. That is, optimum fuel volatility characteristics may depend upon the choice of operating conditions and combustor design.

Fuel volatility. - Typical effects of fuel volatility on combustor performance are illustrated in figures 73 and 74. Combustion efficiency of an annular combustor is plotted against altitude in figure 73 for three types of fuel varying from highly volatile aviation gasoline to low-volatility Diesel fuel (ref. 10). These data illustrate the same trend of combustion efficiency with simulated flight altitude that was observed in figure 58. The combustion efficiencies of the fuels tend to converge near 100 percent at a low altitude, indicating that at sea level the differences among fuels may not be great. At high altitude, however, the more volatile fuel, aviation gasoline, produces considerably higher efficiencies.

The effect of fuel volatility on the altitude operational limits of an annular combustor is illustrated in figure 74 (ref. 10). At engine speeds in excess of 60-percent rated engine rotor speed, Diesel fuel produces the highest altitude limit; at lower speeds the more volatile gasoline gives higher limits. This result is consistent with the studies discussed previously in this chapter, where it is pointed out that a too-rapid vaporization rate may, at some conditions of operation, produce a mixture too rich to burn. Very fine atomization and rapid vaporization occur at the higher engine speeds that correspond to higher fuel flows in the engine; at these conditions gasoline vaporizes too rapidly, and Diesel fuel, because of its lower volatility, vaporizes more slowly and at a more nearly optimum rate. At low engine speeds the reverse is true; that is, the fuel flows are low, and the vaporization required is more nearly fulfilled by the more volatile aviation gasoline.

The interrelation between fuel volatility and fuel-spray characteristics is further illustrated in figure 75. The combustion efficiencies obtained with Diesel fuel and aviation gasoline using two nozzles of widely different spray characteristics are shown. With the larger nozzles giving coarser atomization at the same flow rate, the more volatile gasoline produced the higher combustion efficiencies. With the smaller nozzles giving finer atomization, overenrichment of the primary combustion zone occurred and the lower volatility fuel, Diesel fuel, gave higher combustion efficiencies.

The results of tests in a 7-inch-diameter tubular combustor with a larger number of fuels of varying volatility are presented in figure 76. The fuels represented in figure 76(a) were relatively pure materials that vary only slightly in their fundamental combustion characteristics (discussed in a later section of this chapter). As the average boiling temperature, represented by the A.S.T.M. 50-percent distillation temperature, was increased, combustion efficiency first increased and then decreased, indicating an optimum distillation temperature of about 200° F for these particular operating conditions. The distillation (or boiling) temperature of a fuel is only one of several fuel factors that may affect vaporization rate. For example, the evaporation rate of single drops into high-temperature surroundings can be correlated with the total heat required to evaporate a unit mass of fuel (ref. 15). This quantity of heat is a function of the initial temperature, the boiling temperature, and the latent heat of vaporization of the fuel. Plotting the combustion-efficiency data of figure 76(a) against the heat required for evaporation would result in curves of the same form as those shown in the figure because of observed relations between boiling temperature and latent heat of vaporization of hydrocarbon fuels.

The general trend in combustion efficiency with boiling temperature shown in figure 76(a) is not usually encountered in turbojet combustors. In most cases, the range of fuel volatility, operating range, and combustor design used results in a continuous decrease in efficiency with an increase in boiling temperature, as shown in figure 76(b). These data (ref. 16) were obtained with mixed hydrocarbon fuels of the general type that may be supplied for turbojet-engine use.

Fuel and air temperature. - Since the effects of fuel volatility on combustion performance are intimately related to the design of the combustion chamber and to the fuel-injection technique, it is possible to design a combustion system around either a low- or a high-volatility fuel to provide both high efficiency and satisfactory stability. The difficulty of achieving this design, however, may be considerably greater with very-low-volatility fuels. If, for economic or other reasons, it is desirable to use low-volatility fuels, the effects of volatility can be reduced by preheating or prevaporizing the fuel. In figure 77, a comparison is made of the combustion efficiencies obtained at two fuel temperature conditions in an experimental annular combustor using MIL-F-5624A, grade JP-4 fuel. Preheating the fuel to 300° F appreciably improved the combustion efficiency at the low combustor-inlet pressure of 2.5 pounds per square inch absolute (ref. 17). This trend is also apparent in figure 78, which shows the effects of air and fuel temperature on combustion efficiency of a tubular combustor for JP-1 fuel and for monomethylnaphthalene, two fuels that differ considerably in both volatility and composition. Increases in fuel and air temperature caused an increase in combustion efficiency for both fuels. Comparison of the two parts of figure 78 shows that variations in inlet-air temperature had a more pronounced effect on combustion efficiency than did variations in fuel temperature. Increasing the temperature of monomethylnaphthalene to 300° F did not increase performance sufficiently to equal the performance with unheated (100° F) JP-1 fuel. For unheated monomethylnaphthalene, increasing the air temperature to 200° F increased efficiency to a value just slightly below that obtained with unheated JP-1 fuel at an air temperature of 100° F.

The pronounced effect of inlet-air temperature on combustion efficiency shown in figure 78 may be expected from spray evaporation studies. Experimental studies of the evaporation of gasoline-type fuel sprays cited in chapter I show that the rate of evaporation is proportional to the 4.4 power of the air temperature. Data of reference 18 show that evaporation of a fuel boiling between 317° and 346° F increased 1 percent for each 4° F increase in air temperature and for each 7.5° increase in fuel temperature. Furthermore, it should be recognized that increases in inlet-air temperature will increase the rate of chemical reaction as well as the rate of evaporation.

Fuel prevaporization. - From the results presented in figures 77 and 78, it may be concluded that methods of increasing the rate of evaporation of the liquid fuel spray can improve combustion efficiency. Other investigations (e.g., refs. 4 and 19) have also shown that the use of a completely vaporized fuel will increase combustion efficiencies in current liquid-atomizing combustors. A number of turbojet combustion systems have been designed with fuel "prevaporizers," which generally incorporate flame-bathed fuel-vaporizing tubes. With a fuel prevaporizer, the effects of fuel volatility on combustion efficiency would be expected to disappear. The combustion efficiencies obtained in a commercial vaporizing combustor with eight fuels of varying volatility are reported in reference 20. The least-volatile fuel tested was a kerosene. Over the range of fuel-air ratios investigated, all the fuels gave about the same combustion efficiencies. The inlet-air operating conditions were not given in reference 20; however, they were presumably severe enough to cause significant differences in the performance of the fuels in a liquid-atomizing combustor.

3080

Investigations of the combustion performance of monomethylnaphthalene and JP-3 fuel in a different vaporizing combustor are reported in reference 21. Combustion efficiencies were determined for a range of combustor inlet-air temperature, inlet-air pressure, and air velocity. Representative results are presented in figure 79, which shows that in all cases the performance of the more volatile JP-3 fuel exceeded the performance of the high-boiling hydrocarbon monomethylnaphthalene. With regard to stability, the data show that the more volatile JP-3 fuel sustained combustion at lower inlet pressures and at higher velocities. Thus, the use of the fuel prevaporizer in this case did not eliminate the effect of fuel volatility on combustion performance. It should be noted that the compositions of JP-3 fuel and monomethylnaphthalene are considerably different. Variations in composition may also affect combustion performance. The data of figure 79 are compared in reference 21 with similar data obtained with the same fuels in a liquid-atomizing combustor. The trends indicated that the vaporizing combustor did diminish the effect of fuel properties on combustion efficiency. The fact that the differences were not entirely eliminated may be attributed to inadequate vaporizing capacity of the combustor for the high-boiling monomethylnaphthalene, and to differences in fuel composition.

It was suggested that increased inlet-air temperature improves combustion efficiency in one way by causing more rapid vaporization of liquid fuel sprays. The use of a fuel prevaporizer, then, should diminish the effect of inlet-air temperature on combustion efficiency. Figure 79 shows that, in the prevaporizing combustor tested, combustor inlet-air temperature had some effect on the efficiencies obtained with monomethylnaphthalene and essentially no effect on those obtained with the JP-3 fuel. These trends again indicate that, since the prevaporizer was not designed to handle fuels such as monomethylnaphthalene, prevaporization of this fuel was probably not very complete.

Vapor fuel distribution. - Even if the combustor design is such that complete fuel prevaporization occurs, performance difficulties may still result from improper distribution of the vaporized fuel. The effect of vapor fuel distribution on the combustion efficiency of a tubular combustor is studied in reference 22; results obtained with four different fuel injectors are presented in figure 80. The injectors were similar to several of those discussed in the section of this chapter entitled Fuel Atomization Factors (fig. 70). Even with the fuel vaporization step completely eliminated, combustion efficiency was markedly affected by the design of the vapor fuel injector. A comparison of the two injectors having single orifices indicates that the larger orifice provided a higher combustion efficiency. It may be considered that the lower-velocity jet issuing from the larger nozzle was mixed more uniformly with the air, while the higher-velocity jet from the smaller nozzle maintained a fuel-rich region in the center of the combustor. Also, the smaller-orifice injector may have increased fuel penetration sufficiently to reduce residence time of the fuel in the combustion zone, resulting in decreased combustion efficiencies. The radial spoke-type injector distributed the fuel more uniformly over the cross section of the combustion zone, thereby affording greater mixing rates and, hence, higher combustion efficiency. The best performance was obtained with the tube injector, which distributed the fuel axially along the length of the primary zone, mixing the fuel with the incoming air jets and, also, possibly mixing with reverse air-flow currents within the combustor. Additional studies of the effect of vapor fuel distribution on the performance of an annular combustor are described in reference 23.

Air Admission Factors

The effects of the fuel atomization and vaporization steps on the performance of turbojet combustors are discussed in the preceding sections of this chapter. The data presented emphasize the need for maintaining optimum fuel-air-mixture conditions in the combustion zone. Two ways of accomplishing this (at least partially) were described (1) control of fuel properties and (2) proper design of the fuel-injection system. The third factor that influences the fuel-air mixture is the design of the air admission ports.

The design of the air admission system in the turbojet combustor is based not only on the requirements of high combustion efficiency and wide limits of operation but also on factors such as outlet-temperature distribution, carbon deposition, ignition, and durability of the combustor. The present discussion is limited to a brief review of the trends in limits and efficiency of combustion that have been observed with variations in air admission geometry of the primary combustion zone.

The primary-air-admission ports are designed (1) to provide adequate quantities of air for combustion and (2) to promote a high rate of mixing of the fuel with the air. It is apparent that the air admission characteristics must be matched to the design of the fuel injectors and to the fuel properties in order to achieve optimum fuel-air-mixture conditions in the primary combustion zone. Current turbojet combustor configurations do not provide completely separated, well-defined primary combustion zones. For discussion purposes, however, the primary zone is generally assumed to occupy the first one-third to one-half of the total combustor length. The amount of air introduced into this region is not independently controlled but rather is a function of the air-admission-port design over the entire length of the combustor, combustor cross-sectional geometry, and pressure loss (ch. II).

Effects of primary-air admission. - Some laboratory studies have been conducted with combustors incorporating separated and controlled primary-air admission. Figure 81 presents results of one such study in a tubular combustor operating at over-all fuel-air ratios from 0.0057 to 0.0145 (ref. 24). For a given over-all fuel-air ratio, increasing the percentage of primary air above a critical value resulted in a decrease in temperature rise, and hence in combustion efficiency. This decrease in efficiency may be attributed to over-lean primary-zone mixtures. The trends may also be explained on the basis of primary-zone velocity; as primary-air flow is increased, velocity is also increased, and residence time of the fuel-air mixture is decreased. These and other data reported in reference 24 indicate, however, that mixture fuel-air ratio in the primary zone was the principal factor influencing the performance of this tubular combustor. The data also show that smaller percentages of primary air are required at low over-all fuel-air ratios to maintain high efficiency. The parametric curves of constant primary fuel-air ratio indicate that a minimum primary fuel-air ratio of about 0.05 is required to assure best performance.

The data of figure 81 indicate that, so long as the percentage of primary air is less than about 10 percent, maximum efficiency is obtained. The data presented in this figure are limited to a relatively narrow range of operating conditions; data presented previously in this chapter indicate that overenrichment of the primary zone can also cause decreases in efficiency. One example of the more general trend that can be expected is presented in figure 82 (ref. 25). These and all subsequent data presented in this section were obtained in combustors not incorporating separately controlled primary air. The amount of air entering the primary zone is assumed to be proportional to the open area of the air admission ports in that region. While this assumption is reasonably satisfactory for observing general performance trends, it is accurate for high-pressure-loss combustors only (ch. II, fig. II-13). More precise methods for estimating air distribution in turbojet combustors are noted in chapter II. Figure 82 shows that at fuel-air ratios less than about 0.014 a decrease in open area at the front end of the combustor (a decrease in primary-air flow) increased combustion efficiency, a trend similar to that shown in figure 81. At high fuel-air ratios, however, overenrichment of the primary zone occurred, and a decrease in open area in the primary zone decreased combustion efficiency. Similar trends are illustrated in figure 83 by data obtained in a 9.5-inch-diameter combustor (ref. 26). The air-entry-hole area of a 5.8-inch-diameter primary zone (pilot chamber) was varied over a range from about 25 to 10.9 square inches. At low fuel-air ratios, intermediate open areas gave the best performance; at fuel-air ratios greater than about 0.012, there is a regular trend of increasing efficiencies with increasing open area.

Optimum air admission design. - As is apparent from the data of figures 82 and 83, a single, fixed, air admission geometry will be optimum for specific operating conditions only. Unless variable air admission controls are incorporated into a combustor design, compromises are required to achieve the best over-all combustion characteristics of the combustor. Research studies have been conducted in many laboratories to determine the air admission design criteria for optimum combustion performance. Illustrative results obtained at the Lewis laboratory are presented in the following discussion. These results were obtained primarily in direct-connect-duct facilities, utilizing both annular and tubular combustors.

While most current liquid-atomizing combustors use longitudinal rows of circular holes for introducing air (e.g., fig. 71(b)), the experimental combustors described here incorporate a variety of hole shapes and locations. For example, the experimental annular combustors used in reference 27 incorporated long rectangular slots for admission of primary combustion air, while those of reference 17 had small circular holes. Figure 84 presents one-quarter cutaway views of these particular experimental combustors. Figure 85 illustrates a variety of air admission techniques investigated in a tubular combustor (ref. 25), each of the configurations shown tending to produce a different air-flow pattern within the combustion zone.

The altitude operational limits obtained with two circular-hole designs in an early annular combustor are presented in figure 86. Near-optimum design increased altitude operational limits about 12,000 feet; combustion efficiency was also increased considerably. The air-admission-hole designs of the two combustors are represented in figure 87 by the plot of percentage of open area against axial distance from the upstream end of the combustor liner. The design giving the higher performance had substantially reduced open area in the first portion of the combustor, approximately 16 percent of the total open area being located in the first half of the combustor length. The total-pressure losses through the two combustor designs were approximately the same. The reduction in open area in the upstream region may be considered to have increased local fuel-air ratios and to have reduced local flow velocities.

The extent to which air admission design affects performance depends very markedly on operating conditions. The axial distributions of air-entry-hole area for three experimental annular combustors designed for high combustion performance (ref. 28) at high-altitude (low-pressure) operating conditions are presented in figure 88. The combustors used very similar patterns of circular holes for admitting air into the primary zone and, as shown in figure 88, also had very similar axial distributions of open area. Even these small differences in primary-air-admission design produced the large differences in performance shown in figure 89. Figure 90 presents the axial distribution of open area for each of two widely different combustor designs investigated in reference 29. Combustor A utilized circular holes for admitting primary air; combustor B, slots and louvers. The combustion efficiencies obtained with these combustors over a range of inlet-air-pressure conditions are presented in figure 91. At low-pressure conditions simulating high-altitude, low-speed flight, large differences in performance were observed. At inlet-air pressures above about 1 atmosphere simulating higher-speed flight, higher-pressure-ratio engines, or lower-altitude conditions, the large differences in open-area distribution did not markedly affect combustion efficiency. 3080

It is apparent from the data presented herein that the best axial distribution of open area of a combustor will depend, partially, on the required operating conditions. It will also depend on the fuel-injection and fuel-volatility characteristics, since these factors will affect the amount of vapor fuel present at any location. Finally, it will depend on the combustor design itself, the pressure-loss characteristics and the shape of the air-entry ports. Examples of near-optimum air-entry-hole-area distributions for a number of experimental combustor designs varying in all the above factors are presented in figure 92, where the principal features of the various combustors are noted. Combustors C and E injected prevaporized fuel, and D and F injected atomized liquid fuel into the combustion zone. Primary air was admitted through circular holes, longitudinal slots, or both. The various designs represented had from about 20 to about 50 percent of the total liner open area located in the first half of the combustor.

It has been shown that in the turbojet combustor air admission design influences the limits and efficiency of combustion to a very great extent. Its effects are related to the fundamental combustion requirements of a low-velocity combustion zone containing flammable fuel-air mixtures. If these proper burning conditions at any particular combustor operating condition are to be obtained, the air admission design must be matched with the fuel-injection and vaporization characteristics. Because of the desirability of fixed combustor geometries with a minimum of moving parts, the fuel-air mixture will be optimum over only a part of the entire combustor operating range, and compromises in performance must be expected at some conditions. The effects of adverse fuel-air-mixture conditions are most pronounced at low-pressure and low-temperature (high-altitude) conditions. As would be expected, then, in engines having higher pressure ratios and operating at high flight speeds, the conditions for combustion are less severe, and more freedom in the design of the combustor components is allowable.

CORRELATION OF OPERATING VARIABLES WITH COMBUSTION EFFICIENCY

One of the principal objectives in conducting engine studies is the development of methods that will enable the engine designer to estimate or predict the performance of new engines. A logical approach to this problem is the development of correlations of engine performance characteristics with the engine operating variables. In the case of the turbojet combustor, one performance characteristic of interest to the designer is combustion efficiency; the operating variables of interest are inlet-air pressure, inlet-air temperature, air velocity, and temperature rise. A preceding portion of this chapter is devoted to a discussion of these variables and their relation to combustion efficiency. This section concerns existing methods of combining these operating variables into suitable parameters for correlation with combustion efficiency.

Losses in combustion efficiency occur because the conversion processes that take place in the turbojet combustor are too slow. These processes include vaporization of liquid fuel, mixing of the fuel and air to form flammable mixtures, ignition, and oxidation. Combustion can be visualized as a competition between these processes and the quenching that occurs when the reacting mixture is swept out of the burning zone and diluted with cold air and when the mixture contacts the relatively cool walls of the combustor liner. Because of the obvious complexity of the combustion process, no exact theoretical treatment of combustion efficiency is currently possible. Nevertheless, correlations have been developed, both empirically and theoretically, by making simplifying assumptions regarding the combustion mechanism.

3080

CC-17 back

Correlation with a Simplified Reaction-Kinetics Equation

The effects of the inlet-air variables on combustion efficiency have been considered to be the result of their effects on the rate of chemical reaction. Second-order reaction equations have been used to explain flame stability phenomena observed in ram-jet combustion chambers (ref. 30). In addition, it has been suggested that chemical-reaction kinetics control the performance of jet-engine combustors (ref. 31).

A theoretical analysis (ref. 32) based on the kinetics of a bimolecular chemical reaction yielded the following relation between combustion efficiency and the combustor-inlet variables:

$$\ln\left(\frac{1 - \frac{N_A}{N_B}\eta_b}{1 - \eta_b}\right) + K_5 = K_3 \frac{(\sigma_A + \sigma_B)^2 (N_B - N_A) e^{-\frac{E}{RT_b}}}{R^{1/2} T_b^{3/2}} \frac{LK_7^2}{K_8 K_9} \frac{p_i T_i}{V_r} \qquad (1)$$

where

E	apparent energy of activation
K_5, K_3, K_7, K_8, K_9	constants
L	length of reaction zone
N_A, N_B	concentration of two reactants in burning zone
p_i	combustor-inlet static pressure
R	gas constant
T_b	static temperature in burning zone
T_i	combustor-inlet static temperature
V_r	combustor reference velocity
η_b	combustion efficiency
σ_A, σ_B	effective molecular diameter

For a given combustor, fuel, and fuel-air ratio, and if the burning-zone temperature T_b is considered independent of changes in inlet conditions and other simplifying assumptions noted in reference 32 are made, then

$$\eta_b = f\left(\frac{p_i T_i}{V_r}\right) \tag{2}$$

Equation (2) is applied, in reference 32, to data obtained in 14 different turbojet engines and combustors. The reference velocity V_r is based on the mass-flow rate, the combustor inlet-air density, and the maximum cross-sectional area of the combustor flow passage. Illustrations of the relation between the parameter $p_i T_i/V_r$ and combustion efficiency η_b are shown in figure 93. Experimental points are shown on this plot to illustrate the extent of scatter in the data. The precision of correlations such as these is not good. Some scatter may be expected since it is difficult, at identical test conditions, to reproduce values of combustion efficiency accurately in day-to-day operation. Studies of this reproducibility show that values of combustion efficiency differing by 4 percent are common with most combustors, but at severe operating conditions the differences may be as great as 10 percent.

3080

The parameter $p_i T_i/V_r$ obviously does not include possible effects of fuel-air ratio on combustion efficiency. Data presented in figure 60(d) indicate that the effect of fuel-air ratio on efficiency varies with combustor design; it may also vary with operating conditions. Many combustors give substantially constant efficiency for a range of fuel-air ratios; when this occurs, the correlation of $p_i T_i/V_r$ with combustion efficiency is generally improved. Thus, some of the scatter of data noted in the correlations of figure 93 may be attributed to the effect of fuel-air ratio.

The data for the 14 combustors investigated (ref. 32) all produce curves of the same general shape. The examples shown in figure 93 indicate that at higher values of the parameter the efficiencies of the combustor are good, but combustion efficiency may decrease rapidly at low values. This general characteristic of the curves led to the suggestion (ref. 32) that a concept of a critical value of the parameter might be developed to distinguish between satisfactory and unsatisfactory ranges of operating conditions. Combustors could then be rated according to these critical values of the parameter. In other words, an examination could be made of the relative ratings of combustors and engines at a selected value of combustion efficiency, and the rating values would be expressed in terms of the parameter $p_i T_i/V_r$. On such a scale, the best combustors would have low values of critical $p_i T_i/V_r$.

In order to obtain a more critical test of the assumption that the rate of chemical reaction controls turbojet combustion efficiency, combustor tests were conducted with a variable concentration of oxygen in the inlet oxygen-nitrogen mixture. Investigations show marked effects of oxygen concentration on combustion properties such as minimum spark-ignition energy, quenching distance, and burning velocity (ref. 33, pp. 303, 304, 405-407, and 460-467). Oxygen concentration is, therefore, a means of varying the combustion characteristics without appreciably changing such factors as inlet velocity, turbulent mixing as associated with inlet conditions, and fuel-spray characteristics.

The effects of oxygen concentration on combustion efficiencies obtained with both liquid fuel (isooctane) and gaseous fuel (propane) were determined in a 7-inch tubular turbojet combustor (refs. 19 and 34). Typical data are presented in figure 94. Even though such flow parameters as velocity and Reynolds number were constant, the combustion efficiency increased with oxygen concentration, the rate of increase being greater at lower values of oxygen concentration. This observation establishes the importance of molecular processes in the combustion process. As would be expected, combustion efficiency also increased with an increase in inlet-air pressure and was higher with the vapor fuel. These results indicate that, when grosser physical processes associated with combustor-inlet conditions are held constant, variations in the molecular-scale processes will affect the performance of a turbojet combustor.

In the application of the variable-oxygen-concentration data of references 19 and 34 to the basic kinetics equation (1), the burning-zone temperature T_b could no longer be considered independent of inlet conditions, since variations in oxygen concentration result in appreciable changes in the flame temperature of stoichiometric or richer fuel-oxygen-nitrogen mixtures. The burning zone temperature T_b was therefore arbitrarily taken as the stoichiometric adiabatic equilibrium temperature. For these conditions, the ratio of the reactants (fuel and oxygen) $N_A N_B$ is assumed constant in the combustion zone, and equation (1) can be expressed as

$$\eta_b = f\left[\alpha \frac{p_i T_i}{V_r}\left(\frac{e^{\frac{-E}{RT_{eq}}}}{T_{eq}^{3/2}}\right)\right] \tag{3}$$

where T_{eq} is the stoichiometric adiabatic equilibrium temperature, and α is the oxygen concentration.

The application of equation (3) to experimental data of references 19 and 34 is shown in figure 95 for a fuel-air ratio of 0.012. The equilibrium temperatures were computed by methods described in reference 35. An activation energy E of 37,000 calories per gram-mole satisfactorily correlated the data obtained with liquid isooctane. This value is in reasonable agreement with the apparent activation energy of 32,000 calories per gram-mole obtained from adiabatic-compression-ignition data (ref. 33, p. 188). For the correlation of the data obtained with gaseous propane (fig. 95(b)), a value of E of 27,818 calories per gram-mole was used. However, because of the sensitivity of the correlation parameter to oxygen-concentration measurements in the low-combustion-efficiency range, any value of E between about 27,000 and about 33,000 calories per gram-mole would be satisfactory. A value of 38,000 calories per gram-mole is cited in reference 36.

The scatter of data from the mean correlation curves of figure 95 is considerably less than that of figure 93. Perhaps a major reason for the improvement in the correlation was the removal, in the data of figure 95, of the variable fuel-air ratio. A comparison of data obtained with the liquid fuel at four fuel-air ratios is presented in figure 96. The correlation curve varies considerably with fuel-air ratio, combustion efficiency increasing with an increase in fuel-air ratio. With gaseous propane fuel (ref. 19), fuel-air ratio had a relatively small effect on combustion efficiencies, except at low values of oxygen concentration.

Correlation with Fundamental Combustion Properties

The data presented in the preceding section of this chapter indicate that the combustion reaction step can be a rate-controlling step in the turbojet combustion process. An analysis based on this fact provided a possible means of predicting the effects of operating variables on combustion efficiency. Other attempts to define the rate-controlling step have considered fundamental combustion properties of fuels, such as burning velocity, minimum ignition energy, inflammability limit, or quenching distance. The data required to develop possible relations between these factors and combustion efficiency have been obtained (1) with fuels having different fundamental combustion properties (refs. 5, 37, and 38) and (2) with various inlet oxygen-nitrogen mixtures (refs. 19 and 34).

Minimum spark-ignition energy. - A comparison of the effect of pressure and oxygen concentration on minimum spark-ignition energy and combustion efficiency of isooctane fuel was made (ref. 34) using values of minimum spark-ignition energy arbitrarily taken at the equivalence ratios giving the lowest values of energy. The 3080
following approximate relation for combustion efficiency η_b, combustor-inlet pressure p_i, and minimum spark-ignition energy E_m was developed for data obtained in the single tubular combustor at constant inlet-air temperature, air flow rate, and fuel-air ratio:

$$\eta_b = f\left(\frac{p_i^2}{E_m}\right) \tag{4}$$

The correlation at one fuel-air ratio with liquid isooctane fuel is shown in figure 97. Similar correlations were obtained at other fuel-air ratios.

Attempts were made in the same manner to correlate data obtained with gaseous propane (ref. 19), but there was no consistent relation between combustion efficiency and minimum spark-ignition energy. The inability to obtain a satisfactory correlation was attributed to large errors arising in the required extrapolation of the ignition-energy data. Results obtained in turbojet combustor tests with wide varieties of fuels (refs. 5, 37, and 38) indicate no consistent relation between minimum spark-ignition energy and turbojet combustion efficiency.

Quenching distance. - It has been found (ch. III) that, over wide ranges of pressure and oxygen concentration, quenching distance d and minimum spark-ignition energy E_m are approximately related by the expression

$$E_m = kd^2$$

where k is a constant. Quenching distance would, therefore, be expected to correlate satisfactorily the combustion efficiency data obtained with isooctane in reference 34 but not to correlate the date of references 5, 19, 37, and 38. Attempts to correlate the combustion-efficiency data obtained with gaseous propane (ref. 19) with quenching-distance data for propane (ref. 39) have not been successful.

Burning velocity. - Another combustion characteristic of interest in the evaluation of combustor performance is burning velocity. Basic investigations of burning velocity are discussed extensively in chapter IV, and certain relations are developed to show the effect of variables on burning velocity. An effort is made in reference 34 to relate basic burning-velocity considerations to combustor performance data obtained with varying inlet oxygen concentration. The equation developed in reference 34 relates combustion efficiency and maximum laminar-flame speed u_f by the expression

$$\eta_b = f\left(p_i^{1/3}\frac{u_f}{V_r}\right) \tag{5}$$

This equation assumes constant inlet-air temperature and constant flow rate of fuel and oxygen-nitrogen mixture. For constant inlet temperature and for flame speed assumed independent of pressure and Reynolds number (ref. 36), the maximum flame speed of at least some fuel oxygen-nitrogen mixtures has been found to be proportional to the term $(\alpha - K)$ (ch. IV), where K is a constant dependent on fuel type, and α is the oxygen concentration by percent. Substitution of this term in equation (5) gives

$$\eta_b = f\left[\frac{p_i^{1/3}(\alpha - K)}{V_r}\right] \tag{6}$$

As shown in figure 98(a), the flame-speed parameter of equation (6) satis-
3080 factorily correlates combustion-efficiency data obtained with liquid isooctane ($K = 12$) at one fuel-air ratio and over a range of combustor-inlet pressure and oxygen concentration. Equally satisfactory correlations were obtained at other fuel-air ratios. Equation (6) was also found to be suitable for correlation of gaseous-propane ($K = 11.5$) data (ref. 19), as shown in figure 98(b).

Investigations conducted with five different hydrocarbon fuels in a turbojet combustor (ref. 5) indicated that the most consistent performance trends were obtained with maximum fundamental burning velocity. Combustion efficiency generally increased with an increase in burning velocity. Exceptions to this trend occurred, particularly at very low air-flow rates, indicating the presence of other controlling factors not considered. Other fundamental combustion properties that were considered in reference 5 included minimum ignition energy, spontaneous-ignition temperature, and flammability range. The fuels that were chosen have minimum variations in physical properties. With this restriction the possible range in combustion properties was necessarily quite small.

Investigations of 13 hydrocarbon and nonhydrocarbon fuels having considerably greater variation in combustion properties are reported in reference 37. Tests were conducted in the same combustor and at the same operating conditions as those used in reference 5. Figure 99 shows the variation in combustion efficiency with maximum burning velocity for the data of references 5 and 37 at one of the two inlet-air temperatures investigated. Included in the figure are comparable combustion-efficiency data obtained with isooctane and varying mixtures of oxygen and nitrogen (ref. 34). There is a definite trend towards an increase in combustion efficiency with an increase in maximum burning velocity. Nevertheless, wide deviations from the single curve are apparent. Less distinct trends were obtained with the other fundamental combustion properties.

The 18 fuels represented in figure 99 vary markedly not only in composition, including hydrocarbons, oxygenated hydrocarbons, and fuels containing nitrogen, sulfur, and silicon, but also in physical properties, particularly those reflecting vaporization rate. Consequently, the fundamental burning velocity u_f was combined, empirically, with the latent heat of vaporization H into the correlating parameter $u_f/H^{0.33}$. Figure 100, which shows the relation between this empirical parameter and combustion efficiency using data of figure 99, indicates some degree of correlation; however, several fuels, notably carbon disulfide, deviate considerably from the faired curve.

The range of combustion properties represented by the data of references 5 and 37 was considerably greater than would be encountered in conventional, readily available turbojet fuels; therefore, insofar as combustion efficiency is concerned, fuel composition is not regarded as an important factor in the selection of fuels for general operational use. Evidence that the rate of combustion reactions may influence the performance of the combustor at some conditions of operation has led many investigators to study the effectiveness of fuel additives. A large number of additives have been examined, including oxygenated materials and organo-metallic compounds, but in general, no significant improvements in combustion efficiency have been noted. These observations are consistent with results of fundamental studies described in chapter IV.

Significance of Combustion-Efficiency Correlations

Satisfactory correlations between combustion efficiency and operating variables have resulted from assumptions that the efficiency was limited by either (1) the rate of oxidation of the fuel or (2) the rate of spreading of the flame into unburned mixture. These assumptions yielded two distinct correlating parameters, $p_i T_i / V_r$ from the reaction-kinetics analysis and $p_i^{1/3} u_f / V_r$ from the flame-spreading analysis. The parameter $p_i^{1/3} u_f / V_r$ is applicable only for conditions of constant combustor inlet-air temperature. For a given fuel, a more general form of this parameter that includes the inlet-air temperature as a variable but neglects the effect of pressure and Reynolds number on flame speed is $p_i^{1/3} T_i^{1.1} / V_r$ (ref. 40). The similarities between the two parameters derived by different methods of analysis are now apparent. Since the exponents of the pressure and temperature variables are not the same in the two cases, it is also apparent that both parameters will not adequately correlate combustion-efficiency data obtained over wide ranges of inlet-air conditions.

The chemical reaction parameter $p_i T_i / V_r$ is equal to a dimensional constant times the parameter p_i^2 / w_a, where w_a is air-flow rate. The flame-spreading parameter $p_i^{1/3} T^{1.1} / V_r$ is, similarly, equivalent to a dimensional constant times $p^{1.3} T_i^{0.1} / w_a$. The ratio of exponents on the pressure and air-flow terms in the two cases are 2 and 1.3, respectively.

Tests were conducted in a turbojet combustor operating on gaseous propane fuel over a wide range of pressure and air flow in order to determine experimental values of the exponents (ref. 40). Representative results at one fuel-air ratio are shown in figure 101. The slope of a line indicates the ratio of exponents of the correlating parameter that best fits the experimental data. At low values of pressure and weight flow, the slope is about 2, which corresponds to that predicted by the reaction-kinetics parameter. At high values of air flow and pressure, the slope is about 1.3, a value corresponding to that of the flame-spreading parameter. These data indicate a shift from one rate-controlling process to another as combustor operating conditions are varied through wide ranges. The fact that the reaction-kinetics parameter appears to control combustion only at very low-pressure conditions might be attributed to the dependence of the chemical reaction on the square of the pressure. At the higher pressures, the reaction is very rapid and is no longer the rate-controlling step.

The correlations of combustion efficiency with the reaction-kinetics and the flame-spreading parameters are based on very limited data obtained over a relatively narrow range of operating and design variables. Hence, the conclusions drawn from the correlations must be considered very tentative.

The conversion processes just discussed are not, of course, the only ones that might be considered to limit combustion efficiency. Theoretical analyses have been made at the Lewis laboratory assuming one of the following as the rate-determining step: (1) fuel vaporization, (2) fuel-air turbulent mixing, and (3) fuel droplet burning (ref. 41). With each of these assumptions, however, the theoretical predicted effects of operating variables on combustion efficiency differed markedly from the effects observed experimentally. Nevertheless, empirical correlations have

3080

been developed that illustrate a very important effect of at least one of these steps, fuel vaporization. In figure 100, for example, combustion efficiency was correlated with the parameter $u_f/H^{0.33}$. Data presented in figure 102 (ref. 42) indicate a relation between combustion efficiency and the Sauter mean diameter of the fuel spray, combustion efficiency increasing as the mean fuel drop size decreases. This relation and that shown in figure 100 both predict an increase in efficiency with an increase in the rate of fuel vaporization. The data presented in figure 65(b) indicate that reduced efficiencies can result from either too fine or too coarse a degree of atomization, depending upon the operating conditions. Thus, although fuel atomization and vaporization factors have marked influences on combustor performance, they may not be used successfully to correlate combustion-efficiency data over a wide range of conditions.

The preceding discussion indicates that either of at least two of the conversion processes that occur in the turbojet combustor, fuel vaporization, or combustion, may be rate-controlling, depending upon the choice of operating conditions and combustor design. Furthermore, the ways in which each step limit the conversion process may vary with operating conditions. It is reasonable to expect, then, that the combustion-efficiency trends of the turbojet combustor will be completely described only by a complex parameter that accounts for changes in the rate-controlling steps with changes in operating conditions.

