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AUTOIGNITION CHARACTERISTICS OF AIRCRAFT-TYPE FUELS

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SUMMARY

An applied research program was undertaken to evaluate the autoignition characteristics of five liquid hydrocarbon fuels in air over ranges of air temperature, pressure and equivalence ratio appropriate to advanced aircraft gas turbine engines. Ignition delay times were measured using a continuous flow test apparatus which permitted independent variation and evaluation of the effect of temperature, pressure, flow rate and fuel/air ratio on ignition delay time. Since the generation of a uniform mixture is a prerequisite for the evaluation of the importance of fuel/air ratio, techniques for obtaining rapid vaporization and mixing with a minimum flow disturbance were also studied and several candidate fuel injectors were fabricated and evaluated. The most durable of these injectors, a multiple conical tube configuration consisting of nineteen parallel venturi elements with independent fuel control to each element was used for most of the testing, although nearly uniform fuel-air mixture distributions were also obtained with a more fragile, distributed source strut-type injector. Measurements of the spray distribution produced by candidate injectors were made by isokinetically sampling the flow at reduced temperatures with water injection.

Parametric tests to map the ignition delay characteristics of Jet-A, JP-4, No. 2 diesel, cetane and an experimental referee broad specification (ERBS) fuel were conducted at pressures of 10, 15, 20, 25 and 30 atm, inlet air temperatures up to 1000K and fuel-air equivalence ratios of 0.3, 0.5, 0.7 and 1.0. Ignition delay times in the range of 1 to 50 msec at freestream flow velocities ranging from 20 to 100 m/sec were obtained. In accord with classical chemical kinetics, the ignition delay times for all fuels tested appeared to correlate with the inverse of pressure and the inverse exponent of temperature; viz:

$$\tau = \frac{A}{P^n} \exp\left(\frac{E}{RT}\right)$$

In general, the data were very repeatable. With the exception of pure cetane, which had the shortest ignition delay times, the differences between the

fuels tested did not appear to be significant. The apparent global activation energies for the typical gas turbine fuels ranged from 38 to 43 kcal/mole, while the activation energy determined for cetane was 50 kcal/mole. In addition, the data indicate that, for lean mixtures, ignition delay times decrease with increasing equivalence ratio. It was also noted that physical (apparatus dependent) phenomena, such as mixing (i.e., length and number of injection sites) and airstream cooling (due to fuel heating, vaporization and convective heat loss) can have an important effect on the ignition delay. Finally, preheating the inlet fuel up to 400K did not have a significant effect on the results.

INTRODUCTION

Studies of low-emission combustor concepts for advanced gas turbine engines have indicated that lean combustion of prevaporized/premixed fuels is a most promising approach for reducing NO_x emissions. However, an intrinsic problem to be treated in the design of prevaporizing/premixing combustors is the potential for inadvertent autoignition of the fuel-air mixture prior to injection into the primary combustion zone. In this context, the high combustor inlet temperatures and pressures associated with advanced gas turbine engines can easily promote ignition and flame stabilization in premixing passages, if the residence time is sufficiently long. Consequently, mixing and vaporization must be completed rapidly. In addition, although the spontaneous ignition characteristics of hydrocarbon fuels in air have been a subject of investigation for many years, none of the previous investigators has been successful in isolating and evaluating each of the experimental variables in a controlled manner over ranges of conditions representative of those encountered in advanced gas turbine engines. Thus, the existing body of autoignition data does not permit a satisfactory quantitative evaluation of the presumed effects of all the controlling parameters.

Therefore, an applied research program was undertaken to design and develop a critical experiment capable of determining the autoignition characteristics of aircraft-type fuels in air over a variety of conditions, including those representative of advanced gas turbine combustors. The program comprised analytical and experimental efforts directed toward (1) development of a comprehensive knowledge and understanding of previous autoignition research as a basis for formulation of a critical experiment, (2) design of the experiment and fabrication of the test equipment, (3) experimental verification of the approach and apparatus through a limited number of tests with Jet-A fuel over ranges of inlet air temperatures and pressures up to 1000K and 30 atm, respectively, and finally (4) compilation of an extensive data base describing the ignition delay (autoignition) characteristics of Jet-A, JP-4, No. 2 diesel, cetane, and a research test fuel designated by NASA as experimental referee broad-specification (ERBS) fuel over ranges of inlet air temperature, pressure, flow rate and fuel/air ratio typical of the mixing/combustion zones in advanced gas turbine engines. Parametric tests to map the ignition delay characteristics of these five fuels were conducted at pressures of 10, 15, 20, 25 and 30 atm, inlet air temperatures up to 1000 K, fuel-air equivalence ratios of 0.3, 0.5, 0.7 and 1.0, and residence times (required to observe the autoignition event) from approximately 1.0 to 50 milliseconds. The flow velocities associated with these tests ranged from 20 to 100 m/sec, depending on the pressure level.

REVIEW OF AUTOIGNITION LITERATURE

The spontaneous ignition characteristics of hydrocarbon fuels in air have been a subject of investigation for many years; however, none of the previous investigators has been completely successful in isolating and evaluating each of the experimental variables in a controlled manner and over ranges representative of those encountered in advanced gas turbine engines. Consequently, a thorough examination of past efforts in this area was undertaken in order to properly define a critical experiment that enabled a determination of the effects of all known or suspected variables on autoignition. A survey of the current combustion literature compiled in the Engineering Index, NTIS, Chemical Abstracts, Physics Abstracts, and Mechanical Engineering Abstracts was performed to obtain a more complete background of previous autoignition research. The Lockheed DIALOG Information Retrievel Service was used to perform a rapid and cost-effective computer search of over three million citations and abstracts from technical reports, journal articles and other technical publications. The survey produced a total of 1073 citations, of which approximately 70 were judged to be relevant to the present program. This review (1) presents a phenomenological description of the autoignition process, (2) summarizes the previous experimental techniques, indicates their areas of applicability, relative advantages and limitations, and (3) provides insight into some of the reasons for variations in the existing test data.

Preignition Processes

Wentzel (Ref. 49)* was one of the first investigators to conclude that the ignition delay time comprises a series of overlapping physical and chemical processes. The physical delay is the time required for droplet formation, heating, vaporization, diffusion and mixing with the air. The chemical delay is the time elapsed from the instant a combustible mixture has been formed until the appearance of a hot flame; it involves the kinetics of preflame reactions which result in the decomposition of high molecular weight hydrocarbon species and the formation of critical concentrations of intermediate free-radial species, so called ignition precursors. It is believed that the chemical processes start immediately upon the introduction of fuel and air in a combustion chamber; however, initially they proceed at a very slow rate and consequently the mass of fuel vapor which undergoes chemical reaction is very small compared to the mass necessary to cause a detectable temperature or pressure rise due

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* References are included in a bibliography of relevant autoignition research at the end of this report.

to combustion. Therefore, the very early stages of the preignition processes are probably dominated by the physical processes and the later stages by the chemical processes. The relative effects of the physical and chemical processes on the magnitude of the ignition delay have been studied by many investigators (e.g., Refs. 39, 43 and 48), and it has been concluded that in conventional combustion systems (e.g., gas turbine and diesel engines) the chemical delay is typically the more important of the two periods. Ample evidence has been derived from theoretical analyses and experimental investigations to indicate that chemical reaction is the rate controlling factor for autoignition. For example, Henein (Ref. 43) has calculated the time required to form a combustible mixture at the droplet surface (i.e., droplet heating, evaporation and mass transfer) for conditions representative of the start of injection in an open-chamber diesel engine and concluded that it is very short compared to the ignition delay. In addition, several investigators (Refs. 44, 65 and 66) have measured longer ignition delay times for certain of the relatively high-volatility fuels than for diesel fuel and distillate fuel oil. There is no doubt that the rate of the physical processes increase with the fuel volatility; therefore, if physical processes control the ignition delay, one would expect the opposite result. Also, it is a well known fact that the addition of small amounts of tetraethyl lead to gasoline significantly affects the ignition delay without having any known effect on the physical delay.

Cool-Flame Phenomena

In many instances the chemical portion of the ignition delay comprises two stages -- cool flame ignition and hot flame ignition. The cool flame is a relatively low temperature phenomenon ($T \lesssim 700K$ at one atm pressure) which emits a characteristic pale blue chemiluminescence in the spectral range 3000A to 5000A, due exclusively to fluorescence of electronically-excited formaldehyde, and is not accompanied by a high heat release. It is chemically distinct and should not be confused with the "blue" flame which may form in the products of the cool flame and which results in much higher heat release and flame temperatures in excess of 900K. Cool flame reactions occur when organic compounds are heated in the presence of oxygen and involve the formation of intermediate species such as peroxides and aldehydes (Ref. 11). No carbon is formed in the products of the cool flame and only a small fraction of the reactants is consumed. The temperature rise across a cool flame at one atmosphere pressure is always less than 400K, and may be as little as 300K. In comparison, normal hot flame ignitions of hydrocarbon fuels yield temperature rises in excess of 1500K. Increasing the ambient pressure or the temperature of the reactants decreases the time required for transition from a cool flame to a hot flame. A detailed explanation of the mechanisms responsible for the production of cool flames and two-stage ignition is beyond the scope of this review; however, a discussion of the general features including, the kinetics and reaction products is presented in Ref. 9. Cool flames are pertinent to the present investigation since under certain conditions (temperature, pressure, and reactant species concentration) sufficient heat is released to initiate a self-accelerating chain reaction which culminates in autoignition. The existence of cool flames just prior to autoignition has been reported by many investigators using different types of test apparatus. Mullins for example (Ref. 64), measured the emission spectra of flames resulting from the injection of liquid kerosene into a stream of high-temperature combustion products. Three stages of combustion were identified. At the lowest temperatures the spectrum consisted only of emission from excited formaldehyde; at intermediate temperature CH, OH, and strong HCO bands appeared; and at the highest temperatures the normal flame spectrum, C_2, CH and OH appeared. Similar spectral evidence of preflame reactions has been reported in flat-flame burners, reciprocating engine studies and in constant volume bomb experiments (e.g., Refs. 5 and 46).

Previous Experimental Techniques

Autoignition is generally detected by measuring a sudden increase in temperature, pressure, light emission, or concentration of free radical species. Consequently, many of the previous investigators differ in their definition of the delay period, mainly because different phenomena were used to indicate the end of this period. In addition, they have used many different types of transducers for measuring the ignition delay time. However, differences in the definition of the point at which combustion begins and the variation between the types and sensitivities of the transducers used can account for a significant portion of the discrepancy in the reported data. For example, Henein and Bolt (Ref. 42) concluded that in high-speed direct-injection diesel engines the pressure rise delay is generally shorter and more reproducible than the illumination delay. Since there is little doubt that the relative importance of the various ignition phenomena and the individual transducer sensitivities will vary over the range of fuels and test conditions of interest (e.g., cool flames are more difficult to detect than hot flames), investigators should strive to make simultaneous measurements of the illumination, pressure rise, and temperature rise delay times using different types of rapid response transducers.

A great variety of equipment and procedures has been used to measure the ignition delay of liquid hydrocarbon fuels (see Table 1), including constant volume bombs (Refs. 15 through 32), reciprocating engines (Refs. 39 through 49), and steady-flow test apparatus (Refs. 56 through 69). However, the spontaneous ignition temperature of a combustible substance is not an absolute property of the substance and, consequently, all spontaneous ignition data need to be interpreted carefully in the light of the test apparatus and methods used for their determination. Existing experimental data are generally dependent on the particular experimental configuration employed and are, therefore, too inconsistent for universal design use. For example, the automotive literature contains numerous accounts of investigations of autoignition in intermittent combustion systems; however, the effects of continuously varying pressure, temperature, velocity and turbulence, and injector spray characteristics (droplet size and distribution) prevent an unambiguous determination of the influence of any one of these variables because autoignition is a path-dependent phenomenon. Rapid compression machines lessen, but do not eliminate, the effects of transients and permit external premixing of high-vapor-pressure fuels. However, they are not readily adaptable for use with low-vapor-pressure fuels, and transients and localized phenomena which stem from nonuniform heating remain a disadvantage. Heated bomb techniques, on the other hand, usually are limited to low levels of velocity and turbulence and yield results which are configuration (shape, surface, and volume) and surface material dependent. In addition, this latter technique usually requires relatively long fuel-air mixing times and results in physical delay times which are much longer than those encountered in conventional spray-type combustion systems. Shock tube studies are limited by short test times, local nonuniformities, and usually are restricted to homogeneous gaseous mixtures. In contrast, continuous combustion devices permit ample time for measuring and regulating many of the physical variables of interest prior to spontaneous ignition while providing an opportunity to minimize those effects more subject to design variation (e.g., injector spray characteristics and degree of mixing). Furthermore, they permit an accurate simulation of autoignition in many continuous flow combustion devices, including the gas turbine.

Constant Volume Bomb Studies

Much of the early autoignition research and, in particular, investigations concerned with evaluating the minimum spontaneous ignition temperature (ignitability hazard) of a fuel, was conducted using constant volume bombs. With this type of apparatus, liquid fuel is usually injected into a cylindrical- or spherical-shaped sealed container and the pressure or light emission is continuously monitored. Consistent with classical ignition theory (Ref. 4), autoignition temperatures determined using this technique decrease with increasing container volume and decreasing surface area to volume ratio.

Wolfer (Ref. 30) measured the pressure rise delay for diesel fuel in both cylindrical and spherical bombs over a range of pressures (8 to 48 atm) and temperatures (590 to 780 K) and for low air turbulence levels. The shortest delay time recorded was 45 msec. The data were correlated with an expression for the delay period as a function of the air pressure and temperature whose general form is similar to those determined by more recent investigators (Refs. 25, 47 and 66).

$$\tau = Kp^{n}e^{C/T}$$

where K, C, and n are constants. He also concluded that, in his apparatus, ignition delay was independent of fuel/air ratio, air turbulence, and fuel injection characteristics.

Starkman (Ref. 29) studied the effects of pressure, temperature, and fuel/air ratio on the pressure-rise delay in a CFR diesel engine and in a bomb. The volume of the bomb was equal to the clearance volume of the engine. He found that the pressure rise delay is reduced by an increase in any of the above factors, and that it is shorter in the engine than in the bomb.

Hurn, et al., (Refs. 20 and 21) in two separate investigations studied the effect of pressure, temperature and fuel composition on the pressure-rise delay and the factors governing the magnitude of the physical and chemical delays. They tested several different fuels using a constant volume bomb that was precharged with one of several different gas mixtures which varied in oxygen concentration. Tests were conducted over ranges of pressures (19 to 46 atm), temperature (728 to 840 K), and oxygen concentration (15 to 40 percent). They concluded that for a constant oxygen partial pressure there is an optimum oxygen concentration that results in a minimum ignition delay time, and that the physical delay was primarily dependent on the properties of the ambient gas while the chemical delay was influenced by the fuel composition.

More recently Kadota, et al., (Ref. 25) used a constant volume bomb to determine the ignition delay of a single droplet of hydrocarbon fuel. Tests were conducted at pressure of 1 atm to 41 atm and ambient gas temperatures of 500K to 975K. The shortest delay time measured was approximately 100 msec. Their data were correlated by an expression similar to Wolfer's (Ref. 30) but which also included the oxygen concentration as a variable.

$$\tau = Kp^n \phi^D e^{C/T}$$

where Φ is the oxygen concentration and D is a constant. They concluded that ignition delay was independent of droplet size and decreased with increased oxygen concentration.

Rapid Compression Methods

The use of rapid-compression machines for studying the autoignition characteristics of homogenous fuel-air mixtures was originated by Falk (Ref. 33) in 1906. Since that time devices of this type have undergone continuous development and have been used by a number of investigators. The MIT Rapid Compression Machine (Ref. 38), developed in 1950, is the most advanced apparatus of this type. Ideally, a rapid-compression machine compresses a mixture adiabatically and maintains it at its peak temperature and pressure for the duration of the delay period. Compression is accomplished by the rapid motion of a piston in a closed-end cylinder. Ignition is determined from the pressure-time record or from optical measurements. Compression should be rapid, but without the formation of shocks; consequently, the minimum compression time in the MIT apparatus is approximately 6 msec. Therefore, short ignition delay times (on the order of 5 msec) cannot be investigated without preliminary chemical reaction during the last phase of compression. Also, measurement of the compressed gas temperature is a problem for short delay times.

Leary, Taylor, Livengood, et al., (Refs. 36, 37 and 38) used the MIT apparatus to determine the ignition delay time and the rate of pressure rise during autoignition of several hydrocarbon fuels at various fuel-air mixture ratios, compression ratios, and inlet temperatures. It was reported that a minimum value of ignition delay occurred at approximately stoichiometric mixture conditions and that the delay time decreased with an increase in compression ratio and initial temperature. High-speed motion pictures of the luminous flame revealed that the reaction was not homogeneous, and that a large number of small bright spots first apeared locally and then spread through the mixture. Schlieren photographs proved the existence of temperature gradients in the compressed gas. A two-stage autoignition reaction for iso-octane and n-heptane was also observed.

Reciprocating Engine Studies

Many investigators have studied ignition delay in diesel engines and have correlated their results with various operating conditions and fuel properties. Uncertainties regarding the measurement of temperature and, in some cases, pressure at the end of the delay period hampered these studies; however, in 1939 Schmidt (Ref. 47) provided a correlation for the chemical delay in diesels which reduced to the Wolfer equation for a constant volume bomb. More recently, Lyn and Valdmanis (Ref. 45) and Henein and Bolt (refs. 42 and 44) have performed comprehensive studies of the effects of cylinder pressure and temperature, inlet air temperature, overall fuel/air ratio, cooling water temperature and engine speed. They concluded that cylinder pressure and temperature are the major factors affecting the delay and that an increase in any of the above parameters reduced the ignition delay time. However, continuously varying pressure, temperature, velocity, turbulence and fuel spray characteristics precluded an unambiguous determination of the effects of individual parameters. Also, as is the case for rapid-compression machines, temperature gradients result in localized ignitions.

Garner, et al., (Refs. 40 and 41) measured the illumination delay in a single-cylinder research diesel engine and reported that the delay time decreased with increasing compression ratio until some critical ratio was reached, after which the delay began to increase. Henein and Bolt (Ref. 44) have also reported a slight increase in ignition delay with increased temperature at cylinder temperatures above 1100K. They suggest a possible mechanism for this phenomenon based on two-stage combustion.

Shock-Tube Studies

Shock tubes have been widely used to investigate the high-temperature ($T > 1000K$) oxidation of low molecular weight gaseous hydrocarbons; however, there is considerable scatter in the data reported. Some investigators have measured the ignition delay using systems in which reaction was initiated by an incident shock wave, and others have chosen systems in which reaction was initiated by a reflected shock wave. The latter system offers the advantage of maintaining the reacting mixture at a constant temperature (apart from wall losses) for a known period of time; however, the initial temperature behind a reflected shock can usually only be calculated to an accuracy of ±50 K. In addition, both the type of diluent (e.g., air, nitroge , argon, and helium) and concentration of diluent used have varied from one investigator to another, as have the experimental criteria for definition of the delay time (e.g., the rapid increase in characteristic emission of free radial species, a sudden rise in pressure or heat flux measurements, etc.).