Methods of Estimating Combustion Efficiency of Turbojet Combustor

The preceding discussions have illustrated several methods by which combustion efficiency has been correlated with combustor operating variables. The simplified form p_iT_i/V_r of the reaction-kinetics parameter (eq. (2)) was chosen in further investigations (ref. 43) to develop a convenient method for estimating combustion efficiency at altitude flight conditions from a minimum quantity of combustor test data.

The method developed is illustrated in figure 103. Sections I, II, and III of the figure convert the effects of pressure ratio, flight Mach number, air-flow rate per unit cross-sectional area, and flight altitude on combustor-inlet variables into the parameter V_r/p_iT_i. In section IV of the chart, V_r/p_iT_i is plotted against combustion efficiency for three combustors to give typical correlation curves. The combustion parameter is inverted from the form presented in preceding figures, because the reciprocal form V_r/p_iT_i was found, in reference 17, to give very nearly straight line relations on linear coordinates.

Use of figure 103 requires that the following data be available for the particular combustor and engine under consideration: (1) sufficient combustor data for establishing the V_r/p_iT_i correlation and (2) the sea-level static performance of the engine (for establishing air-flow rate, pressure ratio, and turbine-inlet temperature at various engine speeds). With these data, it is possible to select, in order, the pressure ratio and the flight Mach number (sec. I), the air-flow rate (sec. II), and the altitude (sec. III), and to predict the combustion efficiency that would be obtained with any combustor for which the correlation curve is plotted in section IV. The values of pressure ratio and air-flow rate at the desired altitude conditions are determined from plots of these variables against the corrected engine speed $N/\sqrt{\theta}$.

The chart is based on the assumption that the operating characteristics of engine components other than the combustor do not vary with changes in altitude; that is, corrected air-flow rates, pressures, and temperatures of these components are assumed to be unique functions of corrected engine speed. It must also be recognized, of course, that the accuracy of prediction is no greater than the accuracy of the relation between V_r/p_iT_i and combustion efficiency. As discussed previously in this chapter, some combustors may give very poor correlations, particularly if combustion efficiency varies appreciably with fuel-air ratio.

CORRELATION OF OPERATING VARIABLES WITH COMBUSTION LIMITS

At high-altitude operating conditions turbojet engines may encounter an altitude 3080
operational limit (figs. 59 and 74). As in the case of combustion efficiency, attempts have been made to correlate these limits with operating variables. In addition to facilitating prediction of full-scale engine operating characteristics from limited laboratory tests, such correlations indicate the relative importance of the various operating variables concerned.

Altitude operational limits occur when the combustor is unable to supply the temperature rise required to operate the engine at the desired altitude and engine-speed conditions (fig. 61). Although the lean fuel-air-ratio limit may, in some engines, restrict the idling speed of the engine, the rich limit (maximum temperature rise) will usually establish the altitude ceiling in the normal operating speed range. For this reason, the maximum-temperature-rise characteristics of combustors have been emphasized in most combustion studies, and the correlations discussed herein consider only these characteristics.

The combustor inlet-air variables that affect the maximum combustor temperature rise include inlet-air pressure, temperature, and velocity. The effects of these variables on stability are, in many cases, similar to their effects on combustion efficiency; thus, as pressure and temperature are decreased, and as velocity is increased, the maximum combustor temperature rise is generally reduced. As a result of these trends, correlations of similar form have been developed for both combustion stability and combustion efficiency. The maximum combustor temperature rise obtainable at selected flow conditions is correlated with a modification of the combustion-efficiency parameter p_iT_i/V_r in reference 44. Typical data are presented in figure 104, with the ratio of maximum temperature rise to combustor inlet temperature plotted against the factor $p_i^{1.46}/w_a$ for two laboratory-scale and three full-scale combustors. For a given combustor inlet temperature, higher combustor temperature rises are obtainable at higher pressures and lower velocities (lower air flows).

Additional data obtained in laboratory-scale and full-scale prevaporizer combustors are correlated with a slightly modified parameter $(\sqrt{p_i}T_i/V_r)$, which is proportional to $p_i^{1.5}/w_a$, in references 45 and 46. Stability-limit data obtained at the Lewis laboratory in two full-scale combustors (refs. 3 and 5) are plotted against the modified parameter $\sqrt{p_i}T_i/V_r$ of reference 45 in figure 105. A fair correlation was obtained. For comparison purposes the stability data of figure 105 are replotted against the combustion-efficiency parameter p_iT_i/V_r in figure 106. Some increase in scatter of data points is noted in figure 106.

Correlating parameters of the form $p_i^nT_i/V_r$ can be used in conjunction with charts similar to that shown in figure 103 to predict altitude operational limits of a turbojet engine. For example, maximum-temperature-rise values could be plotted against p_iT_i/V_r in section IV of figure 103. Comparisons of the maximum temperature rise obtainable with the combustor and the temperature rise required by the engine at various operating conditions would establish the altitude operational limits of the engine. A chart similar to the one shown in figure 103 could also be constructed by using the parameter $\sqrt{p_i}T_i/V_r$.

Fuel variables, as well as operating variables, affect maximum obtainable temperature rise. With very limited data, a relation is established in reference 5 between maximum temperature rise and the maximum burning velocity of the fuel. This relation is shown in figure 107, where maximum temperature rise generally increased with an increase in burning velocity. However, at some conditions the results obtained with n-heptane deviate from the general trend. Other fundamental combustion characteristics examined in the investigation of reference 5 did not indicate consistent trends.

From the data presented herein it may be concluded that some degree of correlation has been obtained between maximum temperature rise and parameters of the form $p_i^n T_i/V_r$. The correlations indicate the relative effect of operating variables on stability; however, only approximate estimates of engine performance can be obtained at the present time by use of the correlations. Research also indicates some relation between temperature-rise limits and the fundamental flame speed of the fuel. The degree of correlation obtained in these investigations may be influenced significantly by the accuracy of the combustion data considered; data obtained at or near blow-out conditions are frequently difficult to reproduce.

EFFECT OF COOLANT INJECTION ON COMBUSTOR PERFORMANCE

The maximum thrust output of a turbojet engine may be increased, particularly for short periods of operation as in take-off and combat maneuvering, by the injection of a liquid coolant into the airstream. Coolants such as water, water-alcohol mixtures, and ammonia have been injected into the engine inlet, the compressor, and the combustion chambers (refs. 47 to 49) to provide thrust increases of 20 to 25 percent. The quantity of coolant injected, and, hence, the thrust increase, is limited by combustion performance of both the primary combustor and the afterburner (refs. 48 and 49).

The ratios of augmented to normal combustion efficiencies obtained in a turbojet engine equipped with water-alcohol injection ports in tubular combustors (fig. 108) are presented in figure 109 (ref. 47). At altitudes of 30,000 to 50,000 feet combustion efficiency decreased only slightly as the liquid-air ratio was increased to approximately 0.10 (liquid: 30 percent alcohol, 70 percent water). Analysis of the data indicates that at least a part of the alcohol that was introduced burned within the combustion chambers. The effect of coolant injection on combustion efficiency appears to be most significant at the lower altitudes; at sea-level, with a variable exhaust nozzle, combustion efficiency decreased rapidly with an increase in liquid-air ratio above about 0.06. The loss in efficiency at low altitudes was attributed to the greater penetration of the coolant at the higher liquid flow rates (hence, higher pressure drops) required. It may be assumed that the penetrating coolant jet quenched volumes of fuel-air mixture that had not yet burned.

In another investigation (ref. 48) the effect of alcohol-water injection on the combustion efficiency of a tail-pipe burner was determined. Combustion efficiency was reduced as much as 35 percent at some fuel-air-ratio conditions; a reduction of 25 percent was observed at the optimum tail-pipe fuel-air ratio. Unstable operation of the tail-pipe burner accompanied the rapid decrease in combustion efficiency. A similar investigation (ref. 49) using anhydrous liquid ammonia injected at the compressor inlet indicated no loss in combustion efficiency at stoichiometric mixture conditions (including the ammonia as a combustible). Operation at leaner or richer than stoichiometric mixtures resulted in significant decreases in combustion efficiency. Calculations made in reference 50 indicate that approximately 35 percent of the ammonia burned in the engine combustion chambers at high weight flows of ammonia, permitting a decrease in fuel-flow rate.

An investigation (ref. 51) was conducted in a direct-connect-duct installation to determine the effect of water injection on the maximum obtainable combustor temperature rise in a combustor similar to those used in the engine of reference 48. Water was injected from spray nozzles located (1) ahead of the combustor-inlet station, (2) in the upstream end of the combustor liner, (3) halfway along the length of the combustor liner, and (4) in the downstream end of the combustor. With water injection at the first two stations, no indications of liquid water at the combustor outlet were present. With water injection at the last two stations, liquid water in the exhaust was observed at high liquid-air ratios. Figure 110 presents results of this investigation in terms of the variation in maximum total liquid-air ratio with altitude for each of the four injection stations. The maximum liquid-air ratio was limited by either flame blow-out or inability of the combustor to attain the required temperature rise at the rated-engine-speed conditions investigated. The total liquid-air ratio was most severely limited at the lowest and the highest altitudes investigated. Higher liquid-air ratios could be tolerated when the coolant was injected farther downstream in the combustion chamber (stations 3 and 4).

3080

The effect of water injection on combustion is also of significance in considering flight of turbojet-powered aircraft through heavy precipitation. Figure 111 shows the maximum atmospheric water-air ratios that might be expected, based on a precipitation rate of 33.5 inches per hour measured over a 10-minute period and over an area of 1.0 square mile (ref. 52). The curve representing the limiting water-air ratios that could be tolerated, at rated engine speed, by the combustor of reference 51 is included in figure 111. This curve was obtained with water injection 62 inches upstream of the combustor (station 1). Comparison of the curves of figure 111 indicates that no combustion problems should result from ingestion of water by a turbojet engine operating in heavy rainfall. The data were obtained for only one turbojet combustor design, however, and other designs could conceivably be more sensitive to water ingestion.

EFFECT OF AIR-FLOW FLUCTUATIONS ON COMBUSTOR PERFORMANCE

Chapter XI discusses the phenomenon of compressor surge and associated unsteady-state flow conditions existing in turbojet engines during engine acceleration or deceleration. It is pointed out that during transient operation unfavorable mixture conditions may exist in the combustor, resulting in flame blow-out. The discussion (ch. XI) considers primarily the effects of fuel-flow-rate changes on combustor blow-out. It would be expected that rapid changes in air-flow rates resulting from pressure surging may also affect mixture conditions and, hence, flame blow-out characteristics. Another phenomenon that may be considered to cause flow fluctuations is combustion resonance, which has been observed in both single-burner and full-scale-engine test units. The following discussion describes typical effects of flow oscillations, caused by either air-supply fluctuations or burner resonance, on the performance of turbojet combustors.

The variation of combustor temperature rise with fuel-air ratio obtained in an annular combustor operating over a range of air-flow rate and inlet-air temperature is shown in figure 112(a) (ref. 3). Regions of resonating combustion observed in the tests are denoted in the figure by dashed curves. The faired curve representing an air-flow rate of 11.2 pounds per second has been modified somewhat from that presented in reference 3 in order to show more clearly the effect of combustion resonance on performance. Resonant combustion occurred at the higher fuel-air ratios and was accompanied by a decrease in combustor temperature rise and in combustion efficiency based on theoretical temperature rise. Reductions in efficiency that accompanied combustion resonance were more pronounced and were evident over wider ranges of fuel-air ratio as the air-flow rate was increased and the inlet-air temperature was decreased. The resonance encountered in the regions of the dashed curves was described in reference 3 as "temperature fluctuations at combustor outlet" accompanied by either "rapid flickering at base of flame" or "noisy vibration of combustor and adjacent ducting." In general, the resonant combustion was encountered at conditions that approached the operational limits of the combustor.

3080

Similar data were obtained in a single tubular combustor operating over a range of fuel-air ratio and air-flow rate at constant inlet-air pressure and inlet-air temperature; typical results are presented in figure 112(b). In the tubular combustor, resonance was observed only at the lower air-flow rates. Combustor temperature rise and, hence, combustion efficiency increased when resonance occurred in the tubular combustor, whereas in the annular combustor, efficiency decreased (fig. 112(a)). This difference in trend may be attributed to differences in combustor design, operating conditions, fuel characteristics, or to differences in the characteristics of the resonance encountered. A variable-area fuel nozzle operating at a constant pressure differential of 25 pounds per square inch was used to obtain the data shown in figure 112(b). Since it was considered possible for the spring-loaded mechanism in this nozzle to incite the observed resonance, tests were repeated with a fixed-area nozzle. Similar trends were observed, but resonance generally occurred at lower fuel-air ratios with the smaller, fixed-area nozzle.

Data obtained in the same tubular combustor with three fuels varying both in hydrocarbon type and in volatility are presented in figure 113. At these conditions, resonant combustion, accompanied by an increase in performance, occurred with all three fuels. However, the fuel-air ratio and the temperature rise at which resonance first occurred varied with the fuel used. Other data obtained with a number of fuels at various operating conditions in a similar tubular combustor (table II, ref. 5) indicate that combustion resonance was encountered at certain operating conditions; however, no significant effects of the resonance on performance were observed. No explanation for variations in the observed effects of resonance on performance is apparent from the limited data available.

The investigation reported in reference 53 was an attempt to study more thoroughly the effect of inlet-air flow fluctuations on the performance of a 2-inch-diameter turbojet-type combustor. By varying the rotative speed of an inlet-air butterfly valve, an oscillating flow of controllable frequency could be supplied to the small-scale combustor. Figure 114 shows the effect of oscillation frequency on combustion efficiency of two fuels at two operating conditions in the small-scale combustor. At the higher pressure and air-flow rate (fig. 114(a)), an increase in oscillation frequency increased combustion efficiency slightly; at the lower pressure and air-flow rate (fig. 114(b)), an increase in oscillation frequency decreased combustion efficiency. A maximum reduction in combustion efficiency of 15 percent was observed with isooctane fuel with an oscillatory frequency of about 180 cycles per second.

The effect of the oscillation frequency on the maximum stable temperature rise of the combustor is shown in figure 115. As frequency was increased, the maximum temperature rise decreased rapidly, reached a minimum value, and then increased. Similar trends were observed with the two fuels investigated, n-heptane and isooctane. The greatest effect of the induced oscillations on the maximum temperature rise was observed at a frequency of about 80 cycles per second. Data obtained in the same combustor at a lower pressure and a lower air flow (ref. 53) showed that the maximum reduction in temperature-rise limit occurred at a lower frequency of about 40 cycles per second.

From the data presented herein it is concluded that air-flow fluctuations may affect the performance of turbojet combustors. The nature and the degree of the effects are apparently functions of combustor operating conditions, combustor design, fuel characteristics, and possibly combustor accessory ducting. The frequency and perhaps the amplitude of the fluctuations influence the results obtained. Basic considerations of combustion suggest that flow fluctuations probably affect combustion performance by (1) varying the degree of turbulence in the flame zone, (2) altering air-distribution characteristics, (3) altering fuel-spray characteristics, and (4) rapidly shifting the flame front in and out of favorable combustion zones. A more complete discussion of the causes and characteristics of combustion resonance may be found in chapter VIII.

3080

SIGNIFICANCE OF COMBUSTION EFFICIENCY AND STABILITY

DATA IN COMBUSTOR DESIGN

Reduced combustion efficiency and stability of turbojet combustors at high-altitude operating conditions seriously limit the usefulness of the turbojet engine. Examination of the basic factors affecting these performance characteristics indicates that decreased combustor inlet-air temperature and pressure and increased air velocities result in decreased efficiencies and stability. The effects of these combustor inlet-air variables on combustion efficiency are correlated by several parameters derived from theoretical considerations of (1) flame velocity, (2) minimum ignition energy, and (3) reaction kinetics. A simplified form of a reaction-kinetics parameter $V_r/p_i T_i$ appears generally satisfactory for much of the combustion data considered. Its application to the problem of predicting combustion efficiencies of a given combustor in full-scale engines at flight conditions has been described. Parameters of the same general form may also be used to correlate combustion-limit data, allowing estimates to be made of the altitude operational limits of a turbojet engine.

In addition to the inlet-air variables, the over-all fuel-air ratio has very important effects on combustor performance; overlean or overrich fuel-air mixtures in the combustion zone result in decreased efficiencies and in flame blow-out. The fuel-air-mixture conditions are influenced by three factors: (1) fuel atomization and distribution characteristics, (2) fuel vaporization rate, and (3) air admission patterns. Optimum performance of the combustor is obtained only if all these factors are tailored to one another.

The magnitude of the effects of fuel-air-mixture variables on combustor performance depends upon the severity of the inlet-air conditions. More accurate control of these variables is required as inlet-air pressure or temperature is reduced or as air velocity is increased. Thus, the problem of designing high-performance combustors becomes more difficult as the operating altitudes of aircraft are increased and as the air-handling capacities of engines and, hence, combustor flow rates are increased.

REFERENCES

1. Hibbard, Robert R., Drell, Isadore L., Metzler, Allen J., and Spakowski, Adolph E.: Combustion Efficiencies in Hydrocarbon-Air Systems at Reduced Pressures. NACA RM E50G14, 1950.

2. Sobolewski, Adam E., Miller, Robert R., and McAulay, John E.: Altitude Performance Investigation of Two Single-Annular Type Combustors and the Prototype J40-WE-8 Turbojet Engine Combustor with Various Combustor-Inlet Air Pressure Profiles. NACA RM E52J07, 1953.

3. Childs, J. Howard, McCafferty, Richard J., and Surine, Oakley W.: Effect of Combustor-Inlet Conditions on Performance of an Annular Turbojet Combustor. NACA Rep. 881, 1947. (Supersedes NACA TN 1357.)

4. McCafferty, Richard J.: Liquid-Fuel-Distribution and Fuel-State Effects on Combustion Performance of a Single Tubular Combustor. NACA RM E51B21, 1951.

5. Wear, Jerrold D., and Dittrich, Ralph T.: Performance of Pure Fuels in a Single J33 Combustor. I - Five Liquid Hydrocarbon Fuels. NACA RM E52J03, 1952.

3080

6. Wear, Jerrold D., and Jonash, Edmund R.: Combustion-Efficiency and Altitude-Limit Investigations of Five Fuels in an Annular Turbojet Combustor. NACA RM E7L30, 1948.

7. Topper, Leonard: Radiant Heat Transfer from Flames in a Single Tubular Turbojet Combustor. NACA RM E52F23, 1952.

8. Hall, A. R., and Diederichsen, J.: An Experimental Study of the Burning of Single Drops of Fuel in Air at Pressures up to Twenty Atmospheres. Fourth Symposium (International) on Combustion, The Williams & Wilkins Co. (Baltimore), 1953, pp. 837-846.

9. Harp, James L., Jr., and Vincent, Kenneth R.: Altitude Performance Investigation of Single- and Double-Annular Turbojet-Engine Combustors with Various Size Fuel Nozzles. NACA RM E51L14, 1952.

10. McCafferty, Richard J.: Effect of Fuels and Fuel-Nozzle Characteristics on Performance of an Annular Combustor at Simulated Altitude Conditions. NACA RM E8C02a, 1948.

11. Gold, Harold, and Straight, David M.: Gas-Turbine-Engine Operation with Variable-Area Fuel Nozzles. NACA RM E8D14, 1948.

12. Gold, H., and Rosenzweig, S.: Altitude Operation of Gas-Turbine Engine with Variable-Area Fuel-Nozzle System. NACA RM E51A04, 1951.

13. Butze, Helmut F., and Jonash, Edmund R.: Turbojet Combustor Efficiency with Ceramic-Coated Liners and with Mechanical Control of Fuel Wash on Walls. NACA RM E52I25, 1952.

14. Straight, David M., and Gernon, J. Dean: Photographic Studies of Preignition Environment and Flame Initiation in Turbojet-Engine Combustors. NACA RM E52I11, 1953.

15. Godsave, G. A. E.: The Burning of Single Drops of Fuel. Pt. III. Comparison of Experimental and Theoretical Burning Rates and Discussion of the Mechanism of the Combustion Process. Rep. R.88, British N.G.T.E., Aug. 1952.

16. Dittrich, Ralph T.: Combustion-Efficiency Investigation of Special Fuels in Single Tubular-Type Combustor at Simulated Altitude Conditions. NACA RM E7F11, 1947.

17. Norgren, Carl T., and Childs, J. Howard: Effect of Liner Air-Entry Holes, Fuel State, and Combustor Size on Performance of an Annular Turbojet Combustor at Low Pressures and High Air-Flow Rates. NACA RM E52J09, 1953.

18. Longwell, J. P., Van Sweringen, R. A., Jr., Weiss, M. A., and Hatt, F. G.: Preparation of Air-Fuel Mixtures for Ramjet Combustors. Bumblebee Ser. Rep. No. 168, Esso Labs., Standard Oil Dev. Co., Nov. 1951. (Contract NOrd 9233 with Bur. Ord., U.S. Navy.)

19. Graves, Charles C.: Effect of Inlet Oxygen Concentration on Combustion Efficiency of J33 Single Combustor Operating with Gaseous Propane. NACA RM E53A27, 1953.

20. Sharp, J. G.: Fuels for Gas-Turbine Aero-Engines. Aircraft Eng., vol. XXIII, no. 263, Jan. 1951, pp. 2-8.

21. Jones, Anthony W., and Cook, William P.: Combustion Efficiency Performance of a MIL-F-5624 Type Fuel and Monomethylnaphthalene in a Single Vaporizing-Type Combustor. NACA RM E51K30, 1952. 3080

22. McCafferty, Richard J.: Vapor-Fuel-Distribution Effects on Combustion Performance of a Single Tubular Combustor. NACA RM E50J03, 1950.

23. Norgren, Carl T., and Childs, J. Howard: Effect of Fuel Injectors and Liner Design on Performance of an Annular Turbojet Combustor with Vapor Fuel. NACA RM E53B04, 1953.

24. Pavia, R. E.: The Derwent V Combustor with Separated Air Supplies. (ii) The Effects of Primary and Dilution Air Flows. Engines Note 157, Aero. Res. Labs., Dept. Supply, Commonwealth of Australia, Nov. 1951.

25. Dittrich, Ralph T.: Investigation of Low-Pressure Performance of Experimental Tubular Combustors Differing in Air-Entry-Hole Geometry. NACA RM E53G01, 1953.

26. Scull, Wilfred E.: High-Altitude Performance of 9.5-Inch-Diameter Tubular Experimental Combustor with Fuel Staging. NACA RM E54A06, 1954.

27. Mark, Herman, and Zettle, Eugene V.: Axial-Slot Air Admission for Controlling Performance of a One-Quarter-Annulus Turbojet Combustor and Comparison with Complete Engine. NACA RM E52A21, 1952.

28. Norgren, Carl T., and Childs, J. Howard: Performance of an Annular Turbojet Combustor Having Reduced Pressure Losses and Using Propane Fuel. NACA RM E53G24, 1953.

29. Zettle, Eugene V., Norgren, Carl T., and Mark, Herman: Combustion Performance of Two Experimental Turbojet Annular Combustors at Conditions Simulating High-Altitude Supersonic Flight. NACA RM E54A15, 1954.

30. Longwell, John P., Frost, Edward E., and Weiss, Malcolm A.: Flame Stability in Bluff Body Recirculation Zones. Ind. and Eng. Chem., vol. 45, no. 8, Aug. 1953, pp. 1629-1633.

31. Avery, W. H., and Hart, R. W.: Combustor Performance with Instantaneous Mixing. Ind. and Eng. Chem., vol. 45, no. 8, Aug. 1953, pp. 1634-1637.

32. Childs, J. Howard: Preliminary Correlation of Efficiency of Aircraft Gas-Turbine Combustors for Different Operating Conditions. NACA RM E50F15, 1950.

33. Lewis, Bernard, and von Elbe, Guenther: Combustion, Flames and Explosions of Gases. Academic Press, Inc. (New York), 1951, pp. 303-304; 405-407; 460-467.

34. Graves, Charles C.: Effect of Oxygen Concentration of the Inlet Oxygen-Nitrogen Mixture on the Combustion Efficiency of a Single J33 Turbojet Combustor. NACA RM E52F13, 1952.

35. Hottel, H. C., Williams, G. C., and Satterfield, C. H.: Thermodynamic Charts for Combustion Processes. Pts. I and II. John Wiley & Sons, Inc., 1949.

36. Jost, Wilhelm: Explosion and Combustion Processes in Gases. McGraw-Hill Book Co., Inc., 1946, p. 437.

37. Smith, Arthur L., and Wear, Jerrold D.: Performance of Pure Fuels in a Single J33 Combustor. II - Hydrocarbon and Nonhydrocarbon Fuels. NACA RM E55B02, 1955.

38. Calcote, H. F., et al.: Minimum Spark Energy Correlation with Ramjet and Turbojet Burner Performance. TP-36, Experiment, Inc., Richmond (Va.), Mar. 1950. (Final Rep. No. 1 to Bur. Aero. under Contract NOa(s) 10115.)

39. Berlad, Abraham L.: Flame Quenching by a Variable-Width Rectangular-Slot Burner as a Function of Pressure for Various Propane-Oxygen-Nitrogen Mixtures. NACA RM E53K30, 1954. (See also Jour. Phys. Chem., vol. 58, no. 11, Nov. 1954, pp. 1023-1026.)

40. Childs, J. Howard, and Graves, Charles C.: Relation of Turbine-Engine Combustion Efficiency to Second-Order Reaction Kinetics and Fundamental Flame Speed. NACA RM E54G23, 1954.

41. Graves, Charles C.: Burning Rates of Single Fuel Drops and Their Application to Turbojet Combustion Process. NACA RM E53E22, 1953.

42. Nicholson, H. M.: The Correlation of Combustion Efficiency and Burner Characteristics under Simulated Altitude Idling Conditions. Memo. No. M.113, British N.G.T.E., Apr. 1951.

43. Olson, Walter T., Childs, J. Howard, and Scull, Wilfred E.: Method for Estimating Combustion Efficiency at Altitude Flight Conditions from Combustion Efficiency at Altitude Flight Conditions from Combustor Tests at Low Pressures. NACA RM E53F17, 1953.

44. Britton, S. C., Schirmer, R. M., and Fox, H. M.: A Design Study for Equipment to Evaluate Performance of Aircraft Gas Turbine Fuels. Rep. No. 763-49R, Res. Dept., Phillips Petroleum Co., Oct. 12, 1949. (Final Rep. for Navy Contract NOa(s) 9596.)

45. Kittredge, G. D., and Fromm, E. H.: Evaluation of Fuel Characteristics in Thermojet Engine Combustion Processes. Prog. Rep. No. 6, Rep. No. 403-17-52R, Res. Div., Phillips Petroleum Co., 1952. (Navy Contract NOas 52-132-C.)

46. Schirmer, R. M., Kittredge, G. D., and Fromm, E. H.: Evaluation of Fuel Characteristics in Thermojet Engine Combustion Processes. Rep. No. 403-19-52R, Summary Rep., Phillips Petroleum Co., Jan. 1953. (Navy Contract NOas 52-132-C.)

47. Jansen, E. T., and Renas, P. E.: Altitude Investigation of Thrust Augmentation Using Water-Alcohol Injection into the Combustion Chambers of an Axial-Flow Turbojet Engine. NACA RM E52L12, 1953.

48. Useller, James W., and Povolny, John H.: Experimental Investigation of Turbojet-Engine Thrust Augmentation by Combined Compressor Coolant Injection and Tail-Pipe Burning. NACA.RM E51H16, 1951.

49. Useller, James W., Harp, James L., Jr., and Fenn, David B.: Turbojet-Engine Thrust Augmentation at Altitude by Combined Ammonia Injection into the Compressor Inlet and Afterburning. NACA RM E52L19, 1953.

50. Harp, James L., Jr., Useller, James W., and Auble, Carmon M.: Thrust Augmentation of a Turbojet Engine by the Introduction of Liquid Ammonia into the Compressor Inlet. NACA RM E52F18, 1952.

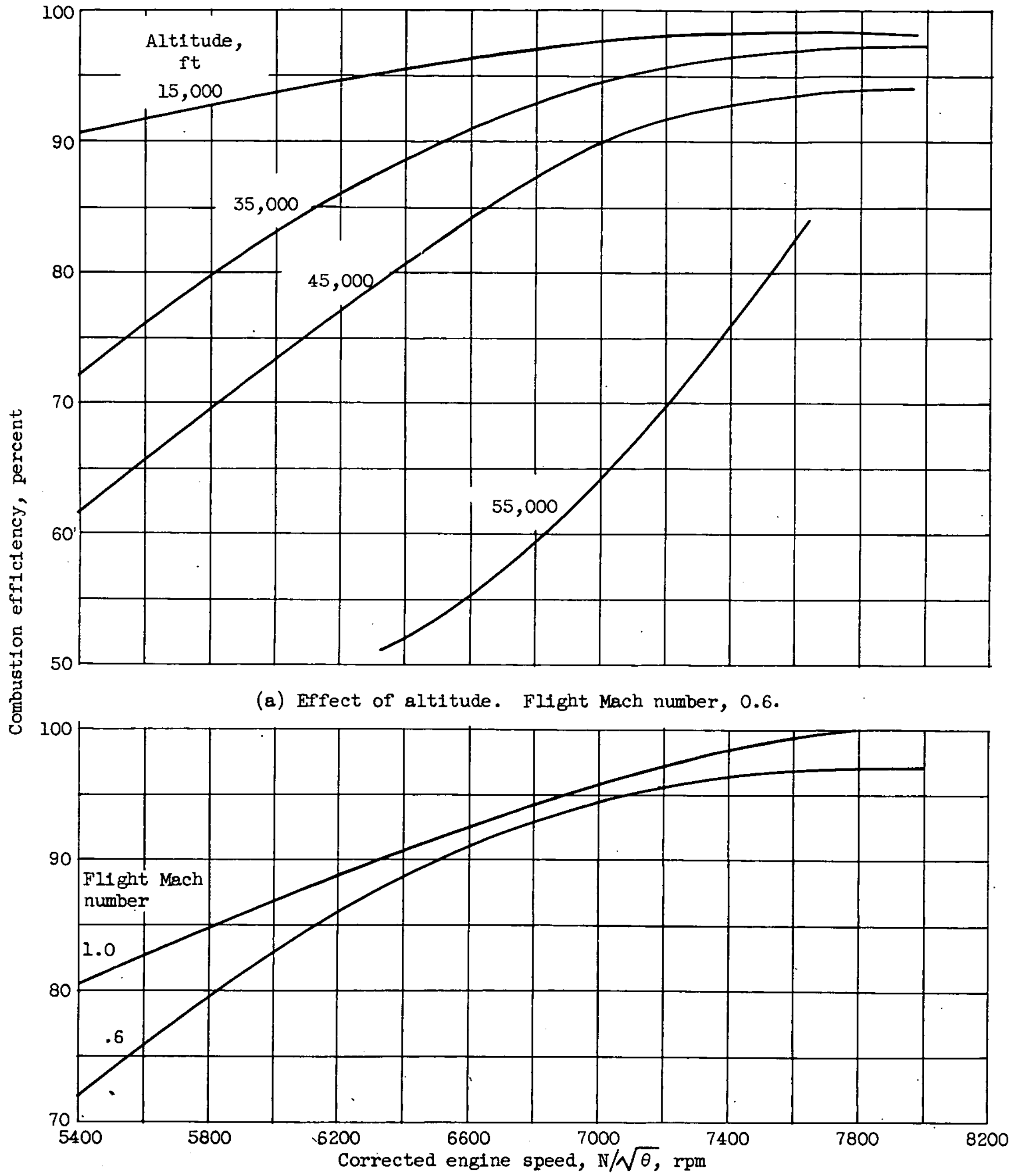
51. Cook, William P., and Zettle, Eugene V.: Performance Investigation of Can-Type Combustor. II - Water Injection at Various Stations in Combustor. NACA RM E8F28, 1948.

52. Useller, James W., Lewis, William, and Zettle, Eugene V.: Effect of Heavy Rainfall on Turbojet Aircraft Operation. Aero. Eng. Rev., vol. 14, no. 2, Feb. 1955, pp. 40-42.

53. Schirmer, R. M., Fromm, E. H., and Kittredge, G. D.: Fuel Characteristics in Thermojet Engine Combustion Processes. Prog. Rep. No. 3, Res. Div., Phillips Petroleum Co., Apr. 15, 1953. (Navy Contract NOas 52-132-C.)

54. Hibbard, Robert R., Metzler, Allen J., and Scull, Wilfred E.: Low-Pressure Performance of Experimental Prevaporizing Tubular Combustor Using Approximately Stoichiometric Admission of Fuel-Air Mixture into the Primary Zone. NACA RM E54F25a, 1954.

55. Norgren, Carl T.: Performance of a Vaporizing Annular Turbojet Combustor at Simulated High Altitudes. NACA RM E54G21, 1954.



(a) Effect of altitude. Flight Mach number, 0.6.

(b) Effect of flight Mach number. Altitude, 35,000 feet.

Figure 58. - Effect of flight conditions on combustion efficiency of turbojet engine over range of engine rotational speed. Engine sea-level pressure ratio, 5; exhaust-nozzle area, 534 square inches (ref. 2).

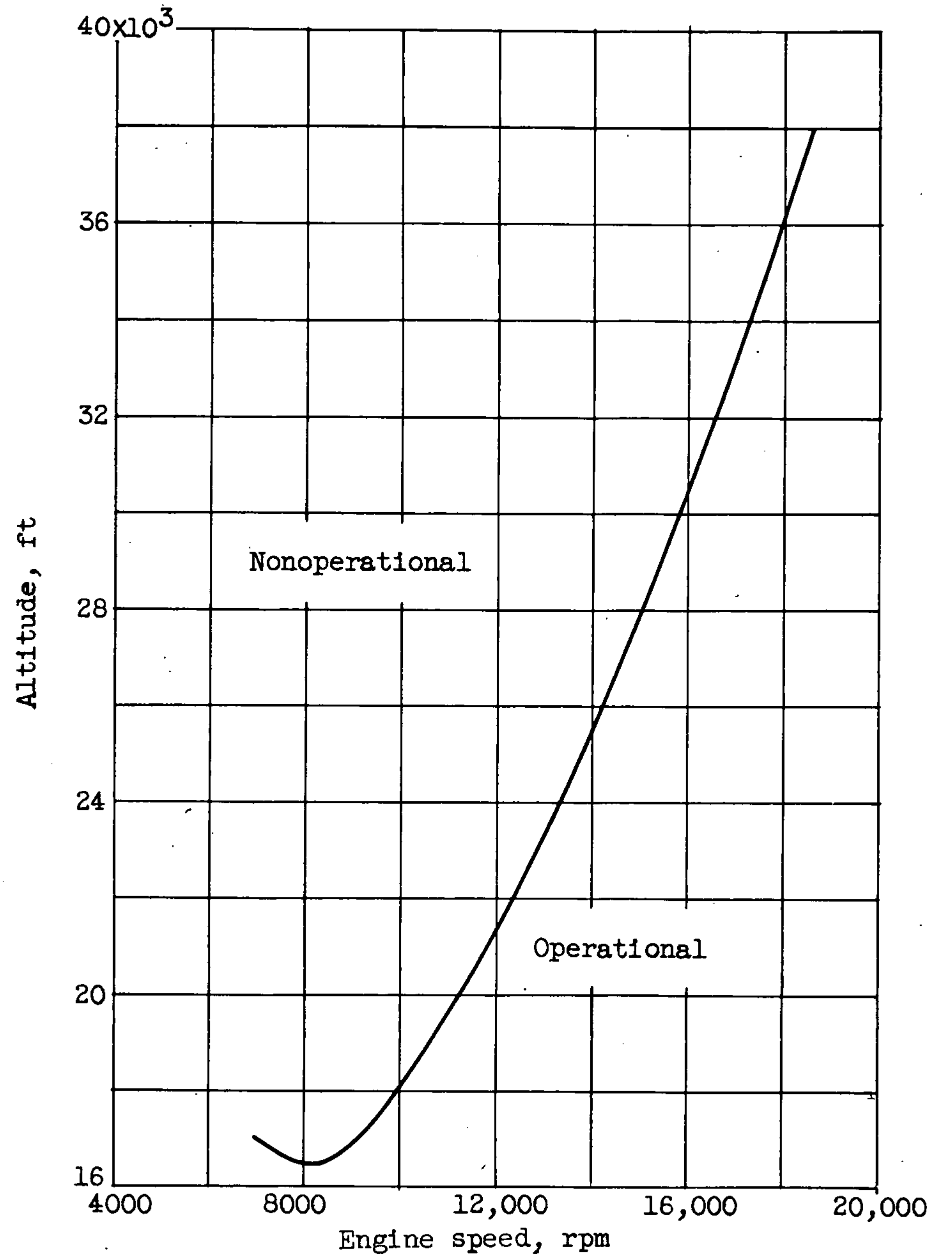
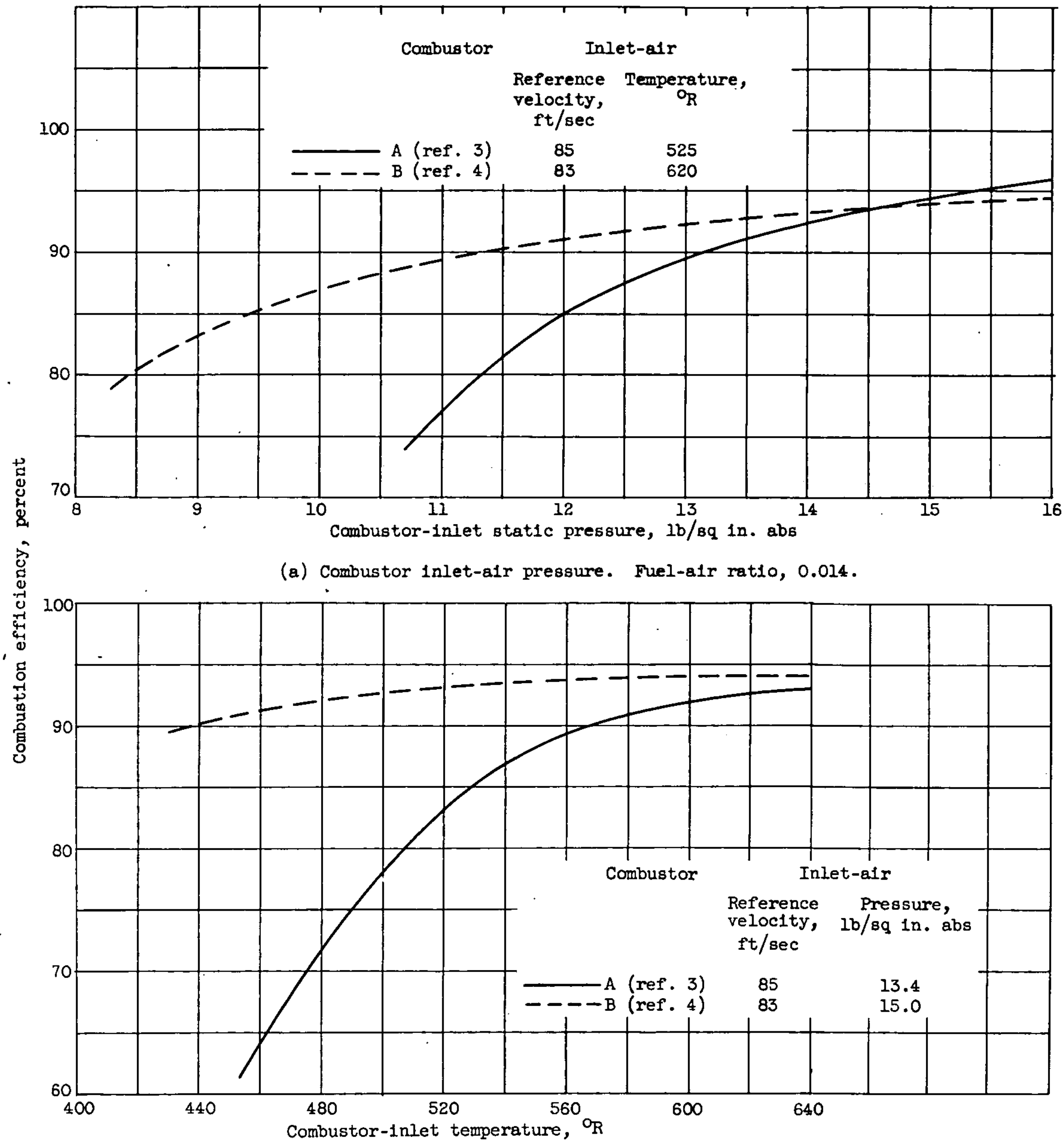


Figure 59. - Altitude operational limits of combustor at conditions simulating static operation. Engine sea-level pressure ratio, 3 (ref. 3).

3080

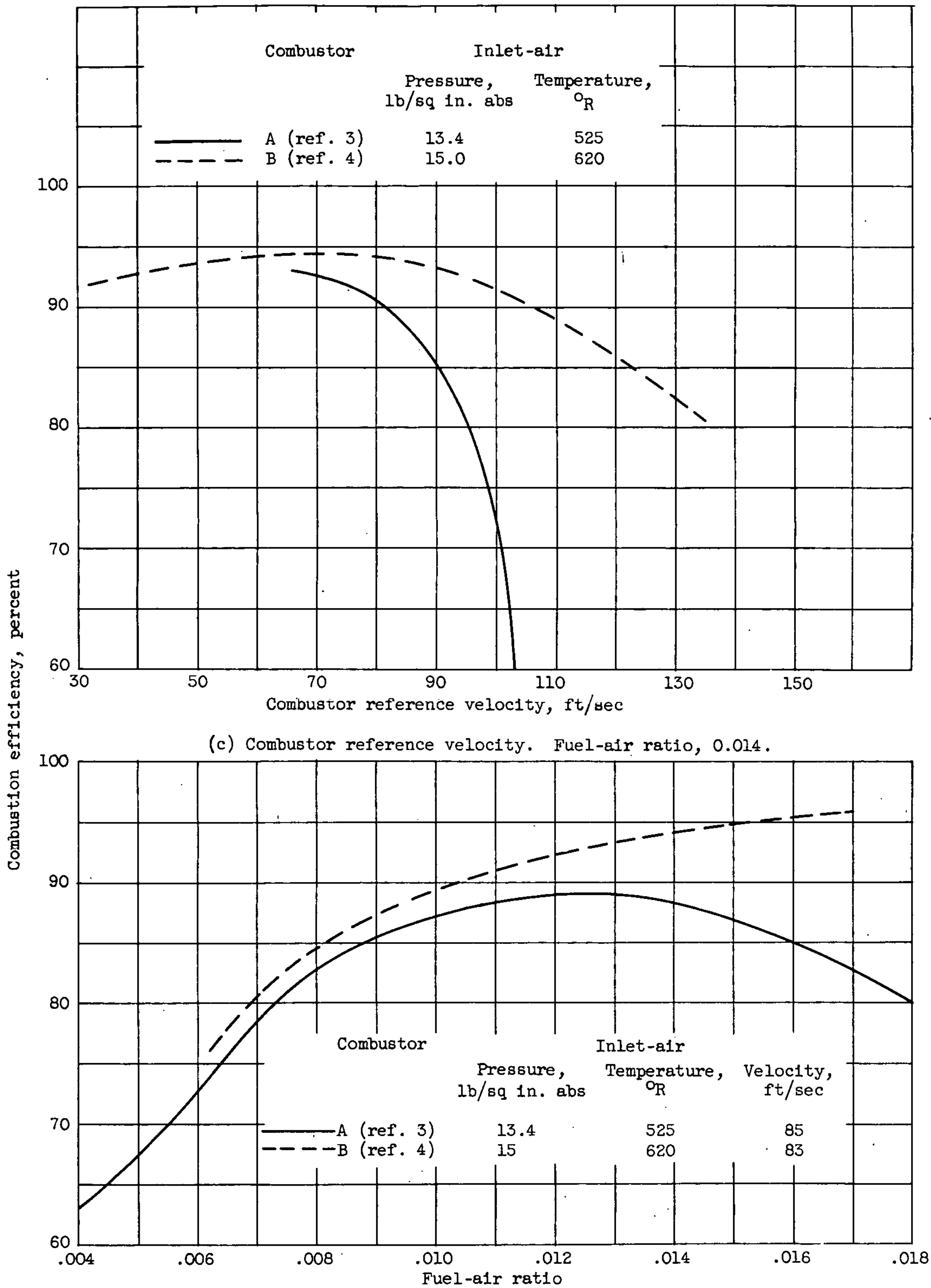


(a) Combustor inlet-air pressure. Fuel-air ratio, 0.014.

(b) Combustor inlet-air temperature. Fuel-air ratio, 0.014.

Figure 60. - Effect of operating variables on combustion efficiency of two different turbojet combustors.

3080



(c) Combustor reference velocity. Fuel-air ratio, 0.014.

(d) Combustor fuel-air ratio.

Figure 60. - Concluded. Effect of operating variables on combustion efficiency of two different turbojet combustors.

3080

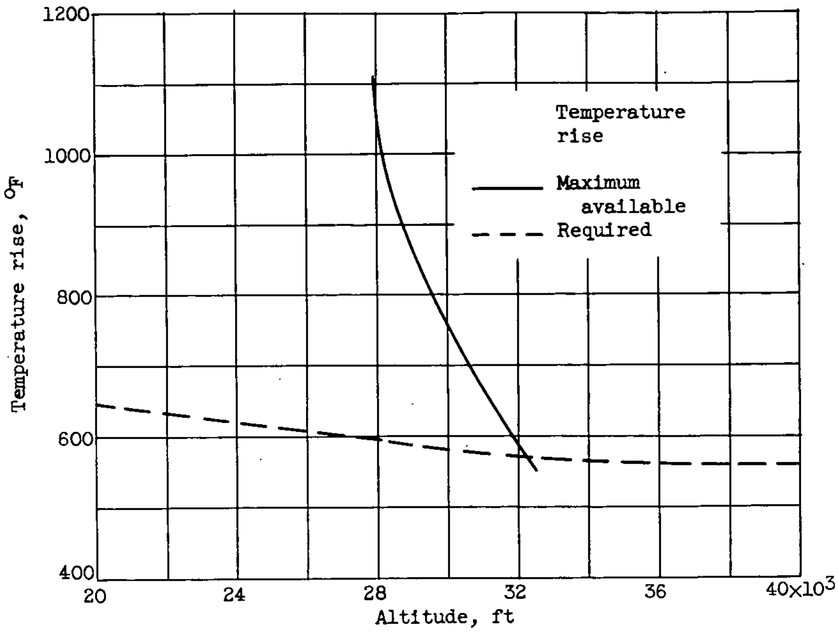


Figure 61. - Effect of altitude on required and available temperature rise of turbojet combustor. Engine rated sea-level pressure ratio, 4; engine rotational speed, 10,000 rpm; fuel, aviation gasoline (AN-F-28).

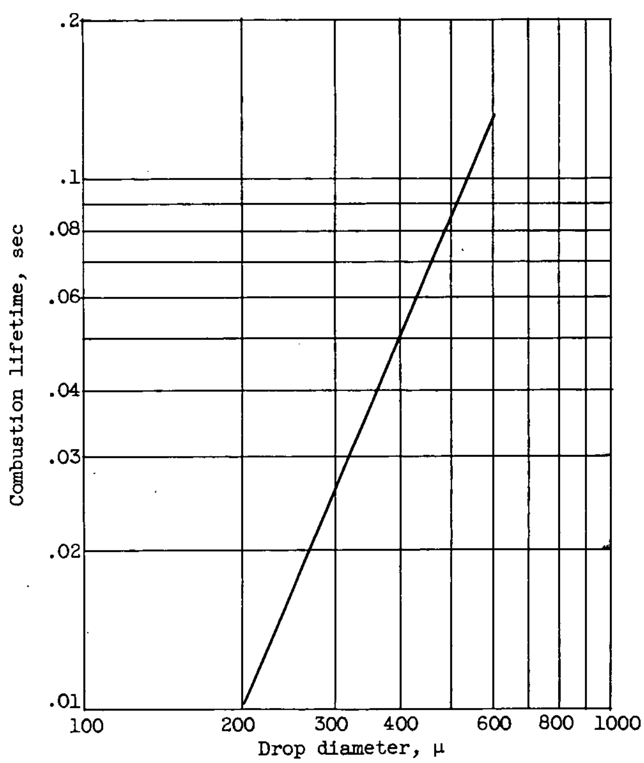


Figure 62. - Combustion lifetime of liquid kerosene drops of varying size. Pressure, 1 atmosphere (ref. 8).

3080

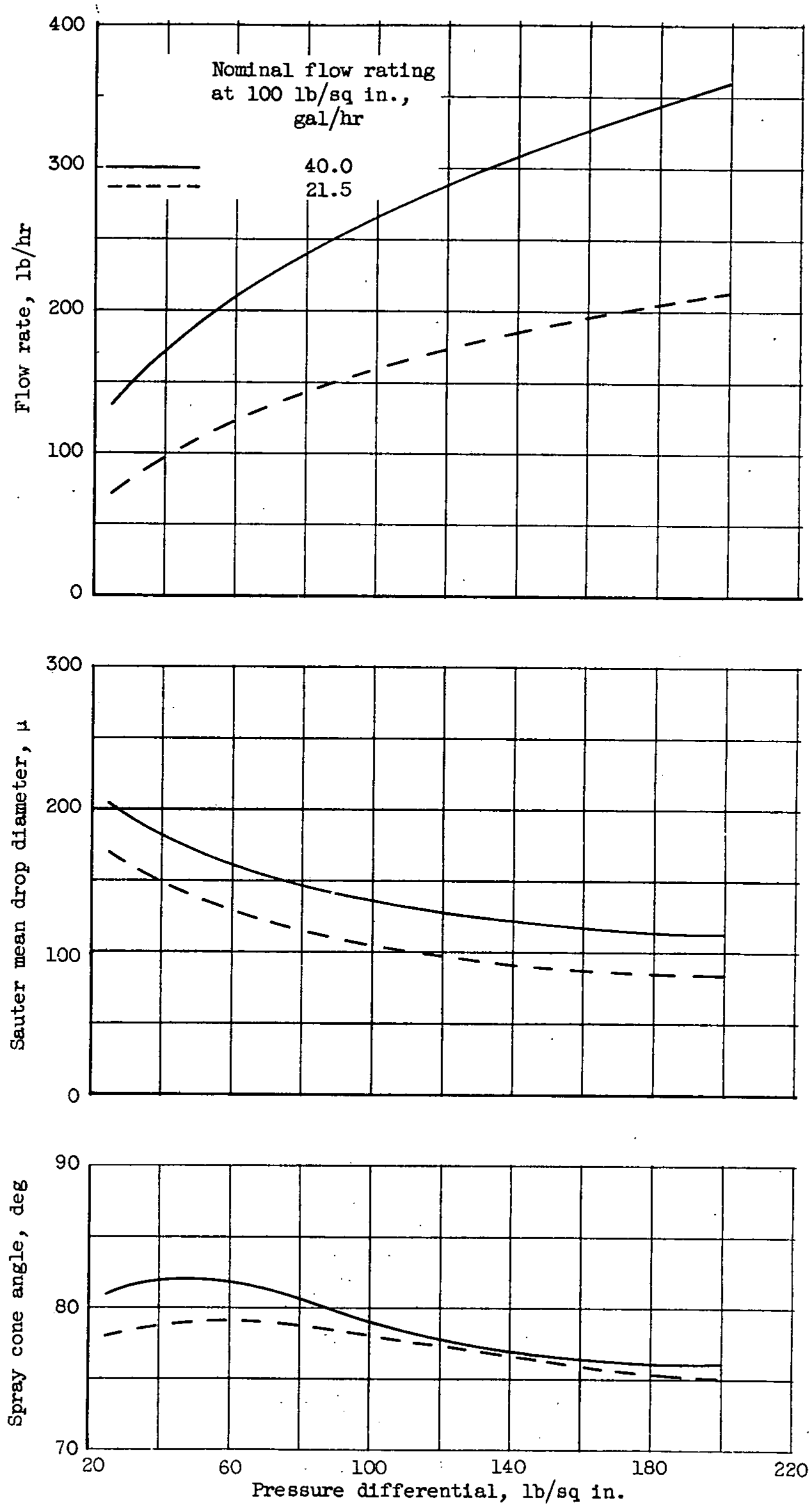
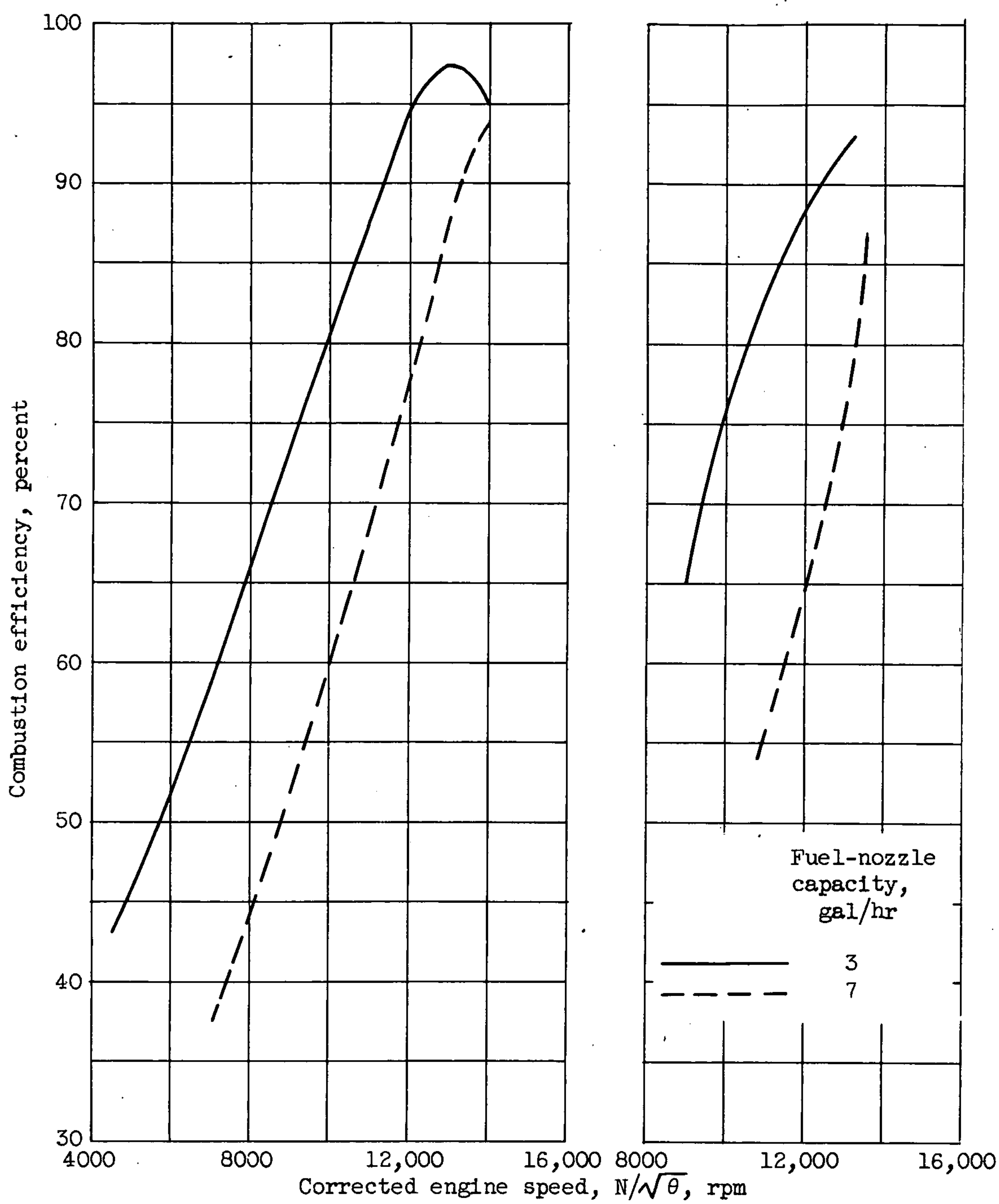


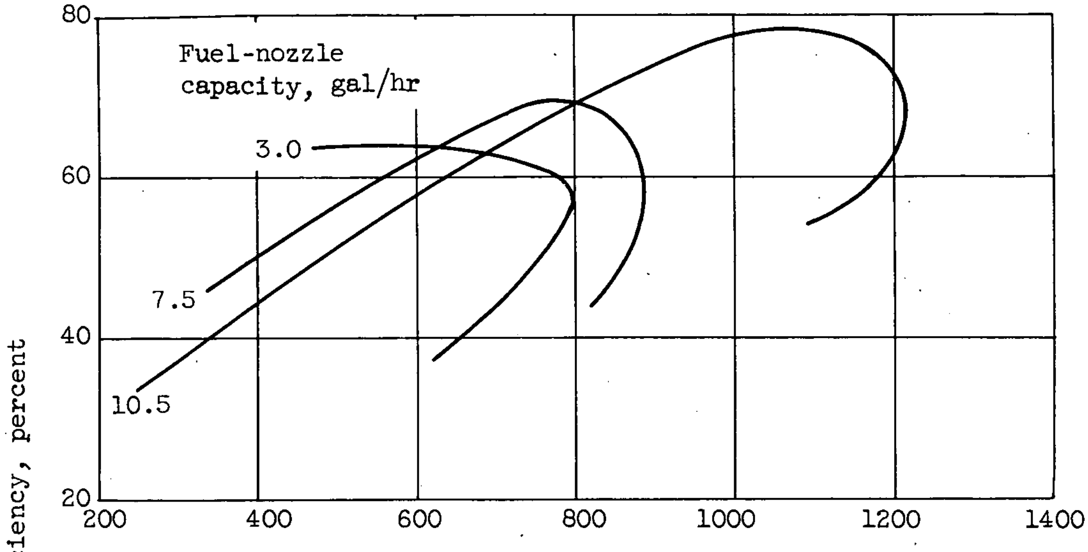
Figure 63. - Spray characteristics of two swirl-type pressure-atomizing nozzles. Nominal cone angle, 80°; fuel, Diesel fuel oil at 111° F (specific gravity 0.802).



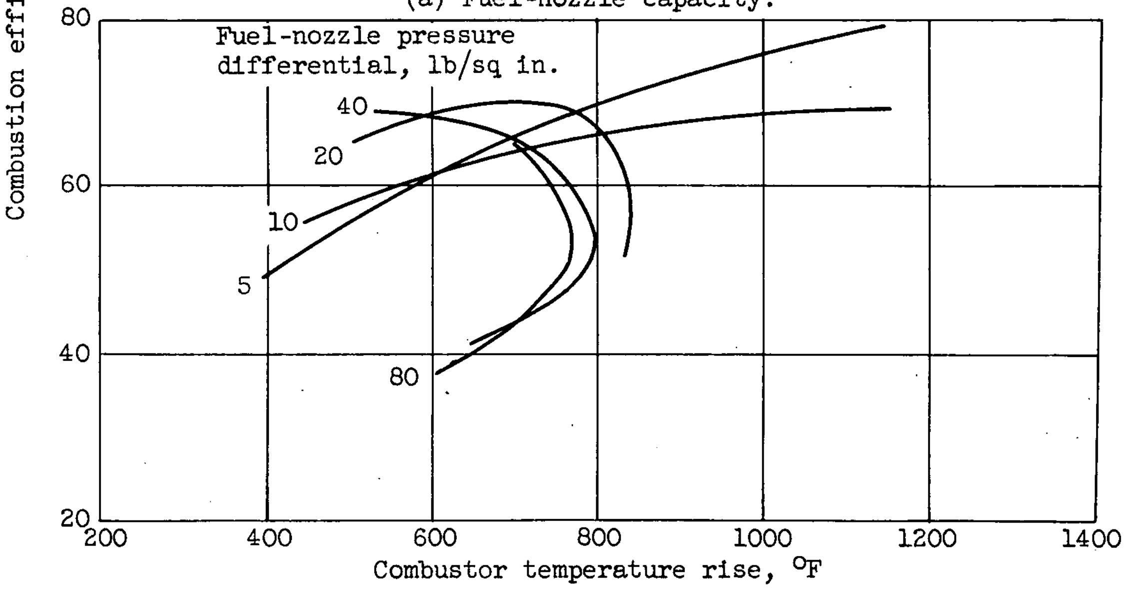
(a) Altitude, 30,000 feet. (b) Altitude, 40,000 feet.

Figure 64. - Effect of fuel-nozzle capacity on combustion efficiency of turbojet engine at two altitude conditions. Flight Mach number, 0.3 (ref. 9).

[redacted]



(a) Fuel-nozzle capacity.



(b) Fuel-injection pressure.

Figure 65. - Effect of fuel-nozzle capacity and injection pressure on combustion efficiency of an annular turbojet combustor using aviation gasoline. Inlet-air pressure, 7.7 pounds per square inch absolute; inlet-air temperature, 530° R; reference velocity, 64 feet per second (ref. 10).

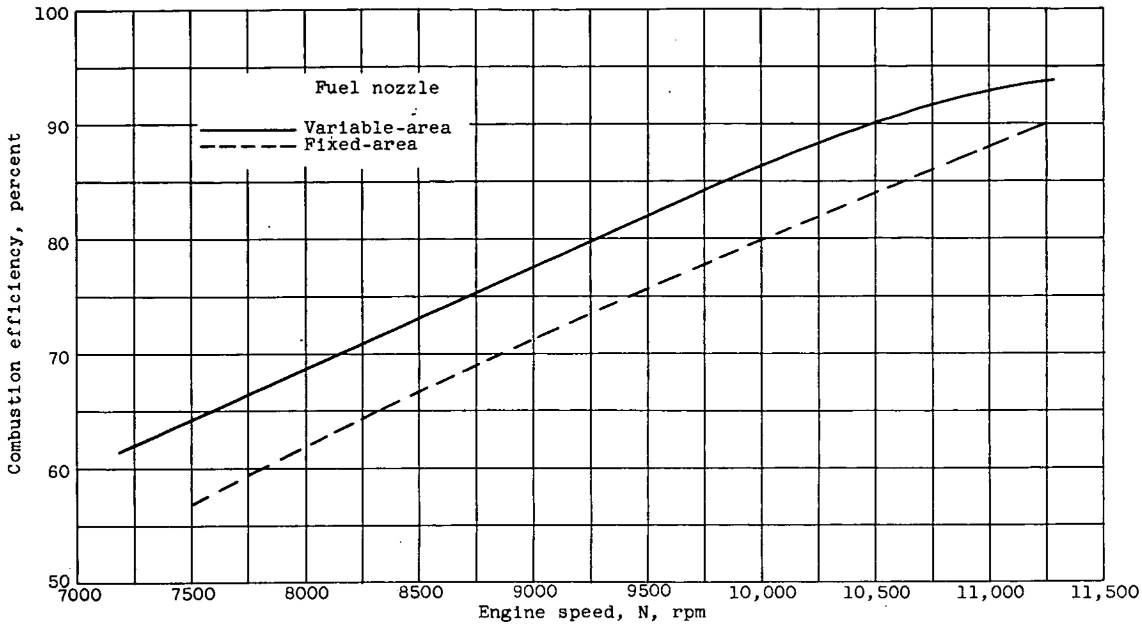


Figure 66. - Combustion efficiency of turbojet engine operating with variable-area or with fixed-area fuel nozzle. Ram pressure ratio, 1.00; altitude, 40,000 feet (ref. 12).

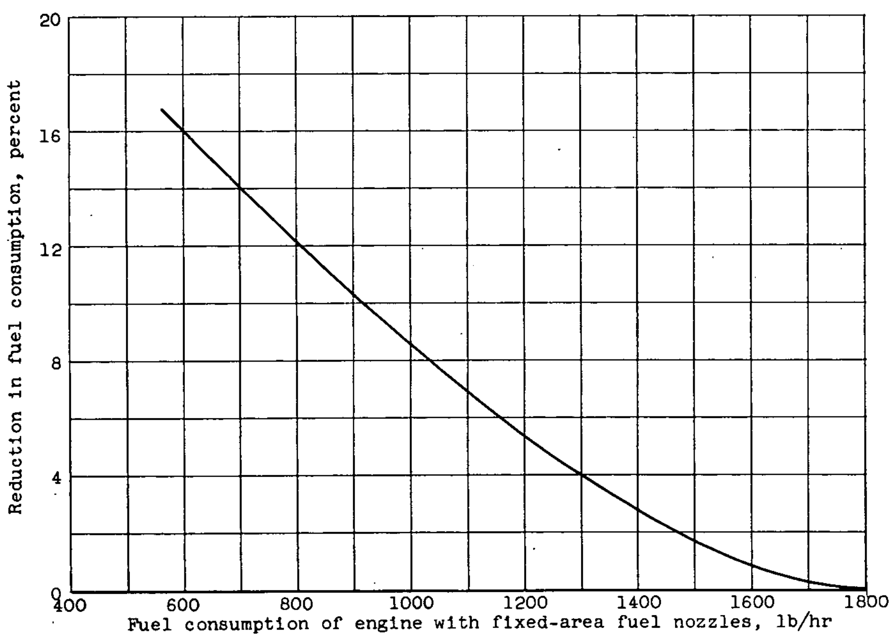
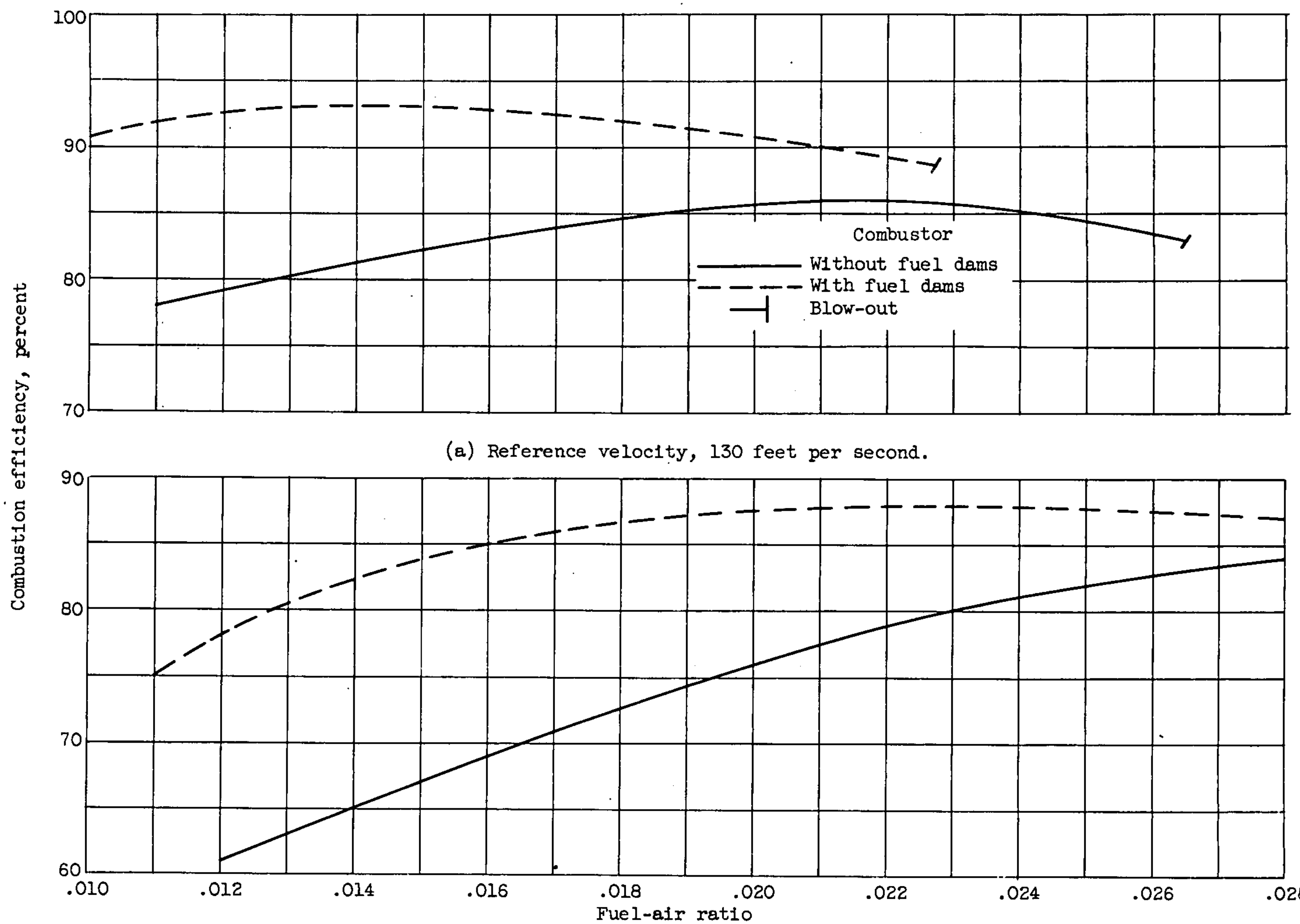


Figure 67. - Reduction in fuel consumption resulting from use of variable-area fuel nozzles in turbojet engine operating over range of altitudes, engine speeds and ram pressure ratios (ref. 12).



(a) Reference velocity, 130 feet per second.

(b) Reference velocity, 78 feet per second.

Figure 69. - Effect of fuel dams on combustion efficiency of single J33 combustor using 40-gallon-per-hour, 80°-spray-angle nozzle. Inlet-air pressure, 7.4 pounds per square inch absolute; inlet-air temperature, 728° R; fuel, MIL-F-5624A grade JP-4 (ref. 13).