The majority of shock-tube investigations have been concerned with methane because of the relative simplicity of its oxidation process as compared to those of higher molecular weight hydrocarbons. Skinner, et al., (Ref. 53) summarized most of the data for methane published prior to 1972 and compared them on the basis of a correlation developed by Lifshitz, et al., (Ref. 51) which is of the form

$$\tau = Ke^{C/T} [Ar]^{n_1} [CH_4]^{n_2} [O_2]^{n_3}$$

The data cover the temperature range 1100 to 2300K at pressures varying from 1 to 10 atm for mixture equivalence ratios of 0.5 to 8.0. For these conditions the induction times varied from 10 to 700 μsec.

A study of the autoignition of n-heptane and iso-octane behind reflected shock waves was conducted by Vermeer, et al., (Ref. 55). Induction time data were obtained over ranges of pressure (1 to 4 atm) and temperature (1200 to 1700K). High-speed schlieren photographs demonstrated the existence of two different modes of ignition--strong ignition, characterized by the formation of a blast wave, and mild ignition wherein chemical reaction was initiated simultaneously at many different points. The pressure-temperature limits defining the regions of mild and strong ignition were determined.

Continuous Flow Methods

Early continuous flow (steady-flow) investigations of the spontaneous ignition characteristics of fuels injected into high-temperature, high-velocity airstreams were conducted by Mullins (Ref. 63) in vitiated air at pressures equal to or below 1 atm. The test apparatus consisted of an axisymmetric diffuser in which the pressure, temperature and mixture flow rate were adjusted to maintain a stationary flame front. High inlet temperatures were achieved by means of precombustion upstream of the test duct. Fuel was injected into the airstream through conventional atomizers and care was taken to localize the spray near the center of the duct in order that the influences of the wall and boundary layer be eliminated. The point of ignition was determined by direct visual observation through a series of windows, and the ignition delay time was considered equivalent to the residence time of the fuel-air mixture between the point of injection and the axial position of the flame. In this system, temperature and oxygen concentration were linked due to vitiation heating, so that as temperature was increased, oxygen concentration decreased and water concentration increased. However, vitiation without oxygen replenishment was shown to have a significant effect on ignition delay. Mullins reported that the ignition delay of kerosene in vitiated air at atmospheric pressure is inversely proportional to the square of the oxygen concentration. (Subsequent investigations (Refs. 20, 21, and 25) have confirmed that an inverse relationship exists between ignition delay time and oxygen concentration for a variety of hydrocarbon fuels.) In addition, the possible effects of combustion product contamination (e.g., increased concentration of water vapor and various free-radial species) are still unknown.

Stringer, et al., (Ref. 66) measured the ignition delay of several pure and distillate hydrocarbon fuels in an oxygen-replenished vitiated airstream over a range of pressures (30 to 60 atm) and temperatures (770 to 980 K). In this study, simulation of combustion in diesel engines was achieved by using a pulsed diesel-type fuel injector situated normal to the airstream, and ignition was detected by photoconductive cells. Of the various physical factors investigated, air temperature and pressure were found to exert the major influence on the ignition delay, while velocity, fuel/air ratio, and turbulence intensity had a negligible effect. The ignition delay data were correlated using an Arrhenius-type expression similar to Wolfer's (Ref. 30) and in addition, an alternative expression of the form;

$$\tau = \frac{1}{P^n\ (BT - A)}$$

was derived where A, B, and n are constants which were determined for several of the more widely used fuels.

The experimental techniques pioneered by Mullins were later adopted and improved upon by Taback (Ref. 68) and more recently by Spadaccini (Ref. 65). Taback conducted an investigation of the autoignition characteristics of JP-4 in vitiated air at ambient pressures of 17 to 28 atm and temperatures of 700K to 900K. The autoignition test section walls were water cooled, and like Mullins, tests were conducted using a centrally-located spray-type injector. Safety considerations precluded direct visual observations of the flame front position; therefore, provision was made for indirect determination of the point of ignition by installing photoconductive cells in the test duct at a multitude of axial locations. In addition, evaluations of (1) the influence of walls and the resulting boundary layer, (2) the flashback potential of a transient ignition source, and (3) the flameholding potential of wake-producing surface imperfections on ignition delay were performed over a limited range of test conditions and for a specific premixing duct geometry.

Spadaccini (Ref. 65) continued the work started by Taback and, using essentially the same test apparatus, investigated the autoignition characteristics of JP-4, No. 2 fuel oil, and No. 6 fuel oil in dry unvitiated air at temperatures in the range 670K to 870K and at pressures in the range 6.8 atm to 16.3 atm. The air was heated by means of an electrical resistance-type heater and the pressure was regulated by a remotely operated throttle valve. The effects of a number of physical factors, including air pressure and temperature, fuel temperature and concentration, and initial spray characteristics (e.g., droplet size and size distribution), upon the ignition characteristics were evaluated. Ignition delay times were shown to vary according to an empirically determined relationship which was also similar in form to Wolfer's. In addition, the possible influence of the flame front on the magnitude of the delay period, e.g., by radiant heating or alternation of the pressure distribution within the diffuser, was evaluated and it was concluded that measurements were unaffected by its presence.

A significant deficiency of the preceding continuous flow types of test apparatus is the difficulty in using them to evaluate the importance of the local fuel-air mixture ratio on autoignition. Continuous combustion devices, such as those described above, preclude the mesurement of delay time for uniform fuel-air mixtures because the wall boundary layer provides a path for the upstream propagation of flame from the autoignition point to the injector (thus obscuring the point of ignition). The advantages of this apparatus, on the other hand, are (1) that it accurately simulates autoignition phenomena occurring as a result of spray injection and (2) that it permits rapid data acquisition, since the flame is continuously present and its axial position, and therefore, delay period can be continuously varied by regulation of the flow variables.

The route to precluding some of the deficiencies of the work of Spadaccini and Taback was incorporated in a steady-flow test apparatus developed by Mestre and Ducourneau. It is described in Refs. 58 and 62 and utilizes a premixing-type injector to investigate the dependence of ignition delay on the local equivalence ratio of kerosene-air mixtures. Experiments were performed in a 42-mm-dia cylindrical tube at pressures in the range of 5.4 atm to 12 atm and over the temperature range 720K to 1075K. The flow velocity was fixed at approximately 70 m/sec by means of a sonic nozzle installed at the tube exit, and the residence time was varied by interchanging four tubes of different lengths. The test procedure consisted of gradually increasing the inlet air temperature until autoignition was visually detected at the nozzle exit at which time the test was abruptly terminated. The ignition temperatures of mixtures in the equivalence ratio range 0.5 to 8.0 were measured for fixed residence times of approximately 3 msec, 6 msec, 7 msec, and 12msec. (The constant velocity constraint imposed by the use of a sonic nozzle restricted the variation of residence time to a fixed number of values.) Their data indicate that fuel-air mixture ratio is an important factor affecting autoignition; minimum ignition temperatures were obtained for an equivalence ratio of 3.0 at 5.4 atm and for an equivalence ratio of 1.0 at 11 atm.

More recently, Marek, et al., (Ref. 61) have studied the autoignition and flashback characteristics of lean mixtures of Jet-A fuel in air at temperatures in the range 550K to 700K and pressures in the range 5.4 atm to 25 atm. The autoignition test apparatus consisted of a 10.2-cm-dia cylindrical "prevaporizing/premixing flame tube", a single element contrastream fuel injector, and a perforated-plate flameholder located 66 cm downstream of the fuel injector. Upon establishing a predetermined pressure and temperature within the flame tube, the fuel flow rate was slowly increased until autoignition occurred and was indicated by a thermocouple positioned 1 cm upstream of the flameholder. The ignition delay time was defined as the residence time between the injector and the flameholder, as it related to the instantaneous pressure and temperature. Ignition delays in the range 15 msec to 100 msec were measured and it was concluded that they varied inversely with the ambient pressure. In addition, preflame reactions, similar to cool-flame phenomena, were reported and flashback velocities of 35 m/sec to 65 m/sec were measured at 5.6 atm and 610K and 700K.

In the latter two test arrangements, as in all others which strive to produce mixture homogeneity, the measurement of delay times may be affected by chemical reactions which can occur in the boundary layer along the walls. Neither of the previous investigators (Refs. 61 and 62) make mention of the occurrence of ignition and combustion in the boundary layer even during tests in which the tube wall was externally heated to the inlet air temperature; however, it appears that autoignition and its precursors may occur in the slower moving (i.e., longer residence time) mixture in the boundary layer in a situation in which the wall temperature is at or near the inlet air temperature. Also, flow disturbances, such as those produced by large-size fuel injectors or high-blockage flameholders, should be avoided since they may create local regions of flow recirculation and, therefore, high residence time.

Summary of Existing Data

It is clear from the above summary that there is considerable disagreement among the previous investigators regarding the importance of mixture ratio on autoignition. Some have reported no effect (Refs. 30 and 63), others have observed a minor effect (Refs. 38, 45 and 66) and still others have found a major effect (Ref. 58 and 62). These apparent inconsistencies underscore the previous admonition that existing data need to be interpreted carefully in the light of the test apparatus and the methods used for their determination. The achievement of a uniform mixture is a prerequisite for an evaluation of the importance of fuel/air ratio; therefore, fuel-air mixture sampling tests should be conducted to obtain a quantitative indication of the extent of vaporization and the degree of uniformity of the fuel-air mixture produced by the injector. The mixture quality, or the degree of vaporization achieved prior to the onset of autoignition, may have a significant influence on the magnitude of the delay time and, therefore, ignition delay data may not correlate solely on the basis of overall equivalence ratio.

Finally, the ignition delay data for typical gas turbine and diesel fuels which have been reported in several of the investigations discussed above are summarized and compared in Fig. 1. The discrepancies between the magnitude of the delay times measured by the various investigators are apparent, particularly at high ambient pressures, as is the disagreement regarding the rate of change of delay time with increasing pressure. A portion of these differences may be attributed to variations in fuel composition, stemming from broad fuel specifications and poor documentation of fuel properties. However, differences in data reported for a particular fuel are often larger than differences measured between various grades of fuel. Therefore, it is likely that the major variations originate from differences in the experimental apparatus and the methods used to identify the autoignition event.

EXPERIMENTAL APPROACH

Description of Apparatus

It can be concluded from the preceding review of autoignition research that parametric autoignition data pertinent to gas turbine engines can best be acquired by conducting a continuous flow experiment using dry, unvitiated air, and providing independent control of pressure, temperature, and mass flow rate (therefore, residence time). The test apparatus used in the present program is shown in Fig. 2. It consists of (1) an electrical resistance-type air heater, (2) an inlet plenum and flow straightner, (3) a premixing-type fuel injector, (4) a cylindrical mixer/vaporizer section comprising several flanged spool pieces to permit length variation over the range 2.5 cm to 150 cm in increments of 2.5 cm, (5) an expander section which provides a sudden expansion and water quench at the autoignition station, (6) a variable area orifice to isolate a fuel scanvenging afterburner from the experiment, (7) a scavenger afterburner, and (8) a remotely operated throttle valve located in the exhaust ducting.

Details of the mixer/vaporizer and expander sections are shown in Fig. 3. The inner surface of the mixer/vaporizer sections are smooth and free of boundary discontinuities capable of producing wakes in the flow. This is accomplished by internal machining and the use of alignment dowels for each section of the mixer/vaporizer. The walls of the mixer/vaporizer sections were water-cooled during all tests in order to preclude the possibility of ignition and flashback via the boundary layer even though theoretical analyses were not able to conclusively demonstrate that cooling was required. Since the facility afterburner, located in the exhaust ducting, represented a continuous ignition source and because autoignition may be initiated at an axial location within the sudden-expansion section, additional precautions were taken to eliminate any path by which the flame might propagate upstream into the mixer/vaporizer section (e.g., through the wall boundary layer and/or by means of recirculation zones). These precautionary measures included (1) direct water injection at the step region, to prevent flame stabilization at the exit of the mixer vaporizer, and (2) installation of a two-dimensional flow nozzle just upstream of the sudden expansion, to accelerate the flow locally and provide additional water injection to rapidly quench the chemical reaction. Thermocouples and photodetectors were used to monitor the step region and identify conditions which would result in flame stabilization. During preliminary testing with Jet-A fuel, it was determined that unsteady combustion in the afterburner generated pressure fluctuations which were transmitted upstream to the mixer/vaporizer section and caused premature (i.e., low temperature) ignition. Therefore, all subsequent tests were performed with the afterburner combustion terminated prior to autoignition.

Test Procedure

The normal operating procedure consisted of establishing a prescribed condition (e.g., pressure and flow rate) within the test duct and gradually increasing the inlet air temperature until autoignition occurred at the exit of the mixer/vaporizer section. The occurrence of autoignition was determined indirectly by (1) a thermocouple probe located in the expander section, (2) photodetectors (located at several positions in the test rig), (3) a differential pressure transducer monitoring the pressure drop across the mixer/vaporizer section, and (4) absolute pressure transducers in the mixer/vaporizer (see Fig. 3). Upon ignition, the test was abruptly terminated by shutting off the fuel flow, reducing the rig pressure and temperature, and purging the fuel injector with water. Subsequent tests were not performed until the system had been purged of residual fuel by the airflow which was maintained at all times. This test arrangement permitted independent variation of each of the important variables (i.e., pressure, temperature, velocity, residence time, and fuel/air ratio) within a fixed range of test conditions. During data reduction, the ignition delay time was equated to the residence time of the fuel-air mixture between the point of fuel injection and the location of the water quench just upstream of the expander section. It was computed based upon the average flow velocity as calculated from the inlet temperature, pressure and airflow rate.

Inlet air temperature and pressure were measured upstream of the fuel injection location. A choked venturi flow meter was used to measure the inlet airflow rate and the fuel flow rate was measured using a calibrated turbine meter. Inlet fuel temperature and pressure were monitored at the injection station. A 12 channel high-speed oscillograph continuously displayed the output of key instrumentation. The occurrence of autoignition was identified by a sudden and very rapid increase in the pressure, temperature and photodetector outputs.

Injector Development

Since the generation of a uniform fuel-air mixture in the shortest distance (time) possible is crucial for determining the effect of fuel/air ratio on autoignition, especially at the more severe test conditions, several candidate fuel injectors were fabricated and evaluated experimentally. Each injector was designed to provide rapid vaporization and mixing while minimizing flow disturbances. A total of four different distributed-source injector configurations were evaluated in this program, each with its own merits and liabilities. In all configurations, precautions were taken to ensure that the fuel delivery pressure level was sufficiently high to render the injection rate insensitive to minor rig pressure fluctuations.

Although injector evaluations are most useful when they are conducted using representative fuels, water was substituted as a fuel simulant to simplify the "fuel" -air sampling procedure used for injector qualification. This approach undoubtedly gave a conservative estimate of injector performance but, nevertheless, provided a valuable comparison of injector design philosophies on a relative basis. Water spray distributions can be representative of fuel distributions when tests are conducted at typical operating conditions and when vaporization rates are low. Therefore, all injector characterization tests were conducted under test conditions which minimized vaporization and duplicated the free-stream velocity and fuel flow rates of a typical autoignition test condition. Measurements of the water spray distribution produced by candidate injectors were made along two mutually perpendicular diameters at a mixing length of 18 cm. The two-phase flow was sampled isokinetically and a water separation and collection system was used to collect samples for a predetermined time period. Prior to measuring the water spray distributions, the uniformity of the airflow was evaluated by measuring the velocity distributions at the entrance of the mixer/vaporizer section and at the sampling station with the candidate injector in place. Typically, the results indicated a symmetric profile that was slightly peaked near the centerline. The maximum deviation of the local velocity from the average velocity was ± 12 percent.

Contrastream Injector

The first distributed-source type fuel injector, shown in Fig. 4, was designed to achieve efficient atomization as a result of high shear forces which are created by (a) the impingement of high velocity fuel jets on stationary splash plates and (b) the interaction of the high velocity airstream and the liquid film issuing from the splash plates. A low convective heat transfer rate to the fuel injector tubing was ensured by the shielding provided by the upstream splash plate and the backwash of fuel over its outer surface. The fuel inlet temperature was continuously monitored using fine wire thermocouples (0.25-mm-dia) which were inserted into the 1.6-mm-dia hypodermic tubing. Results of the injector evaluation tests indicated that significant liquid penetration to the wall occurred. Also, it was hypothesized that the 32-0.25-mm-dia orifices, which at times became partially plugged and required frequent cleaning, and the relatively high velocity liquid jets (V_j = 60 m/sec), which were reflected from the splash plates at various angles might have been too energetic and contributed to mixture nonuniformities.

Cross-Stream Injector

After several improved designs were fabricated and tested, the injector shown in Fig. 5 produced a spray distribution that appeared sufficiently uniform to permit evaluation of the effects of fuel-air mixture ratio on autoignition. In this configuration, fuel was injected normal to the airflow and into segments of approximately equal area from 64-0.38-mm-dia orifices in six 3.0-mm-dia tubes. Splash plates were installed along both sides of the outermost injector elements and baffles were placed between adjacent injection orifices to impede the flow of liquid to the wall. The number and size of the injection orifices was chosen as a best compromise after consideration of liquid jet penetration, orifice plugging, and injector sensitivity to combustor pressure oscillations. Although the results of initial spray characterization tests indicated that the spatial distribution of liquid was parabolic-shaped with a high concentration at the center, a nearly uniform distribution of liquid was obtained by reducing the flow rate to the two central injector elements. The spray distribution 18 cm downstream of the injection station which was obtained subsequent to these improvements is shown in Fig. 6. In the figure, the local fuel/air ratio is normalized with respect to the overall fuel/air ratio as determined from the total water and airflow measurements. The results indicate a concentration peak in the central portion of the mixer/vaporizer with reduced concentration levels near the wall, probably due to diffusion and accumulation of liquid on the wall. However, as indicated in Fig. 6, this injector configuration had implemented the successful retention of a high percentage of the "fuel" in the airstream at the 18 cm station, and the maximum deviation from the mean concentration incurred at the centerline was only ± 5 percent.

The spray distribution from this injector was judged sufficiently uniform to permit evaluation of the effect of fuel-air mixture ratio on autoignition, and therefore parametric testing of the Jet-A fuel was initiated. However, during autoignition testing a flashback was encountered which resulted in structural failure of the injector elements. Therefore, a new injector having higher strength and providing the option for water cooling was designed and fabricated.

Modified Cross-Stream Injector

In view of the limitations of the previous injector design a modified distributed-source cross-stream injector featuring increased strength, water cooling and streamlined-shaped strut elements was fabricated and tested. This injector, shown in Fig. 7, consisted of six 0.32-cm-wide by 3.8-cm-long streamline-shaped struts containing a total of 63-0.38-mm-dia injection orificies. As in the previous design, fuel was injected normal to the airflow from both sides of each strut into airflow cross sections of approximately equal area. The injection orifices extended into the airstream as shown in Fig. 7, to impede the formation of a fuel film on the strut surface. Correlations of circular jet penetration data were used to estimate the fuel jet penetration distances as a function of jet momentum and diameter so that, in the final design, fuel jet impingement on opposing hot surfaces could be avoided. Flow disturbance, and therefore pressure loss, was minimized by the streamlined-shaped design, and because of the increased mass, the individual struts were expected to be much more resistant to damage from flashback. In addition, each of the injector elements was water cooled to maintain the fuel at a prescribed inlet temperature and to protect the injector from overtemperature. The relatively high blockage (approximately 55 percent) was also expected to reduce any inlet airflow nonuniformities. Fuel injection temperature was monitored using a fine wire (0.25-mm-dia) thermocouple inserted midway into the fuel passage of one of the central elements.

Characterization of the water spray distribution produced by the streamline-shaped injector indicated a nearly parabolic-shaped profile with the peak concentration at the centerline. The overall "fuel"-air distribution observed 18-cm downstream of the injector station, see Fig. 8, was inferior to that achieved using the preceding tube-type injector, even though the fuel fraction retained in the airstream appeared to be high. With this injector configuration, the maximum local fuel/air deviation from the overall composition was approximately ±20 percent. In an attempt to understand the cause of the large deviations, static pressure measurements were made along each of the injector elements. It was found that a static pressure gradient of approximately 33 percent of the overall injector pressure drop existed between the outermost and innermost injector elements. Attempts to improve the airflow distribution by increasing the injector pressure loss were unsuccessful.

To gain further insight into the details of the injection and mixing processes, carbon dioxide was introduced into the airflow through the fuel injector. The volumetric flow rate of gas was set equal to the volumetric flow rate of liquid tested previously, and the flow was sampled and analyzed for CO_2 concentration. The results, presented in Fig. 9, indicated a more uniform CO_2-air distribution but there was still a higher than average injectant concentration near the centerline. However, a comparison of Figs. 8 and 9 shows that the droplets were unable to follow the streamline flow, and therefore, it was felt that some improvement in the fuel spray distribution may be realized in actual ignition delay testing, as a result of accelerated vaporization and reduced concentration gradients at the wall due to elevated temperature. Although the degree of uniformity achieved was less than desired, some preliminary autoignition testing was performed using the streamline-shaped injector and the data are included in Appendix A and discussed in the following section under the results for Jet-A Fuel.

Costream Injector

To permit a clear determination of the effect of fuel-air equivalence ratio on autoignition, a new type injector similar to one developed in Refs. 69 and 70, and demonstrated to be capable of producing a more uniform mixture distribution was designed and fabricated. The multiple conical tube-type injector, presented in Fig. 10, consisted of a 19 hole concentric array of venturi-shaped air passages with independently-controlled fuel injection into the converging section of each element. Fuel was supplied to each of the venturis by means of small diameter tubing that was sufficiently long to provide ample pressure loss to minimize the effect of rig pressure fluctuations on fuel flow rate. Downstream recirculation zones were eliminated by extending the diverging sections of the venturis to the points of intersection, thereby eliminating a base region. Also, the relatively high blockage area (approximately 70 percent) acted to reduce inlet airflow nonuniformities. The injector was flow checked and calibrated prior to testing, and it was determined that the flow coefficients of the 19 individual injector elements were all within 2.8 percent of the mean value. Airflow measurements of the static presure at the throat of each of the

19 venturi-shaped passages indicated a maximum difference between elements of only 8.0 percent of the overall fuel injection pressure drop. These variations were considered sufficiently small as to permit the attainment of a nearly uniform fuel injection rate from element to element.

The spray from the multiple-conical tube injector was evaluated at several simulated test conditions and by selectively restricting the flow of water to individual injector elements. The results of the testing are shown in Figs. 11 through 13. As shown in Fig. 11, the spray distribution obtained with all injector elements open was concentrated in the center. Also, even though the "fuel"/air profile distortion decreased at higher flow rates, approximately 30 to 40 percent of the liquid had apparently collected on the wall, as is indicated by a normalized fuel/air ratio of less than 1.0. By shutting off the water flow to the center element, see Fig. 12a, a slight reduction in the centerline concentration was observed, and as might be anticipated, no noticeable change in the "fuel"/air profile at radial positions beyond $R/R_o = \pm 0.5$ was achieved. Capping the injector elements to the twelve outer venturis increased the concentration at the centerline and appeared to suppress liquid transfer to the walls, i.e., most of the liquid could be accounted for in the airstream (see Fig. 12b). When both the center and the twelve outer elements were capped there was still a somewhat center peaked profile, especially at the lower air velocities, as shown in Fig. 13. However, the mean equivalence ratio was close to the overall value, indicating that most of the injected "fuel" had been entrained by the airstream. Consequently, all further autoignition tests with the conical tube injector were conducted with this configuration, i.e., with the center and outer injection elements capped. The data indicate this configuration minimized fuel accumulation along the walls and resulted in a predictable and nearly uniform profile at radial positions up to $R/R_o = \pm 0.5$.

EXPERIMENTAL RESULTS AND DISCUSSION

After selection of the conical tube injector, with the center and outer elements capped, as the configuration giving the best compromise between durability and mixture uniformity, parametric testing was initiated to map the ignition delay characteristics of Jet-A, JP-4, No. 2 diesel, cetane and ERBS fuels. Tests were conducted at pressures of 10, 15, 20, 25 and 30 atm, with fuel-air equivalence ratios of 0.3, 0.5, 0.7 and 1.0, and inlet air temperatures up to 1000K. Ignition delay times in the range of 1 to 50 msec were obtained by interchanging spool pieces to create several different mixer/vaporizer lengths (6.4 cm to 117 cm). Typically, tests were conducted at an airflow rate of 0.5 kg/sec and the resulting free stream velocities were in the range of 20 to 100 m/sec, depending on the ambient pressure level. A few tests were conducted at an airflow rate of 1.0 kg/sec to verify that the ignition delay times were relatively insensitive to changes in flow velocity. Also, several of the Jet-A tests were conducted using the modified cross-stream (streamline) injector. Furthermore, the effect of preheating the inlet fuel up to 400K was evaluated for Jet-A fuel, and selected tests were made with JP-4 fuel with all nineteen injector elements open to investigate the effect of changes in the injection profile on autoignition.

Within the experimental accuracy, the ignition delay times for all the fuels tested appeared to correlate with ambient pressure and inlet air temperature according to the classical Arrhenius type equation

$$\tau = \frac{A}{P^n} \exp \left(\frac{E}{RT}\right)$$

where E is the global activation energy corresponding to all the physical and chemical processes occurring during the induction period, R is the universal gas constant, and A and n are empirical constants. Regression analyses performed on the autoignition data obtained for each of the fuels tested indicated that a pressure exponent of approximately 2.0 yielded the best fit of the experimental data. Therefore, a value of n = 2.0 was used to develop generalized correlations for each of the fuels tested.

Intrinsic ignition delay data require an accurate knowledge of the free-stream conditions at the onset of autoignition. In the present experiment, the free-stream temperature can depart significantly from the inlet air temperature as a result of cooling as the fuel is preheated and vaporized and by convective heat transfer to the mixer/vaporizer wall. The degree of airstream cooling is dependent both on the apparatus (e.g., adiabatic or nonadiabatic boundaries) and the test conditions (e.g., fuel/air ratio, mixture distribution, pressure, temperature, airflow rate and residence time). Convective heat transfer calculations require an accurate measurement of the mixer/vaporizer wall temperature distribution; therefore, although wall temperatures were monitored during several tests (using thermocouples installed at various depths in the mixer/vaporizer wall and on the outer, water-cooled, surface), analytical heat transfer predictions do not have sufficient accuracy. For example, calculations performed using a 2-D turbulent boundary layer code developed at UTRC indicated that at a typical autoignition test condition (T = 811K, P = 30 atm, V = 35 m/sec) and wall temperature (395K), the centerline (free stream) temperature would remain constant for an axial distance equivalent to 40 L/D (172 cm). Beyond this axial distance, the flow would be fully developed and the bulk temperature would decrease at a rate of approximately 0.8K per cm. Although the predictions indicate that there is little cooling of the airstream along the centerline, the precise radial location at which autoignition occurs is not known. Furthermore, since the ignition delay time is an exponential function of the ignition temperature, a small change in the local temperature can significantly affect the correlations developed.

Since direct measurement of the mixture temperature at the onset of autoignition was precluded, to avoid introducing any preferential ignition sites into the flow, the mixture temperature was calculated, assuming an adiabatic wall and complete vaporization and mixing. In addition, in order to elucidate the effect of equivalence ratio on autoignition, the ignition delay data were also correlated as a function of the calculated temperature of the fuel-air mixture. However, because autoignition typically results from the accumulated effects of one or more precursor reactions and/or physical events and is, therefore, dependent upon prior history, the equivalence ratio correlations must be regarded as qualitative, indicating general trends rather than magnitudes.

Because each of the test fuels exhibit similar trends in the ignition delay data, the results for one typical fuel are discussed in greater detail than the others. Also, although the order of testing began with parametric mapping of the conventional jet fuels (i.e., Jet-A and JP-4), the ignition delay data for No. 2 diesel fuel are discussed first because the data scatter was significantly reduced, probably due to improvement of the experimental techniques. In addition, a large experimental data base was obtained for No. 2 diesel fuel. In a few instances, the data exhibited an anomalous behavior in that autoignition failed to occur at temperatures well above the predicted or extrapolated levels. These data were judged spurious and are not included on any of the correlating curves; however, for completeness they are included in a tabulation of all the test data which is presented in Appendix A.

No. 2 Diesel Fuel

Parametric autoignition testing of No. 2 diesel fuel was performed using the standard configuration of the multiple conical tube (costream) injector. A summary of the results is presented in Figs. 14 through 19. As expected, the results indicate that ignition delay decreases with increasing air temperature and pressure. In Fig. 14, the data for the different equivalence ratios tested were commingled and plotted versus the reciprocal of the inlet air temperature. The Arrhenius approximation determined from a linear regression analysis of the data indicated that the apparent global activation energy is 41.6 kcal/mole. This activation energy is in close agreement with the activation energy reported in Ref. 65 for No. 2 fuel oil at similar temperatures and pressures. Activation energies ranging from 10 to 50 kcal/mole have been reported by other investigators for typical liquid hydrocarbon fuels in air; however, it is difficult to make direct comparisons of data because it is seldom possible to separate the physical and chemical phenomena. Also, direct interpretation of the activation energy is only meaningful for simple bimolecular reactions, and is of limited usefulness in the present context. Some scatter is present in the data, particularly at conditions of short mixing length (7.6 cm) and low pressure (highest velocity), suggesting an increased importance of apparatus-dependent phenomena at these conditions.

The combined effects of mixing length and airstream cooling are illustrated more clearly in Figs. 15 and 16, where the temperature scale is expanded and the ignition delay data are differentiated with respect to mixer/vaporizer length and fuel-air equivalence ratio. As can be seen from the figures, length is an important variable in the present experiment, particularly at low equivalence ratio (see Fig. 15). For lean overall equivalence ratios, mixture nonuniformities (such as would be obtained at short lengths) tend to increase the liklihood of autoignition; whereas, increased length leads to increased mixing and cooling and decreases the liklihood of autoignition. Thus, the competing effects tend to increase the data separation and illustrate the importance of the prior history of the fuel-air mixture. For ease of comparison, the commingled data correlation is also shown. At the shortest mixer/vaporizer length (L = 7.6 cm) and lowest equivalence ratio ($\Phi = 0.3$) there is a substantial deviation of the data from the overall correlation (see Fig. 15); however, at higher equivalence ratios ($\Phi \geq 0.5$) and for increased mixing length ($L \geq 22.9$ cm) the agreement is much improved. In addition, an apparent "reduction" in the activation energy is evident at low levels of $\tau \cdot P^2$ (which correspond to conditions of low pressure and high temperature and result in short residence times), and at the low equivalence ratio ($\Phi = 0.3$). Similar "reductions" in apparent activation energies have been observed by other investigators (Refs. 32, 65 and 68) and probably reflect the increased importance of the constituent physical processes at these conditions.

The importance of the fuel-air mixture ratio on autoignition of No. 2 diesel fuel is shown in Figs. 17 through 19. As stated above, the data are correlated as a function of the calculated mixture temperature since there is significant cooling of the airstream as the fuel is vaporized and heated to the air temperature. For example, a temperature depression of approximately 80K will occur at an inlet air temperature of 800K when the equivalence ratio is 1.0 (See Fig. 17). This is particularly significant in view of the disproportionate effect of temperature on ignition delay. The data shown in Fig. 18 were correlated for each of the equivalence ratios tested and the results were cross-plotted in Fig. 19 as a function of mixture temperature. The short mixing length (7.6 cm) data are not included since the extent to which vaporization and mixing are completed at this length is uncertain. The results for a mixture temperature of 700K are shown in Fig. 19, and indicate that, for lean mixtures, increasing fuel/air ratio significantly decreases ignition delay; however, actual measurements of the mixture temperature at the onset of autoignition will likely indicate a more moderate effect as a consequence of the dependence on prior history. This trend is in agreement with the data reported in Ref. 58 for kerosene-air mixtures.

ERBS Fuel

ERBS is a research test fuel being used by NASA as a representation of a future aircraft gas turbine fuel should it become necessary to broaden the current fuel specifications. It is a blend of kerosene (65 percent) and hydrotreated catalytic gas oil (35 percent) and is being used as a reference in research investigations to evaluate fuel character effects on jet engine performance and durability. A comparison of the typical chemical compositions and physical properties of ERBS and No. 2 diesel fuels (See Table 2) indicates that they are very similar, except for small differences in the aromatic and olefinic contents. Therefore, it is not surprising that the ignition delay data for ERBS, shown in Fig. 20, are nearly coincidental with those discussed previously for No. 2 diesel fuel. Correlation of the data in Fig. 20 resulted in a global activation energy of approximately 43.0 kcal/mole.

Jet-A Fuel

Parametric autoignition testing of Jet-A fuel was performed using two of the injectors described above, i.e., the modified cross-stream (streamline) injector and the costream (conical) injector. The ignition delay data obtained are differentiated with respect to injector type and plotted in Fig. 21. Although approximately 50 percent of the Jet-A testing was conducted using the streamline shaped injector, within the accuracy of the measurements, there were no apparent differences in the ignition delay data that were attributable to the injector configuration. Comparison of the injector spray characterization data (cf., Figs. 6 and 13) indicates that the measured water spray distributions were similar at radial positions up to $R/R_o = \pm 0.5$. Also, it was found that at similar free-stream conditions, Jet-A required a shorter delay time for autoignition than any of the other typical gas turbine fuels tested. (A more detailed discussion of the effect of fuel type on autoignition is presented at the conclusion of this section). The global activation energy for Jet-A was 37.8 kcal/mole.

JP-4 Fuel

The results of autoignition testing of JP-4 fuel are summarized in Fig. 22. In general, the trends with variations in temperature, pressure and fuel/air ratio are the same as those observed previously for No. 2 diesel, ERBS and Jet-A fuels. The degree of data scatter is highest for JP-4, stemming from a significantly higher percentage of tests which were conducted at the shortest (7.6 cm) mixer/vaporizer length. As was shown in Figs. 15 and 16, tests conducted at short mixing lengths tend to given an apparent "reduction" in the activation energy when considered by themselves, but their inclusion into a population of tests conducted at longer lengths tends to bias the correlation toward a higher activation energy. Exclusion of these short mixing length data from the regression analysis significantly improves the correlation coefficient and leads to an activation energy of 43.1 kcal/mole which is approximately equal to the activation energies obtained previously for No. 2 diesel, ERBS and Jet-A fuels (see Fig. 22). A similar discrimination of data was performed for each of the other fuels tested and resulted in no significant change in the correlations developed.

Cetane Fuel

Although cetane (hexadecane) is not an aircraft fuel, it was included in this study because it is a well-characterized, pure hydrocarbon which is generally considered as a reference fuel. The autoignition characteristics of cetane are summarized in Fig. 23. Since it is well known that ignition delay time decreases as the cetane number of a fuel is increased, it was not unexpected that cetane was found to autoignite at a much lower temperature than any of the other fuels tested. The global activation energy determined for reaction of cetane (see Fig. 23) was comparatively high (50.4 kcal/mole) indicating that there is a strong sensitivity of ignition delay to inlet air temperature. Comparable activation energies have been reported for other typical paraffin fuels in Ref. 63. In all other respects, cetane behaved in a predictable manner similar to the other fuels tested.

Comparison of Results

A comparison of the autoignition correlations determined for each of the five fuels tested is presented in Fig. 24 and in Table 3. With the exception of cetane, which had the shortest ignition delay times, the ignition delay curves for the other typical gas turbine fuels lie within a relatively narrow band. Although data scatter may have introduced a slight bias in the positions and slopes of some of the ignition delay curves, a statistical analysis indicated that the general trends are meaningful. In this regard, the activation energy reported for Jet-A has an uncertainty (i.e., one standard deviation) of approximately ± 4 kcal/mole, the activation energy for JP-4 (exclusive of L=7.4 cm) is uncertain to approximately ± 3 kcal/mole, and the activation energies for No. 2 diesel, ERBS and cetane fuels are uncertain to approximately ± 2 kcal/mole. In addition to the obvious relationship of ignition delay and cetane number, other investigators (Ref. 66) have reported that for typical hydrocarbon fuels, straight chain paraffins are ignited most readily and that increasing the aromatic content of a fuel increases the ignition delay. The correlations shown in Fig. 24 and the fuels composition and physical properties data summarized in Table 2 are in general agreement with these observations.

In Fig 25 the ignition delay times determined for Jet-A fuel are compared with ignition delays measured by other investigators for typical gas turbine fuels. The data of the previous investigators were correlated in Ref. 71 according to the Arrhenius equation, using a pressure exponent equal to unity ($n = 1.0$). Therefore, in order to permit direct comparisons of results, alternative correlations having $n = 1.0$ were developed for the present data and are listed in Table 2. The figure shows that in the temperature range 675K to 775K there is general agreement of the data; however, at higher inlet air temperatures the present results indicate that autoignition occurs in a shorter time. A major factor contributing to the differences between the present and previous studies is the degree of mixing and extent of vaporization achieved. Indeed, many of the previous investigators were concerned with autoignition of fuel sprays, and none of the those referenced in the figure used a multiple-source injector. Therefore, it is likely that the major variations in the data stem from differences in physical phenomena whose relative importance have been diminished with the present test apparatus.