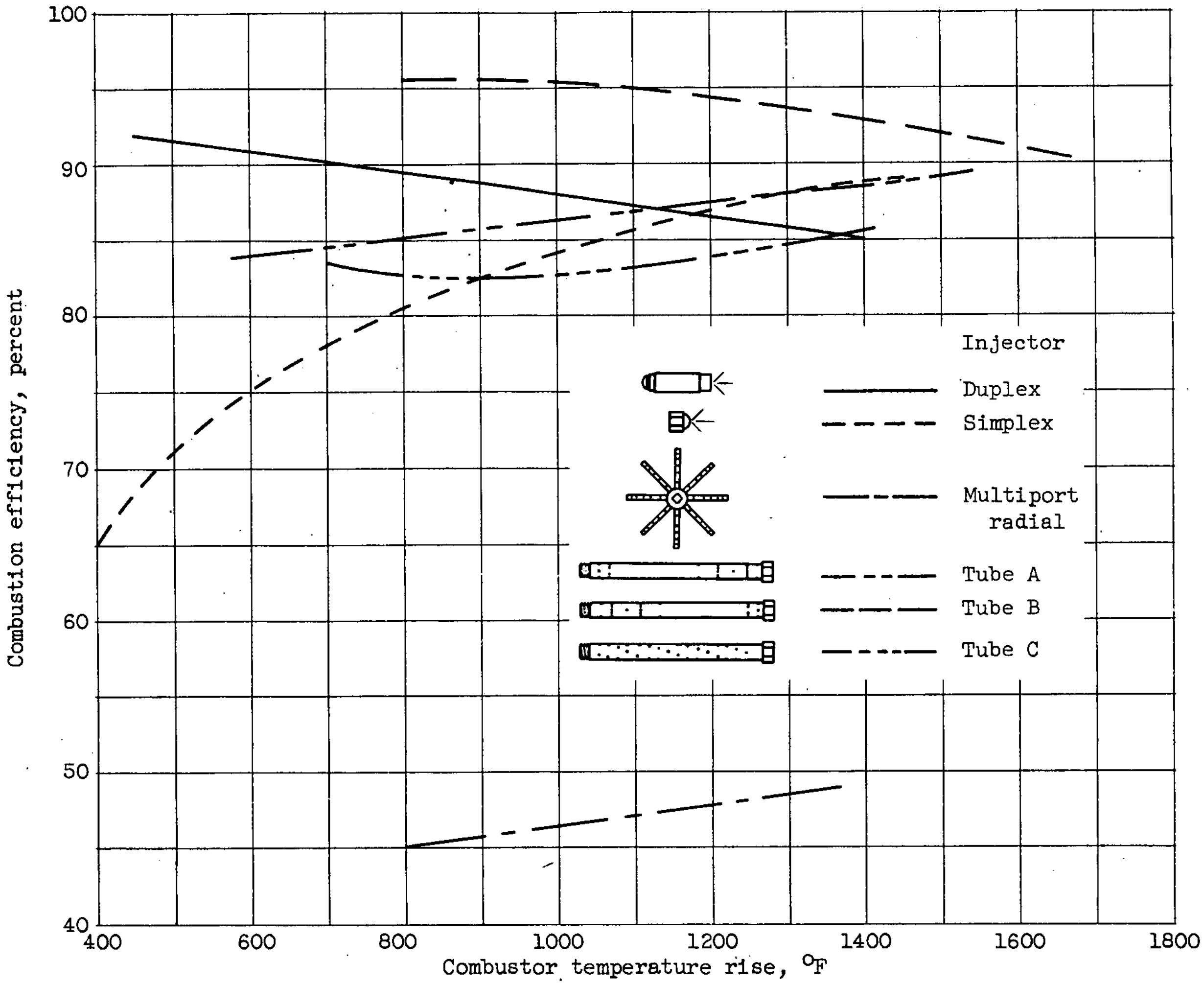
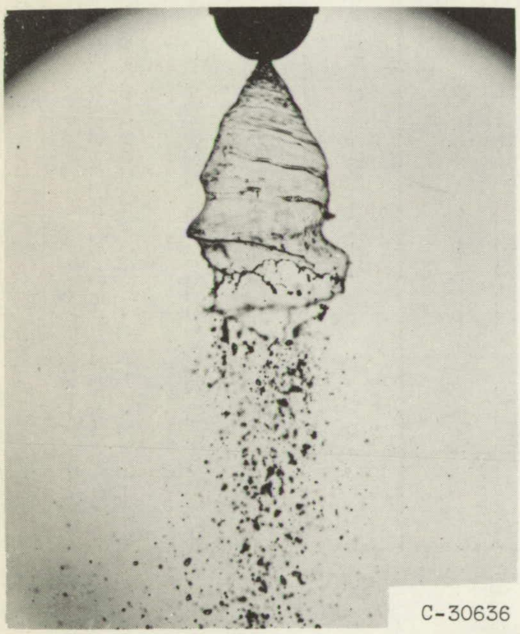
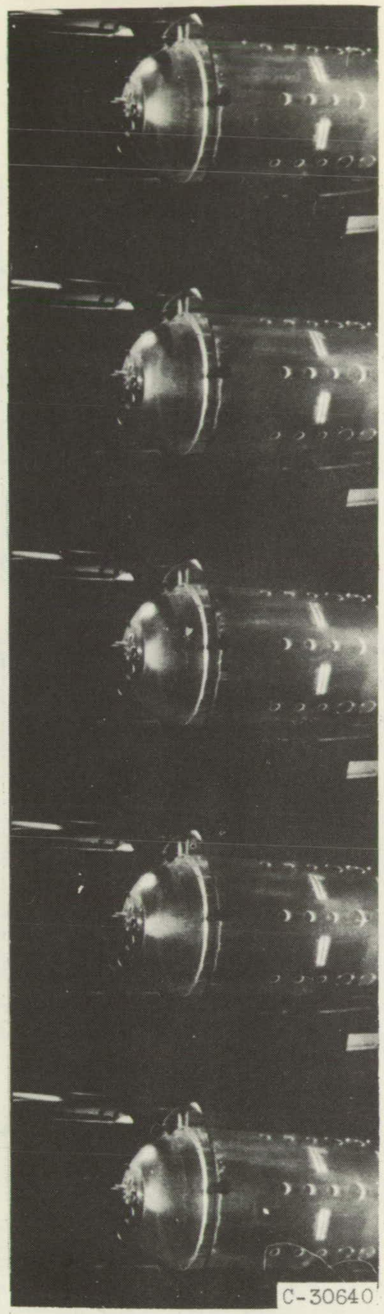


Figure 70. - Variation of combustion efficiency with combustor temperature rise obtained in single tubular combustor using different injectors. Inlet-air pressure, 8.3 pounds per square inch absolute; inlet-air temperature, 620° R; inlet-air velocity, 80 feet per second; fuel, MIL-F-5624A grade JP-3 (ref. 4).

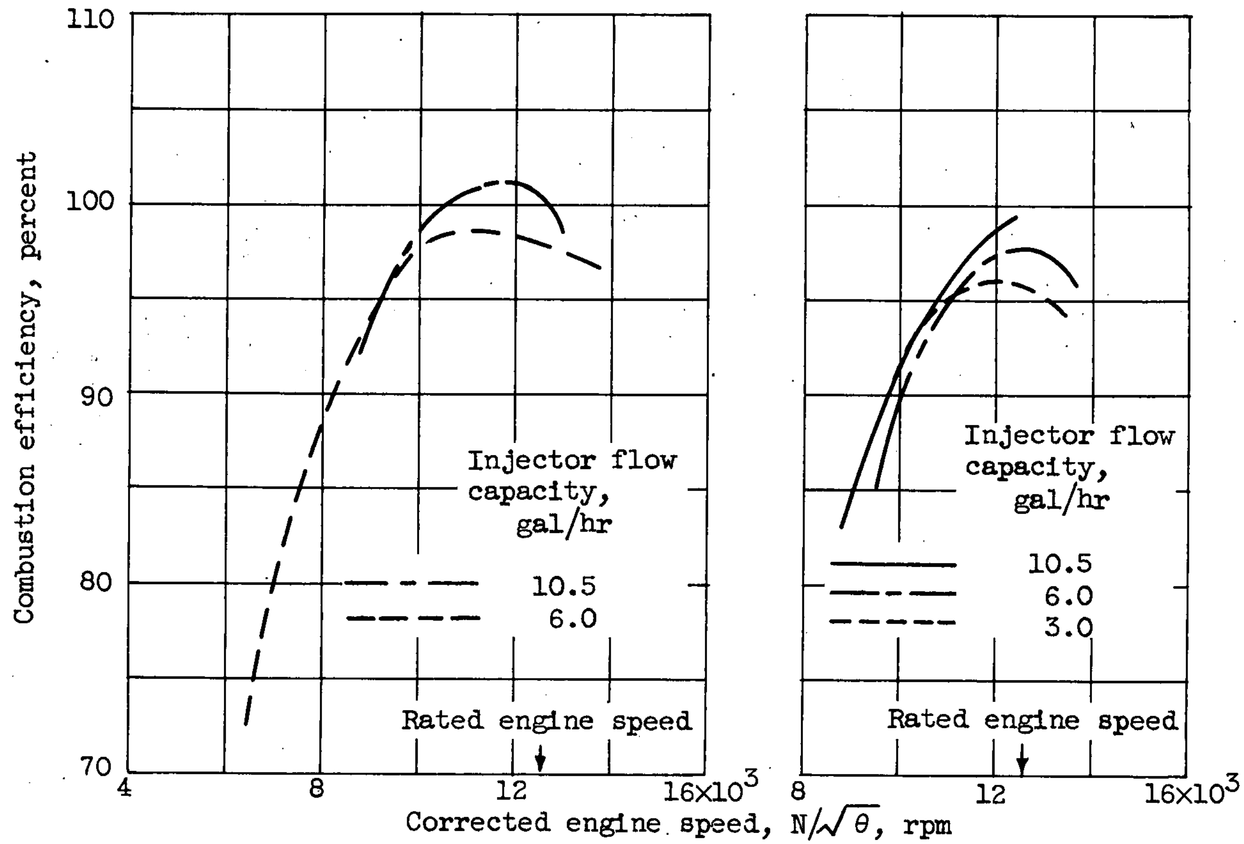


(a) Spray photograph in quiescent air. Fuel-flow rate, 40 pounds per hour.



(b) Spray photograph in turbojet combustor. Fuel-flow rate, 47 pounds per hour; air velocity, 80 feet per second.

Figure 71. - Photographs of fuel sprays in quiescent air and in nonburning tubular turbojet combustor. Inlet-air pressure, 12.8 pounds per square inch absolute; inlet-air temperature, 510° R; 40-gallon-per-hour, 80°-spray cone; fixed-area nozzle (ref. 14).



(a) Altitude, 30,000 feet. (b) Altitude, 40,000 feet.

Figure 72. - Effect of fuel-nozzle size on combustion efficiency of experimental single-annular combustor. Flight Mach number, 0.60 (ref. 9).

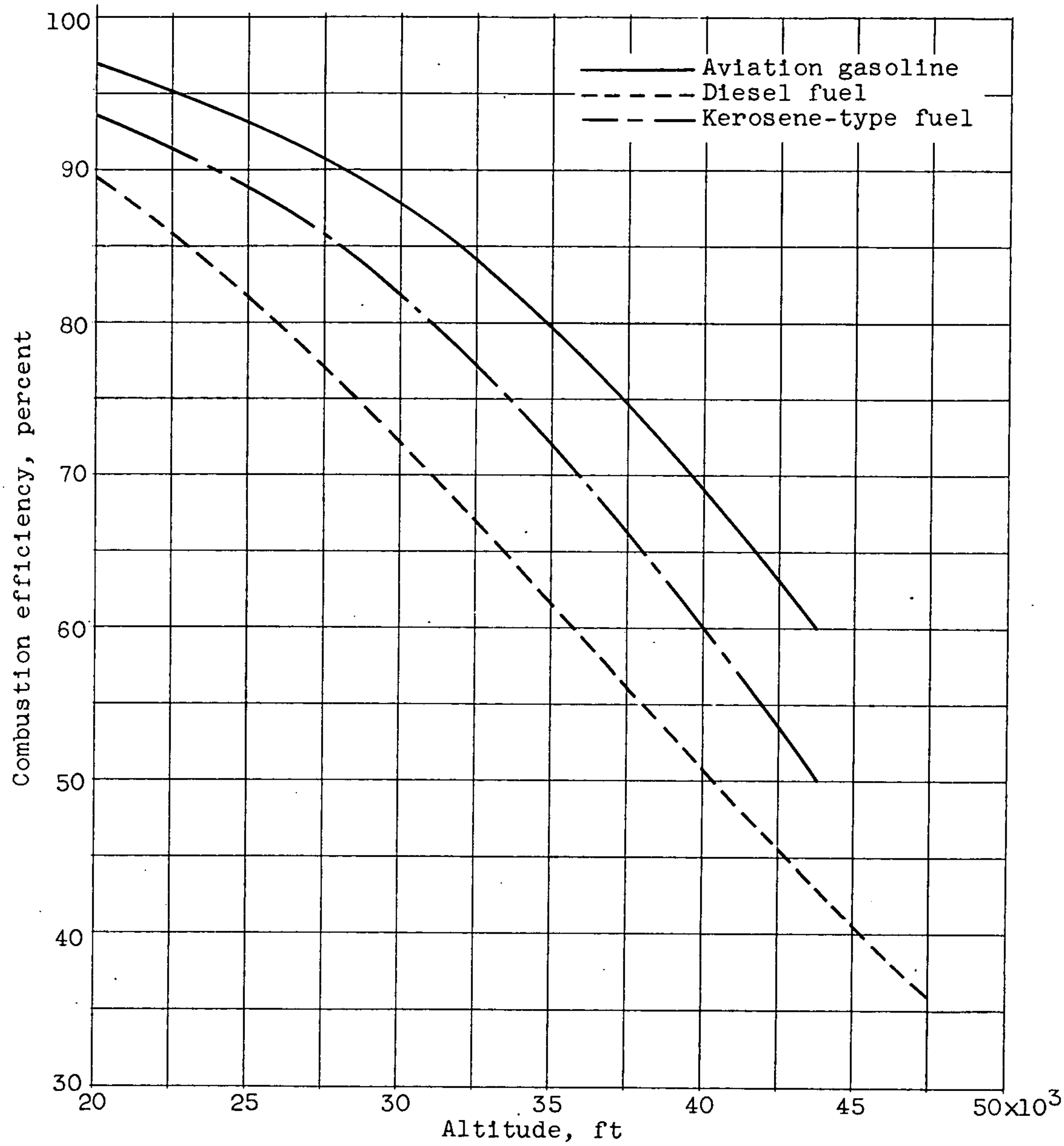


Figure 73. - Variation of combustion efficiency with altitude for three fuels of different volatility in annular combustor. Simulated compressor pressure ratio, 4; engine speed, 80 percent of rated; flight Mach number, 0.0 (ref. 10).

[redacted]

3080

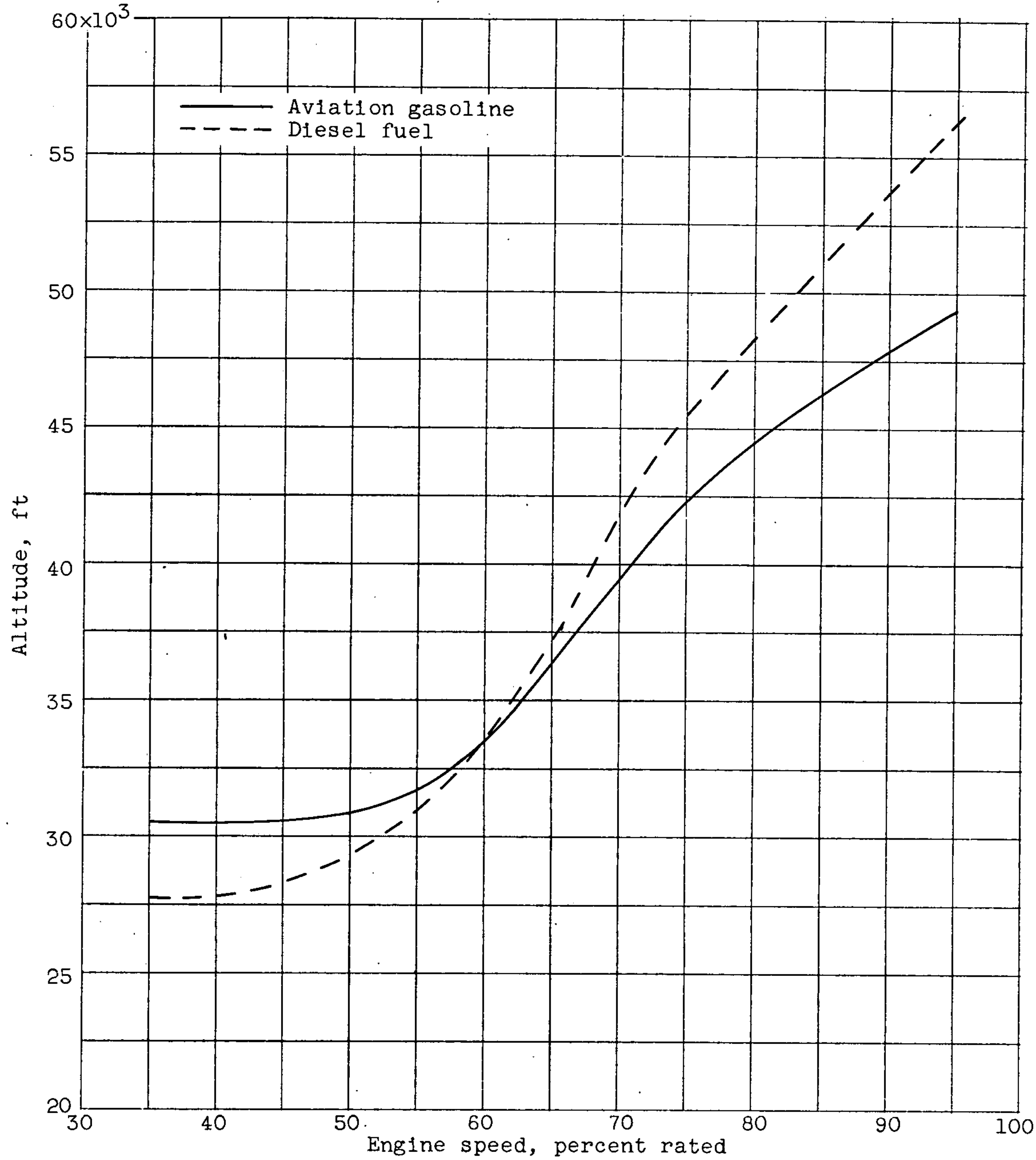
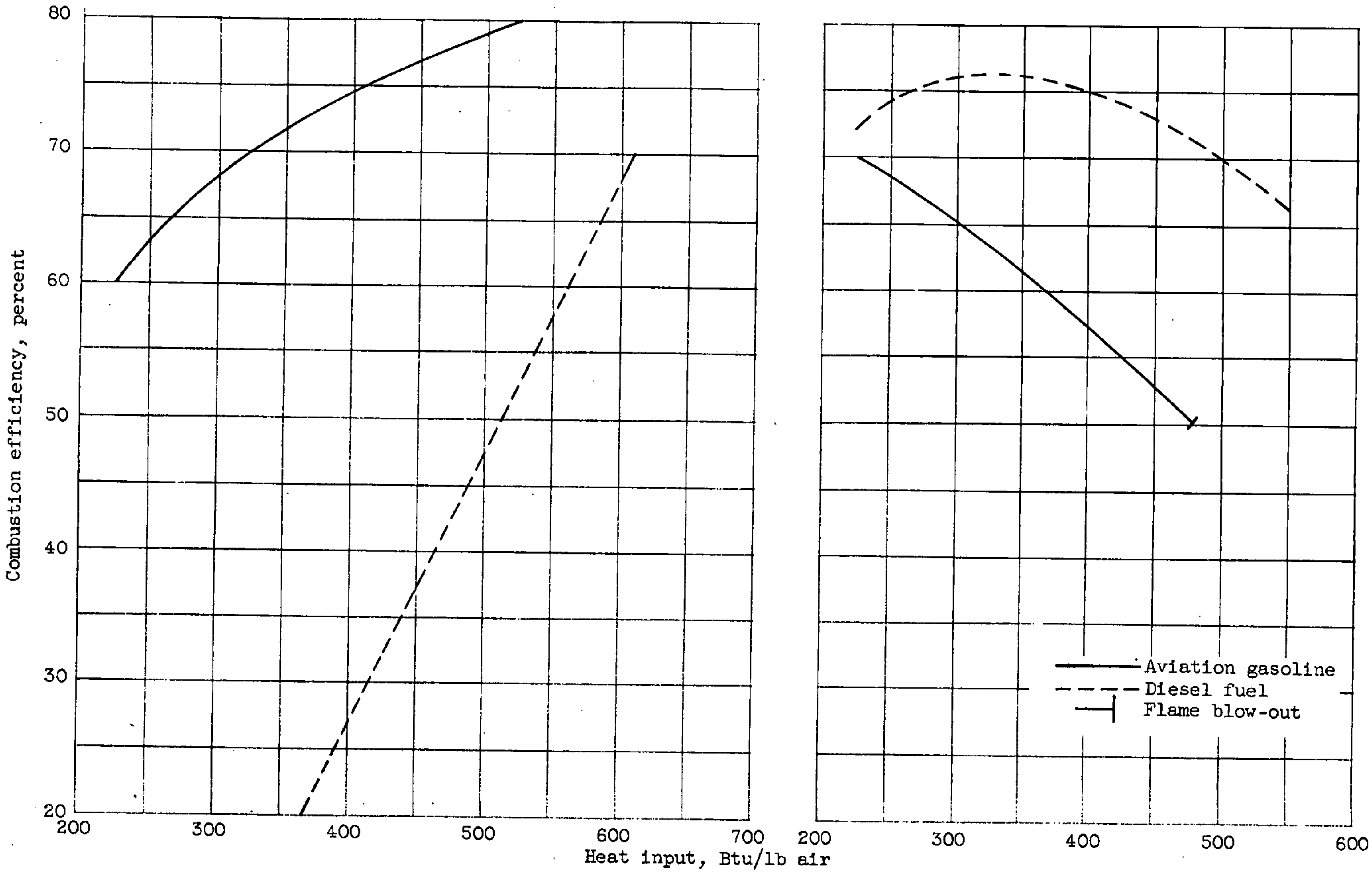


Figure 74. - Comparison of altitude operational limits for two fuels in annular turbojet combustor. Simulated compressor pressure ratio, 4; flight Mach number, 0.0 (ref. 10).

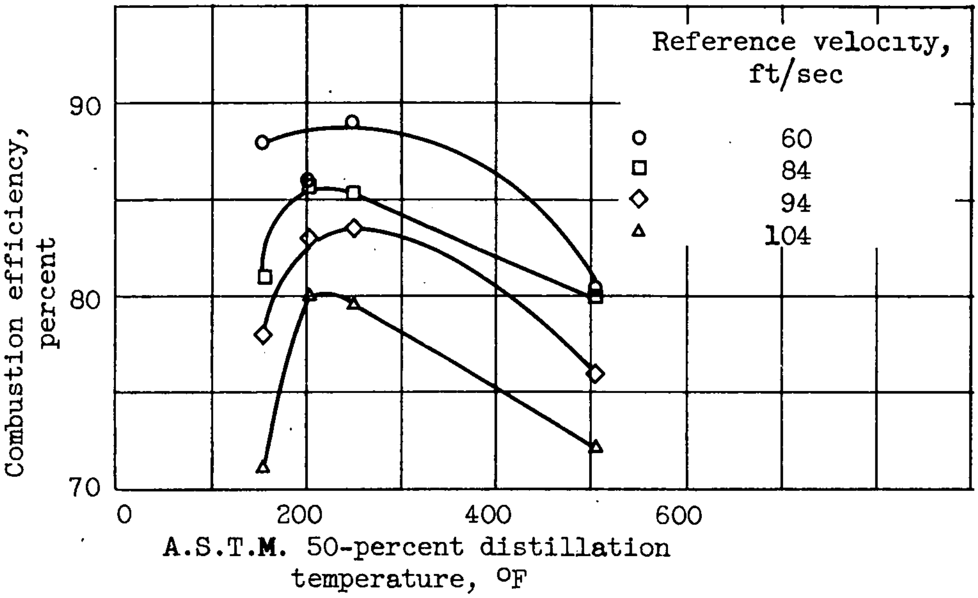
[redacted]



(a) 17.5-Gallon-per-hour nozzle.

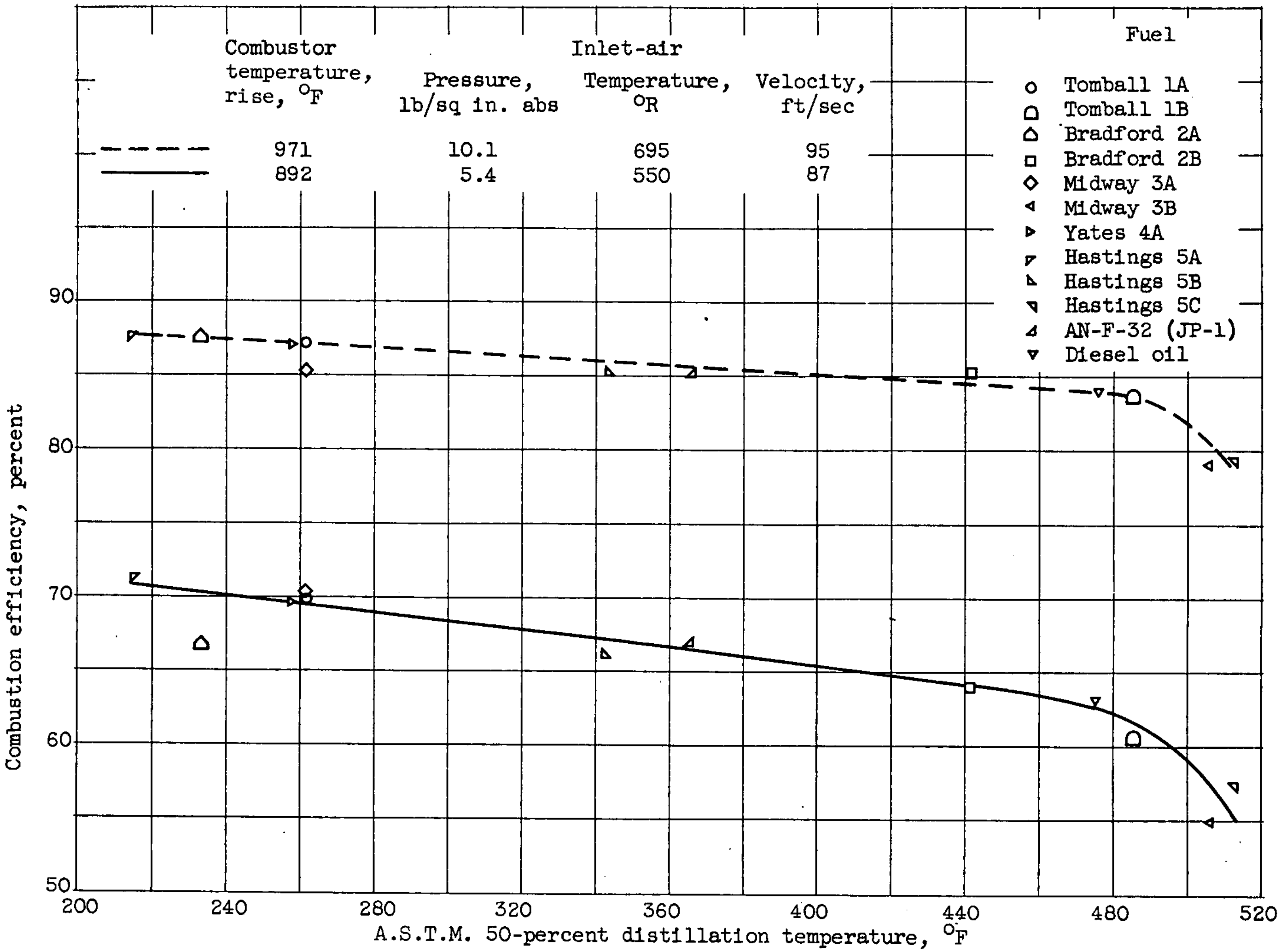
(b) 3.0-Gallon-per-hour nozzle.

Figure 75. - Effect of fuel volatility characteristics of two fuels on combustion efficiency. Inlet-air pressure, 9.2 pounds per square inch absolute; inlet-air temperature, 700° R; reference velocity, 80 feet per second (ref. 10).



(a) Relatively pure straight-chain hydrocarbon fuels. Inlet-air pressure, 7 pounds per square inch absolute; inlet-air temperature, 500° R.

Figure 76. - Effect of fuel volatility on combustion efficiency in tubular turbojet combustor.



(b) Mixed hydrocarbon fuels (ref. 16).

Figure 76. - Concluded. Effect of fuel volatility on combustion efficiency in tubular turbojet combustor.

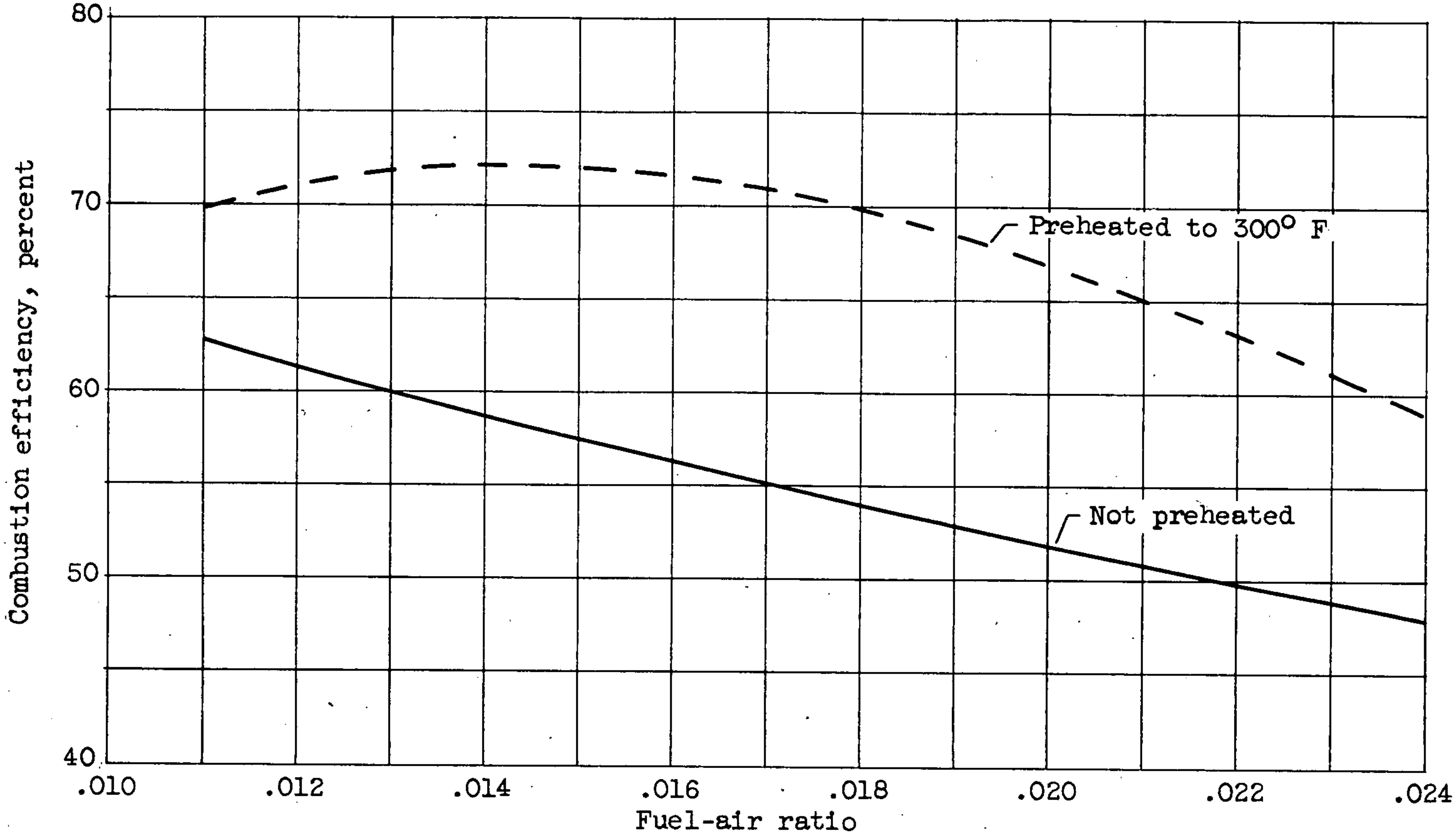


Figure 77. - Effect of preheating JP-4 fuel on combustion efficiency in experimental turbojet combustor. Combustor-inlet total pressure, 2.5 pounds per square inch absolute; combustor-inlet total temperature, 728° R; reference velocity, 103 feet per second (ref. 17).

3080

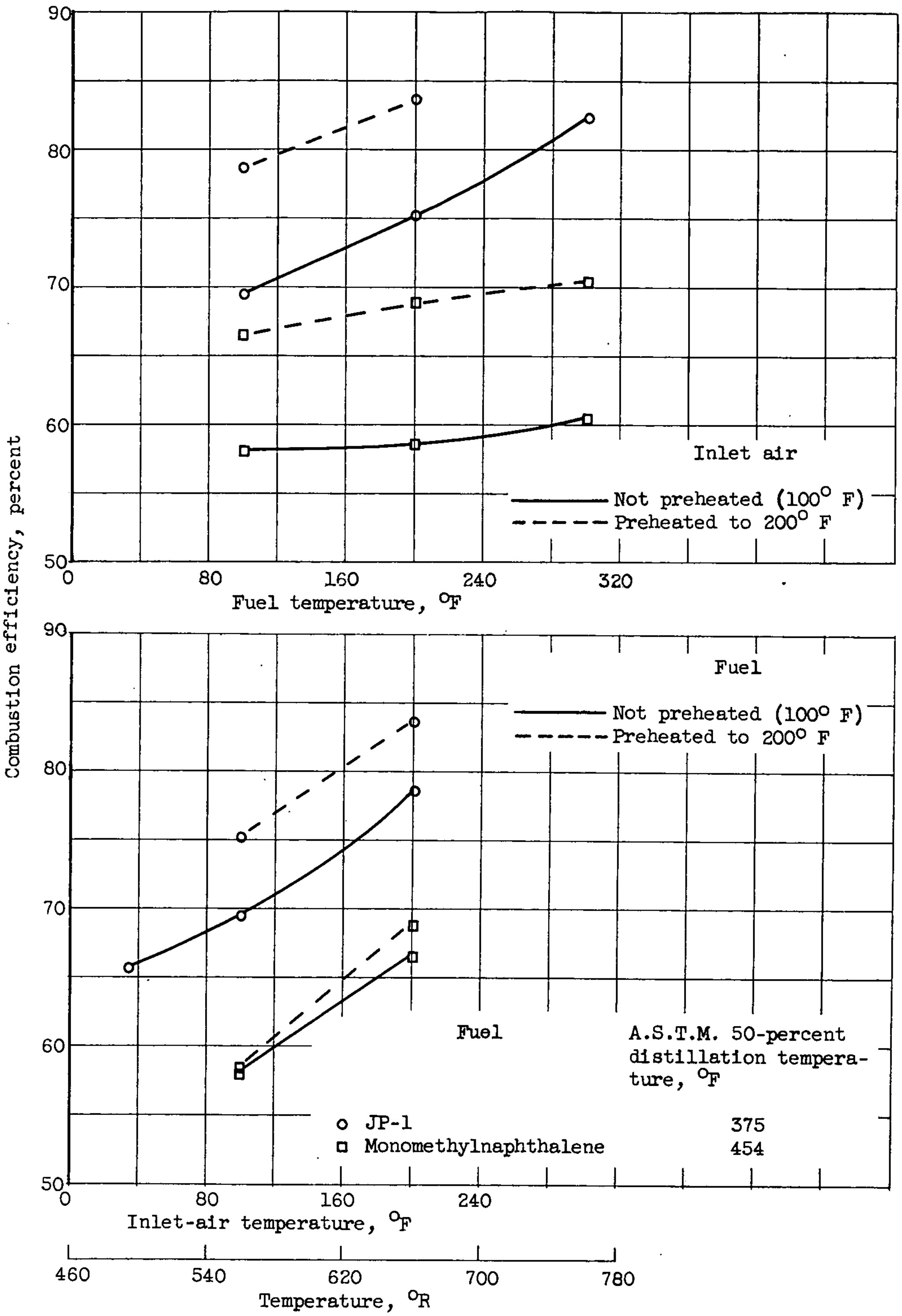
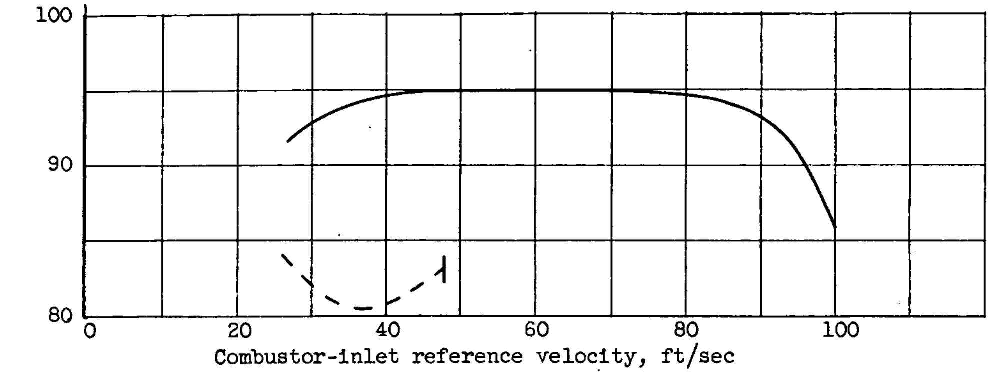


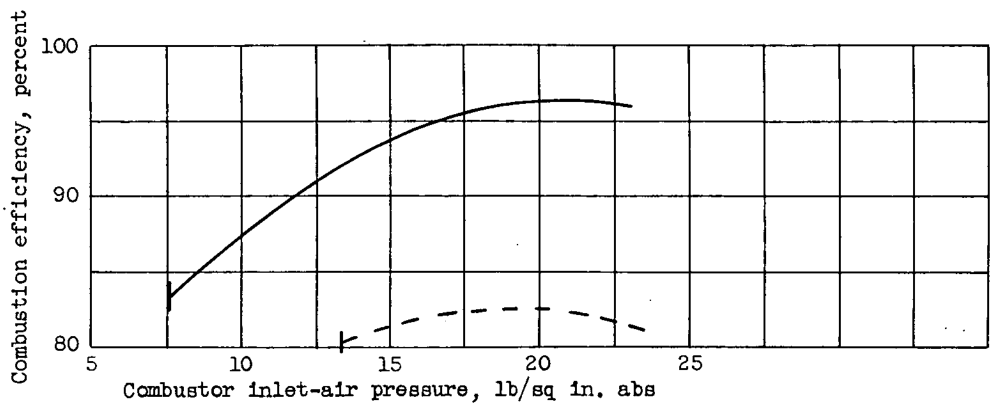
Figure 78. - Effect of fuel and inlet-air temperatures on combustion efficiency of two fuels in tubular turbojet combustor. Combustor inlet-air pressure, 10 pounds per square inch absolute; air-flow rate, 4000 pounds per hour; heat-input rate, 240 Btu per pound of air.