Effect of Mixture Distribution

Tests were conducted with JP-4 fuel to investigate the effect of injector configuration (i.e., fuel concentration profile) on ignition delay. Using the multiple conical tube injector, tests were performed with all nineteen fuel injector elements open and the results were compared with the results obtained for the standard configuration (six elements open). The atomization characteristics of air-blast type atomizers, such as the conical injector, are relatively insensitive to changes in fuel flow rate (Ref. 72); therefore, no difference in droplet size was anticipated between configurations. (Spray distributions measured during injector characterization tests were discussed earlier and are presented in Figs. 11 and 13.) Tests were conducted at pressures of 15 and 20 atm, an inlet airflow of 0.5 kg/sec, and fuel/air equivalence ratios of 0.3, 0.5, 0.7 and 1.0. The results of these tests are summarized in Fig. 26 and compared with the results obtained for the standard injector configuration.

The data indicate a definite effect of fuel concentration profile on ignition delay time; however, the differences decreased with increasing mixer/vaporizer length until, at the longest mixing length tested (116 cm), the difference in ignition delay was negligible. At similar test conditions, longer delay times were required for autoignition to occur when all nineteen fuel elements were functional, a result which would be anticipated if the mean equivalence ratio was less than the theoretical value. In fact, the results of the injector characterization tests did indicate that with all injector elements open there was significant transfer of liquid to the wall and a centerline fuel concentration below the theoretical value, as discussed earlier. The increased importance of the physical processes is also manifested by a decreased sensitivity of ignition delay time to temperature.

Effect of Fuel Temperature

A series of tests was conducted to investigate the effect of inlet fuel temperature on ignition delay. Jet-A fuel was preheated to a temperature of 400K at the point of injection and tests were conducted at pressures of 10 and 20 atm, and fuel-air equivalence ratios of 0.5 and 0.7. The test results indicated that, within the accuracy of the data, no significant difference in ignition delay was observed due to fuel preheating. The effect of fuel preheating on the ignition delay of JP-4 and No. 2 fuel oil was investigated in Ref. 65 and it was reported that ignition delay time decreased with increasing fuel temperature. However, at the lowest level of preheating tested (450K), the reduction in delay time was small.

Small increases in fuel temperature primarily affect the physical delay processes, i.e., atomization and vaporization. The effect on the mixture temperature is negligible. Therefore, in order to interpret the apparently anomalous result, the mean droplet sizes and vaporization rates were predicted, with and without fuel preheat. A correlation developed by Jasuja (Ref. 72) for a similar "air spray injector" was used to predict the droplet sizes produced by the multiple conical tube injector. The correlation used is;

$$SMD = 0.19 \frac{(\sigma_1/\rho_1)^{0.35}}{U_a \rho_a^{0.35}} \left(1 + \frac{1}{AFR}\right)^{0.25} + 1.127 \mu_1 \left(\frac{D}{\rho_1 \sigma_1}\right)^{0.50} \left(1 + \frac{1}{AFR}\right)$$

where: SMD = drop diameter, m
σ_1 = liquid surface tension, N/m
ρ_1 = liquid density, kg/m^3
μ_1 = liquid viscosity, Ns/m^2
ρ_a = air density, kg/m^3
U_a = air velocity, m/s
D = orifice diameter, m
AFR = local air-to-fuel ratio at injection, by weight

The correlation has two terms; the first is dominated by the air velocity while the second is responsive to liquid (i.e., fuel) viscosity. For Jet-A fuel at the conditions of interest, the first term is the more dominant. The UTRC Spray Vaporization Program was used to determine the distances required for complete vaporization. The results of these analyses indicated that the droplet Sauter mean diameter (SMD) was decreased slightly from 30 μm to 26 μm as a result of fuel preheating to 400K, and therefore, the vaporization distance was not changed significantly. This theoretical result is in agreement with the fact that for the multiple conical tube injector, preheating the fuel to 400K does little to influence the physical processes.

CONCLUDING REMARKS

The ignition delay characteristics of five liquid hydrocarbon fuels in air have been investigated. The test apparatus developed permitted independent variation and control of temperature, pressure, air flow rate and fuel/air ratio in order that the effects of each parameter could be investigated independently. All of the fuels tested behaved in a predictable manner, that is, ignition delay time decreased as temperature, pressure and fuel/air ratio increased. The results for the different fuels tested (i.e., Jet-A, JP-4, No. 2 diesel, ERBS and cetane) were directly comparable, since it was shown that the fuel spray characteristics were relatively insensitive to small changes in fuel properties (e.g., viscosity, surface tension and density). The degree of mixture uniformity, as indicated by the shape of the fuel concentration profile at the point of injection, was shown to have an important effect on the ignition delay, and demonstrated the need for careful interpretation of autoignition data and consideration of the test apparatus and methods used for their determination. In addition, other physical phenomena such as airstream cooling due to fuel heating, vaporization and convective heat loss can have a significant effect on ignition delay.

Ignition delay times were correlated with ambient pressure and inlet air temperature according to the equation

$$\tau P^2 = A \exp \left(\frac{E}{RT}\right)$$

and global activation energies ranging from 38 to 43 kcal/mole were determined for reaction of the typical gas turbine fuels and an activation energy of 50 kcal/mole was determined for pure cetane.

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TABLE 1

CANDIDATE TEST APPARATUS FOR IGNITION DELAY MEASUREMENTS RELEVANT TO ADVANCED GAS TURBINES

APPARATUS	ADVANTAGES	DISADVANTAGES
CONSTANT VOLUME HEATED BOMB	. Ease of control . Simple construction . Permits premixing of high-vapor-pressure fuels	. Difficult to premix low-vapor-pressure fuels without significant chemical reaction . Limited to low velocity and low turbulence levels Physical delay time is long relative to spray-type combustion systems . Configuration and material dependent
MOTORED & FIRED RECIPROCATING ENGINES AND RAPID COMPRESSION MACHINES	. Accurate simulation of reciprocating engines . Direct correlation of engine data	. Continuously varying pressure, temperature, velocity, turbulence and fuel spray characteristics . Difficult to evaluate the effects of individual parameters . Nonuniform mixture and local ignition
SHOCK TUBE	. Permits premixing of high-vapor-pressure fuels . Capable of operation at very high pressure and temperature	. Difficult to adapt for use with low-vapor-pressure fuels . Short test times and local nonuniformities
CONTINUOUS FLOW RIG	. Permits establishment of a steady and measurable condition prior to ignition . Permits evaluation of the effects of individual parameters . Good simulation of continuous flow combustors	. Difficult to generate a uniform fuel-air mixture . Flow velocity must exceed flashback velocity

TABLE 2

Measured Properties of Test Fuels

Property	Cetane	Jet-A	JP-4	No. 2 Diesel	ERBS
API Gravity	51.2	45.0	54.1	34.0	37.1
Specific Gravity	.7743	.8017	.7625	.8549	.8381
Freezing Point*(K)	291	233	215	267	244
Viscosity (cs) at 250K	4.35**	5.30	2.14	2.87**	7.20
Surface Tension* (dynes/cm) at 298K	22.1	22.5	21.7	24.3	24.0
Total Sulfur, wt%	0.0	.1152	.0092	.3039	.085
Heat of Combustion*	20400	18622	18714	18600	18275
Distillation (K)					
IBP	560	432	334	428	435
10%	560	450	362	469	461
50%	560	478	423	533	488
90%	560	517	500	600	552
FBP	560	538	522	622	601
Aromatics, vol%	0	11.26	15.37	27.48	35.0
Olefins, vol%	0	1.05	0.49	2.41	0.0
Napthenes, vol%	0	23.94	8.02	15.34	13.15
Paraffins, vol%	100	63.75	76.12	54.77	51.85
Hydrogen, wt%	15.03	14.06*	14.23*	13.11*	12.86

* Typical values
** T = 294K

TABLE 3

Ignition Delay Correlations

$$\tau = \frac{A}{P^n} \exp\left(\frac{E}{RT}\right)$$

$1 \text{ msec} \leq \tau \leq 50 \text{ msec}$
$650K \leq T \leq 900K$
$10 \text{ atm} \leq P \leq 30 \text{ atm}$
$0.3 \leq \phi \leq 1.0$

Fuel	n	A	E kcal/mole
Jet-A	2.0	1.68×10^{-8}	37.78
	1.0	6.89×10^{-9}	35.09
JP-4	2.0	1.17×10^{-9}	43.06
	1.0	4.87×10^{-9}	36.76
No. 2 Diesel	2.0	2.43×10^{-9}	41.56
	1.0	4.00×10^{-10}	39.88
ERBS	2.0	1.11×10^{-9}	42.98
	1.0	5.15×10^{-10}	39.64
Cetane	2.0	4.04×10^{-13}	50.44
	1.0	2.65×10^{-12}	43.84