[redacted]

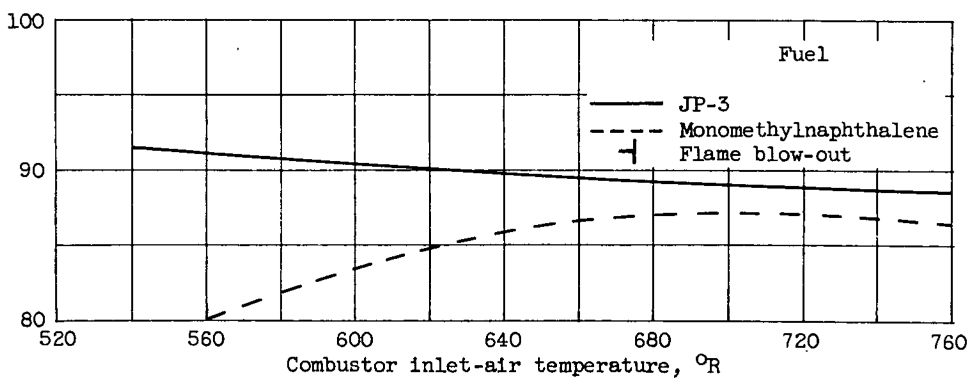
3080



(a) Effect of combustor-inlet reference velocity. Inlet-air pressure, 15 pounds per square inch absolute; inlet-air temperature, 620° R.



(b) Effect of combustor inlet-air pressure. Inlet-air temperature, 620° R; reference velocity, 45 feet per second.



(c) Effect of combustor inlet-air temperature. Inlet-air pressure, 15 pounds per square inch absolute; reference velocity, 45 feet per second.

Figure 79. - Effect of operating variables on combustion efficiency of two fuels in tubular vaporizing combustor. Heat input, 366 Btu per pound of air (ref. 21).

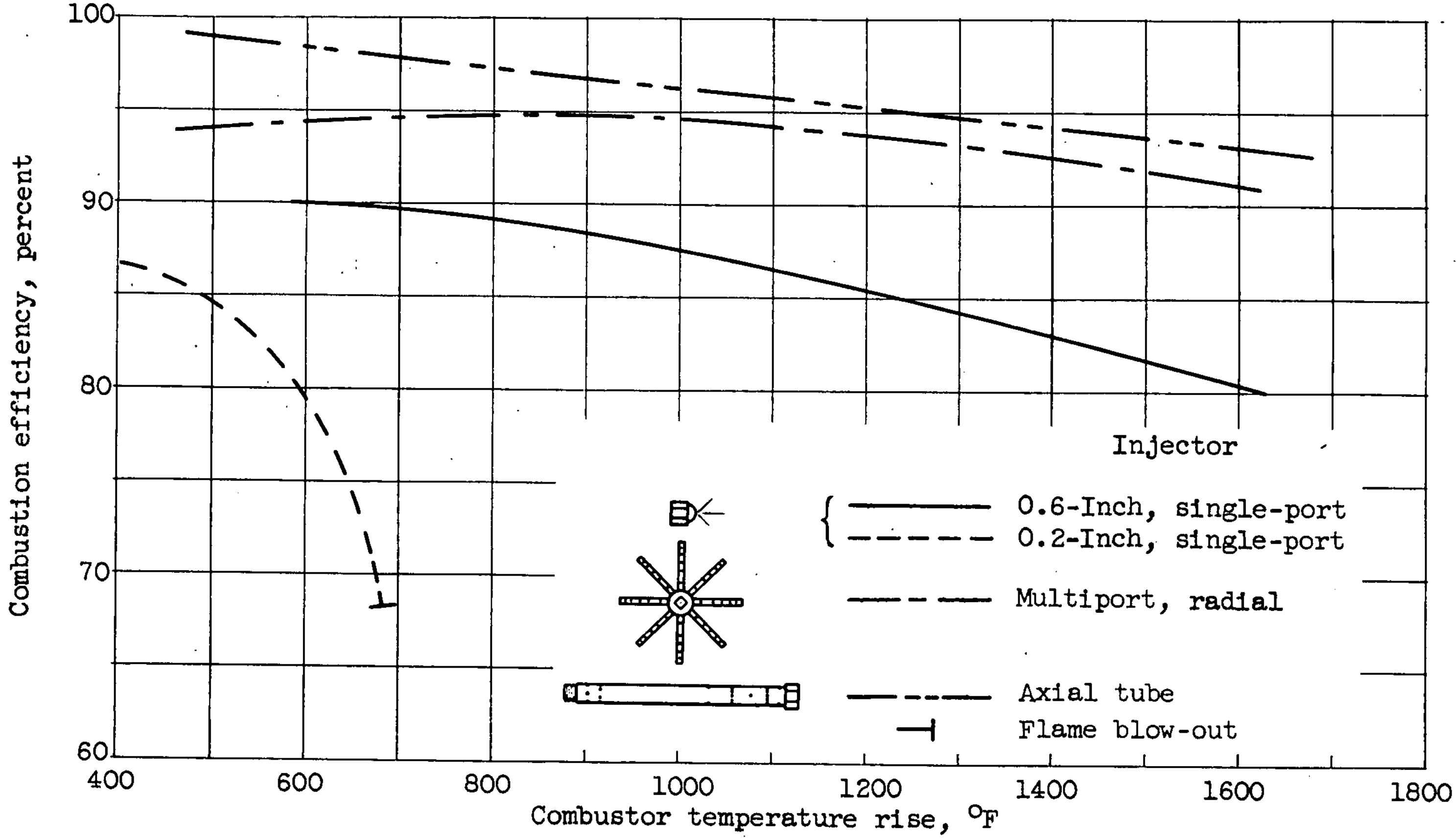


Figure 80. - Variation of combustion efficiency with combustor temperature rise obtained in single tubular combustor. Inlet-air pressure, 8.3 pounds per square inch absolute; inlet-air temperature, 620° R; inlet-air velocity, 80 feet per second; fuel, propane vapor (ref. 22).

3080

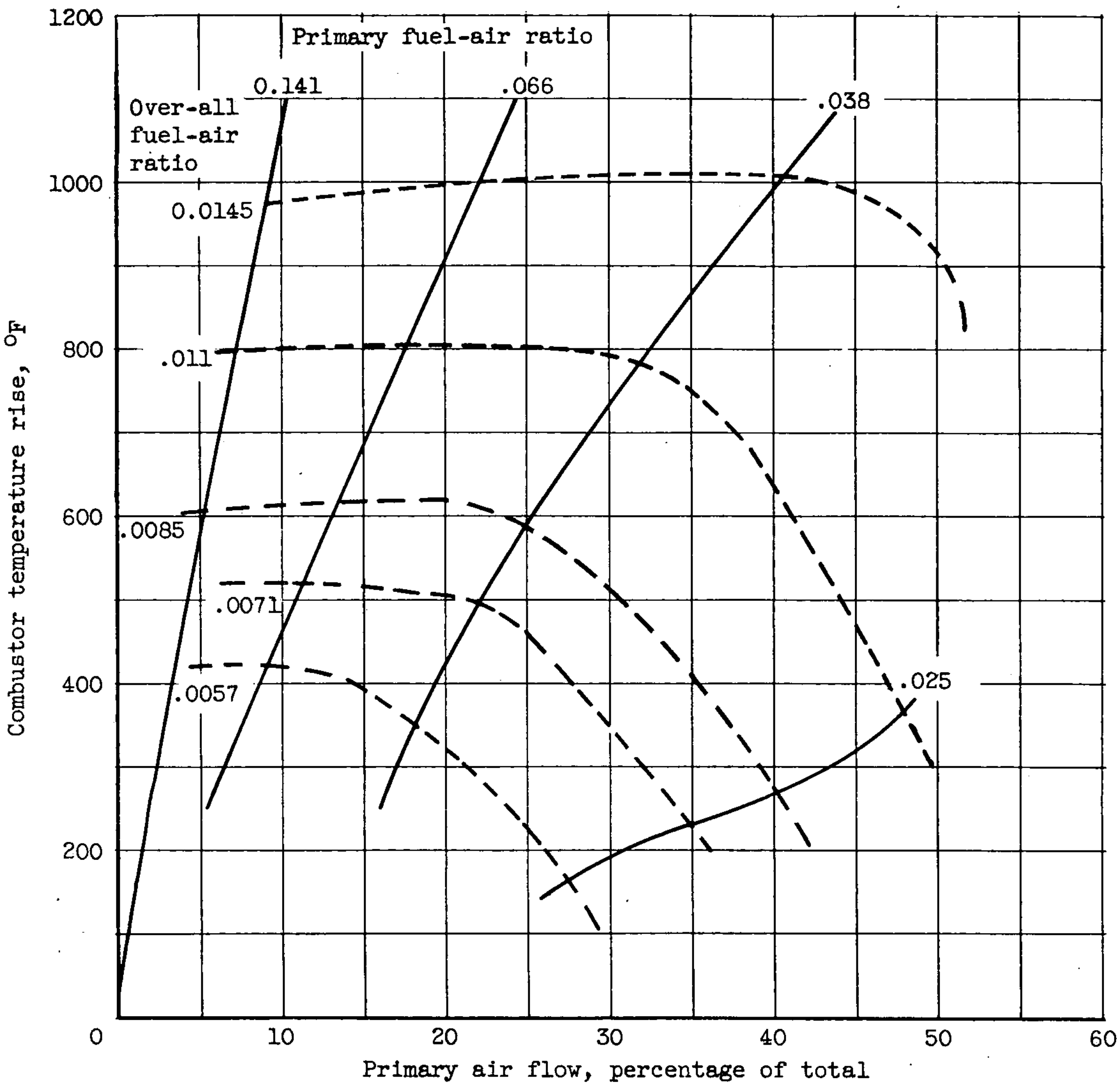


Figure 81. - Effect of varied air distribution on temperature rise obtained in single tubular combustor. Total air-flow rate, 2.36 pounds per second (ref. 24).

[redacted]

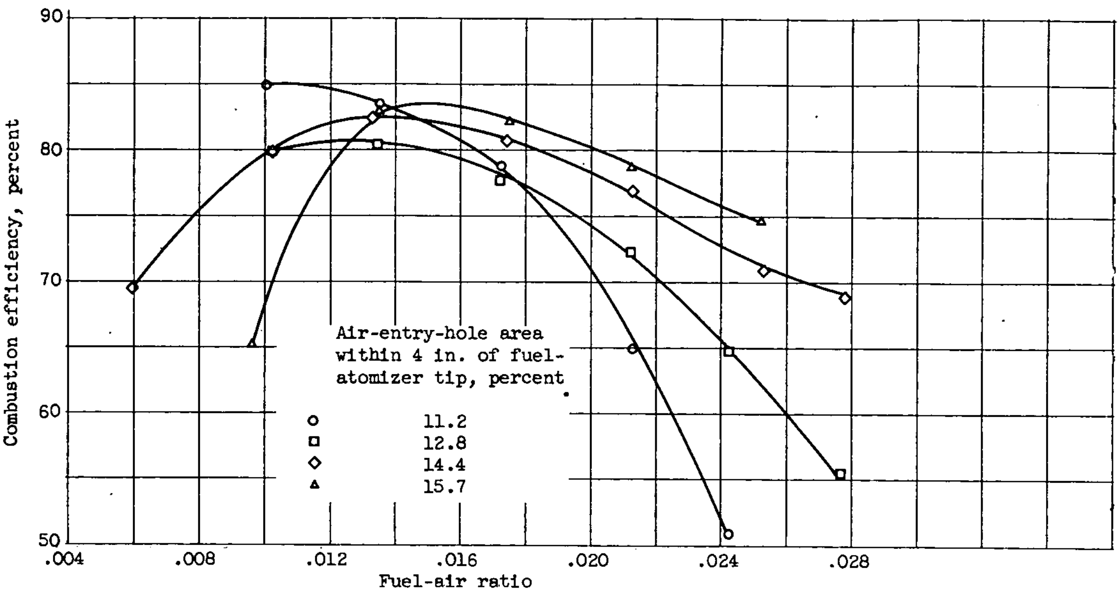


Figure 82. - Effect of variation in percent of total area of air-entry holes within 4 inches of plane of fuel-atomizer tip on combustion efficiency of 6.25-inch-diameter tubular combustor. Inlet-air pressure, 3.9 pounds per square inch absolute; inlet-air temperature, 728° R; reference velocity, 102 feet per second (ref. 25).

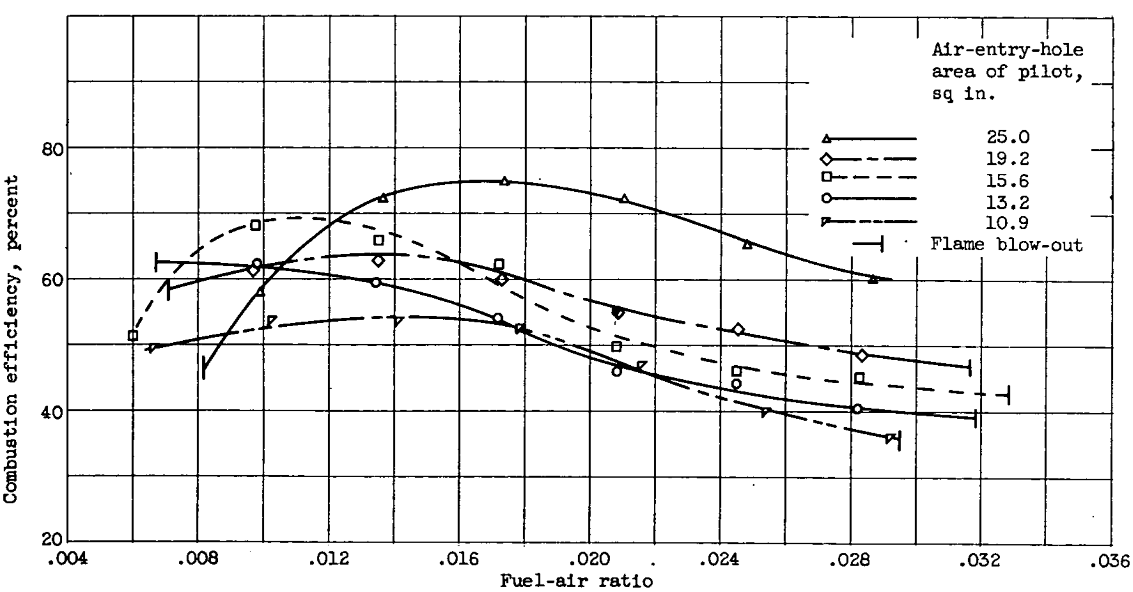
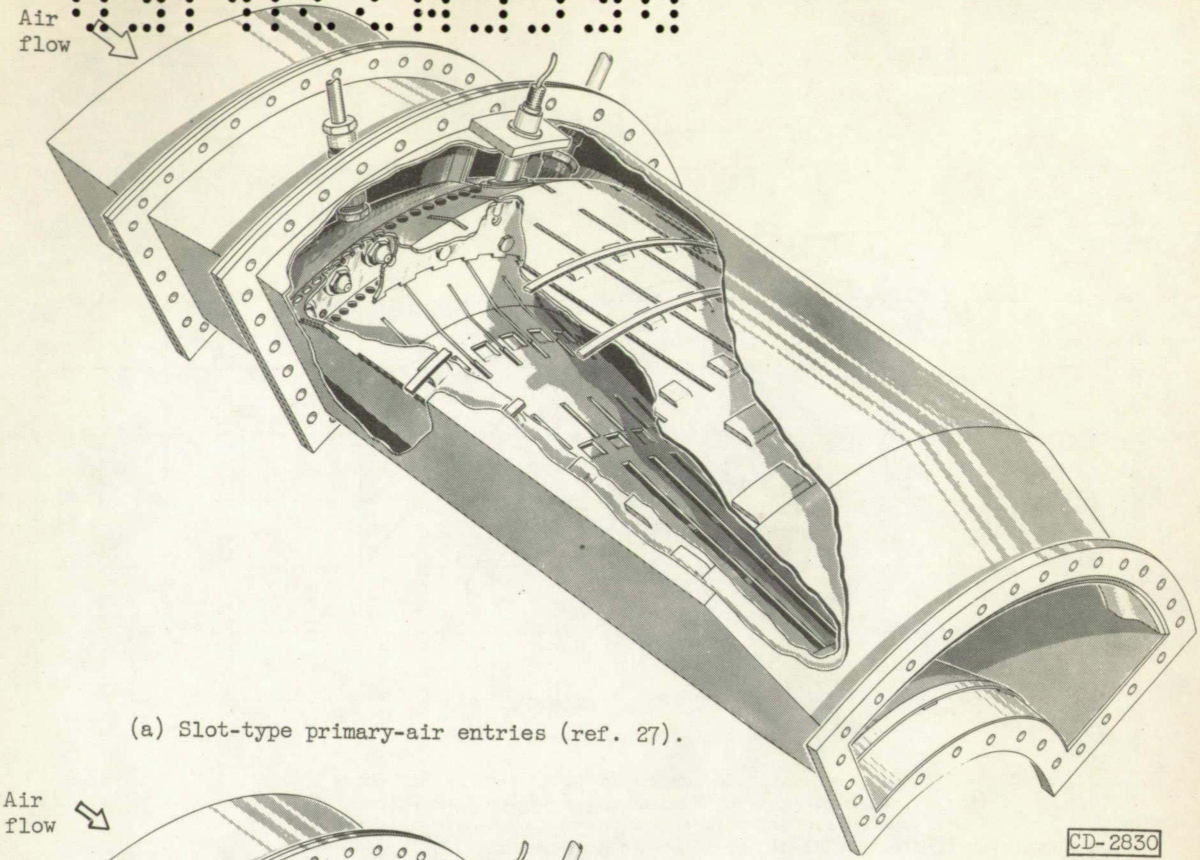
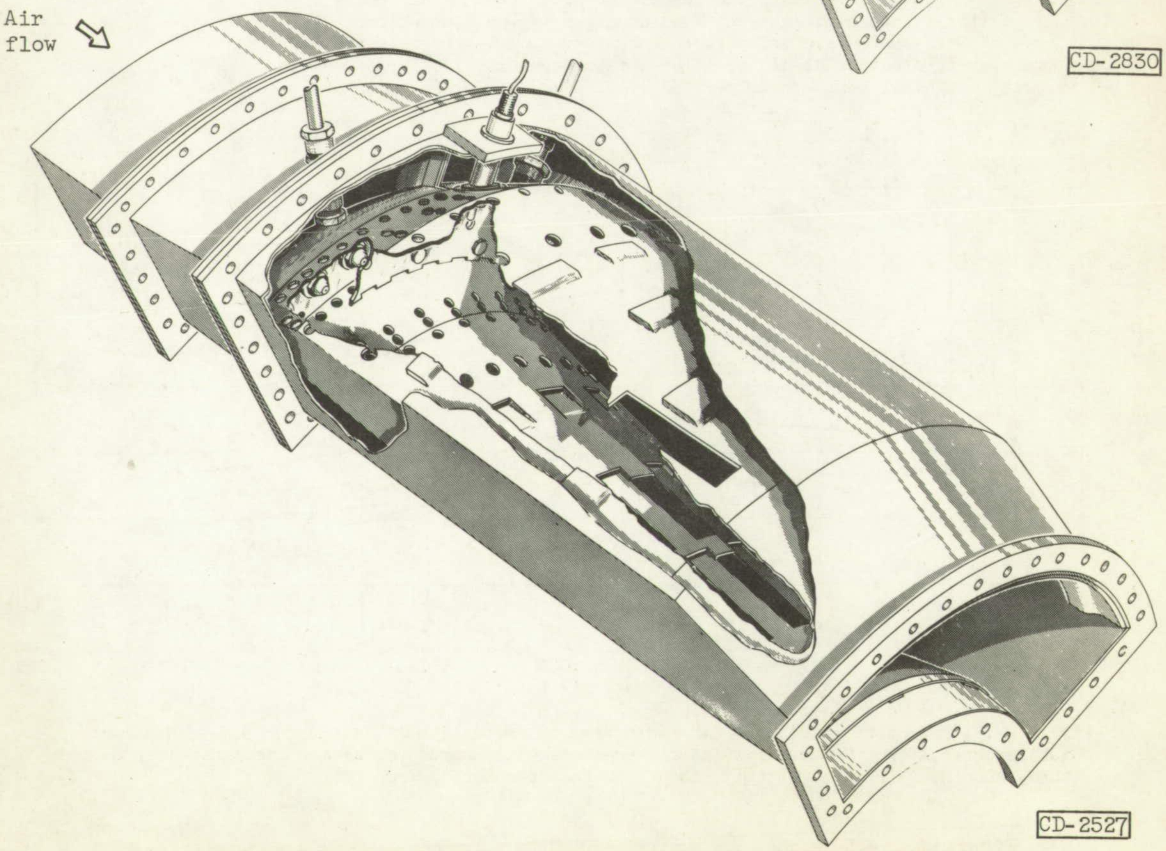


Figure 83. - Effect of pilot air-entry-hole area on combustion efficiency of 9.5-inch-diameter tubular combustor. Combustor inlet-air pressure, 3.9 pounds per square inch absolute; temperature, 695° R; reference velocity, about 100 feet per second (ref. 26).

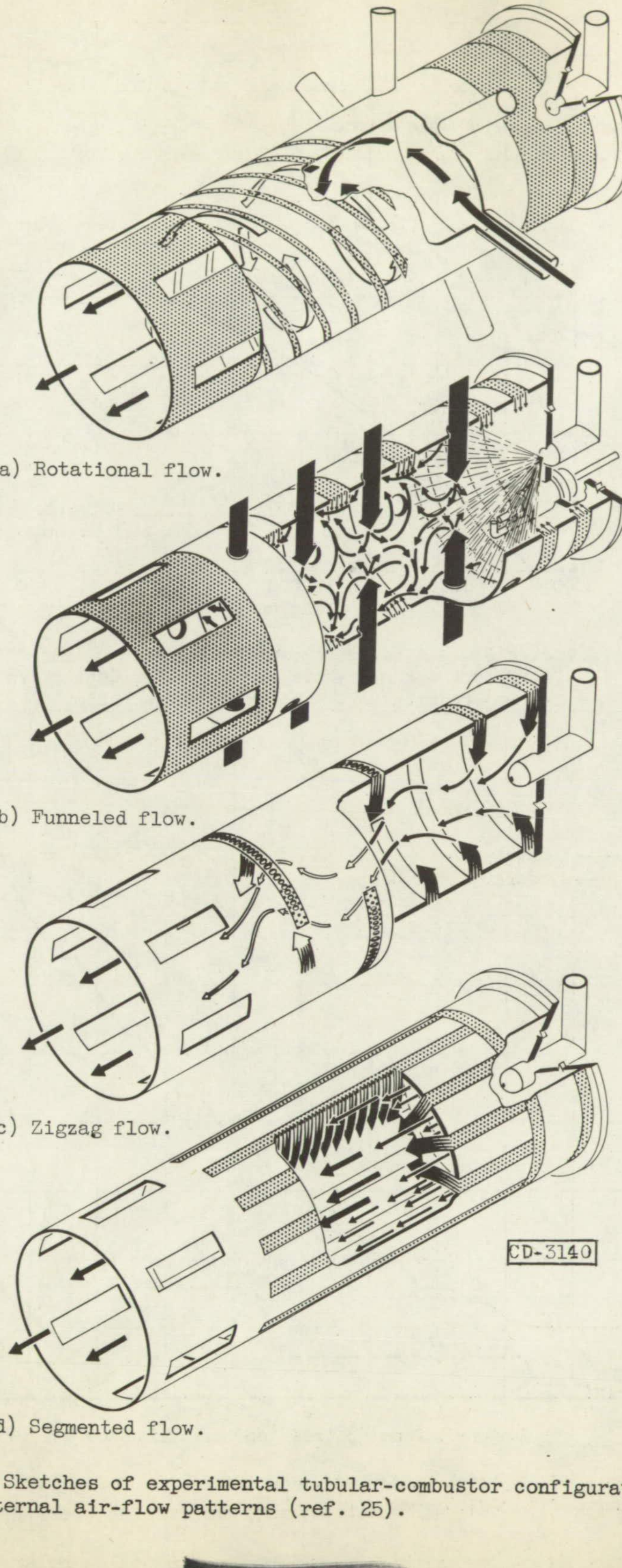


(a) Slot-type primary-air entries (ref. 27).



(b) Circular primary-air entries (ref. 17).

Figure 84. - One-quarter views of experimental annular combustors.



(a) Rotational flow.

(b) Funneled flow.

(c) Zigzag flow.

(d) Segmented flow.

Figure 85. - Sketches of experimental tubular-combustor configurations showing internal air-flow patterns (ref. 25).

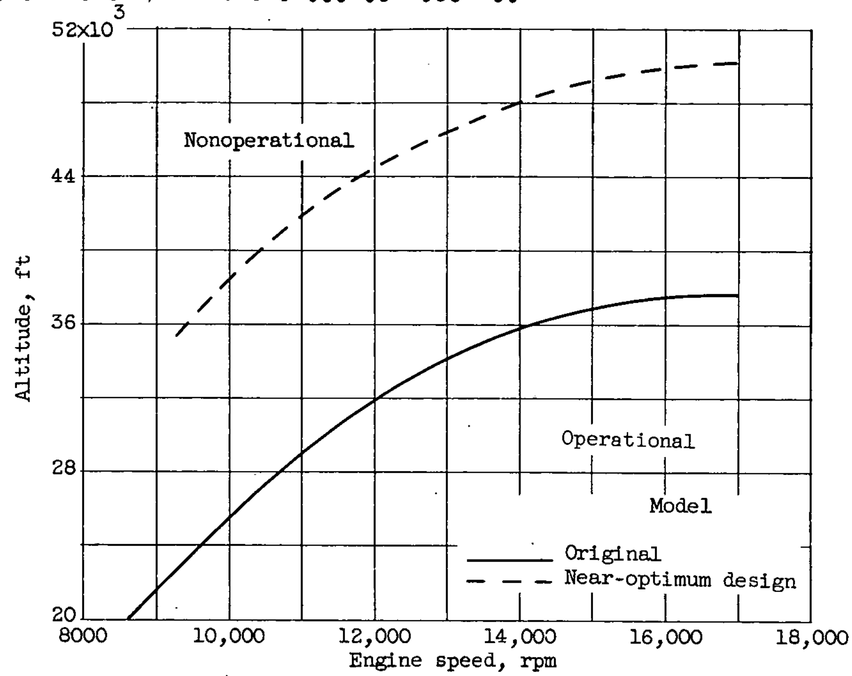


Figure 86. - Altitude operational limits obtained with two different circular-hole air admission designs in annular turbojet combustor. Engine pressure ratio, 4.

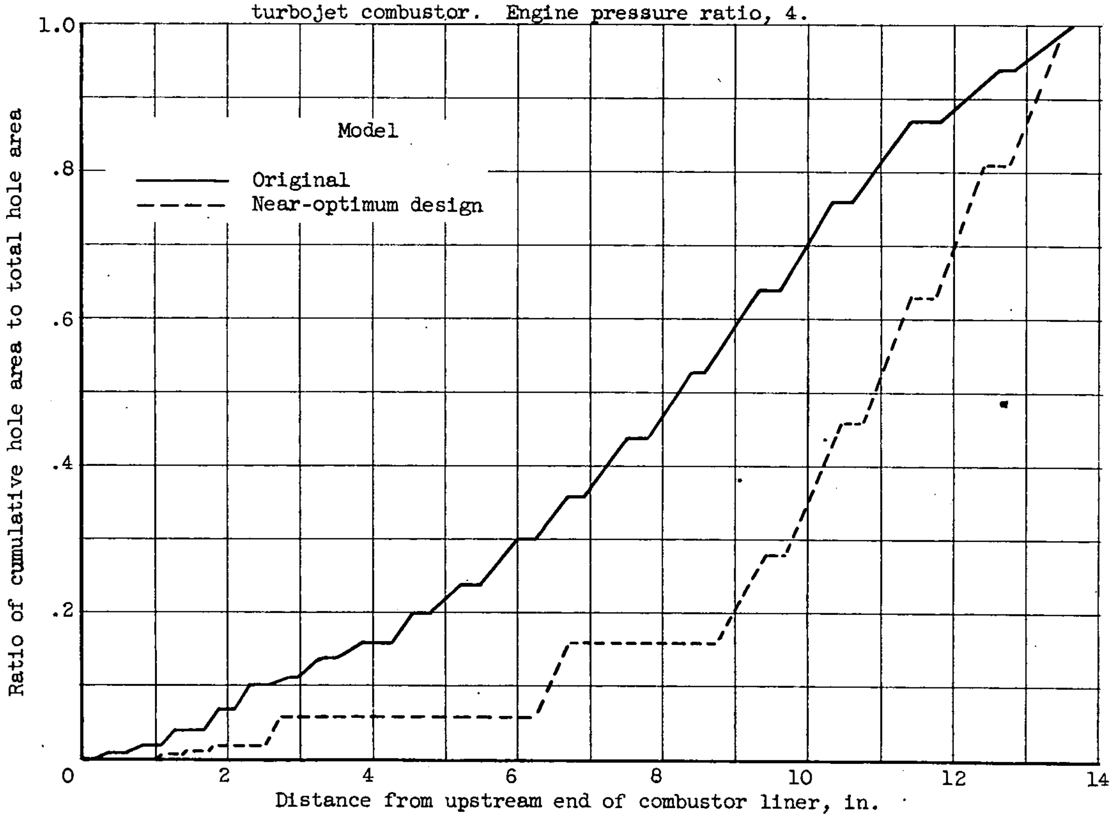


Figure 87. - Axial distribution of hole area in liners of two experimental annular turbojet combustors of figure 86.

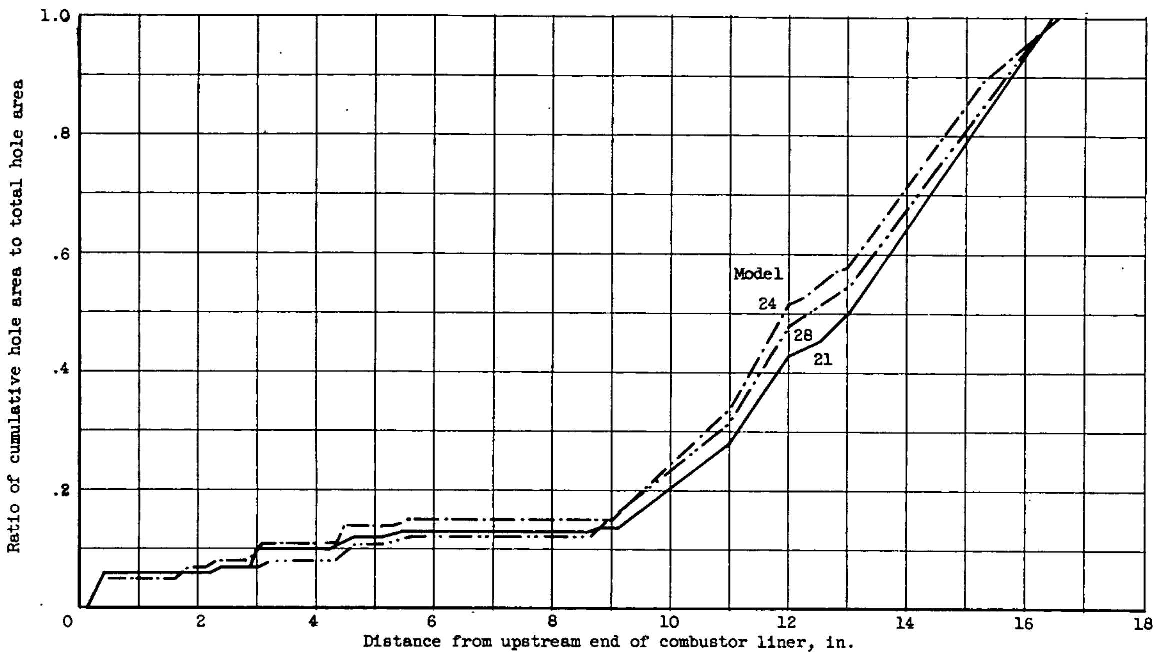


Figure 88. - Axial distribution of hole area in liners of three experimental annular turbojet combustors having similar patterns of circular holes for admission of primary air (ref. 28).

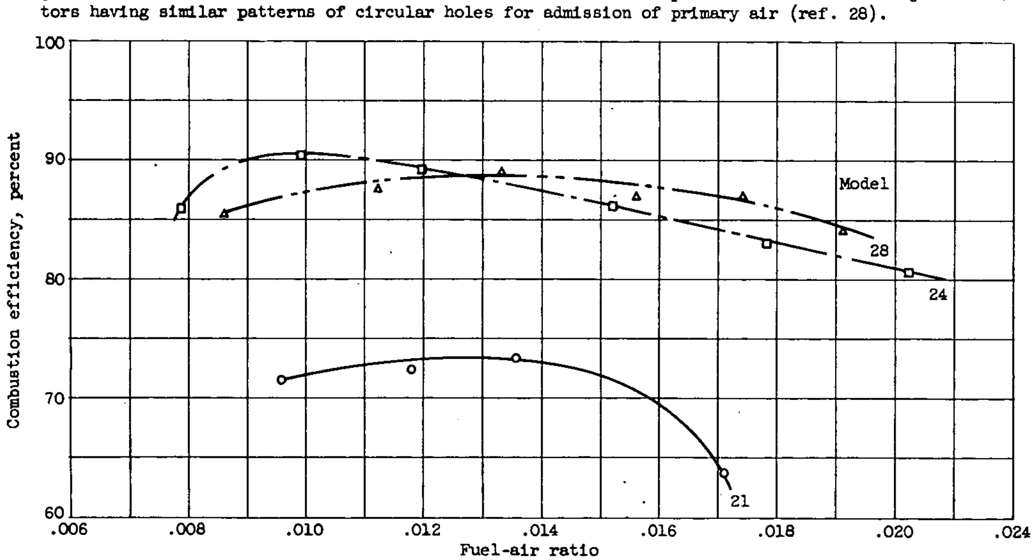


Figure 89. - Combustion efficiencies obtained with three annular turbojet combustor configurations of figure 88. Combustor inlet-air pressure, 2.5 pounds per square inch absolute; inlet-air temperature, 728° R; reference velocity, 80 feet per second (ref. 28).

[redacted]

[redacted]

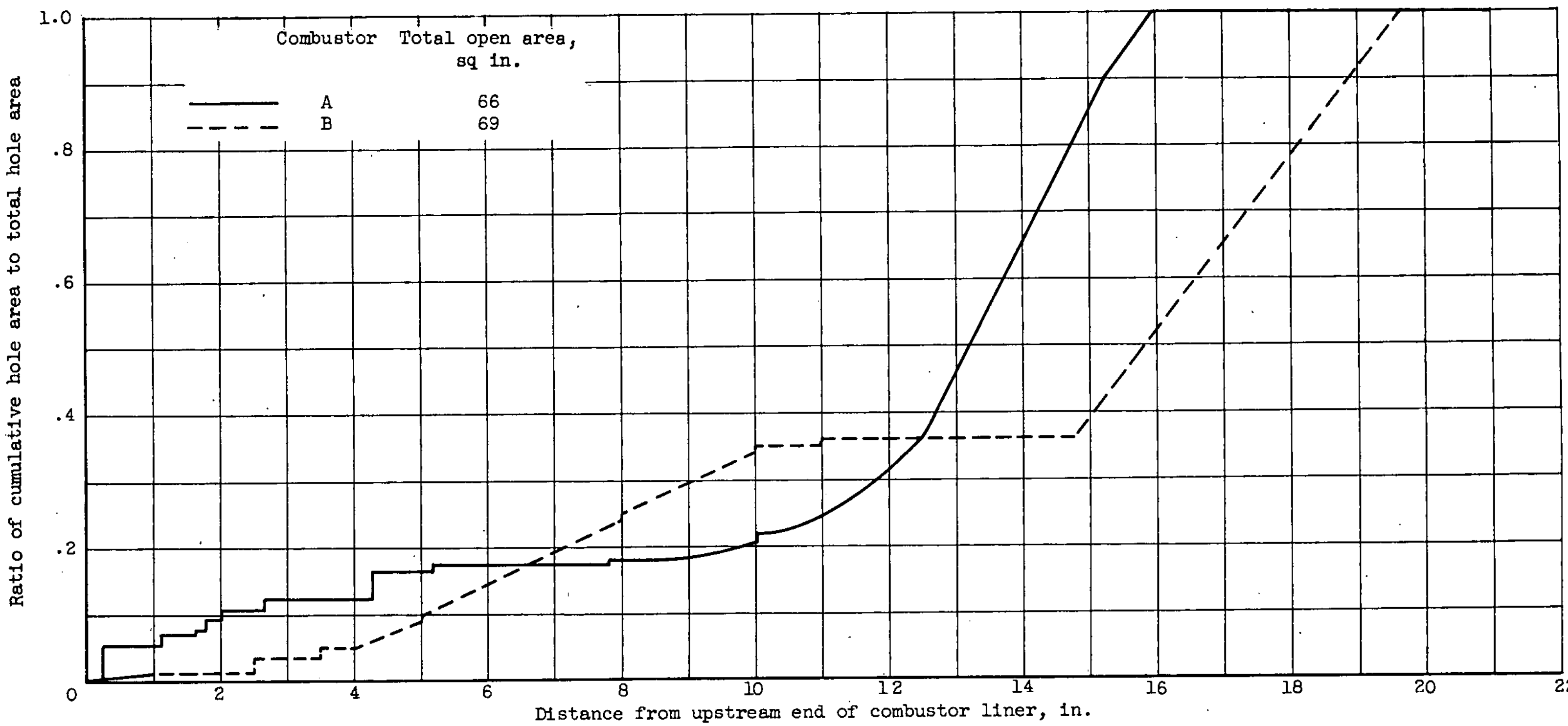


Figure 90. - Axial distribution of hole area in liners of two experimental annular turbojet combustors having dissimilar primary-air-admission designs (ref. 29).

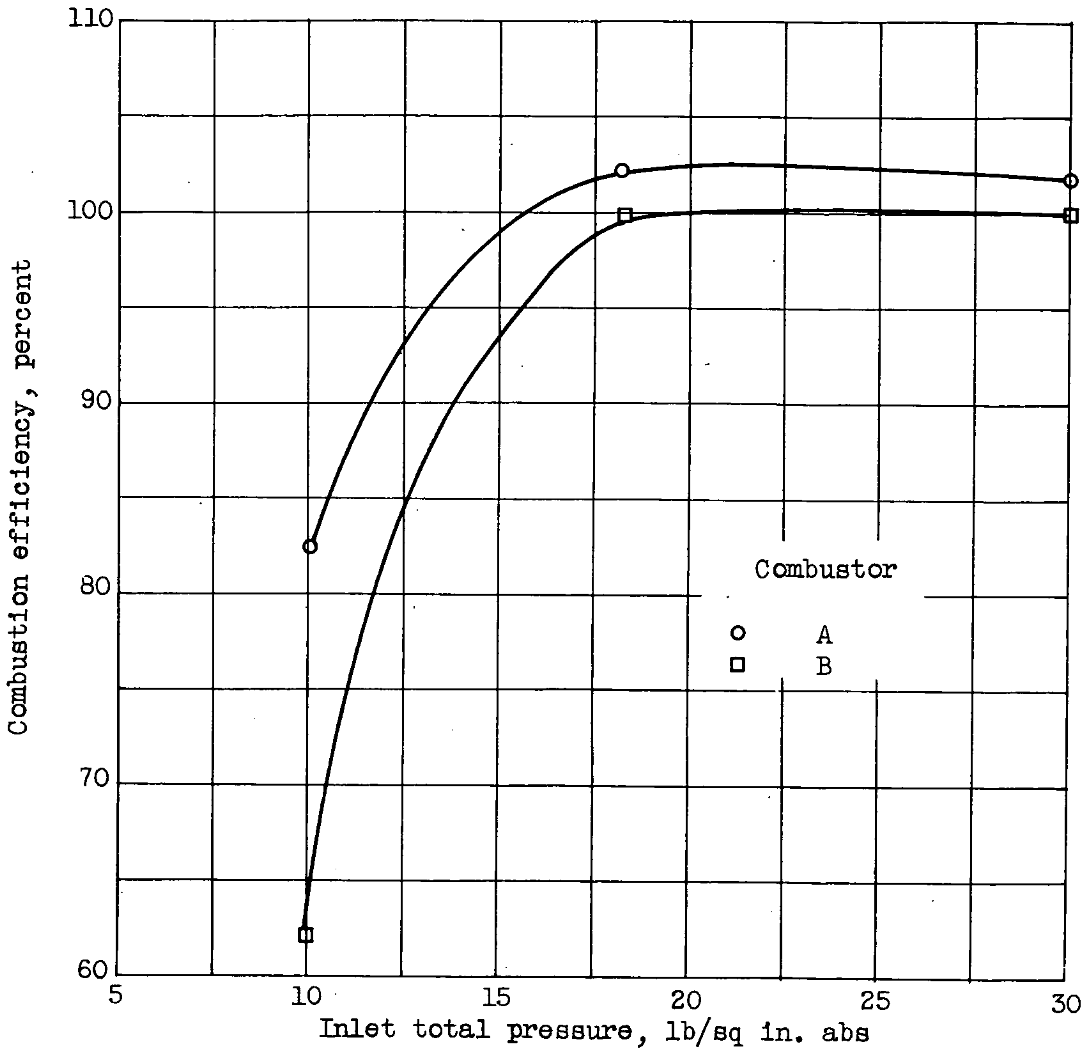


Figure 91. - Effect of pressure on combustion efficiency of two experimental annular turbojet combustors of figure 90. Inlet-air temperature, 1330° R; average outlet temperature, 2260° R; reference velocity, 165 feet per second (ref. 29).

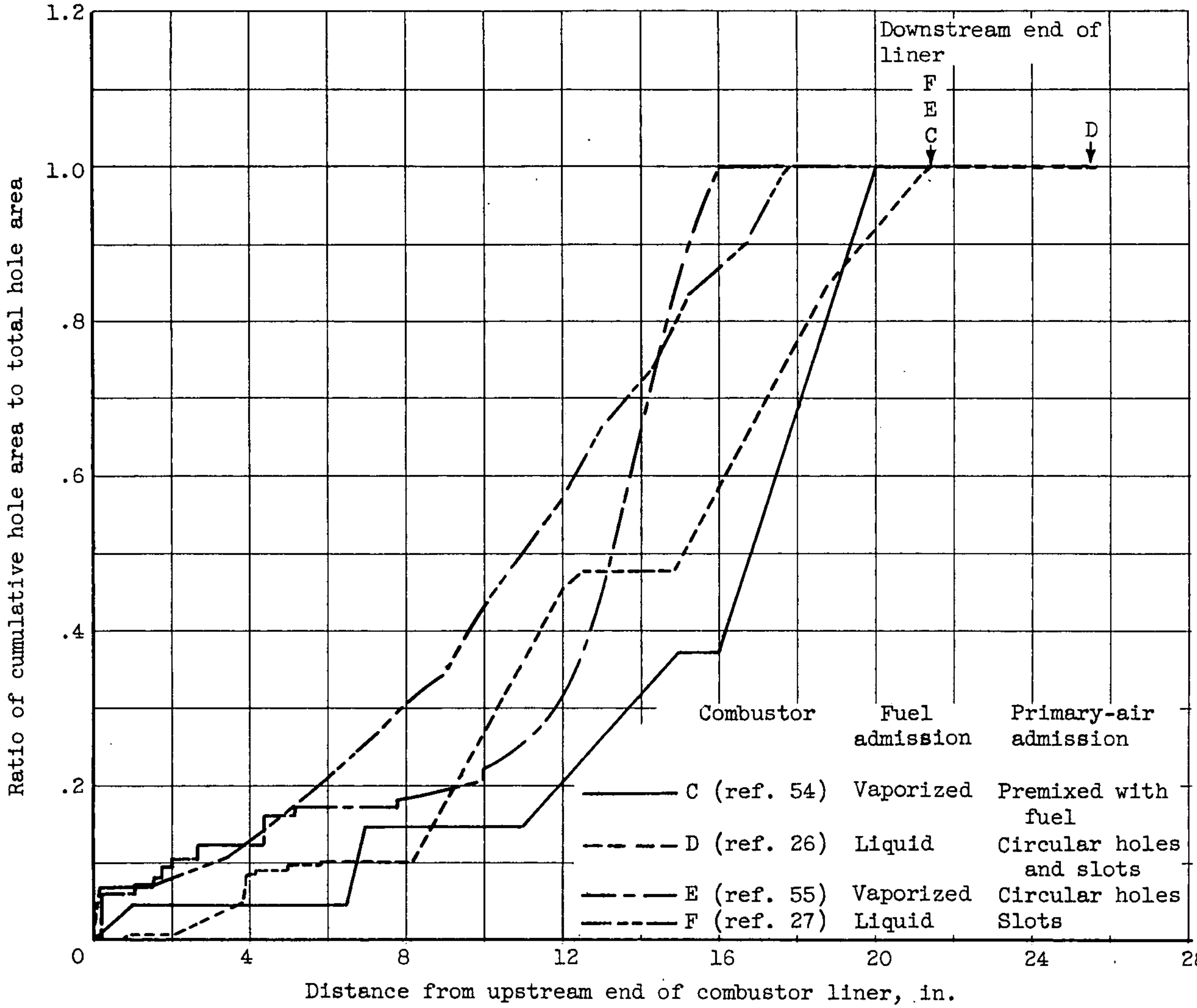
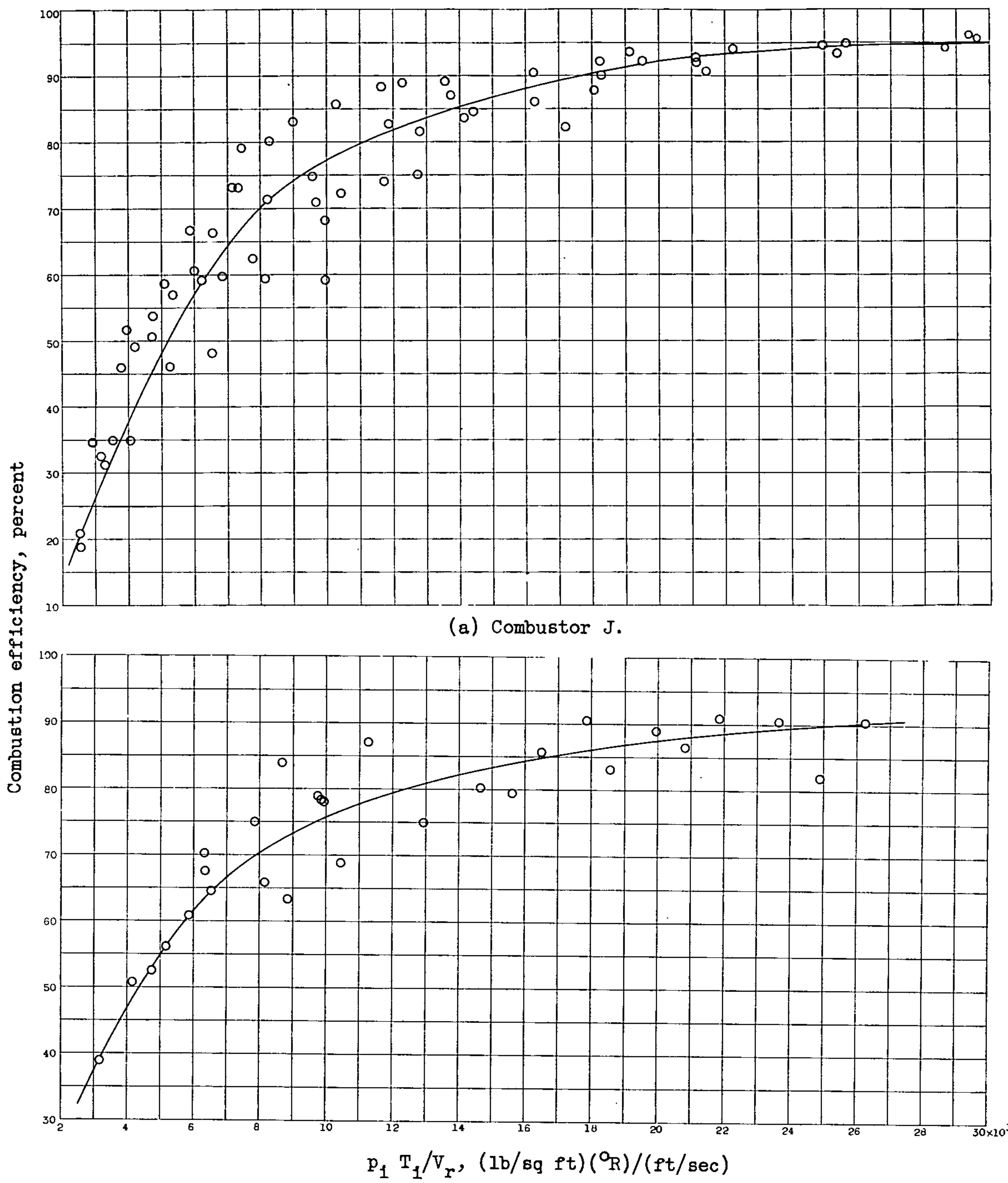


Figure 92. - Axial distribution of hole area of several turbojet combustor configurations designed for high efficiency at low-pressure conditions.

[redacted]



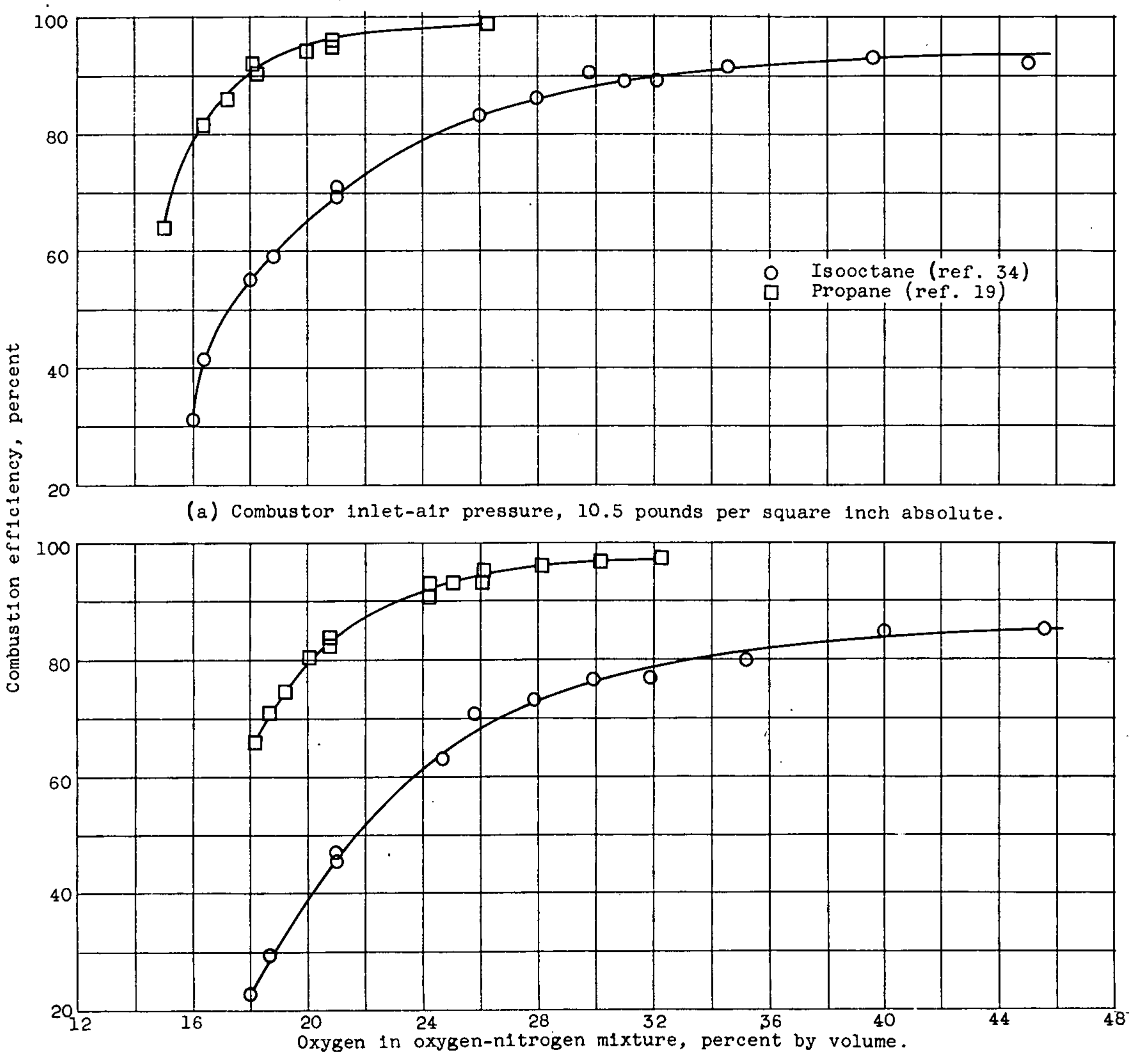
(a) Combustor J.

(b) Combustor M.

Figure 93. - Correlation between combustion efficiency and p_iT_i/V_r for data obtained in two turbojet combustors (ref. 32).

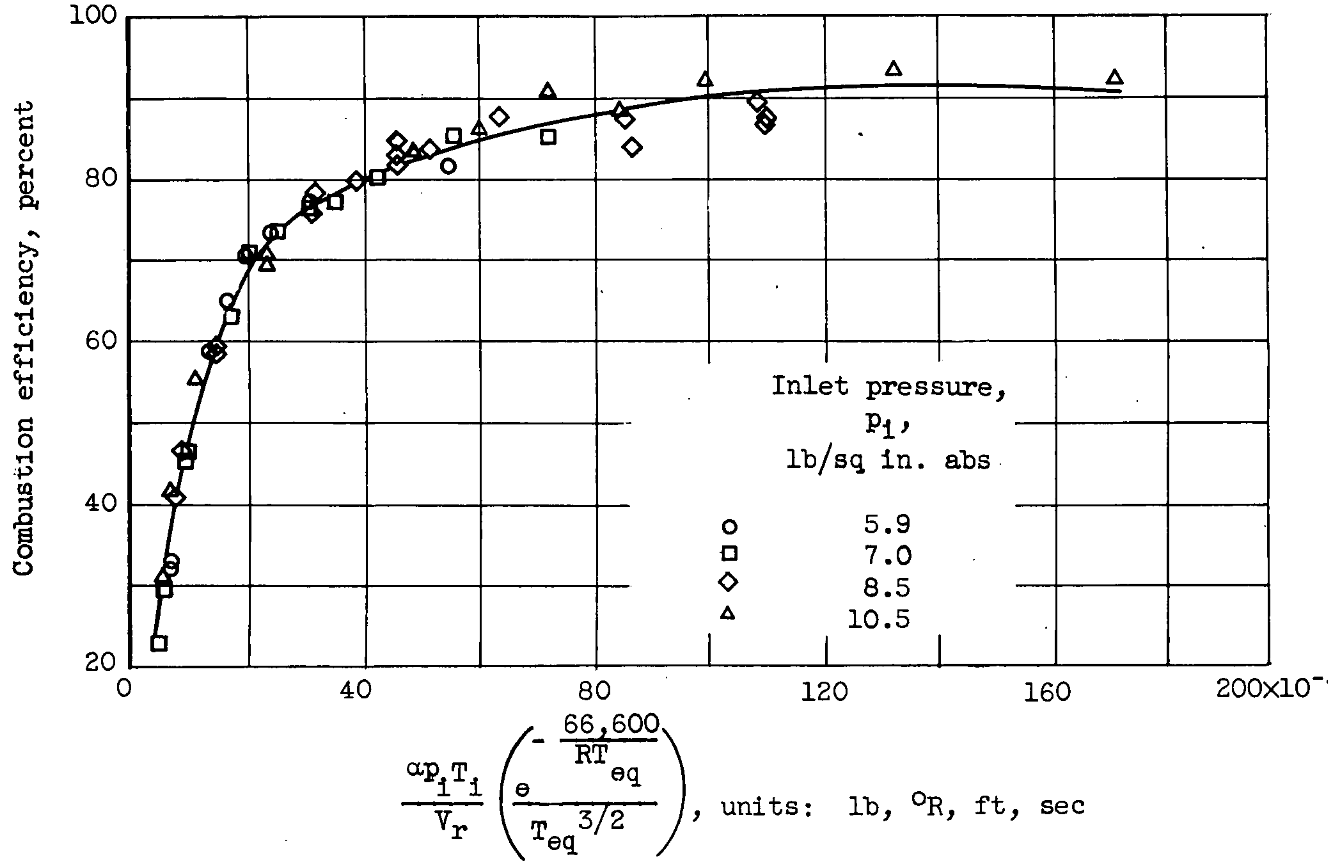
[redacted]

3080



(b) Combustor inlet-air pressure, 7 pounds per square inch absolute.

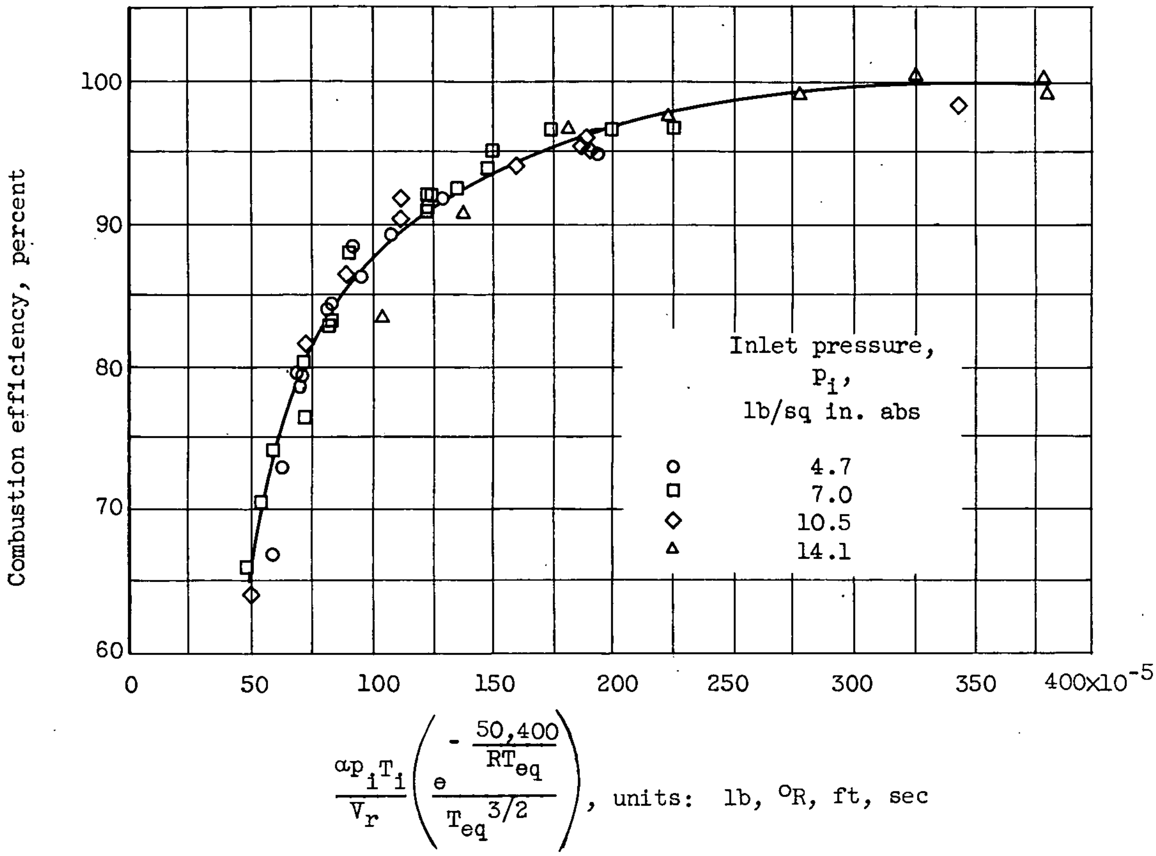
Figure 94. - Effect of oxygen concentration on combustion efficiencies obtained with liquid and gaseous fuels in 7-inch-diameter tubular combustor operating at two different combustor-inlet pressures. Combustor inlet-air temperature, 500° R; oxygen-nitrogen flow rate, 3600 pounds per hour; fuel-air ratio, 0.012.



(a) Isooctane fuel (ref. 34).

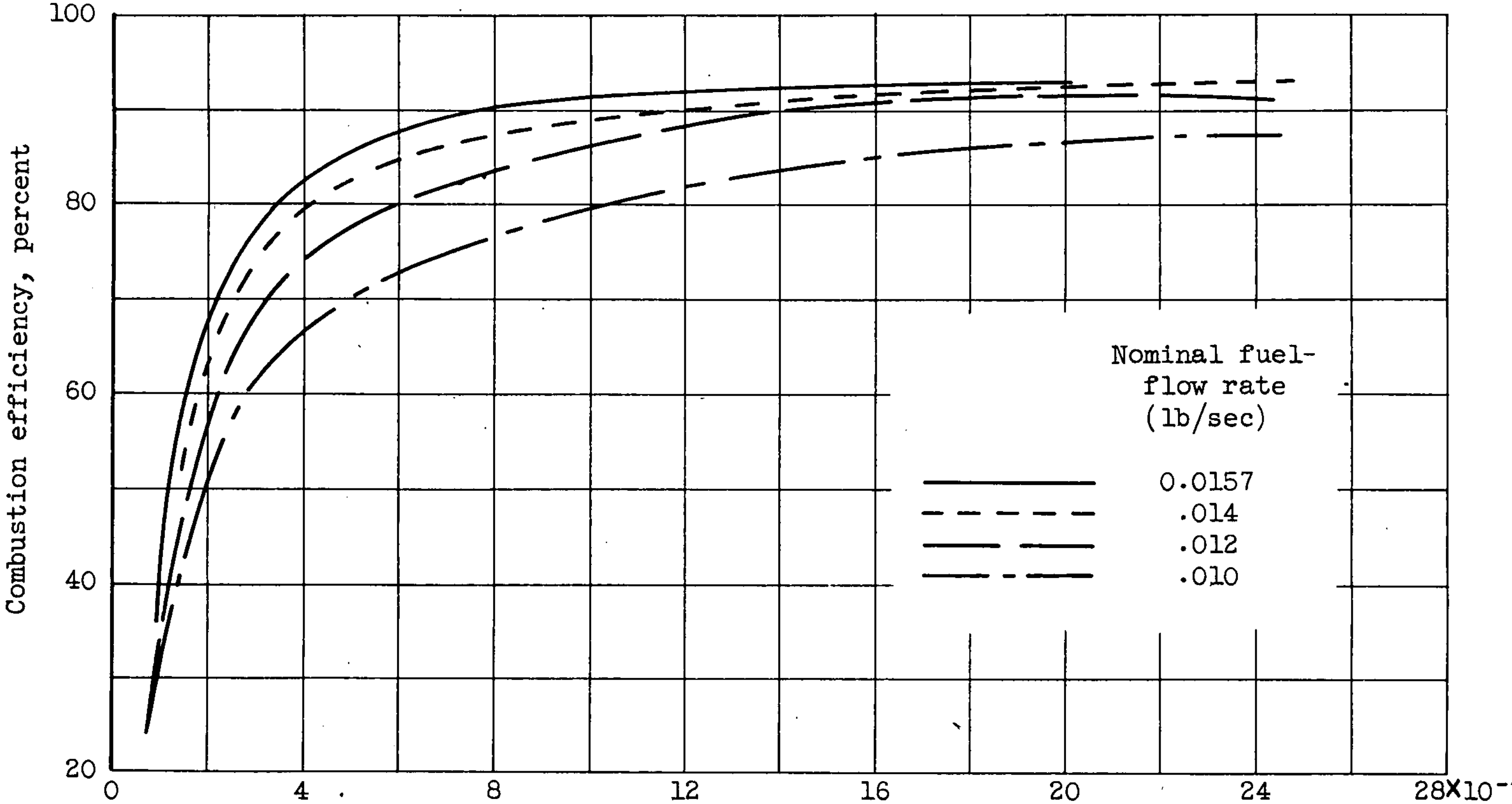
Figure 95. - Correlation of combustion efficiency of single tubular combustor with parameter from second-order-reaction equation. Inlet-air temperature, 500° R; oxygen-nitrogen flow rate, 3600 pounds per hour; fuel-air ratio, 0.012.

3080



(b) Propane fuel (ref. 19).

Figure 95. - Concluded. Correlation of combustion efficiency of single tubular combustor with parameter from second-order-reaction equation. Inlet-air temperature, 500° R; oxygen-nitrogen flow rate, 3600 pounds per hour; fuel-air ratio, 0.012.



$$\frac{\alpha p_i T_i}{V_r}\left(\frac{e^{-\frac{66,600}{RT_{eq}}}}{T_{eq}^{3/2}}\right), \text{ units: lb, } ^{o}\text{R, ft, sec}$$

Figure 96. - Effect of fuel-air ratio on correlation of combustion efficiency with parameter from second-order-reaction equation for single tubular combustor operating with isooctane fuel. Inlet-air temperature, 500° R:, oxygen-nitrogen flow rate, 3600 pounds per hour; (ref. 34).