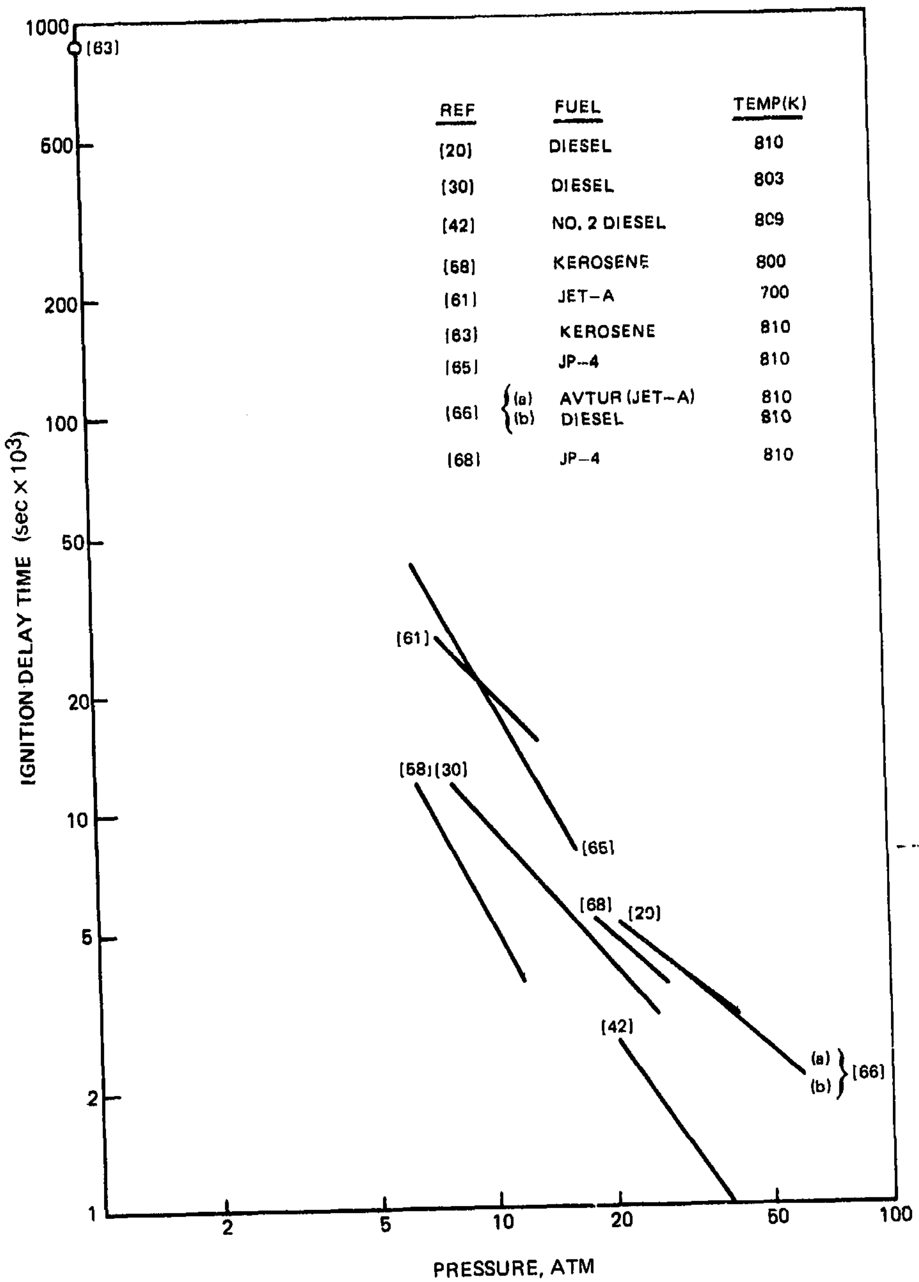

Figure 1 Correlation of Ignition Delay Data

77–08–266–1

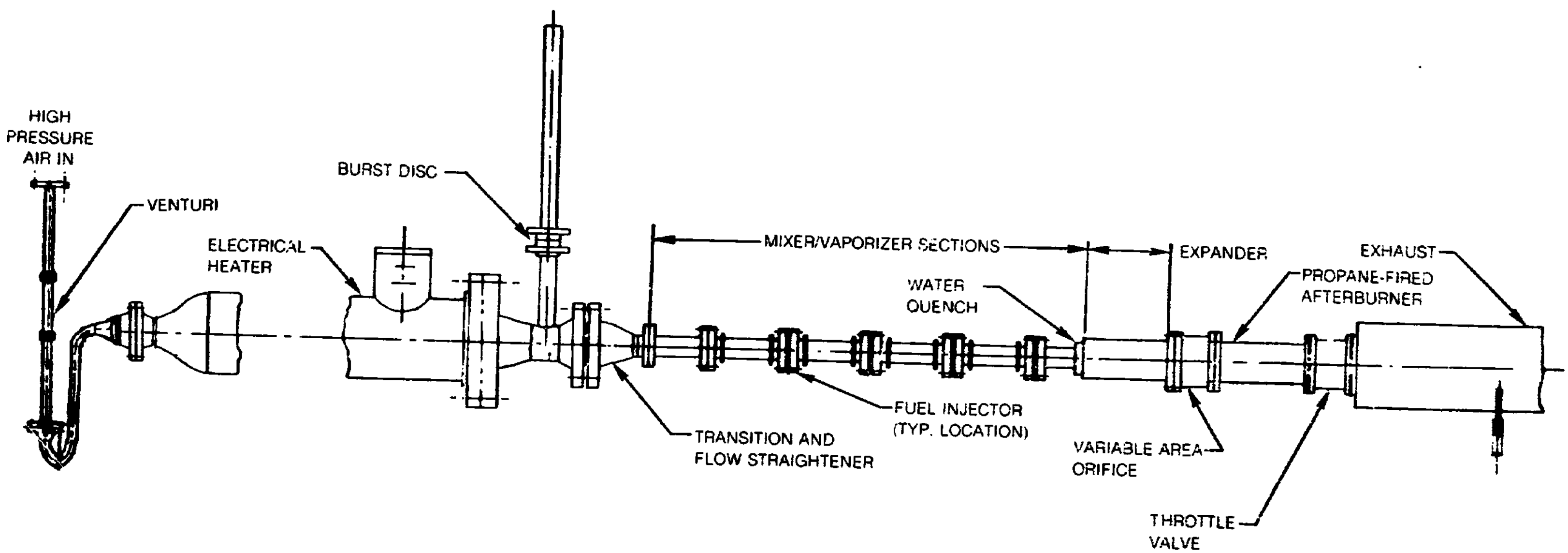

Figure 2 Autoignition Test Assembly

77–07–184–3

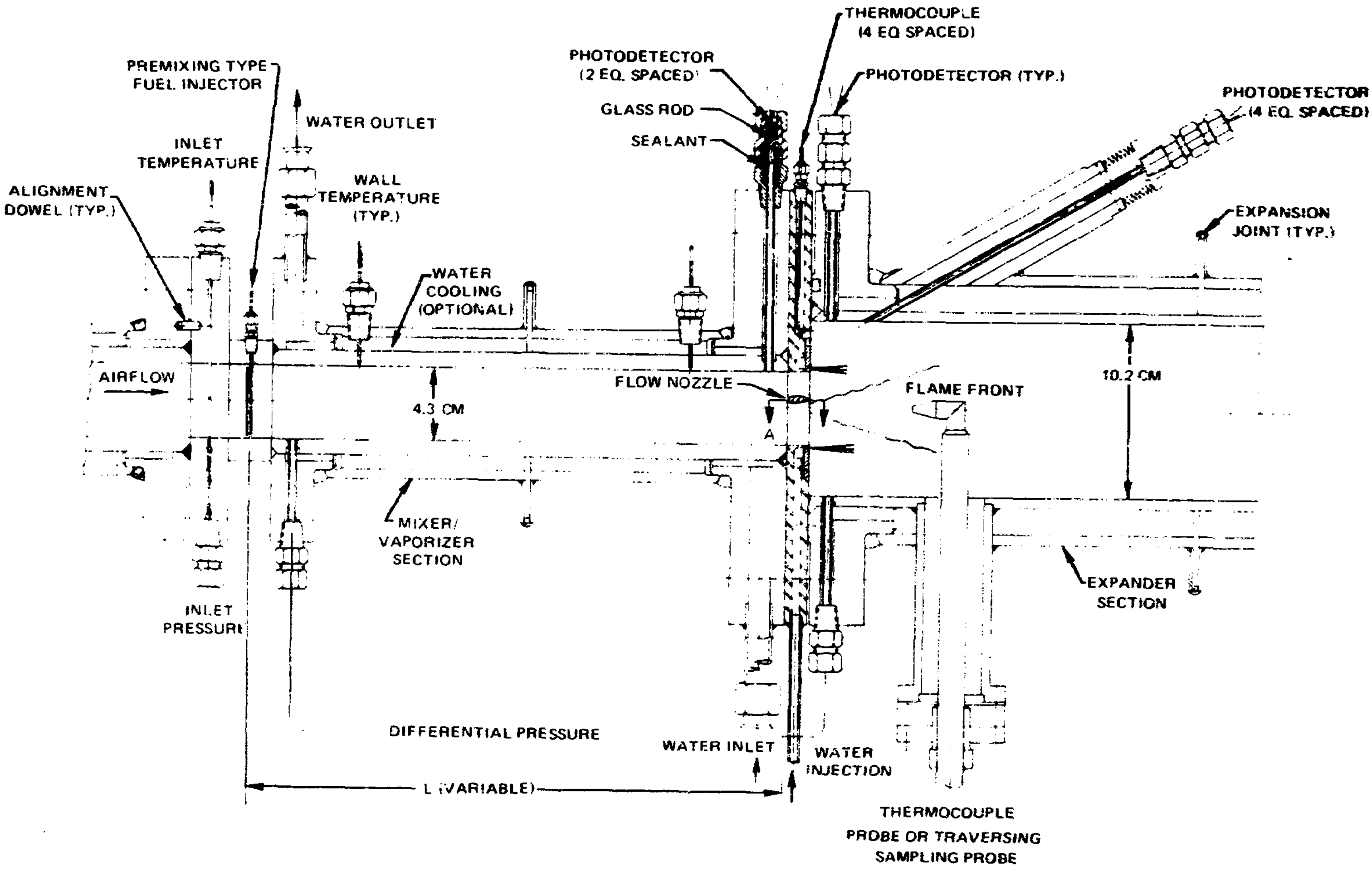

Figure 3 Mixer/Vaporizer and Expander Assembly

77-07-184-4

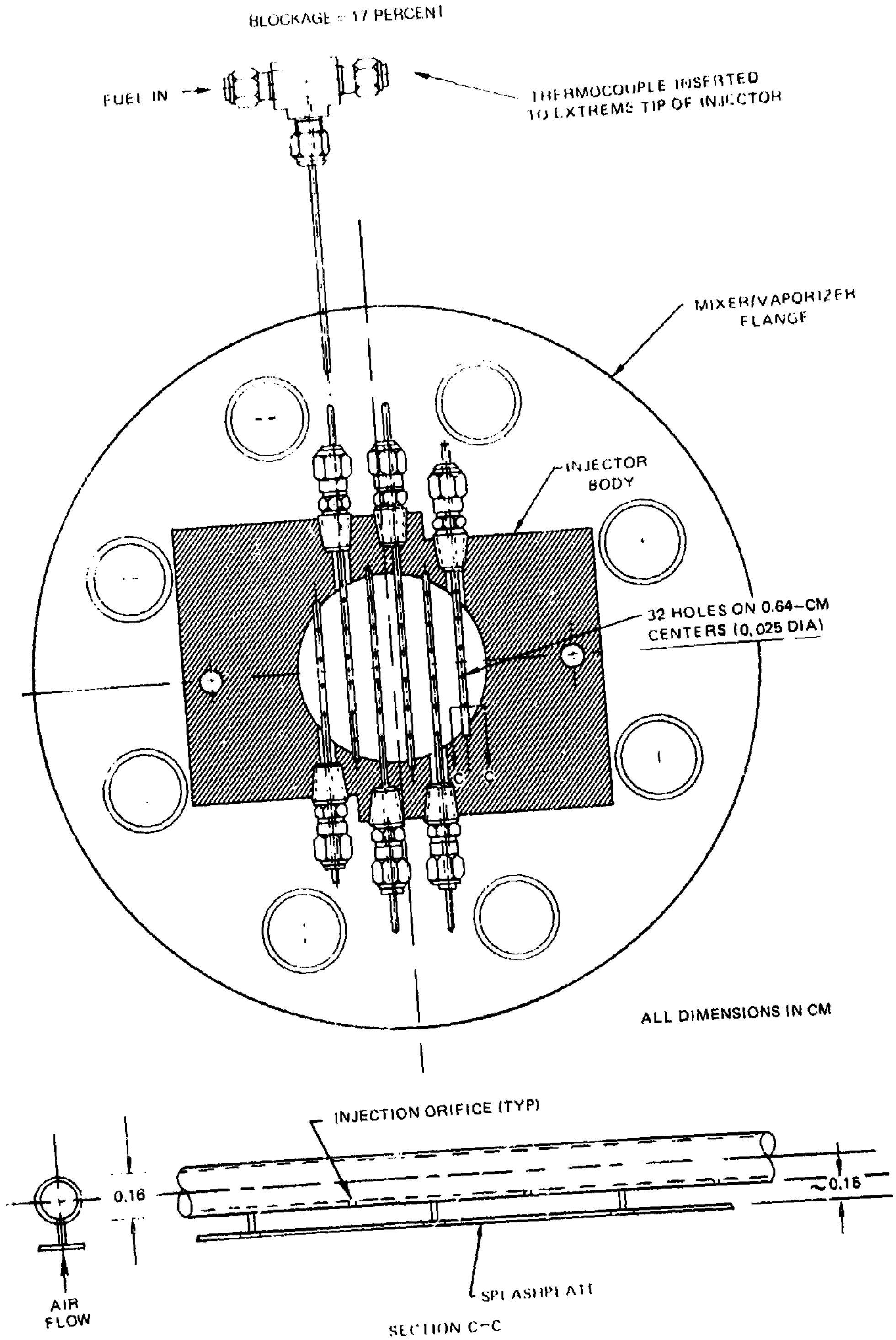

Figure 4 Distributed Source Contrastream Injector

77–07–184–2

BLOCKAGE = 50 PERCENT

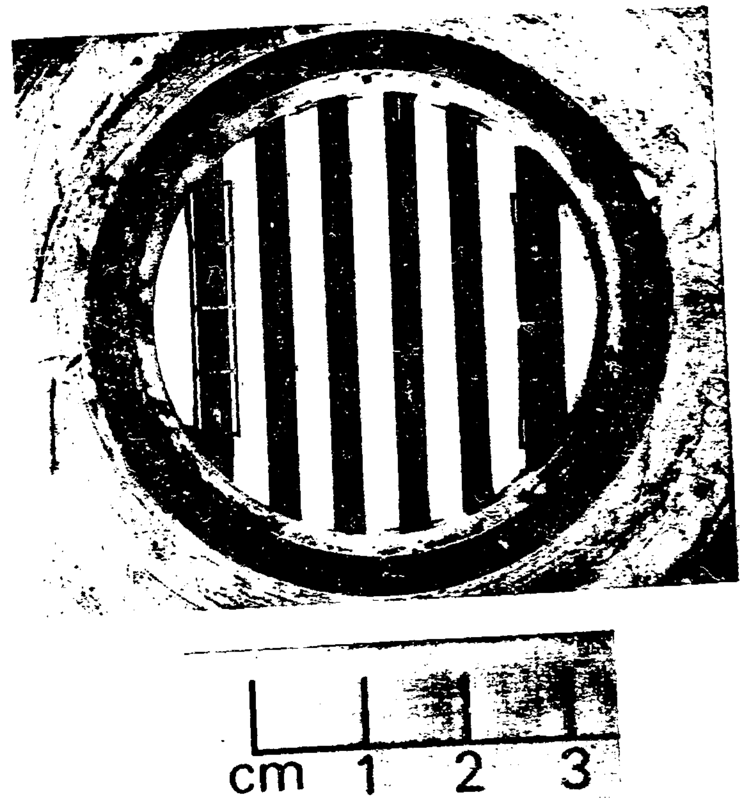

Figure 5 Distributed Source Cross-Stream Injector

78–02–232–1

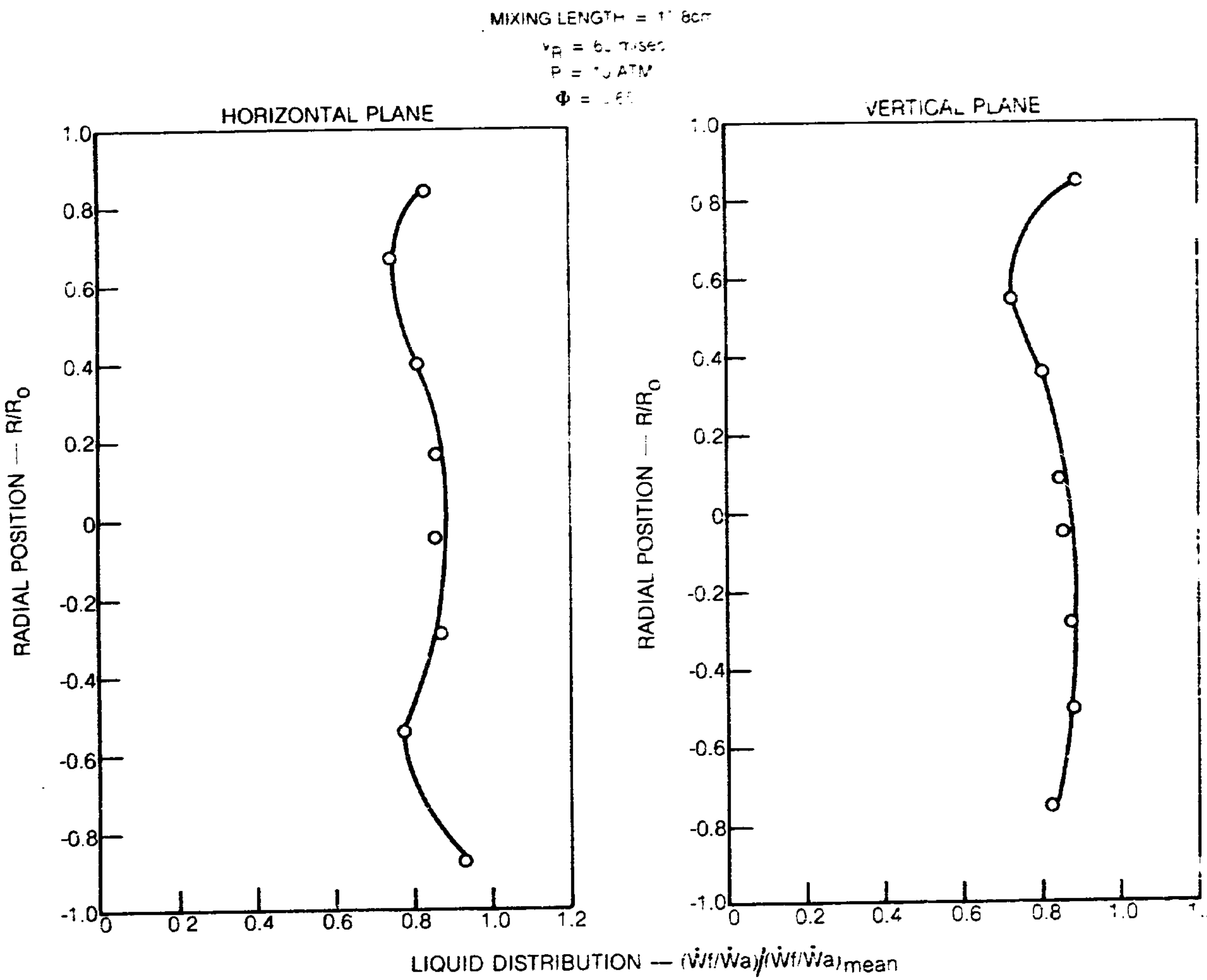

Figure 6 Spray Distribution from Distributed-Source Cross-Stream Injector

80–2–36–1

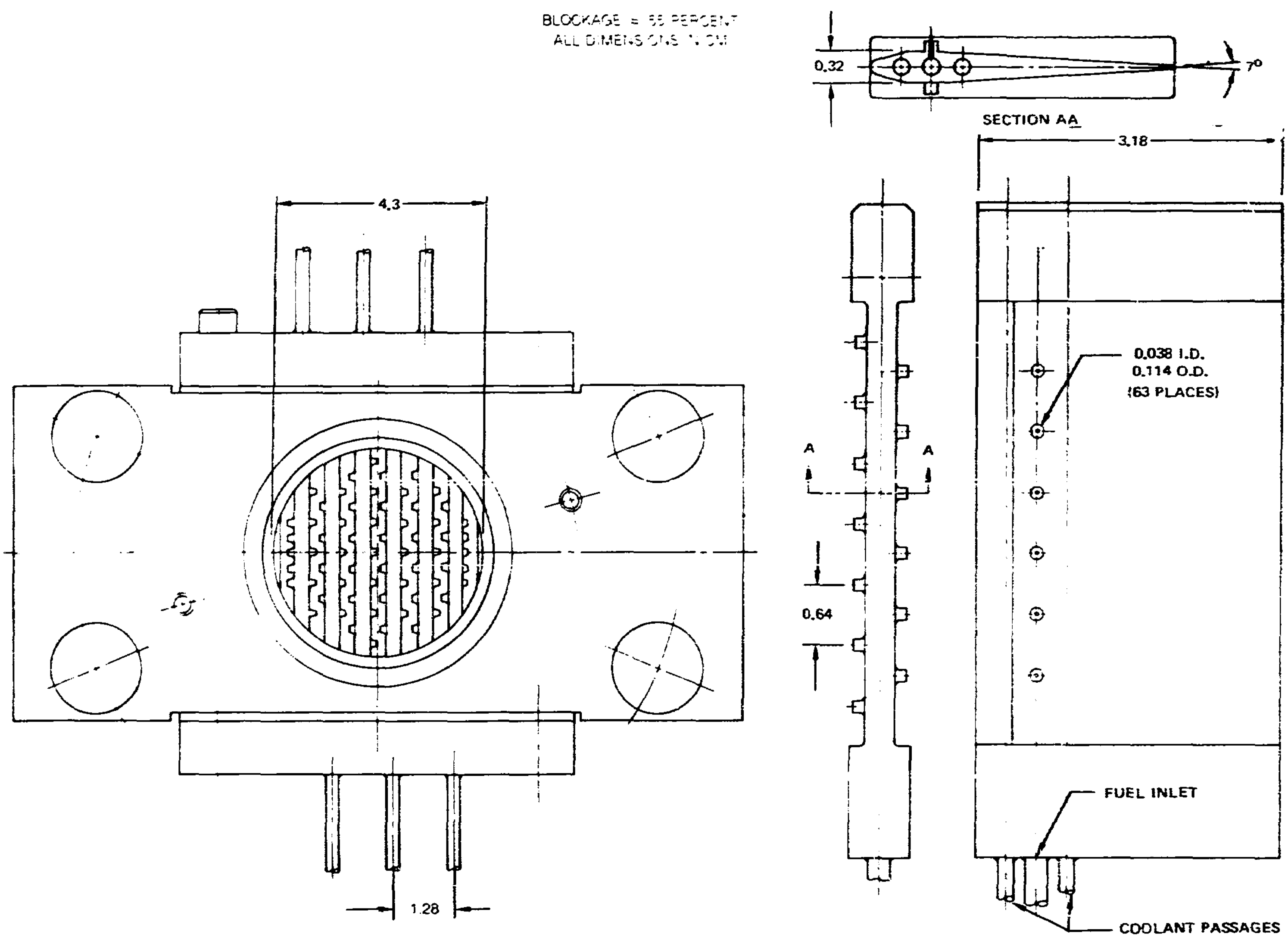

Figure 7 Streamline-Shaped Distributed Source Cross-Stream Injector

78 04 323 1

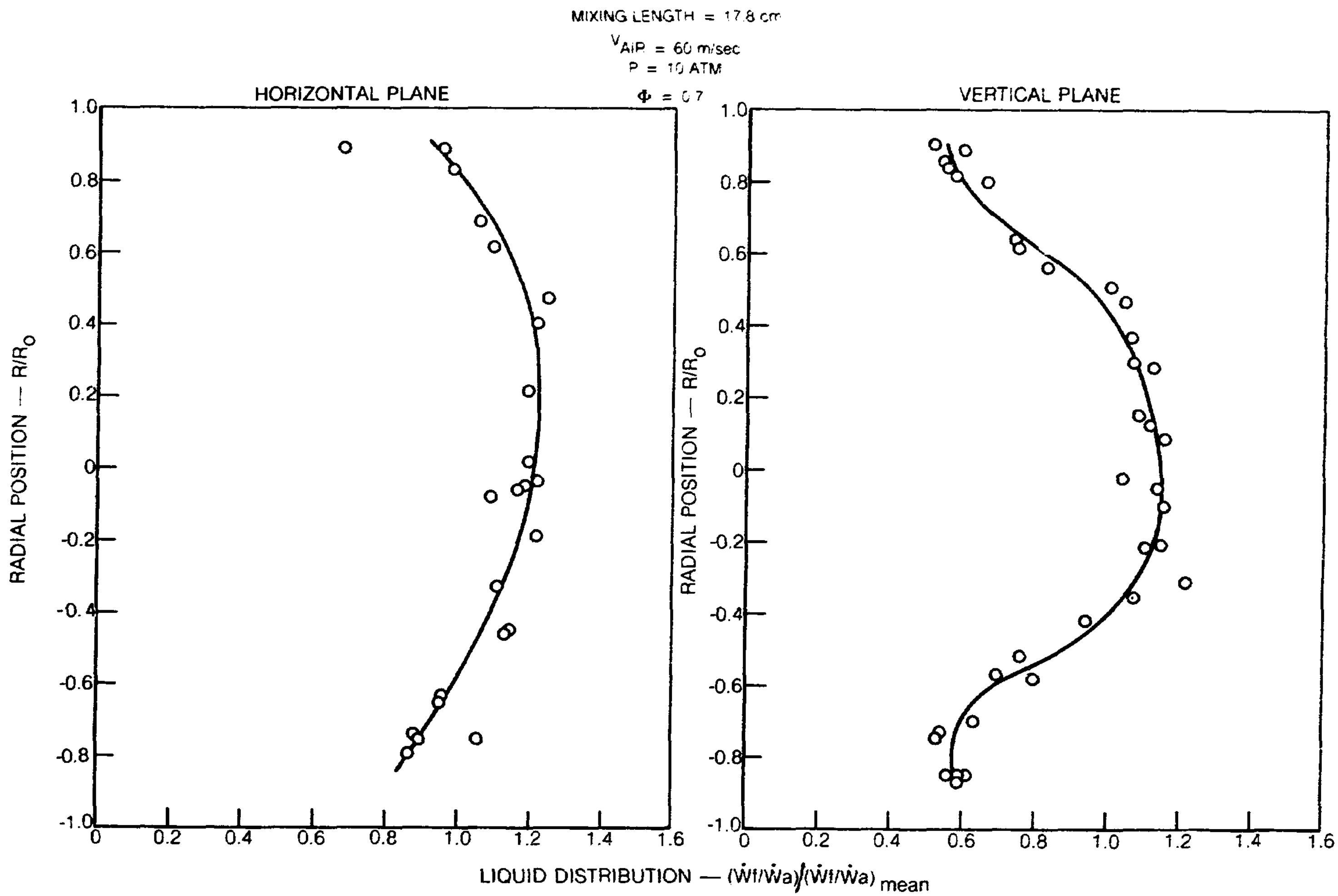

Figure 8 Spray Distribution from Streamline-Shaped Distributed-Source Injector

80–2–36–2

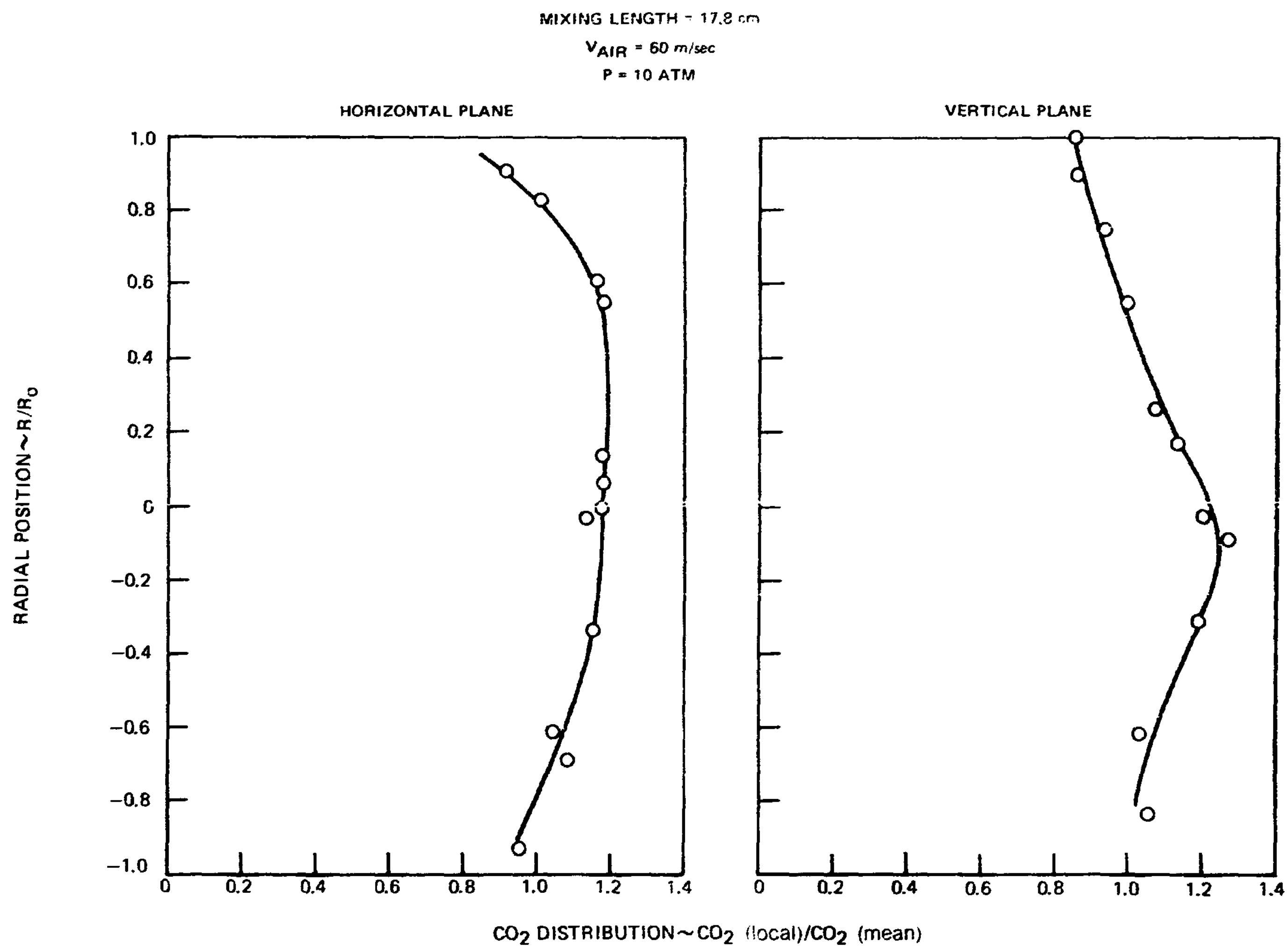

Figure 9 Carbon Dioxide Distribution from Streamline-Shaped Distributed-Source Injector