CONFIDENTIAL

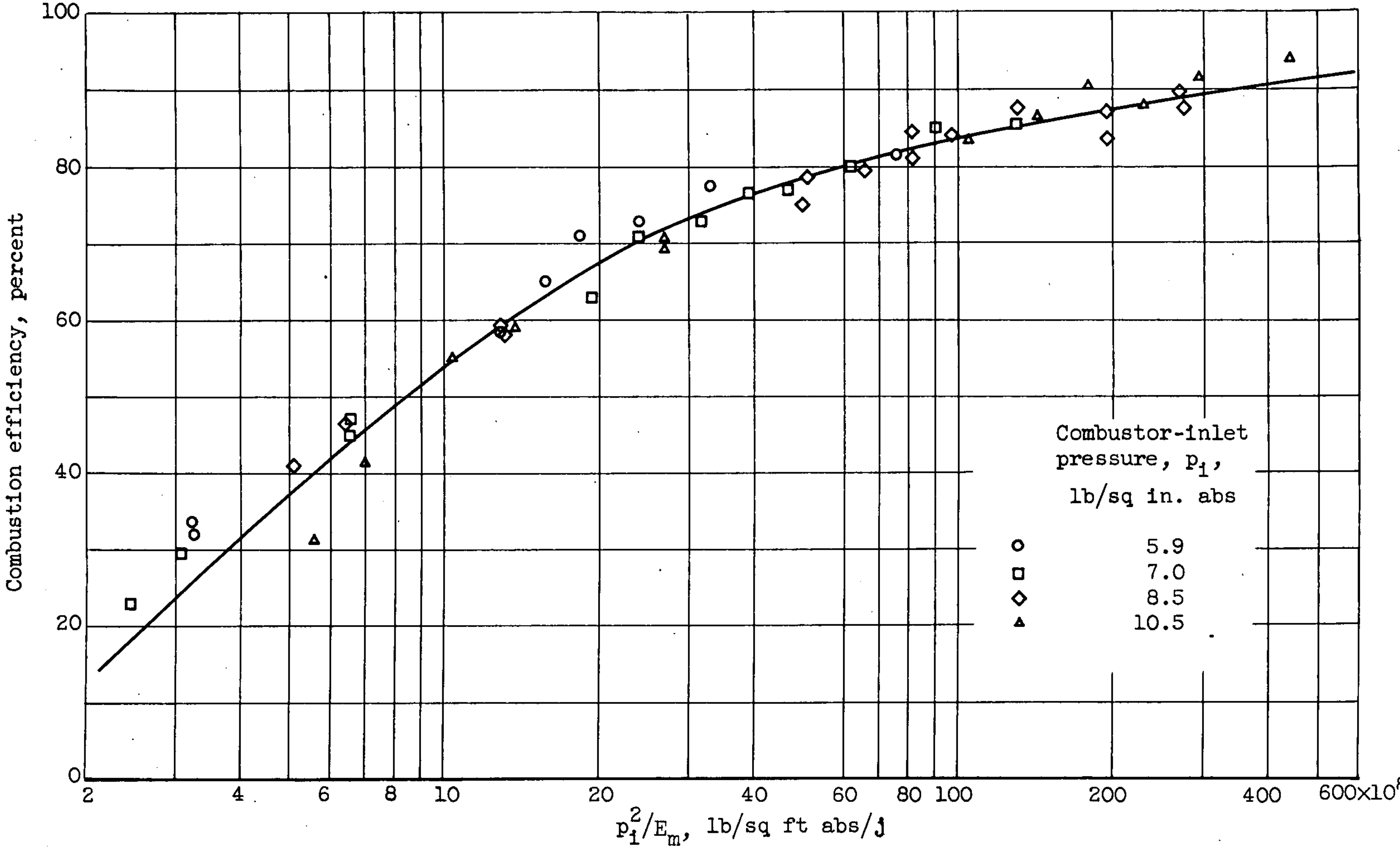
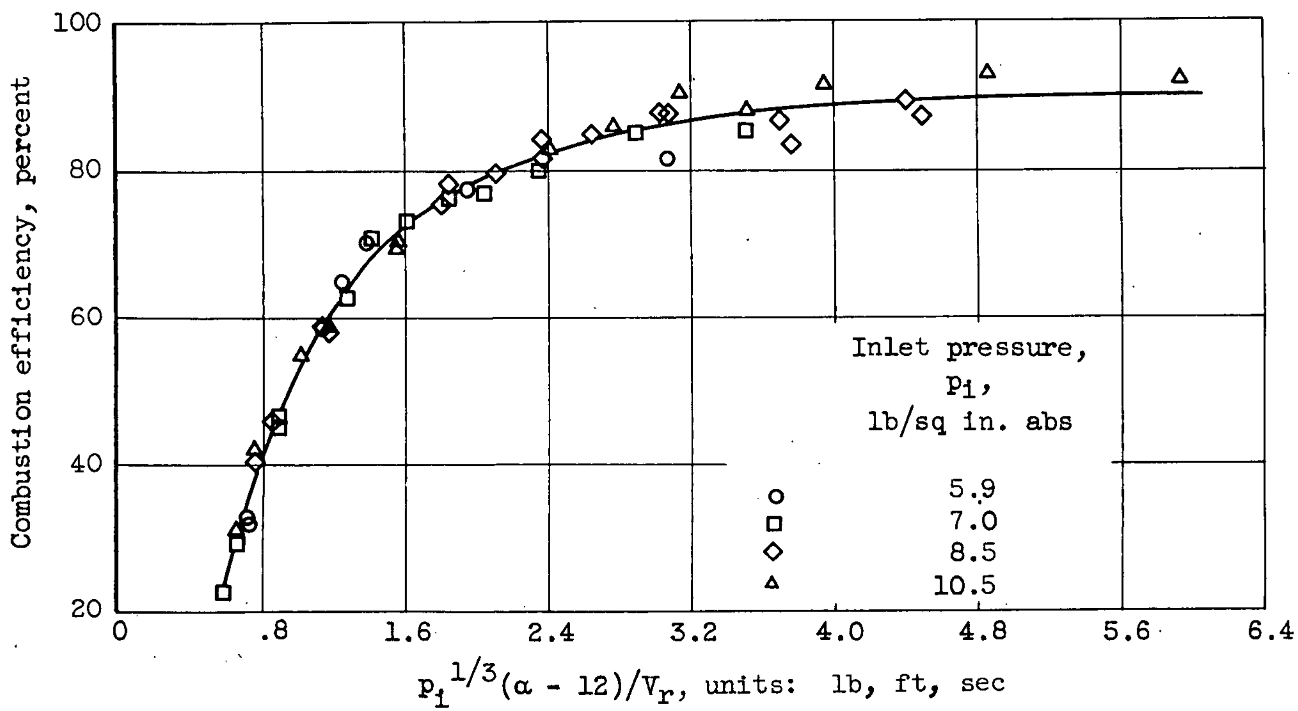


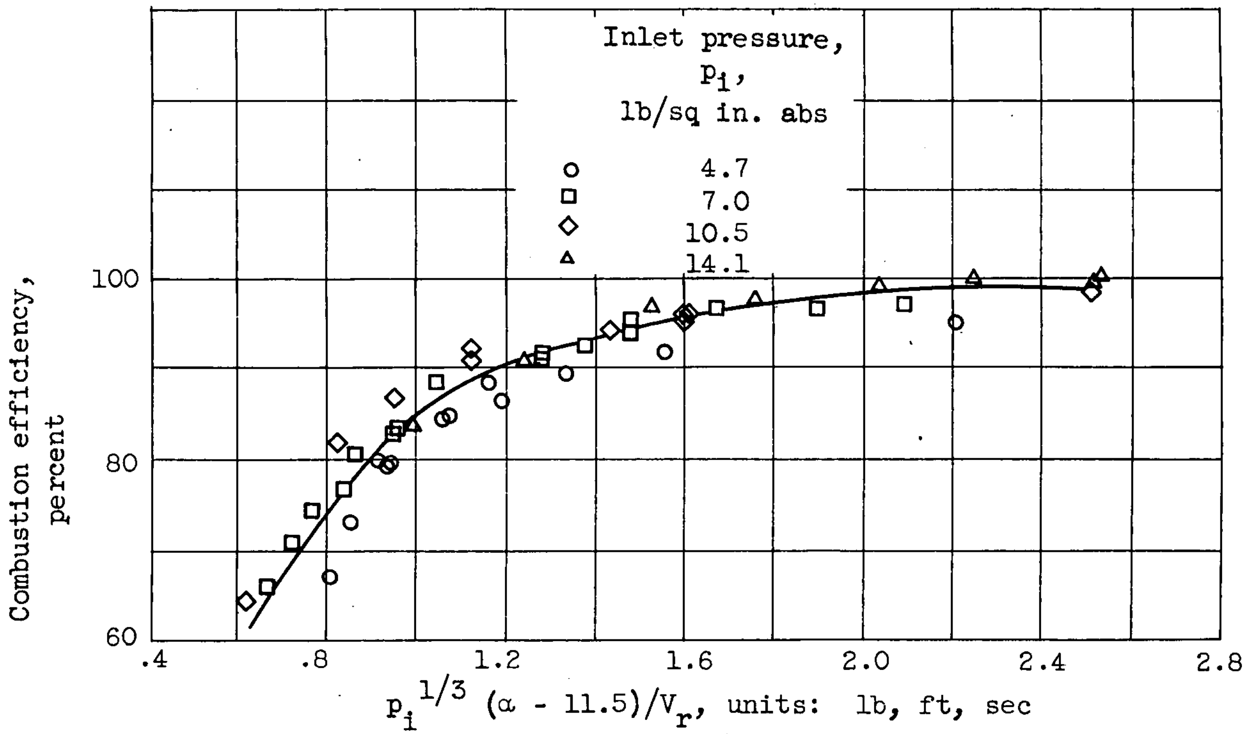
Figure 97. - Correlation of combustion efficiency of isooctane fuel in single tubular combustor with function of minimum spark-ignition energy and combustor-inlet pressure. Inlet-air temperature, 500° R; oxygen-nitrogen flow rate, 3600 pounds per hour; fuel-air ratio, 0.012 (ref. 34).



(a) Isooctane fuel (ref. 34).

Figure 98. - Correlation of combustion efficiency in single tubular combustor with flame-speed parameter. Inlet-air temperature, 500° R; oxygen-nitrogen flow rate, 3600 pounds per hour; fuel-air ratio, 0.012.

CONFIDENTIAL



(b) Propane fuel (ref. 19).

Figure 98. - Concluded. Correlation of combustion efficiency in single tubular combustor with flame-speed parameter. Inlet-air temperature, 500° R; oxygen-nitrogen flow rate, 3600 pounds per hour; fuel-air ratio, 0.012.

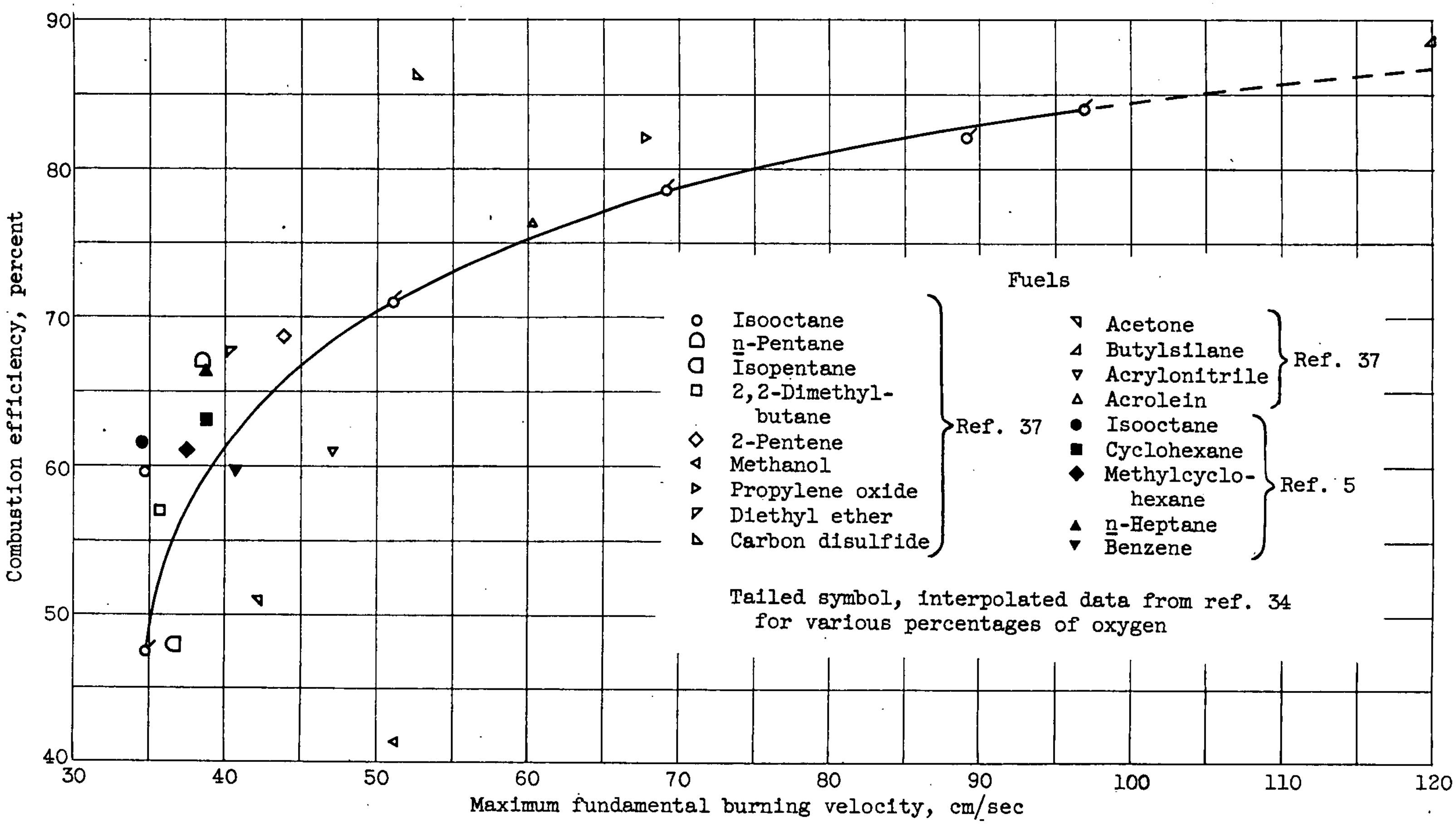


Figure 99. - Correlation of combustion efficiency with maximum fundamental burning velocity. Single tubular combustor; inlet-air pressure, 7 pounds per square inch absolute; inlet-air temperature, 500° R; heat input, 250 Btu per pound of air; air-flow rate, 1.0 pound per second.

3080

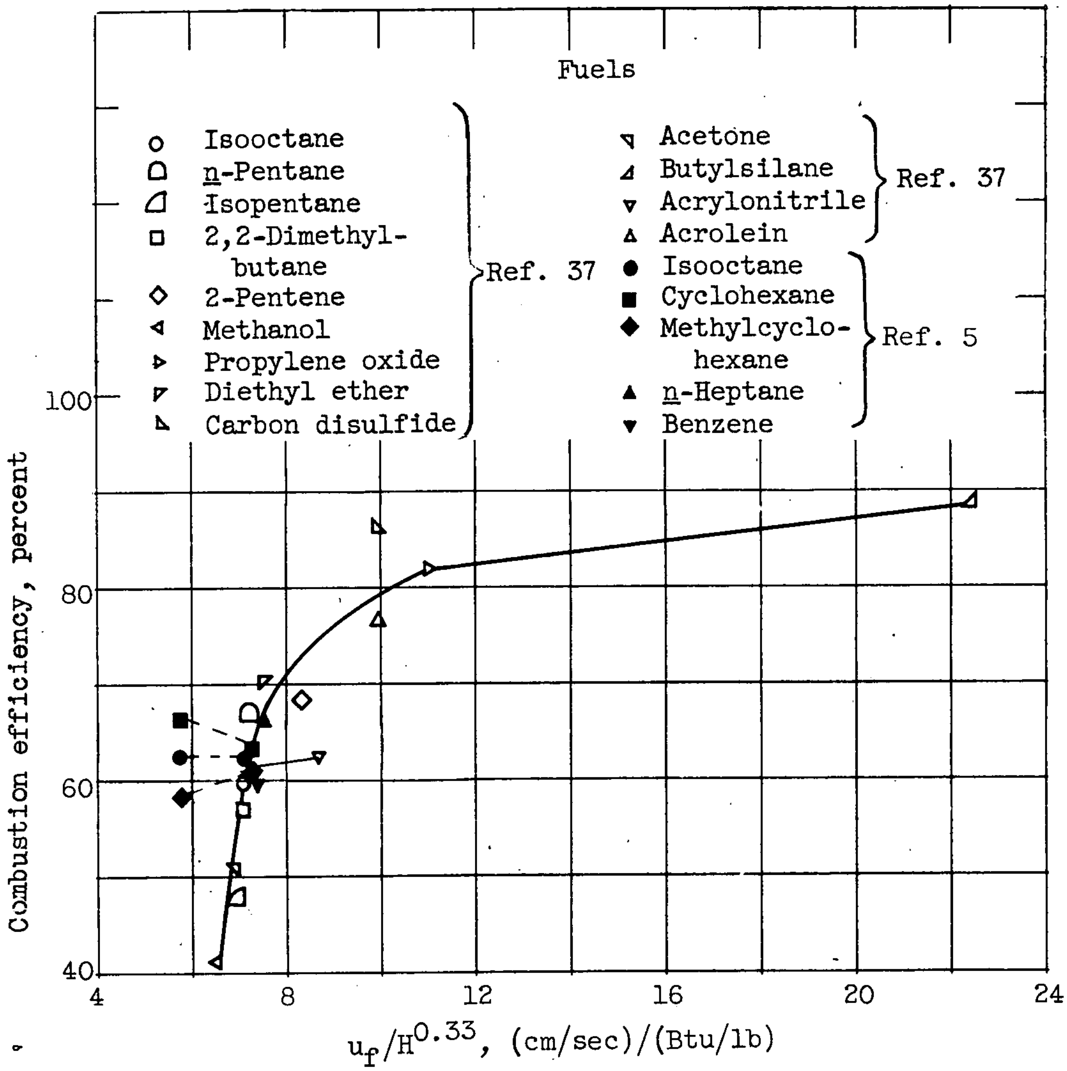


Figure 100. - Correlation of combustion efficiency with parameter $u_f/H^{0.33}$. Single tubular combustor; inlet-air pressure, 7 pounds per square inch absolute; inlet-air temperature, 500° R; heat input, 250 Btu per pound of air; air-flow rate, 1.0 pound per second.

3080

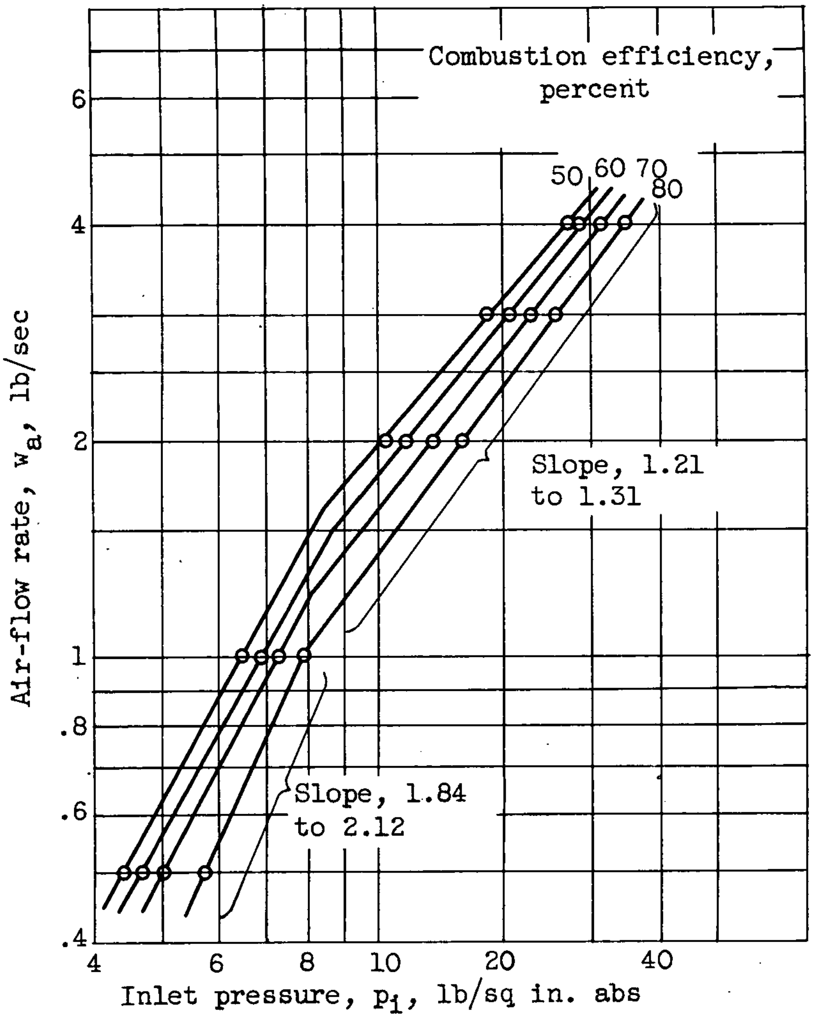


Figure 101. - Relative effects of inlet pressure and air-flow rate on combustion efficiency. Fuel-air ratio, 0.012 (ref. 40).

3080

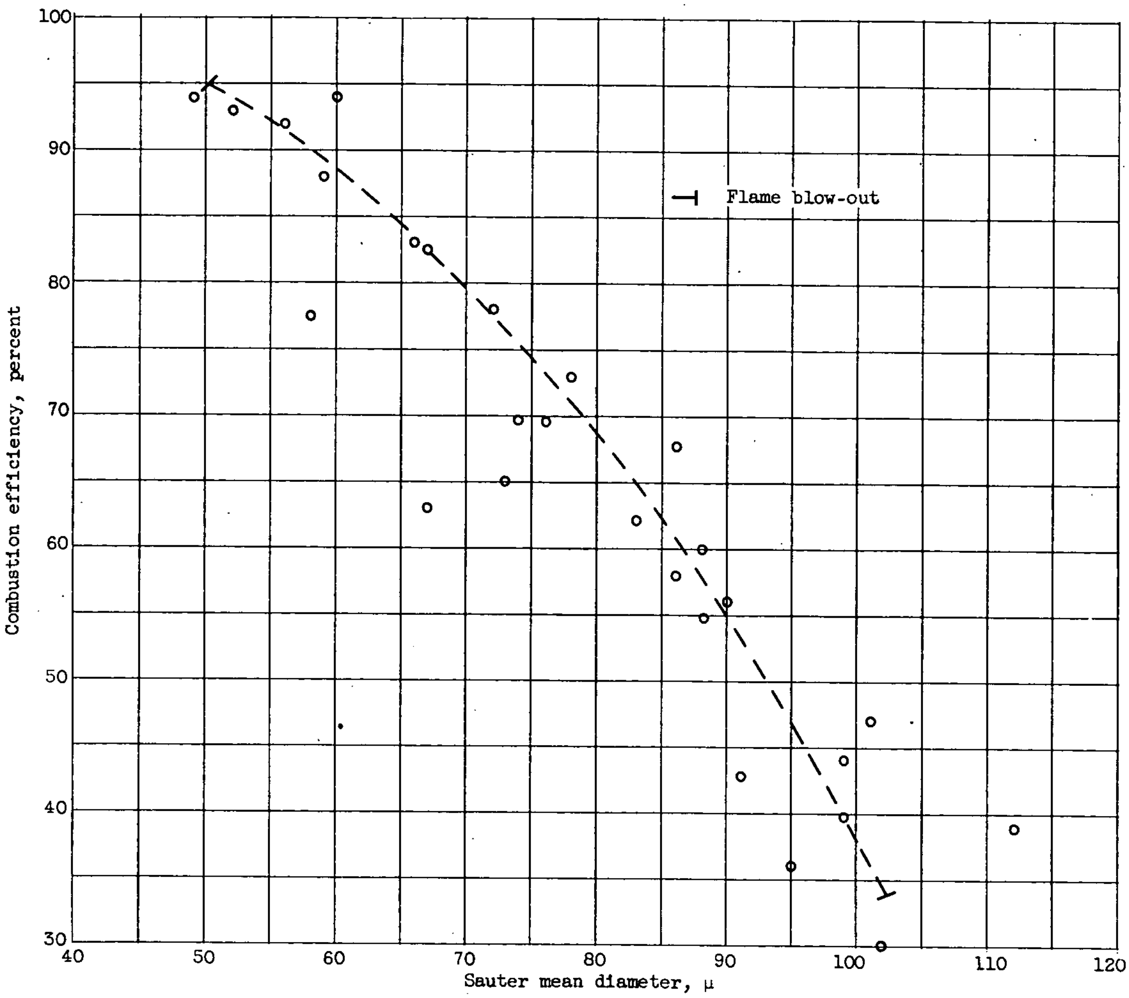


Figure 102. - Relation between combustion efficiency and Sauter mean diameter of fuel spray. Single combustor operating at simulated altitudes from 30,000 to 55,000 feet (ref. 42).

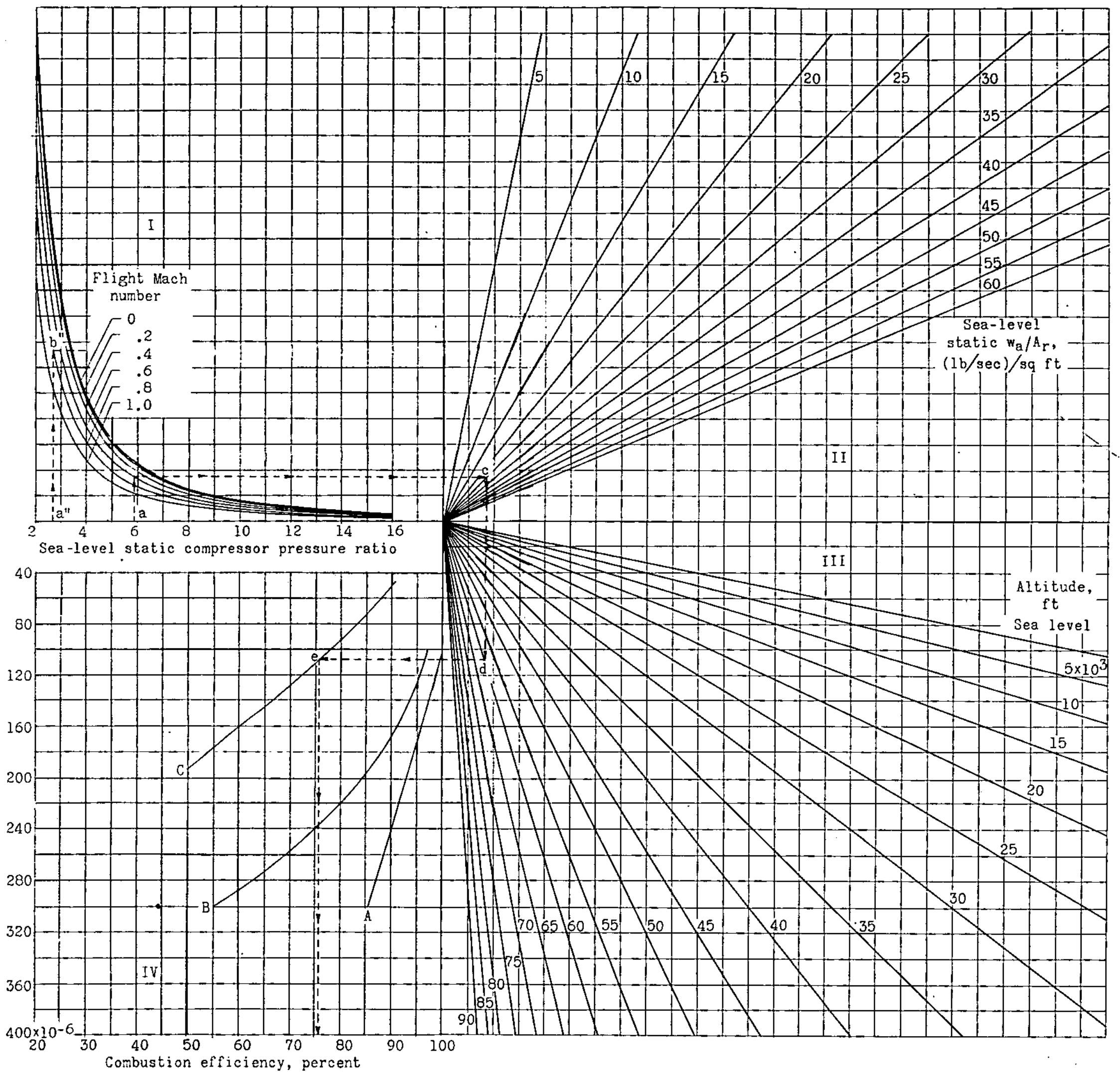
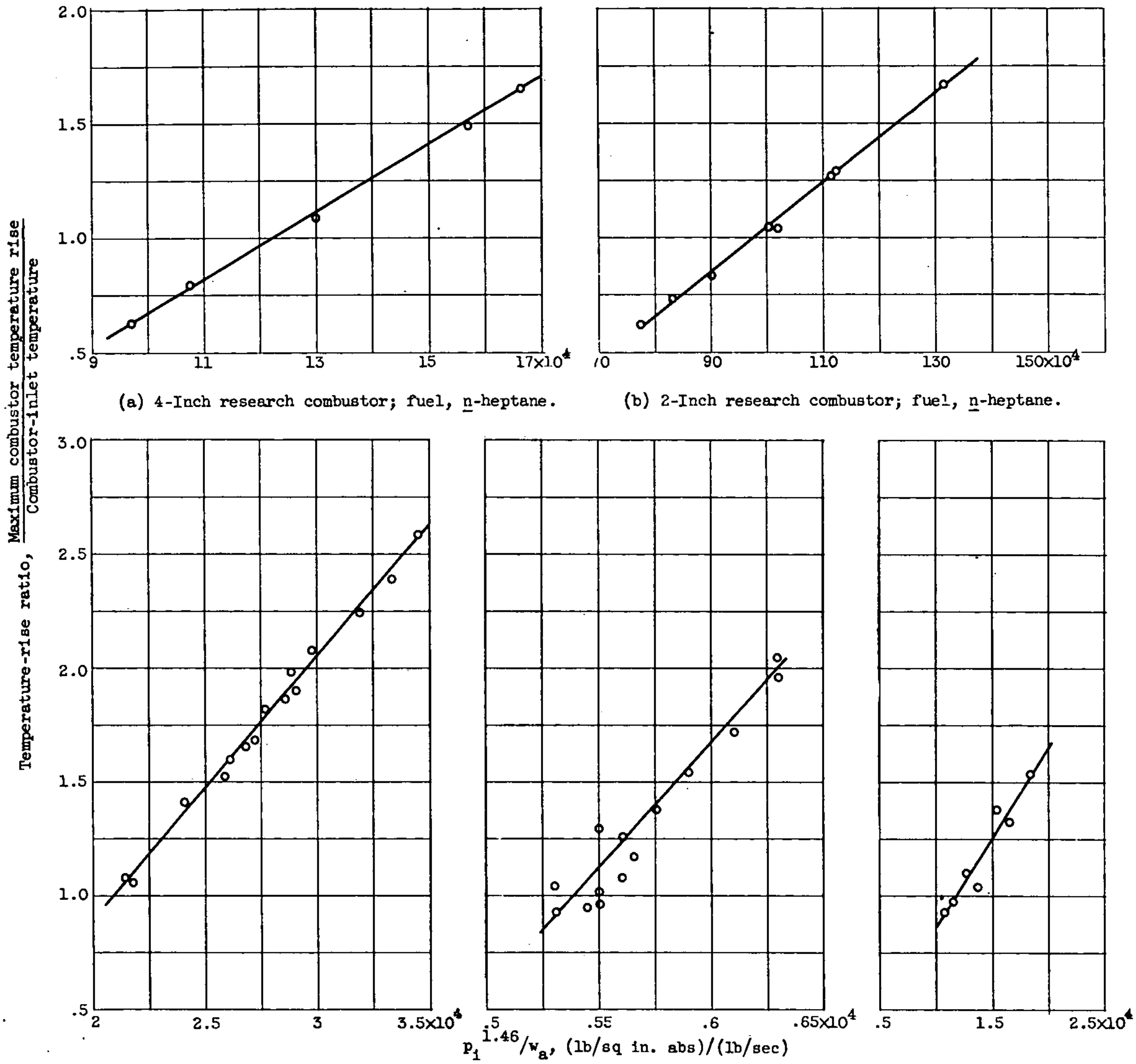


Figure 103. - Chart for estimating combustion efficiency of turbojet combustors at altitude flight conditions. Corrected engine speed, constant; diffuser total-pressure recovery factor, 0.95 (ref. 43).

3080



(a) 4-Inch research combustor; fuel, n-heptane.

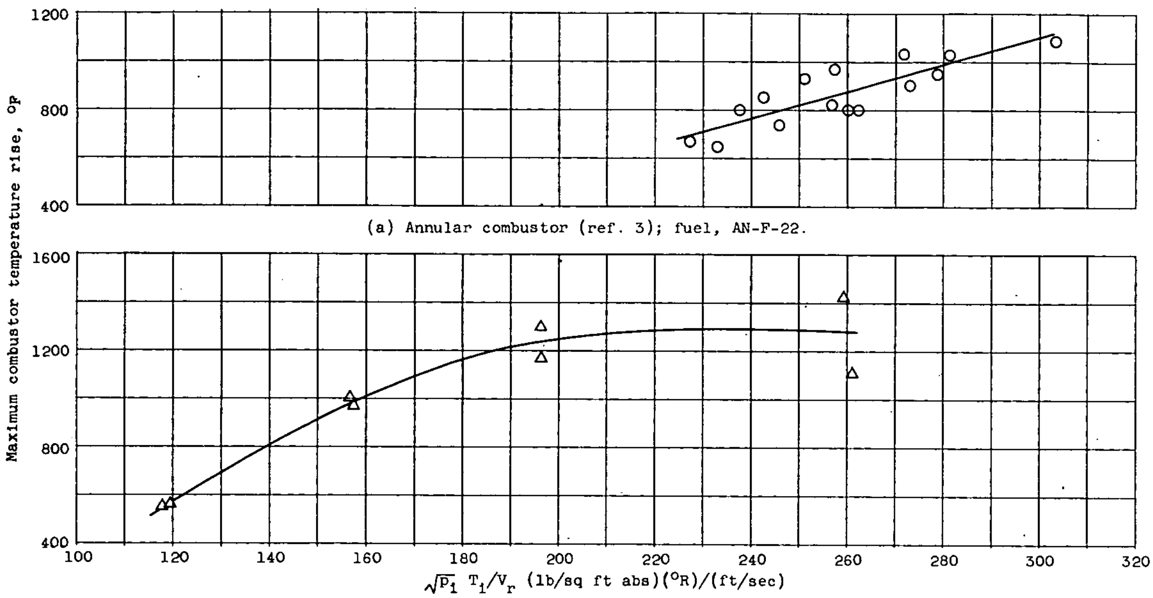
(b) 2-Inch research combustor; fuel, n-heptane.

(c) 9.5-Inch annular combustor; fuel, n-heptane.

(d) 19-Inch annular combustor; fuel, AN-F-28.

(e) Tubular combustor; fuel, AN-F-28.

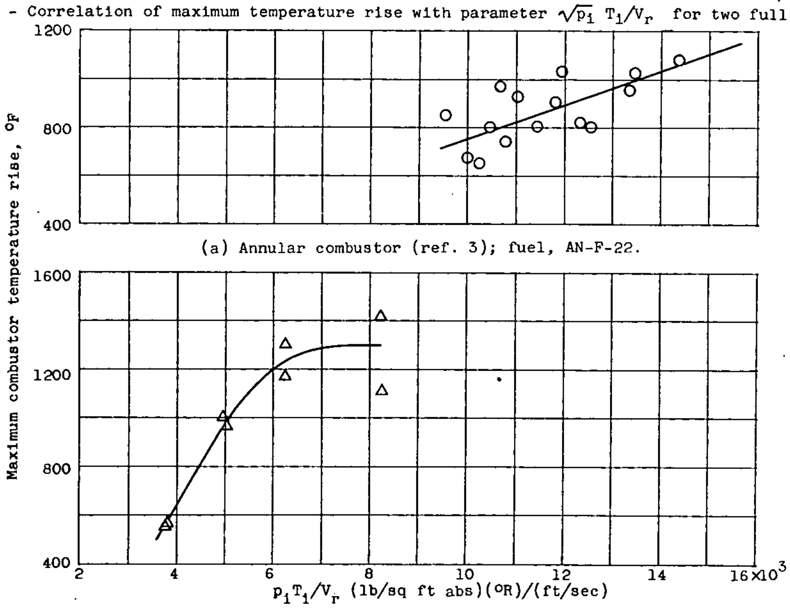
Figure 104. - Correlation of temperature-rise ratio with severity parameter $p_i^{1.46}/w_a$ for several combustors (ref. 44).



(a) Annular combustor (ref. 3); fuel, AN-F-22.

(b) Tubular combustor (ref. 5); fuel, isooctane.

Figure 105. - Correlation of maximum temperature rise with parameter $\sqrt{p_1}\ T_1/V_r$ for two full-scale combustors.

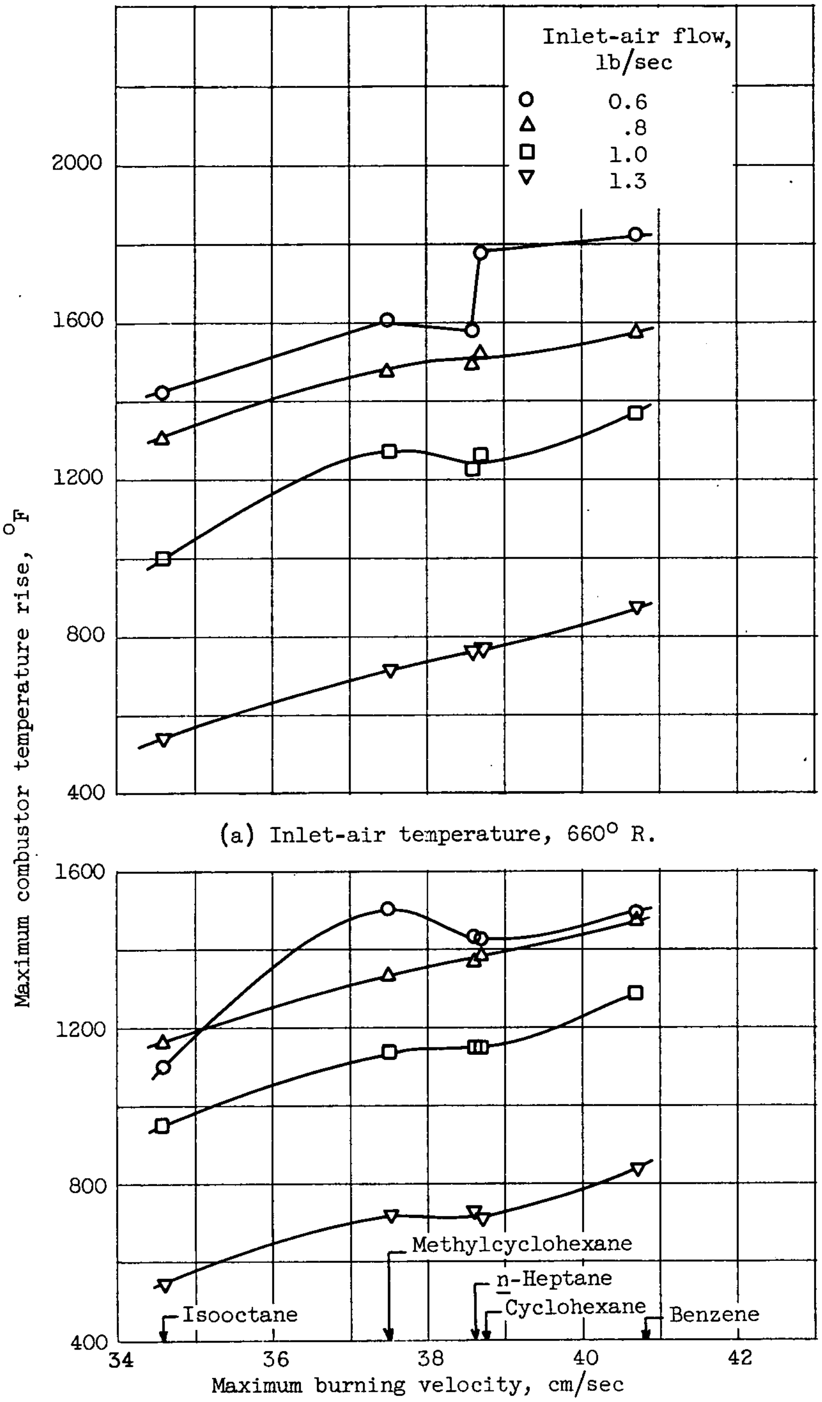


(a) Annular combustor (ref. 3); fuel, AN-F-22.