78 07 07 1

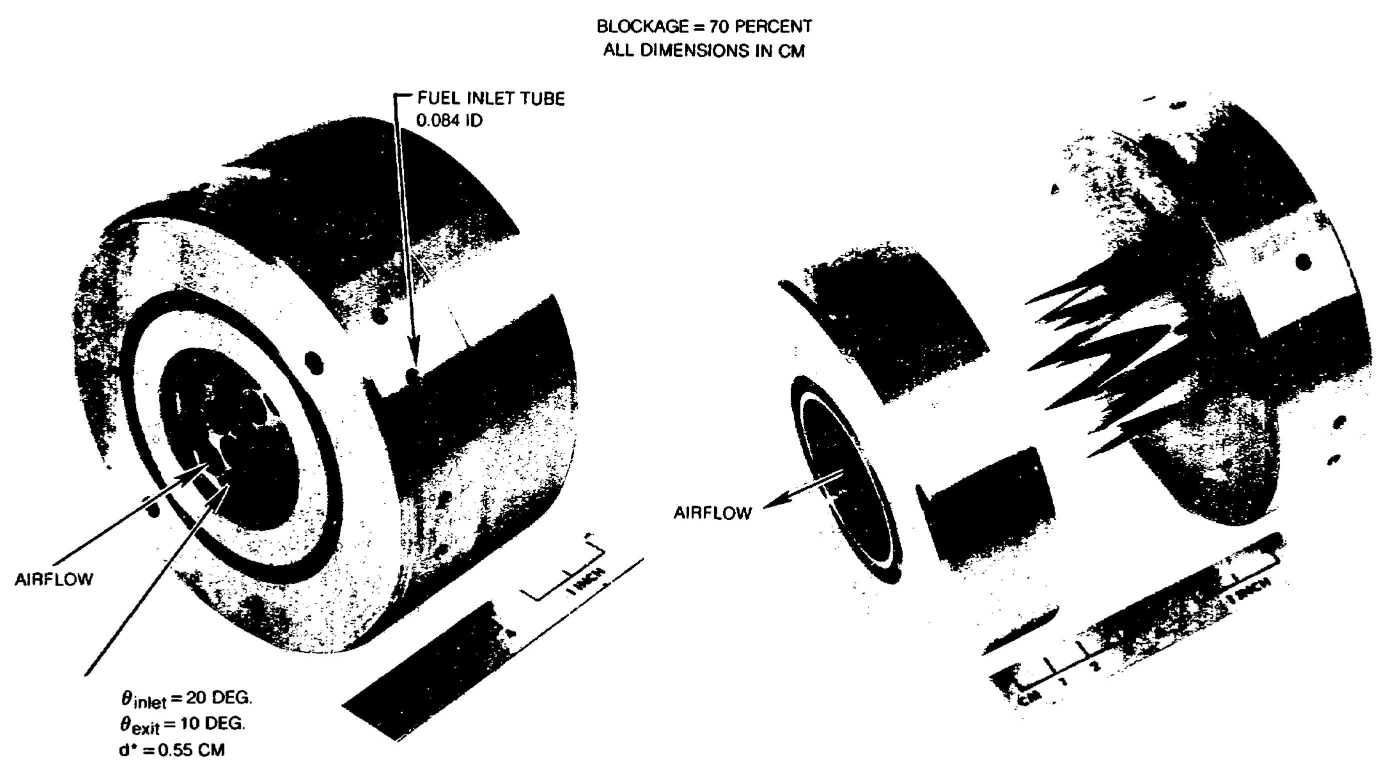

Figure 10 Multiple Conical Tube Costream Injector

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78–12–48–1

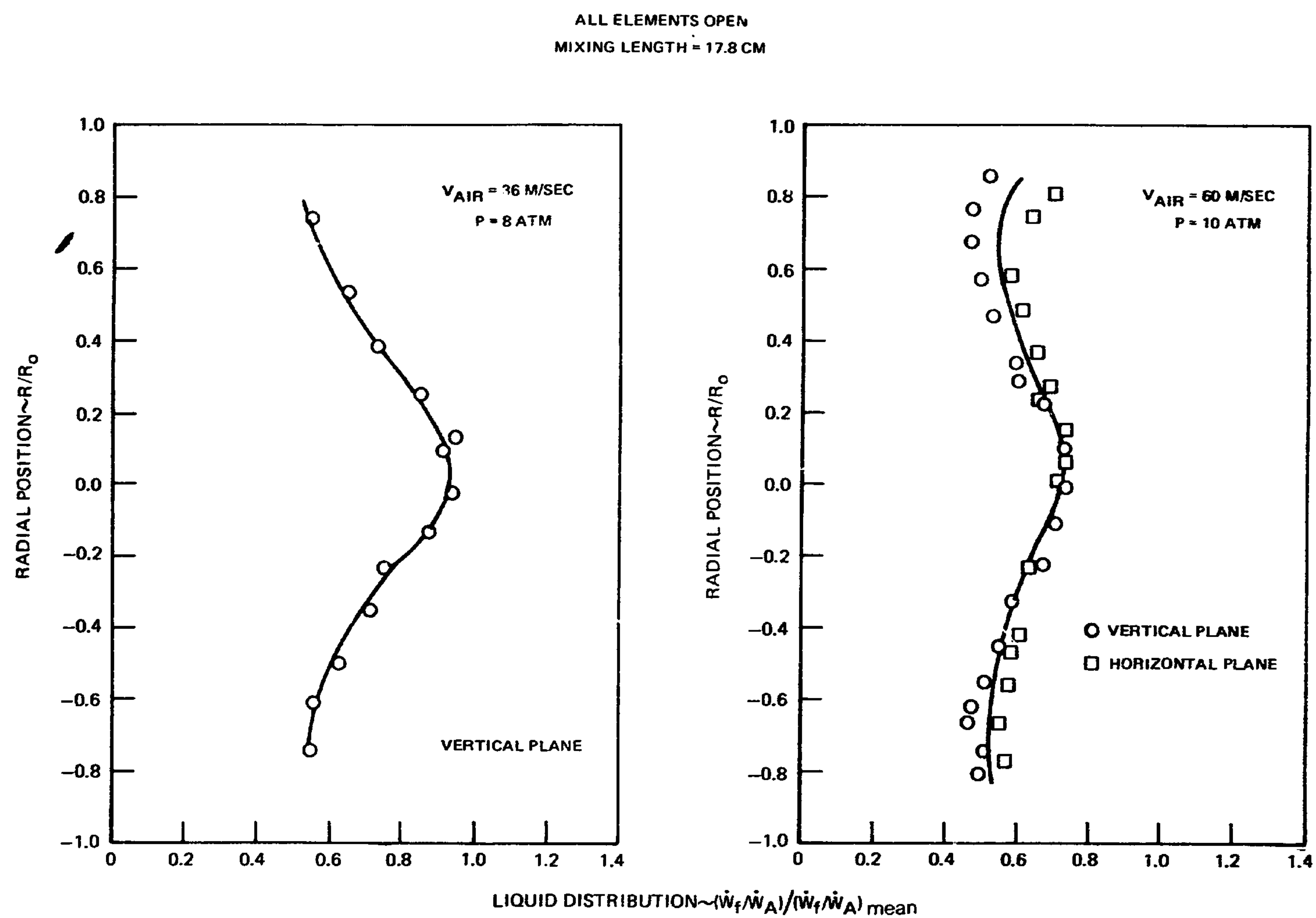

Figure 11 Spray Distribution from Conical Tube Injector

79–07–15–2

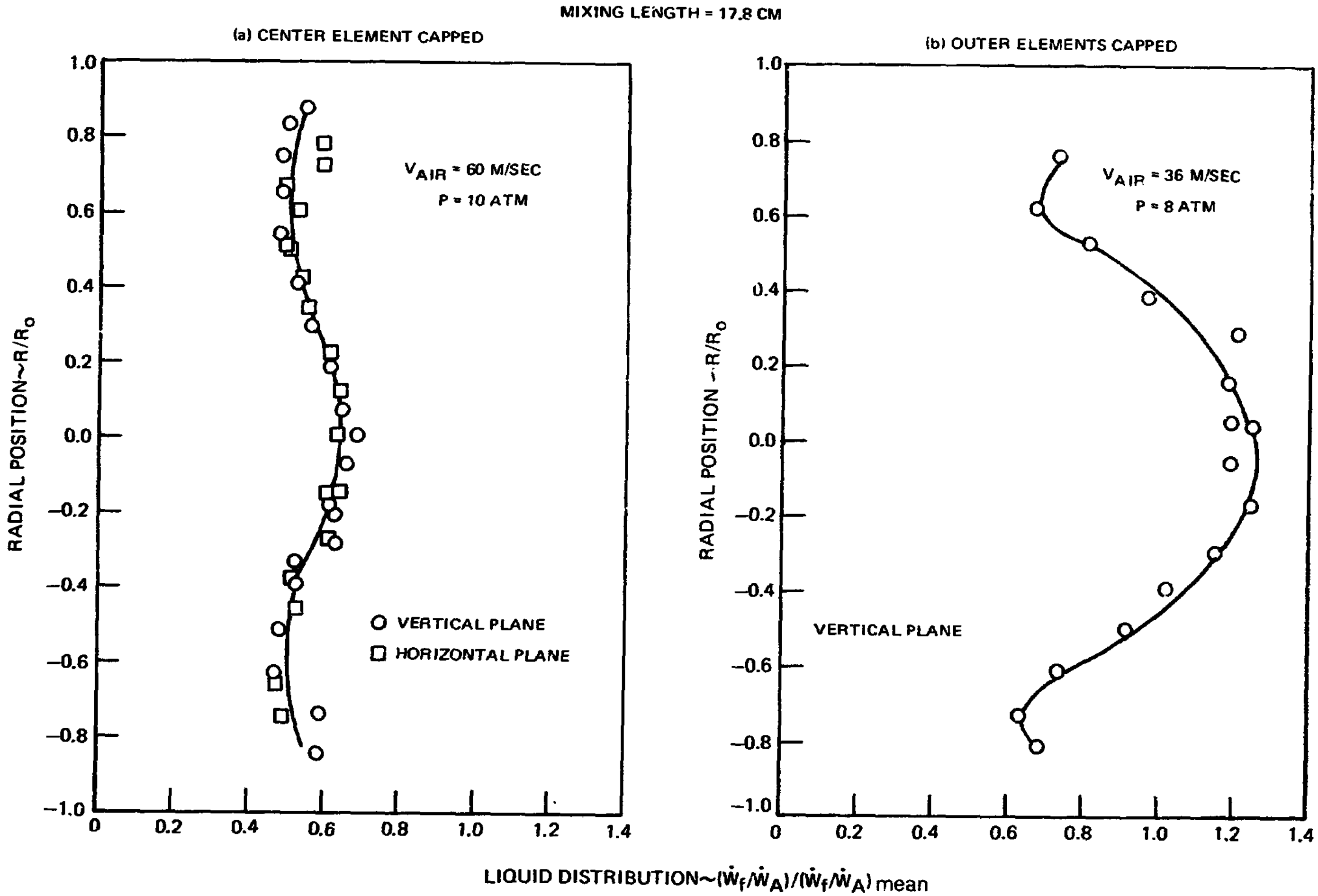

Figure 12 Spray Distribution from Conical Tube Injector

79–07–15–3

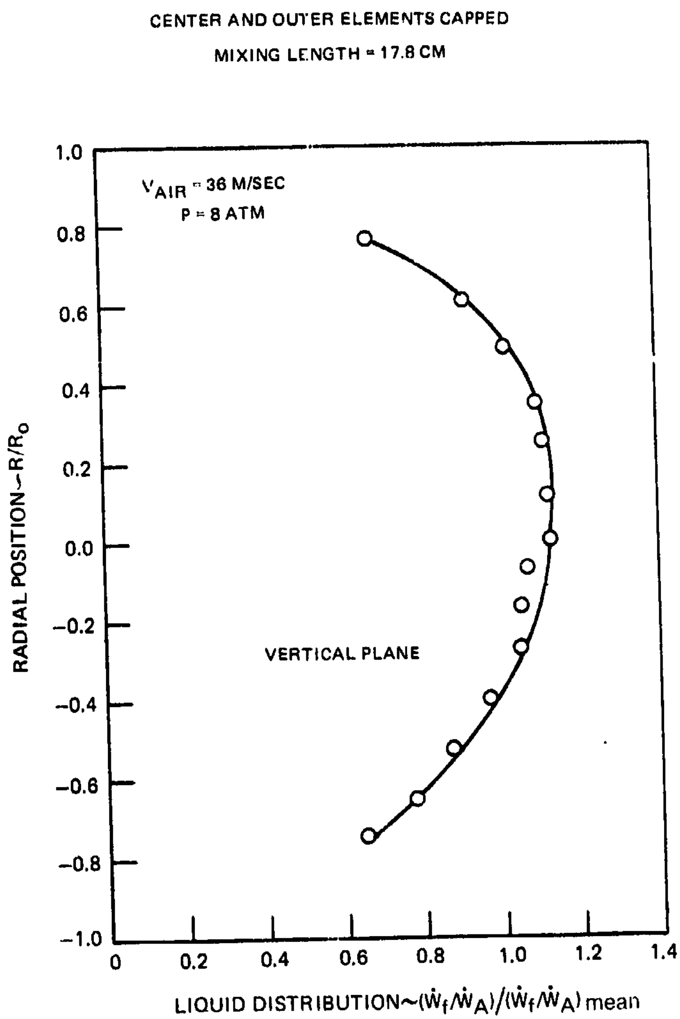

Figure 13 Spray Distributuion from Conical Tube Injector

79–07–15–4

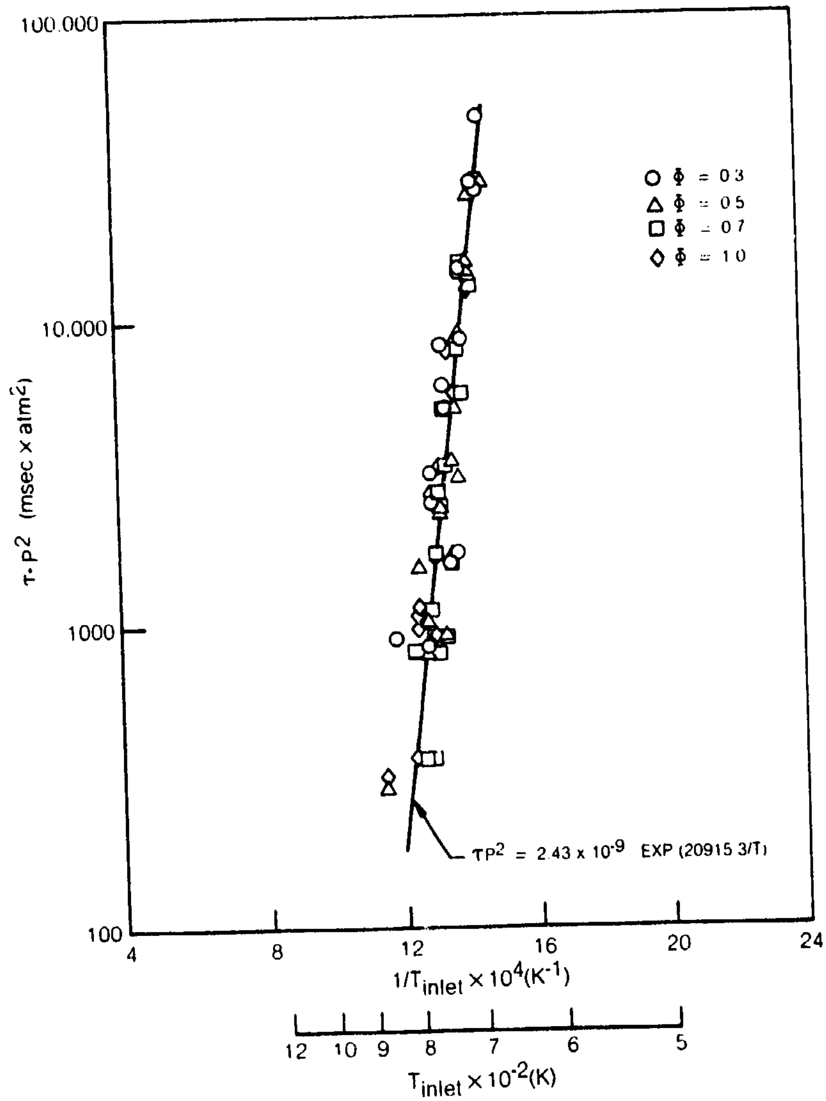

Figure 14 Autoignition Characteristics of No. 2 Diesel Fuel in Air

80-2-36-3

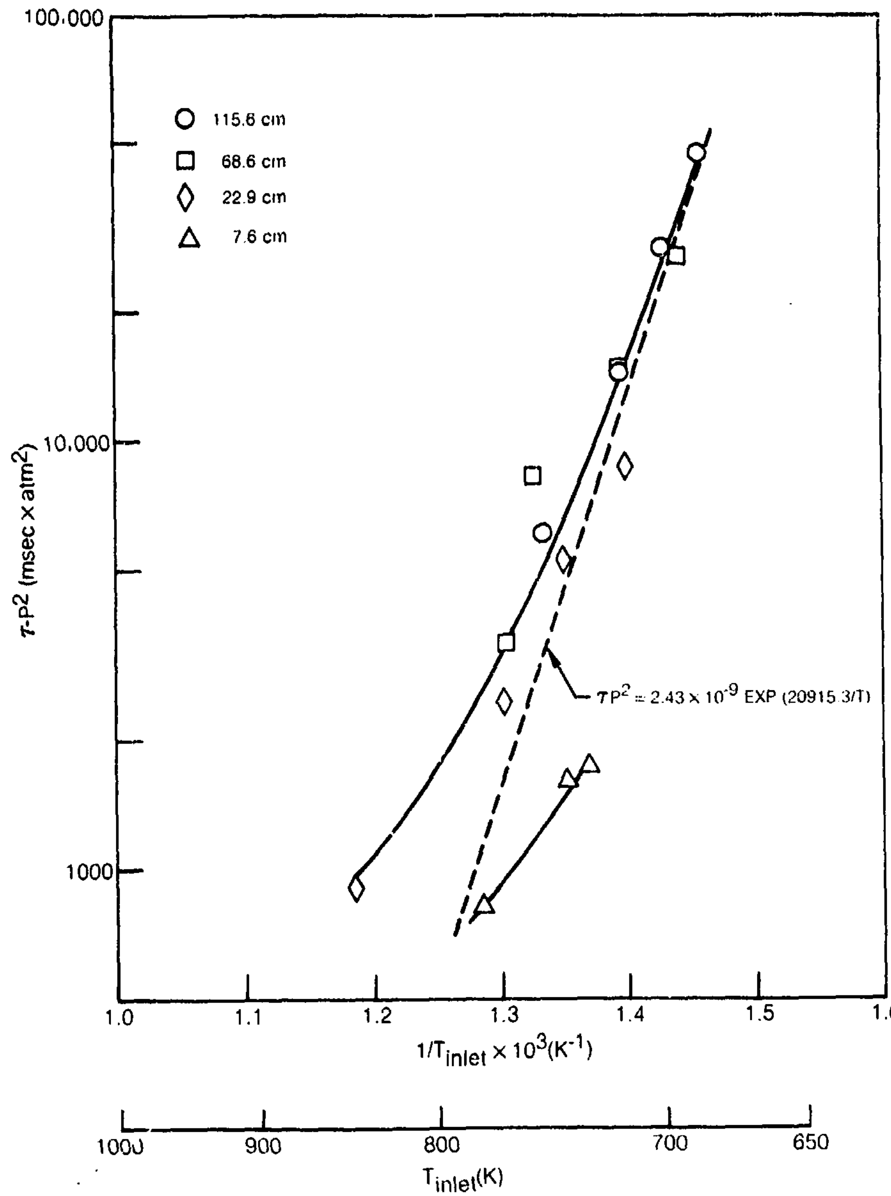

Figure 15 Effect of Mixing Length and Airstream Cooling on the Autoignition Characteristics of No. 2 Diesel Fuel in Air, $\Phi = 0.3$

80–4–30–2

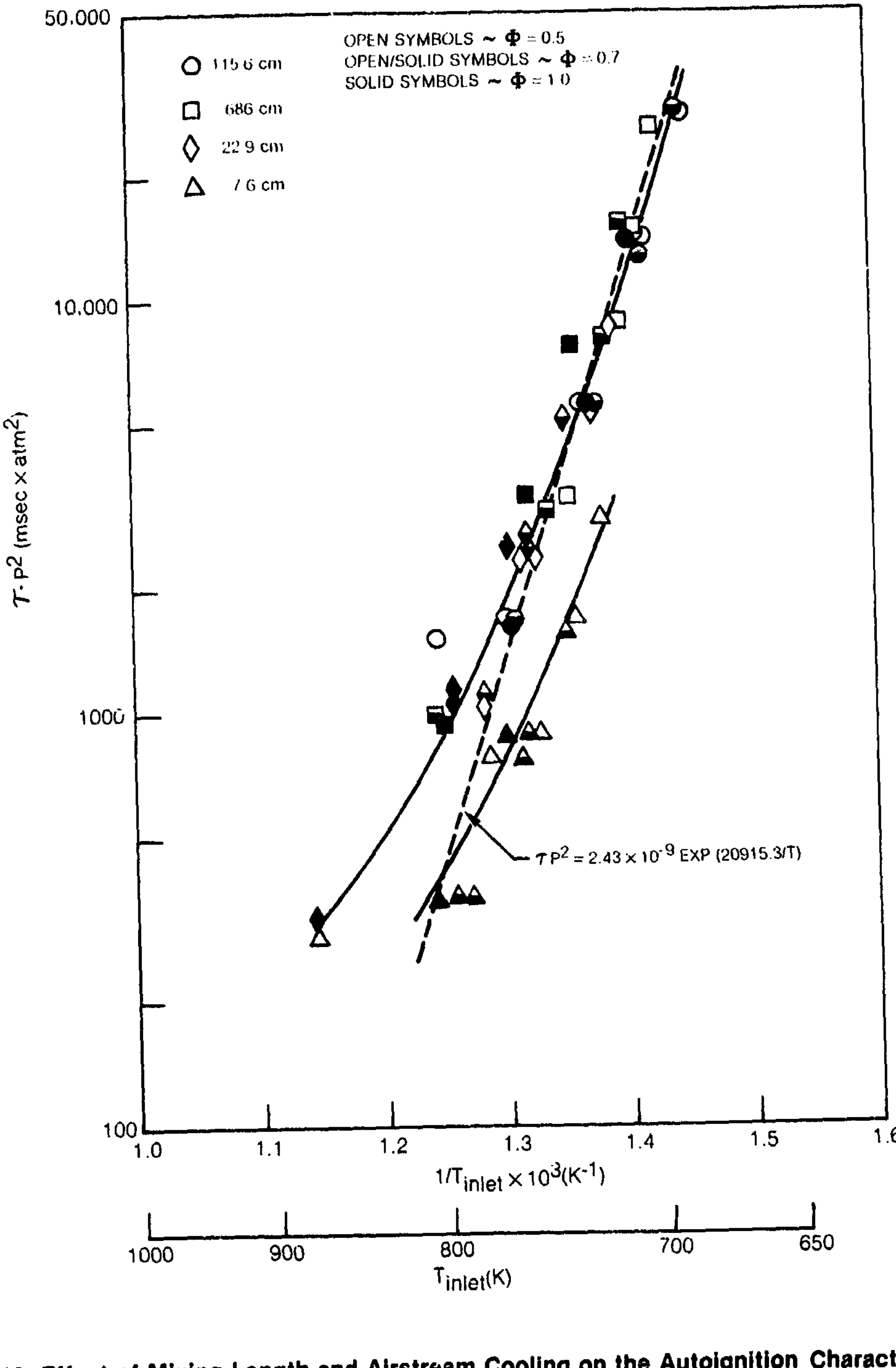

Figure 16 Effect of Mixing Length and Airstream Cooling on the Autoignition Characteristics of No. 2 Diesel Fuel in Air, Φ = 0.5–1.0

80–4–30–3

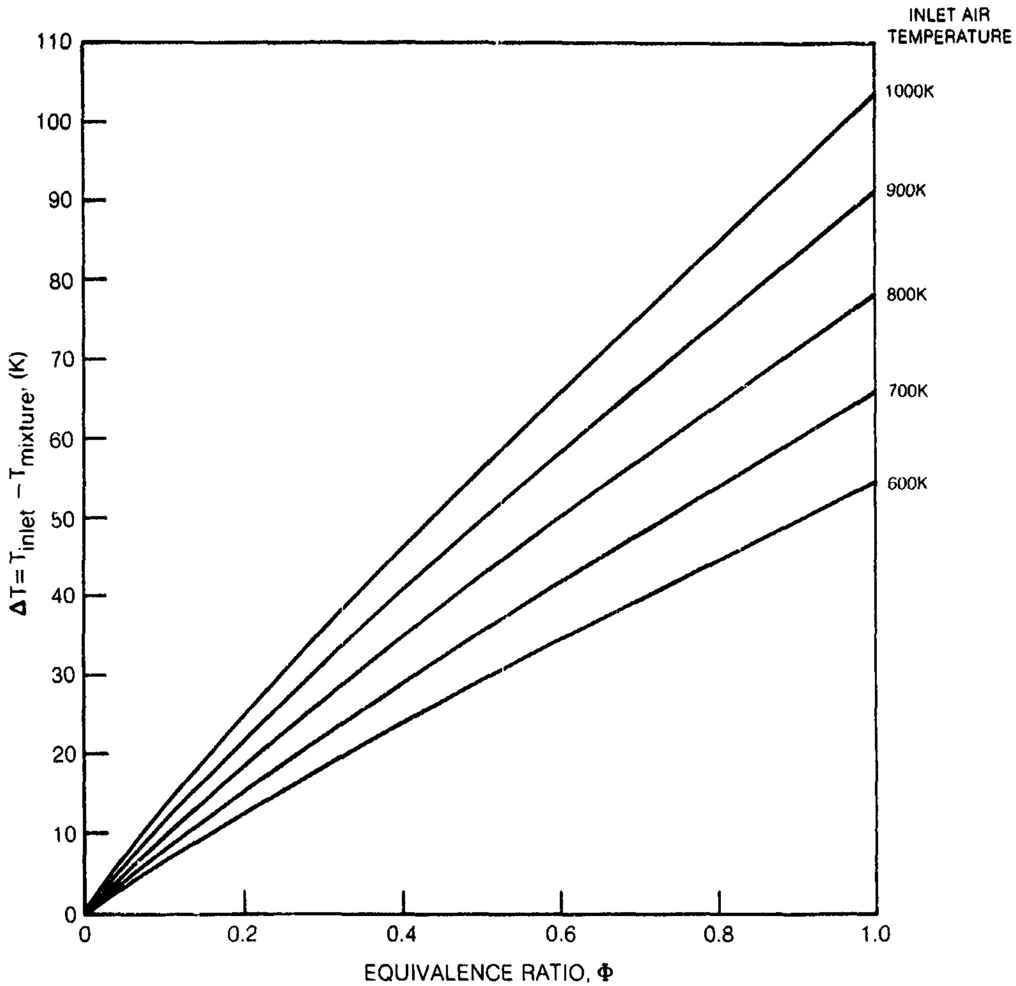

Figure 17 Airstream Cooling Due to Fuel Vaporization

80-4-30-4

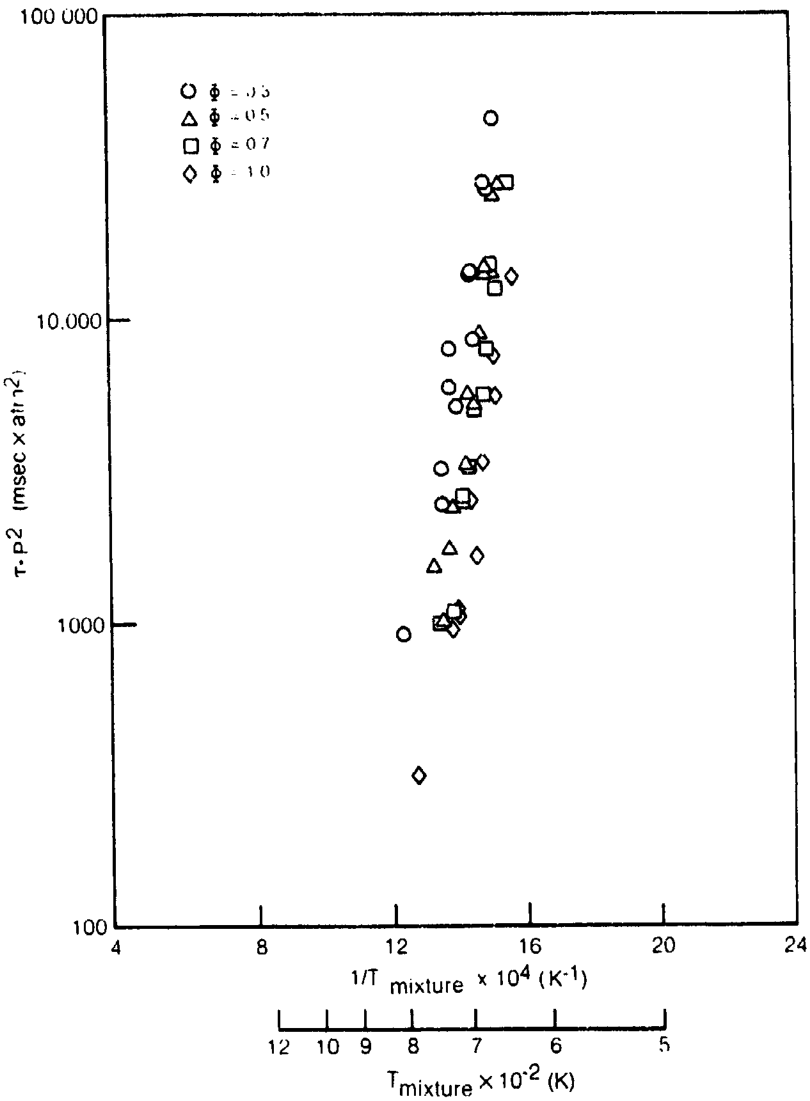

Figure 18 Effect of Equivalence Ratio on Autoignition Characteristics of No. 2 Diesel Fuel in Air

80–2–36–8

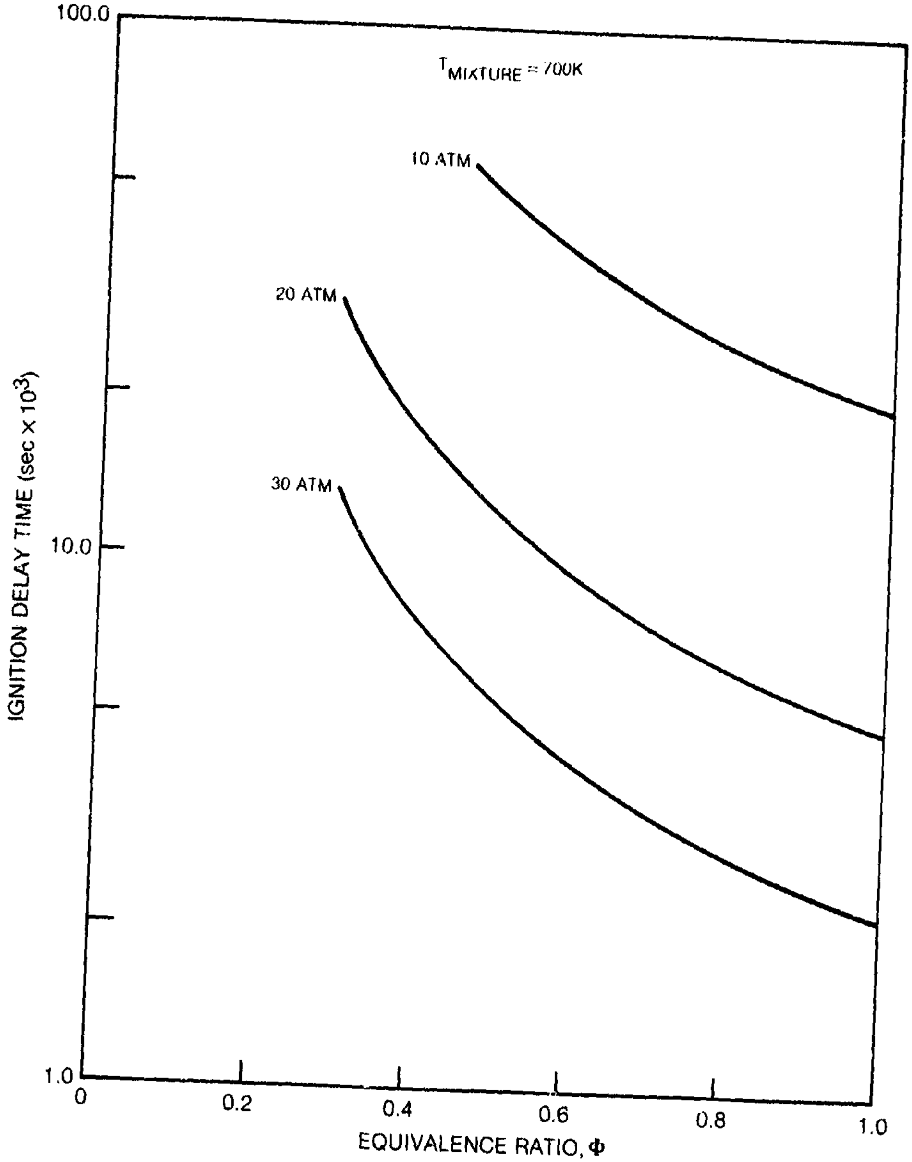

Figure 19 Effect of Equivalence Ratio on the Ignition Delay of No. 2 Diesel Fuel in Air