(b) Tubular combustor (ref. 5); fuel, isooctane.

Figure 106. - Correlation of combustor maximum temperature rise with parameter p_1T_1/V_r for two full-scale combustors.

3080



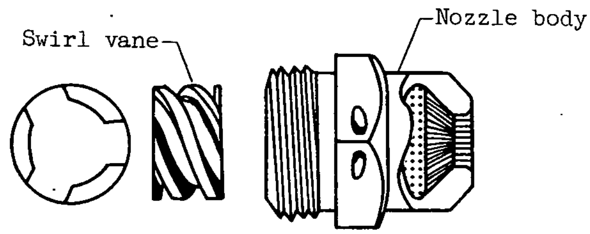
(a) Inlet-air temperature, 660° R.

(b) Inlet-air temperature, 500° R.

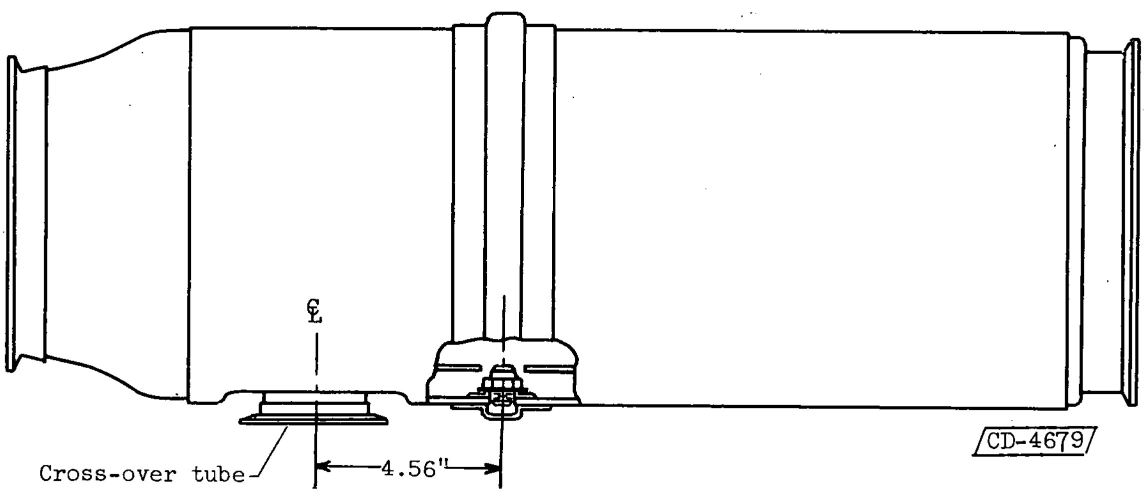
Figure 107. - Variation of maximum combustor temperature rise obtained with pure hydrocarbon fuels with maximum burning velocity in tubular combustor. Combustor inlet-air pressure, 7 pounds per square inch absolute (ref. 5).

[redacted]

3080
CC-25 back



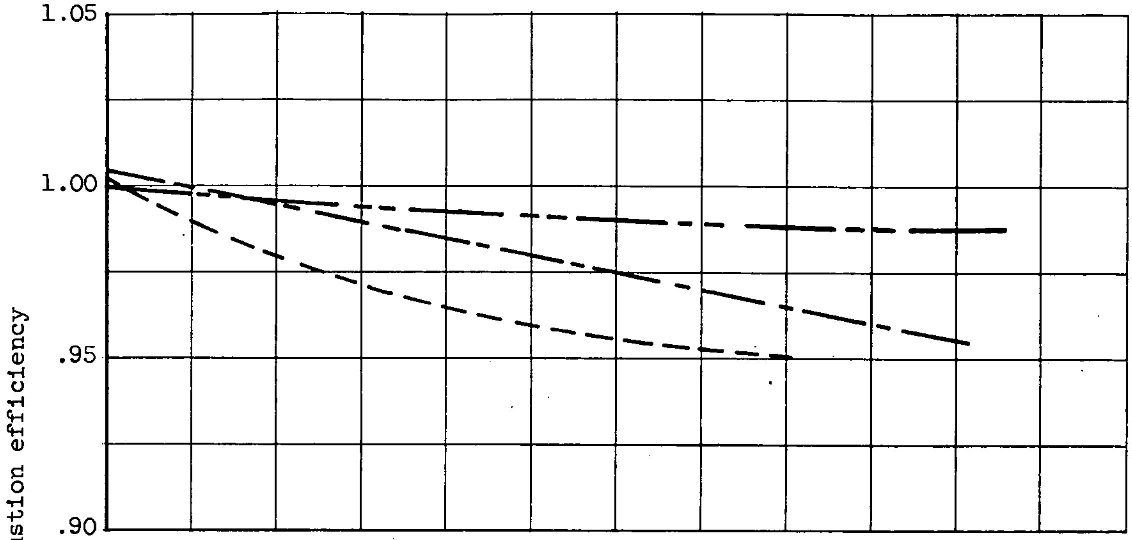
(a) Water-alcohol injection nozzle.



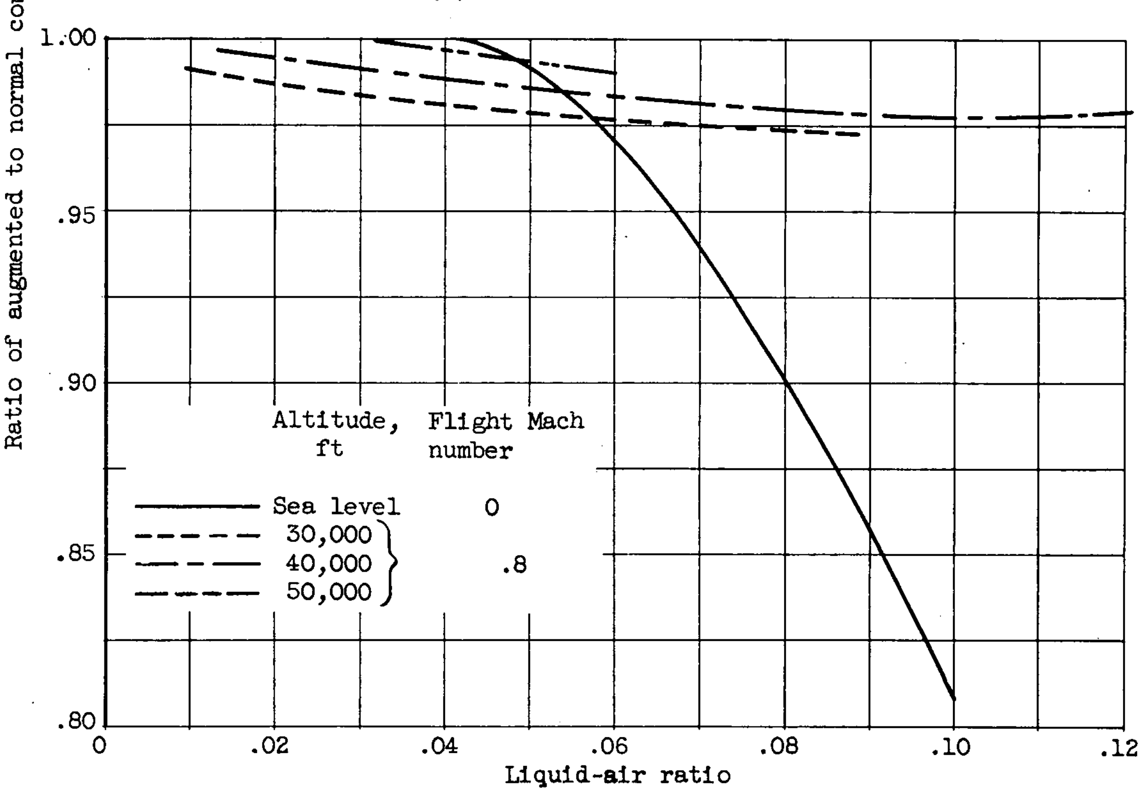
(b) Location of nozzle in combustion chamber (four nozzles per combustion chamber equally spaced around periphery).

Figure 108. - Water-alcohol injection nozzle and its location in tubular combustion chamber (ref. 47).

3080



(a) Standard exhaust nozzle.



(b) Variable-area exhaust nozzle.

Figure 109. - Effect of liquid-air ratio on combustion efficiency of turbojet engine equipped with combustion-chamber water-alcohol injection and standard or variable-area exhaust nozzle. Engine speed for augmented operation, 7950 rpm; engine speed for normal operation determined by rated turbine-outlet temperature (ref. 47).

3080

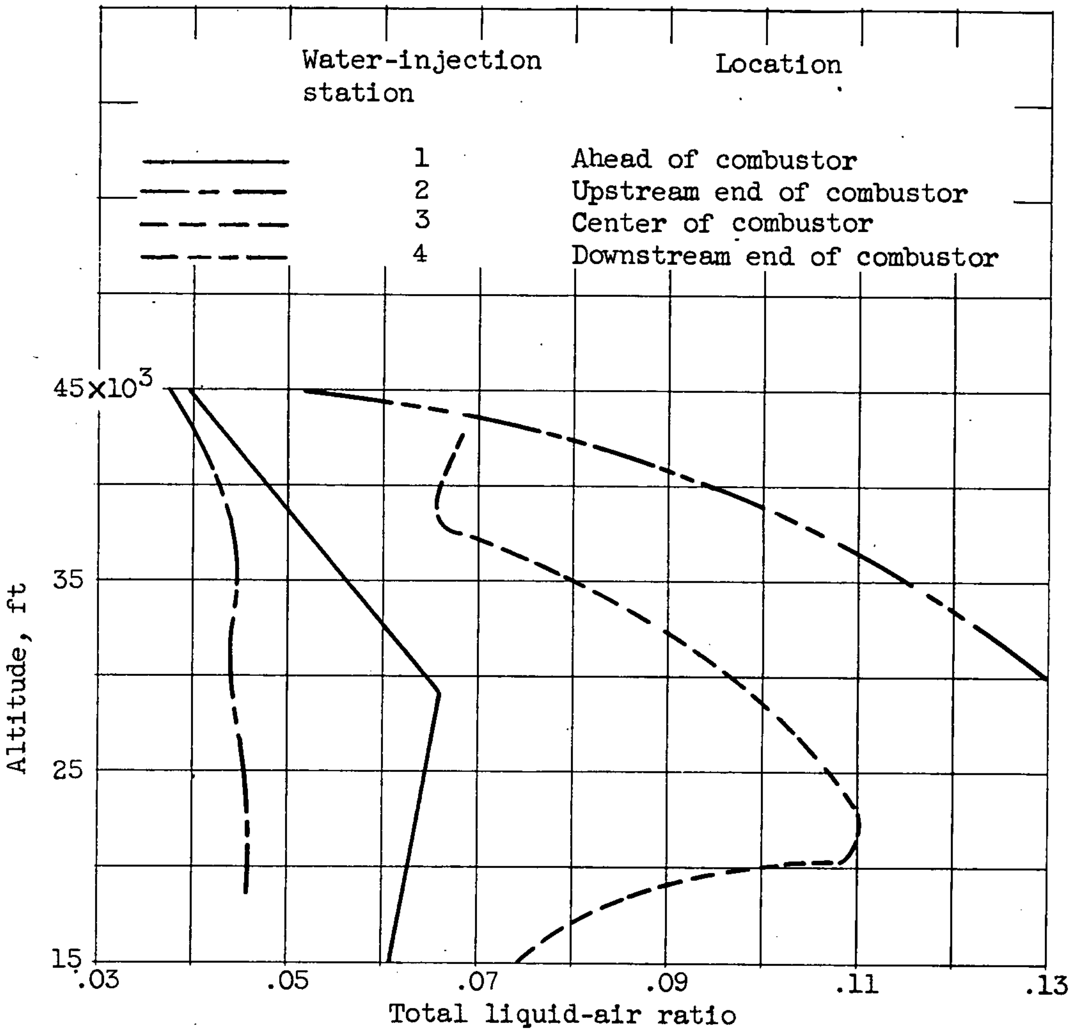


Figure 110. - Effect of altitude on maximum total liquid-air ratio with water injection at various stations in tubular combustor. Simulated operating conditions, zero ram pressure and rated engine speed (ref. 51).

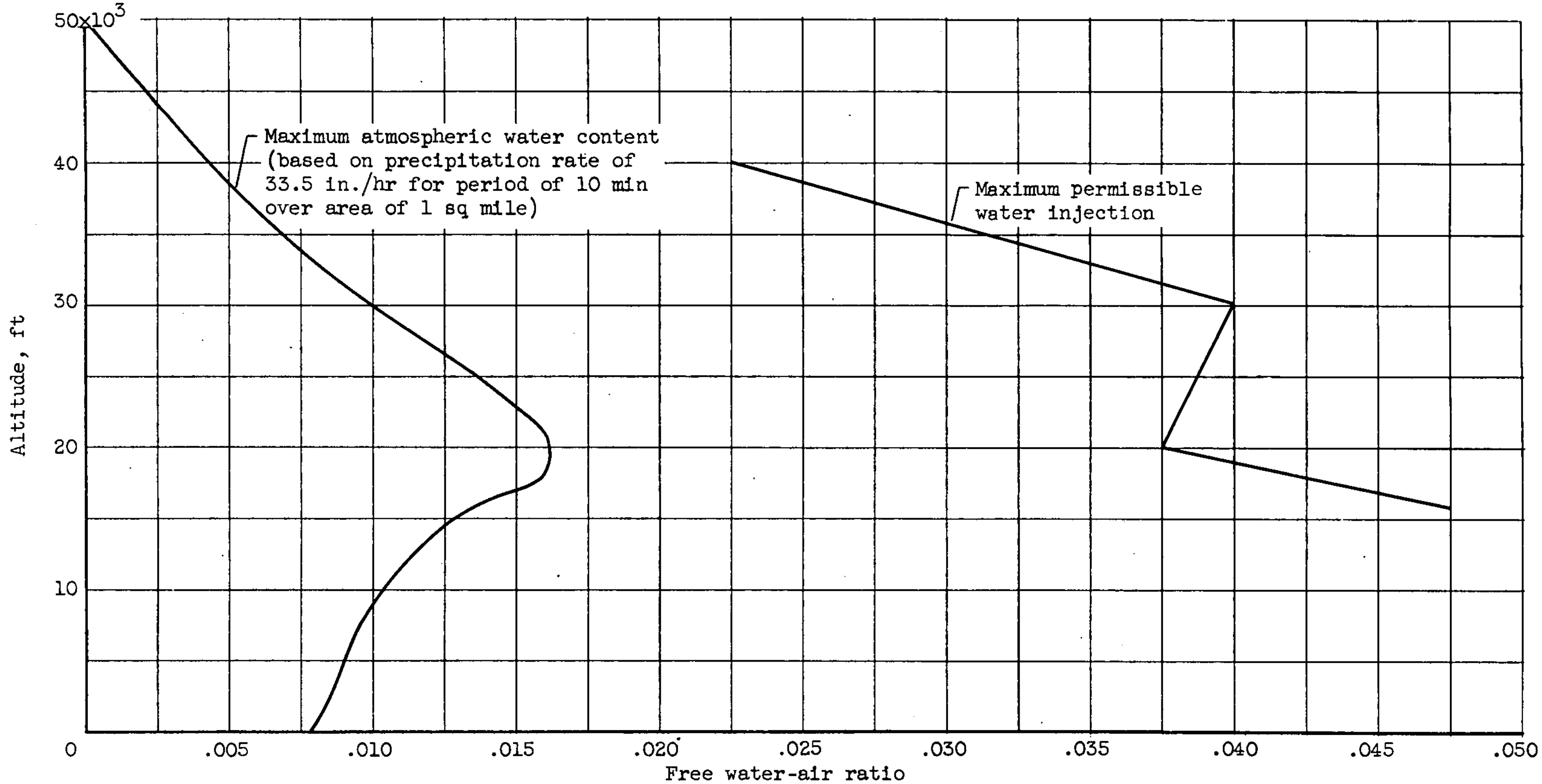
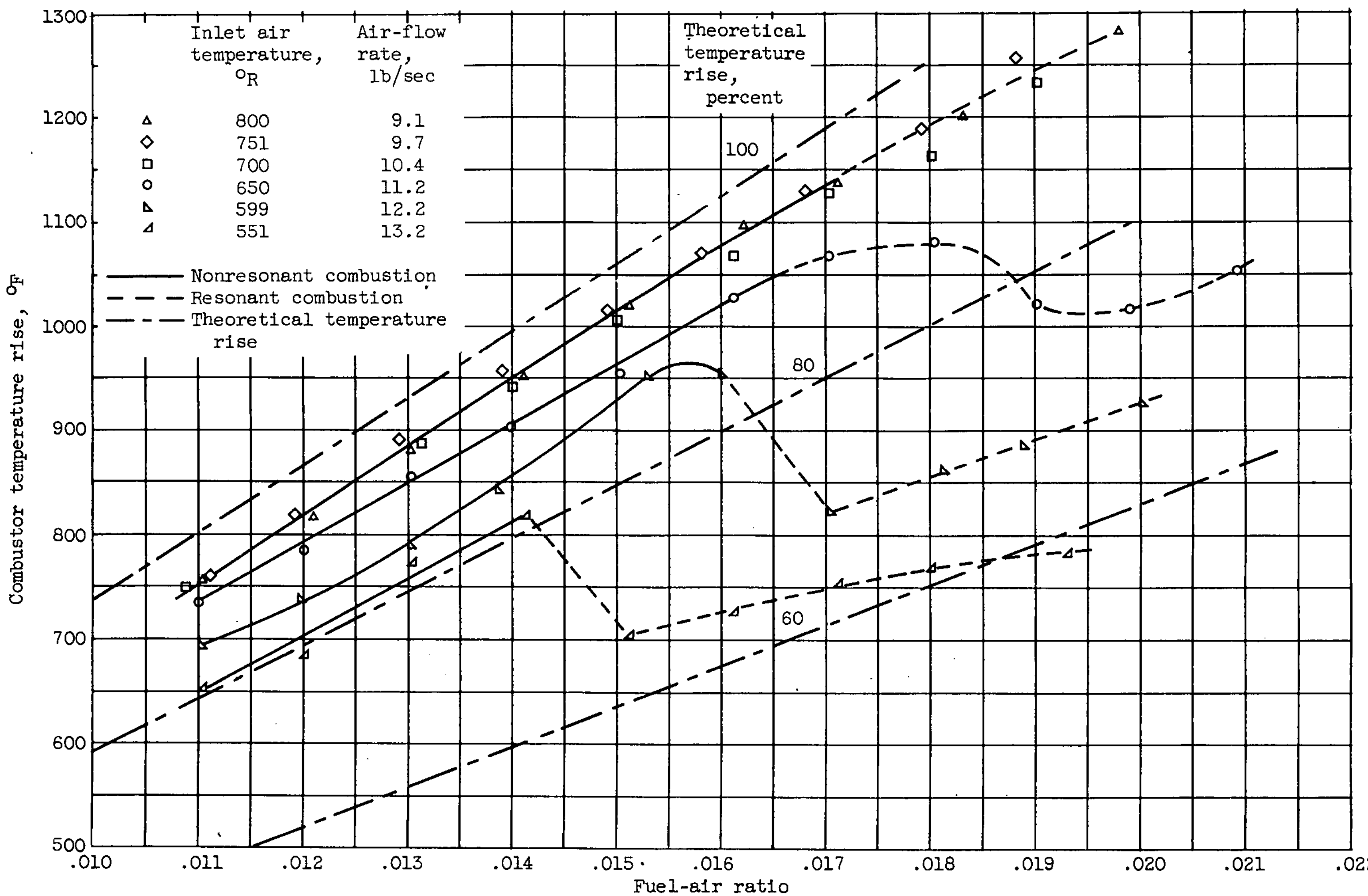


Figure 111. - Comparison of maximum water-air ratios that have been encountered in the atmosphere with those that can be tolerated in single tubular combustor operating at zero-ram and rated-engine-speed conditions (ref. 52).

3080

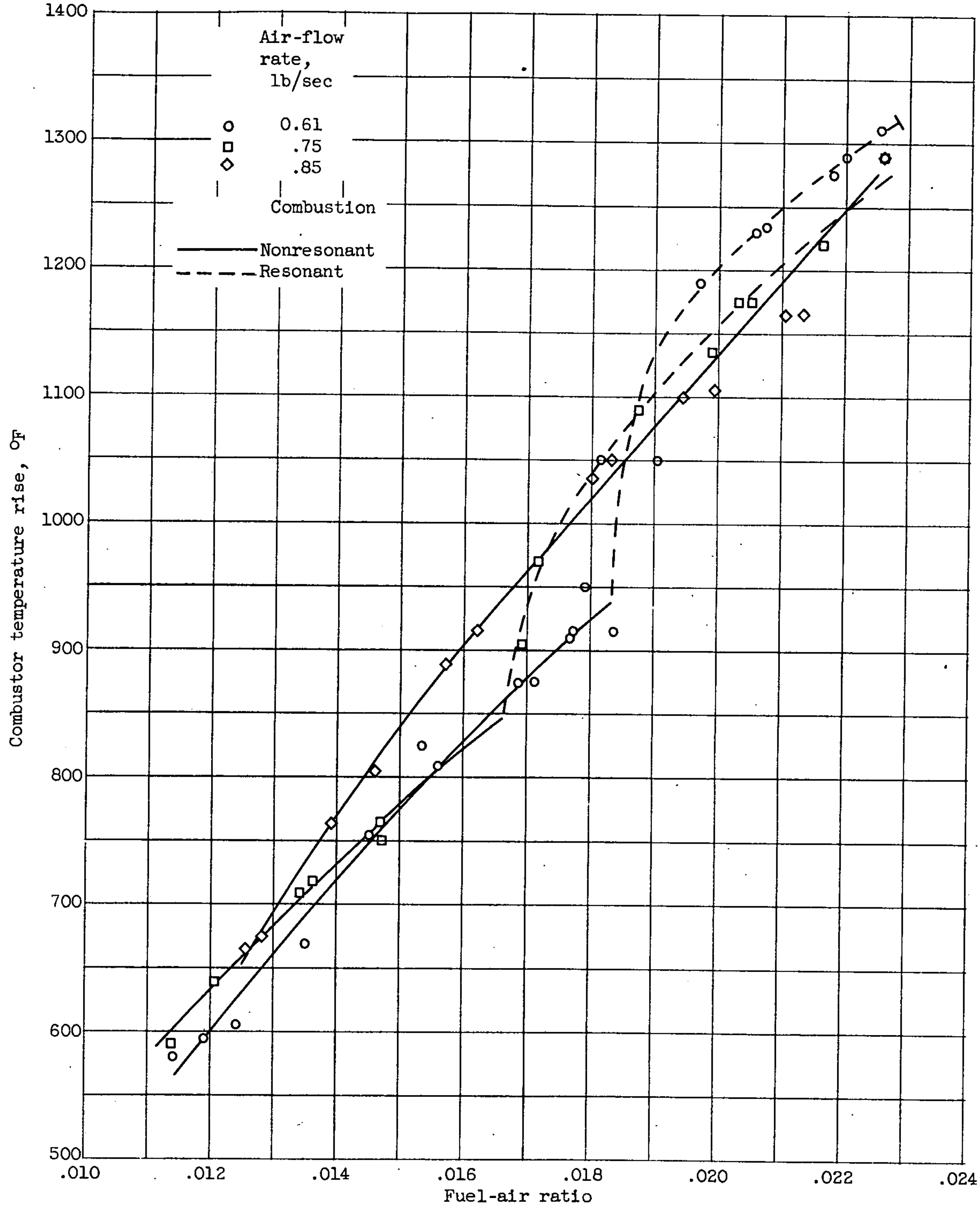


(a) Annular turbojet combustor. Inlet-air pressure, 16 pounds per square inch absolute; reference velocity, 103 feet per second; fuel, AN-F-22 (ref. 3).

Figure 112. - Combustor performance obtained during resonant and nonresonant combustion.

CONFIDENTIAL

3080



(b) Single tubular combustor. Inlet-air pressure, 7 pounds per square inch absolute; inlet-air temperature, 500° R; fuel, high-boiling paraffin.

Figure 112. - Concluded. Combustor performance obtained during resonant and nonresonant combustion.

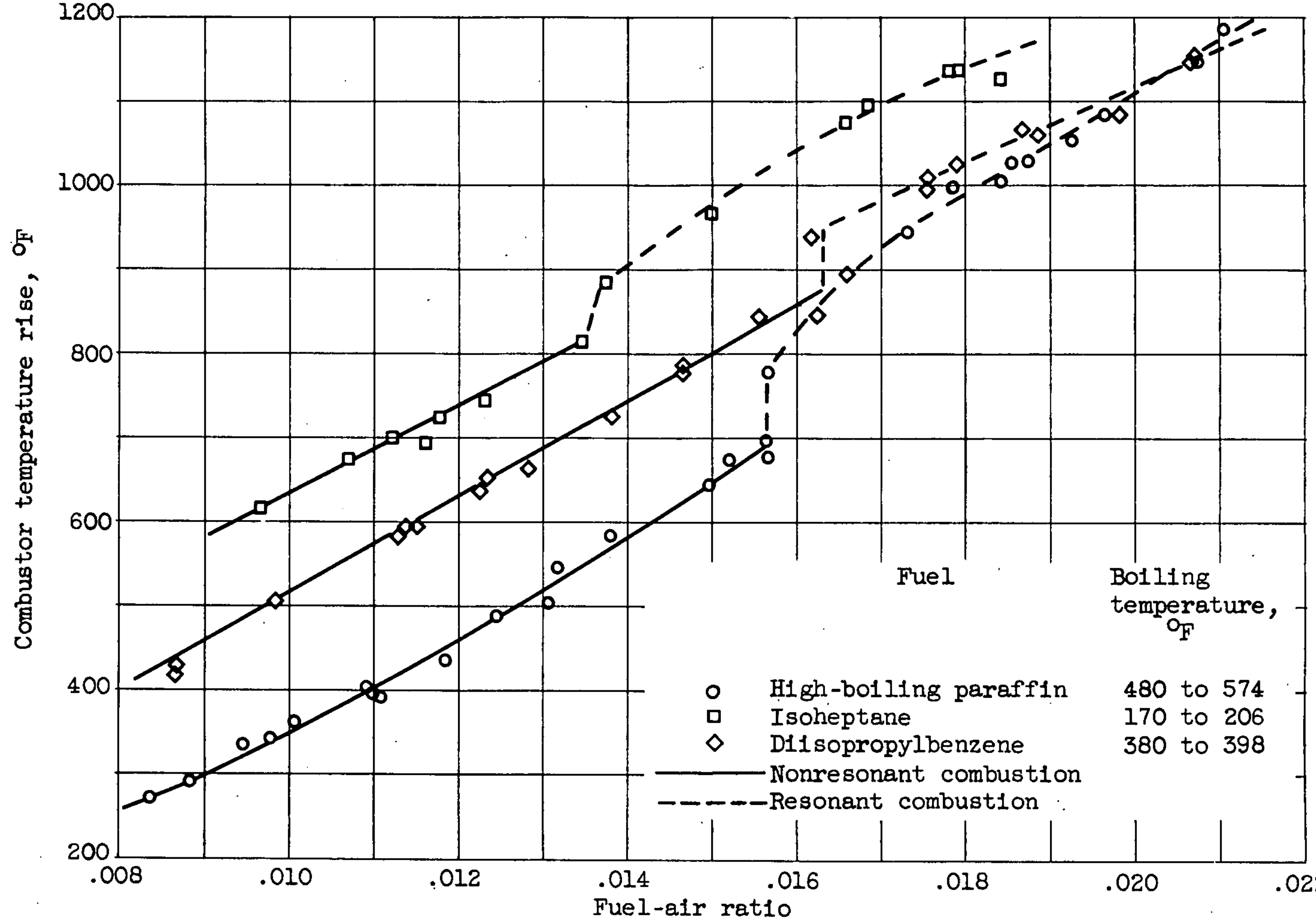
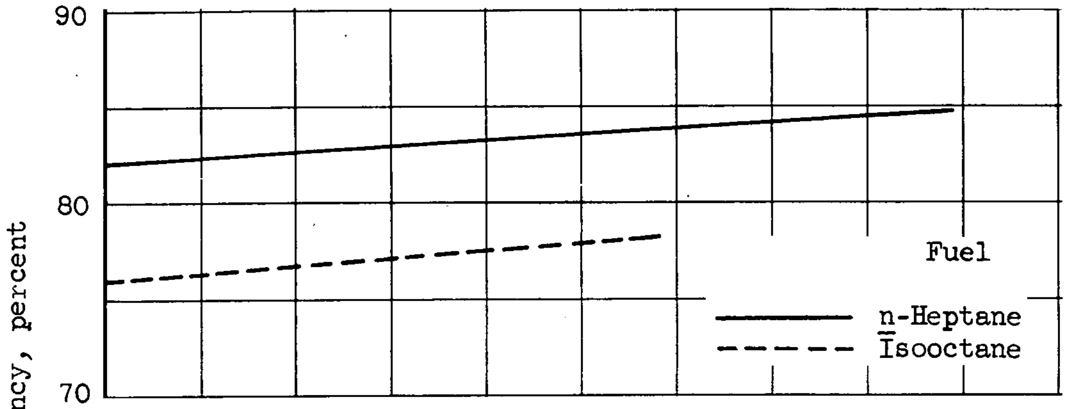
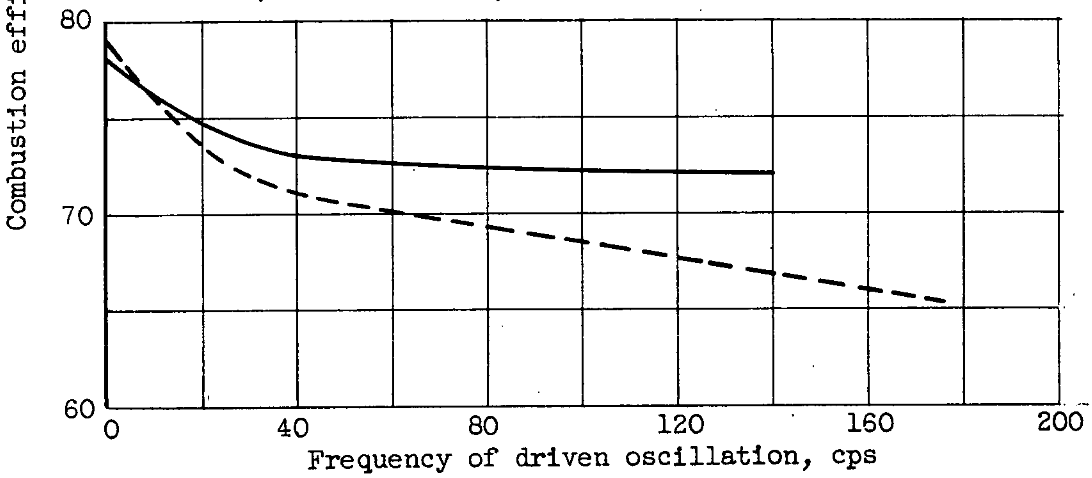


Figure 113. - Effect of fuel characteristics on combustion resonance in single tubular combustor. Inlet-air pressure, 7 pounds per square inch absolute; inlet-air temperature, 500° R; air-flow rate, 0.61 pound per second; variable-area fuel nozzle.



(a) Combustor inlet-air pressure, 29.5 pounds per square inch absolute; air-flow rate, 0.174 pound per second.



(b) Combustor inlet-air pressure, 18.7 pounds per square inch absolute; air-flow rate, 0.093 pound per second.

Figure 114. - Effect of oscillating combustor air supply on combustion efficiency of 2-inch-diameter combustor. Fuel-air ratio, 0.005 to 0.015 (ref. 53).

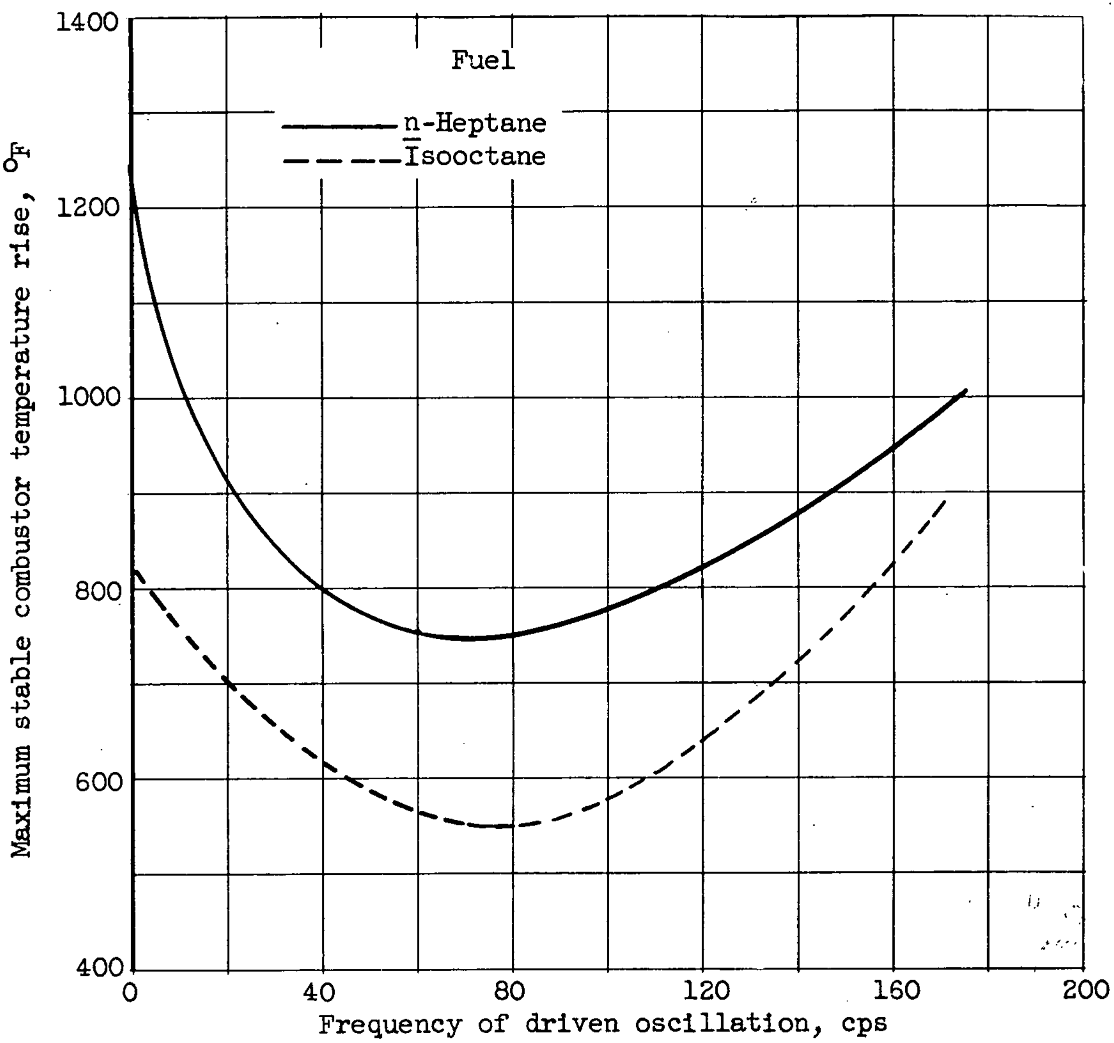


Figure 115. - Effect of oscillating combustor air supply on maximum stable temperature rise of 2-inch-diameter combustor. Inlet-air pressure, 29.5 pounds per square inch absolute; inlet-air temperature, 660° R; air-flow rate, 0.174 pound per second (ref. 53).