80–4–30–6

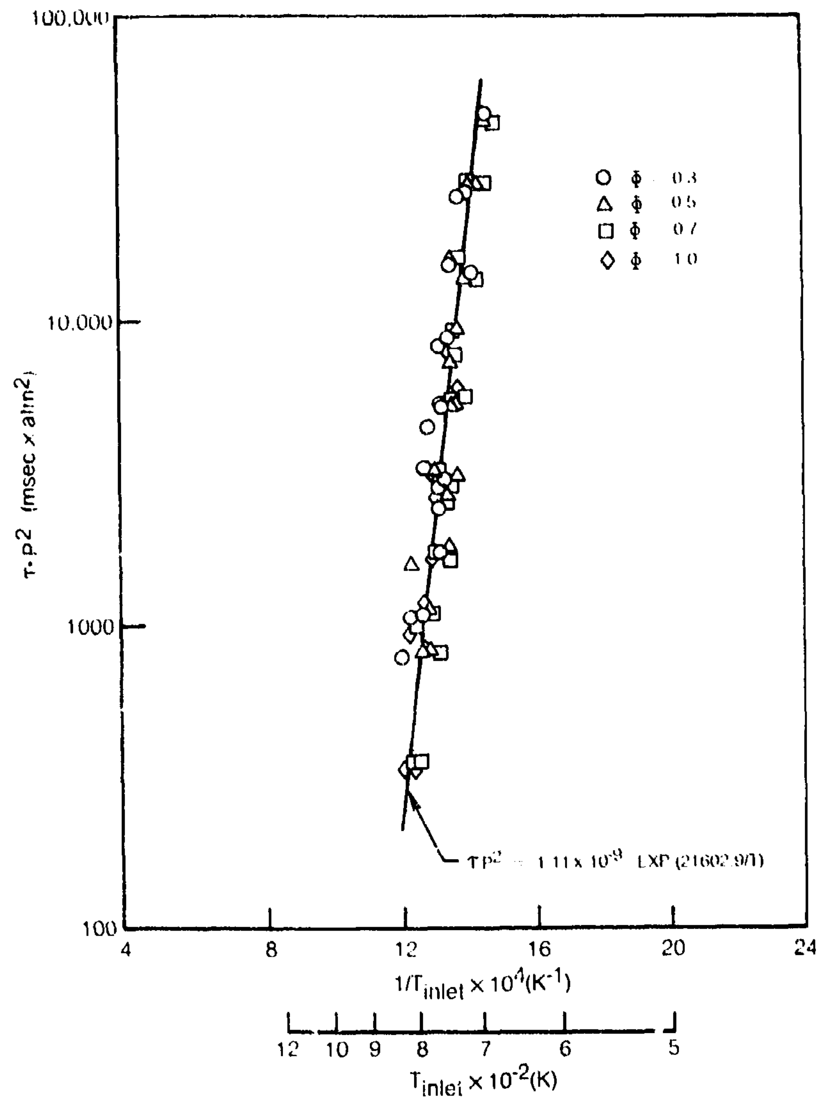

Figure 20 Autoignition Characteristics of ERBS Fuel in Air

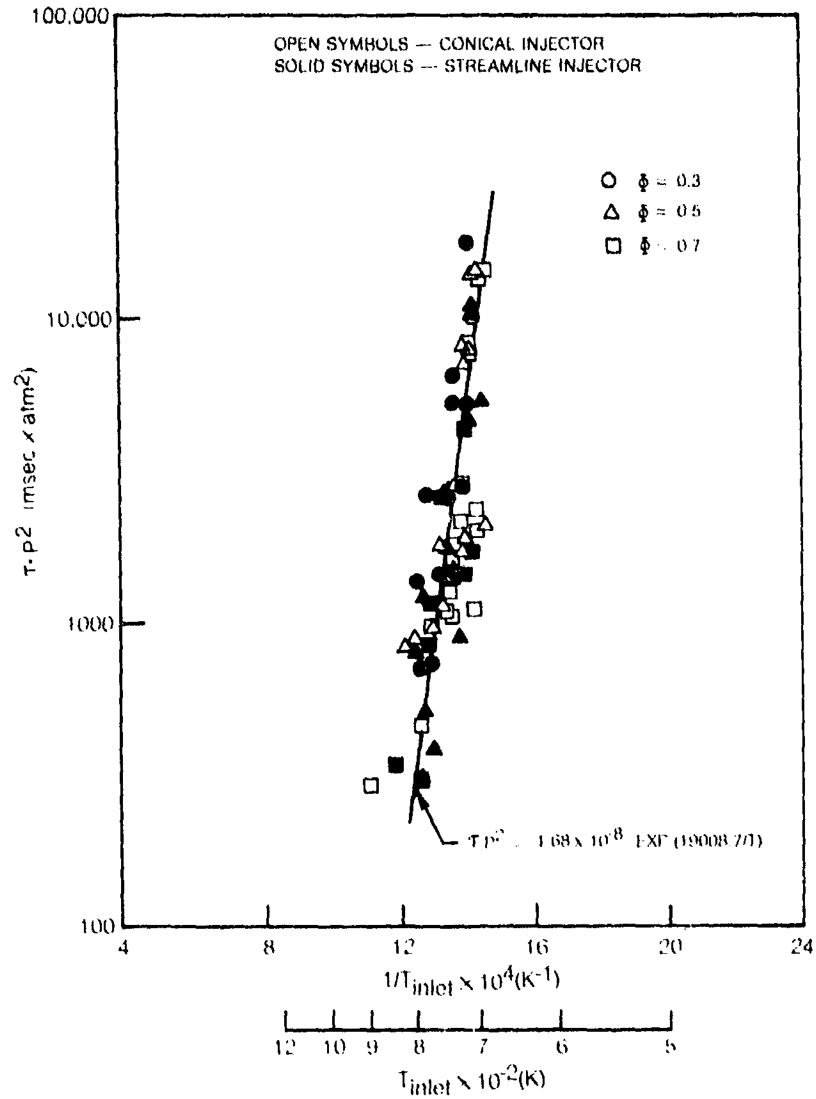

Figure 21 Autoignition Characteristics of Jet-A Fuel in Air

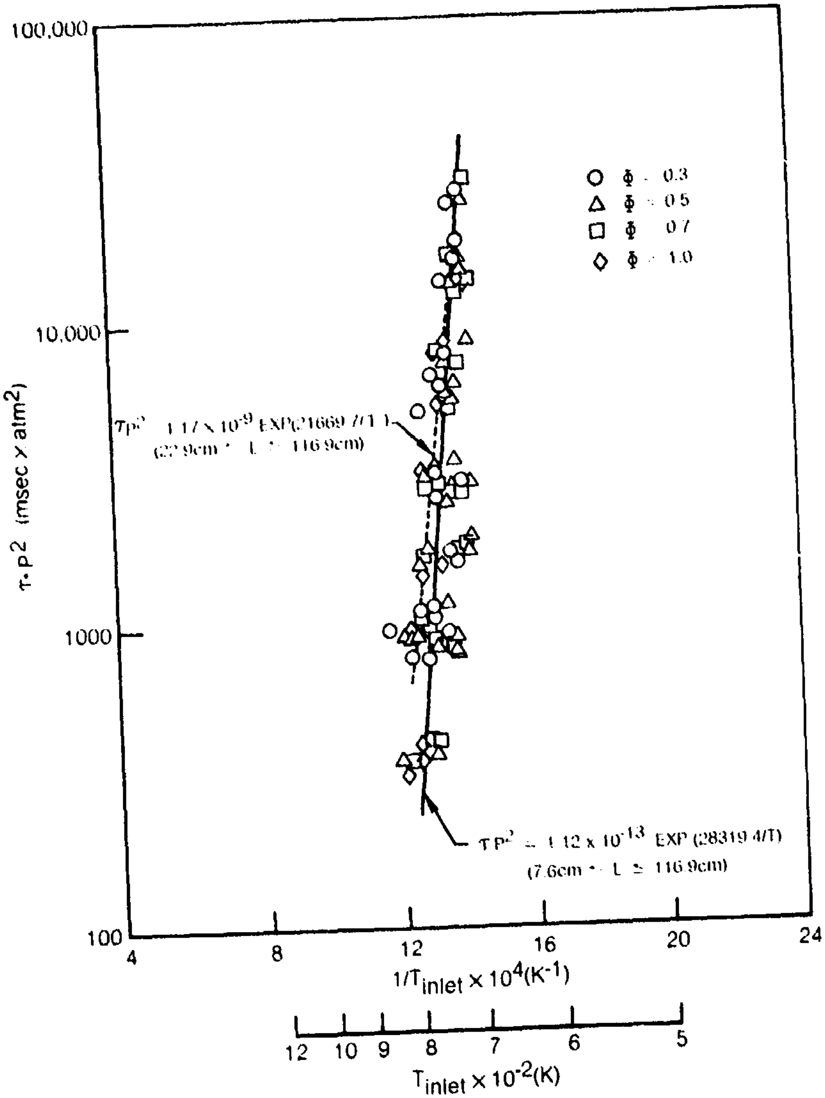

Figure 22 Autoignition Characteristics of JP-4 Fuel in Air

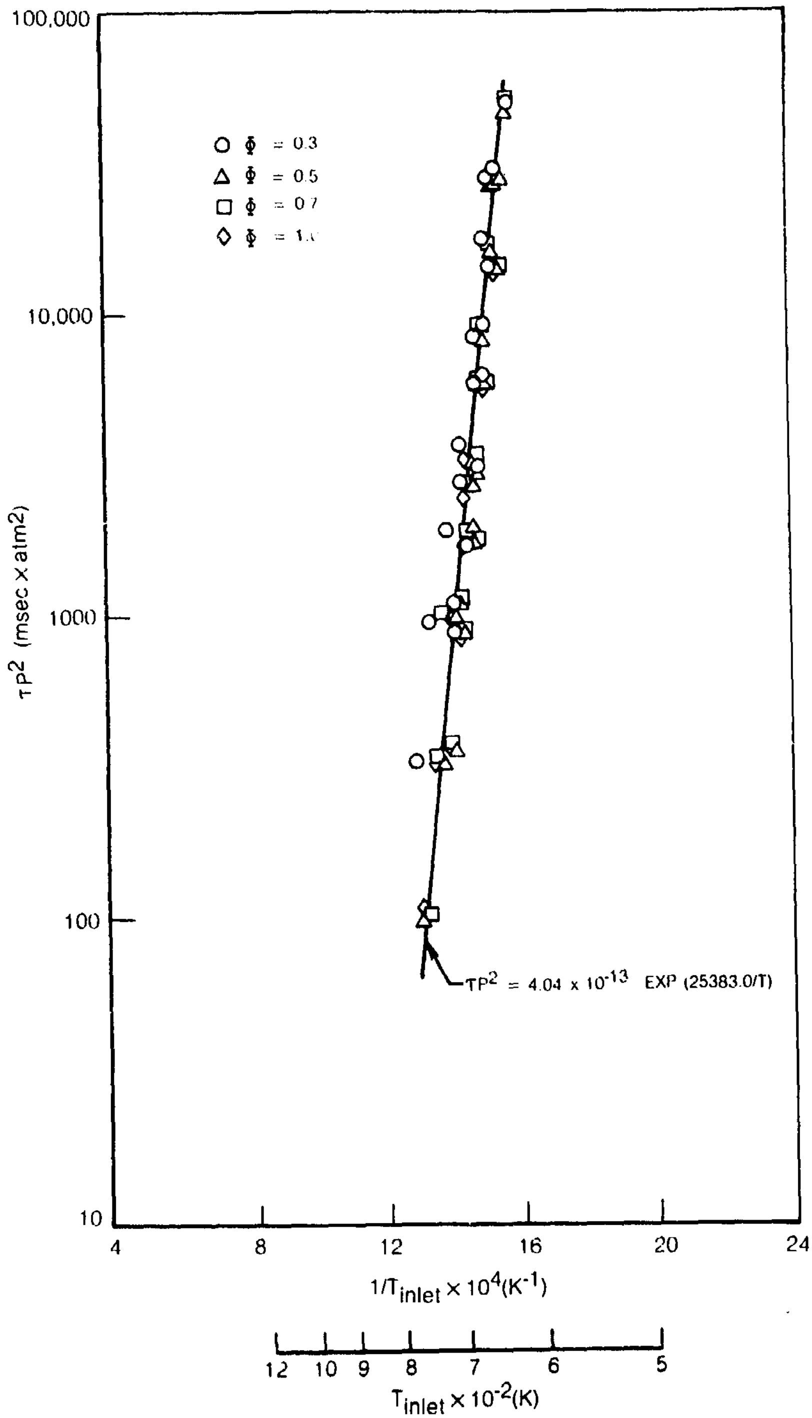

Figure 23 Autoignition Characteristics of Cetane in Air

80–2–36–4

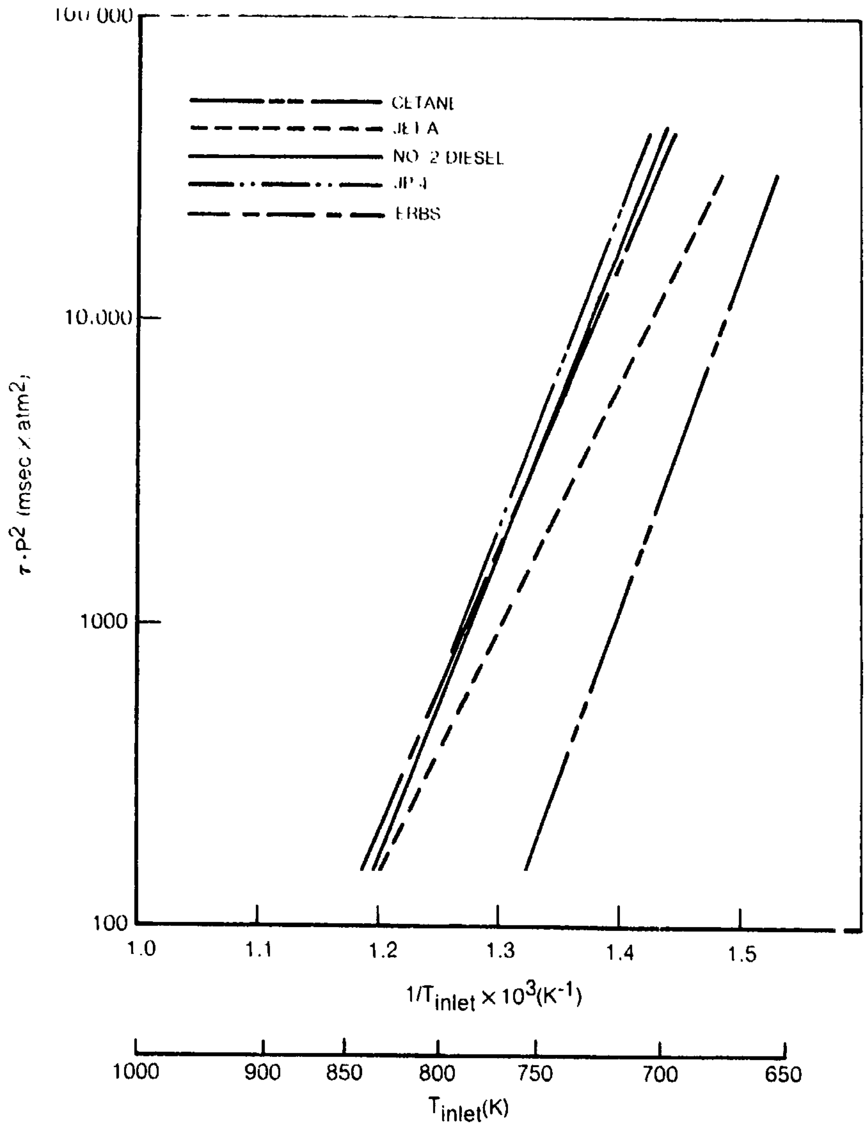

Figure 24 Comparison of Autoignition Correlations for Several Fuels in Air

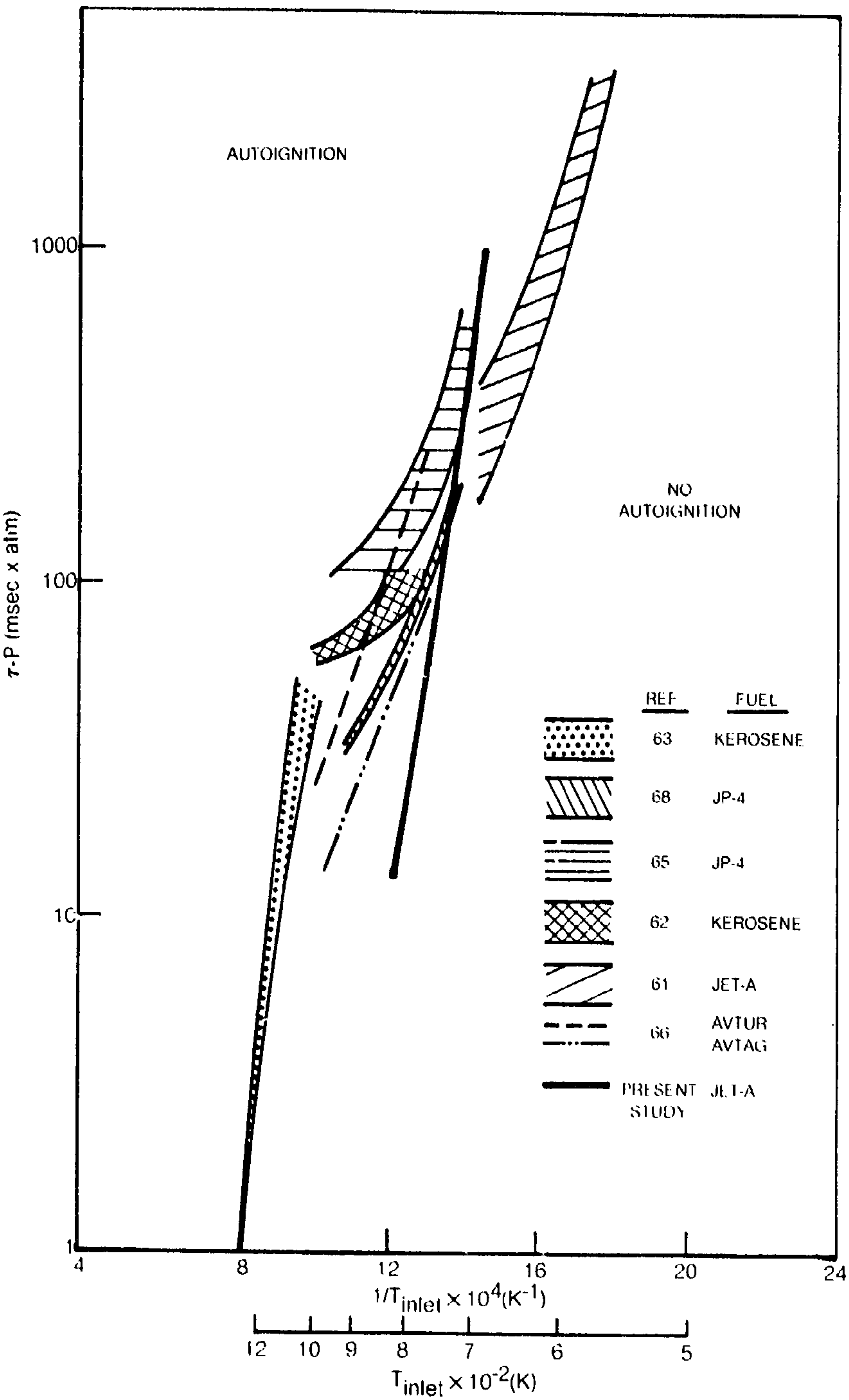

Figure 25 Autoignition of Liquid Hydrocarbon Fuel Sprays in Air (Ref. 71)

80–02–36–25

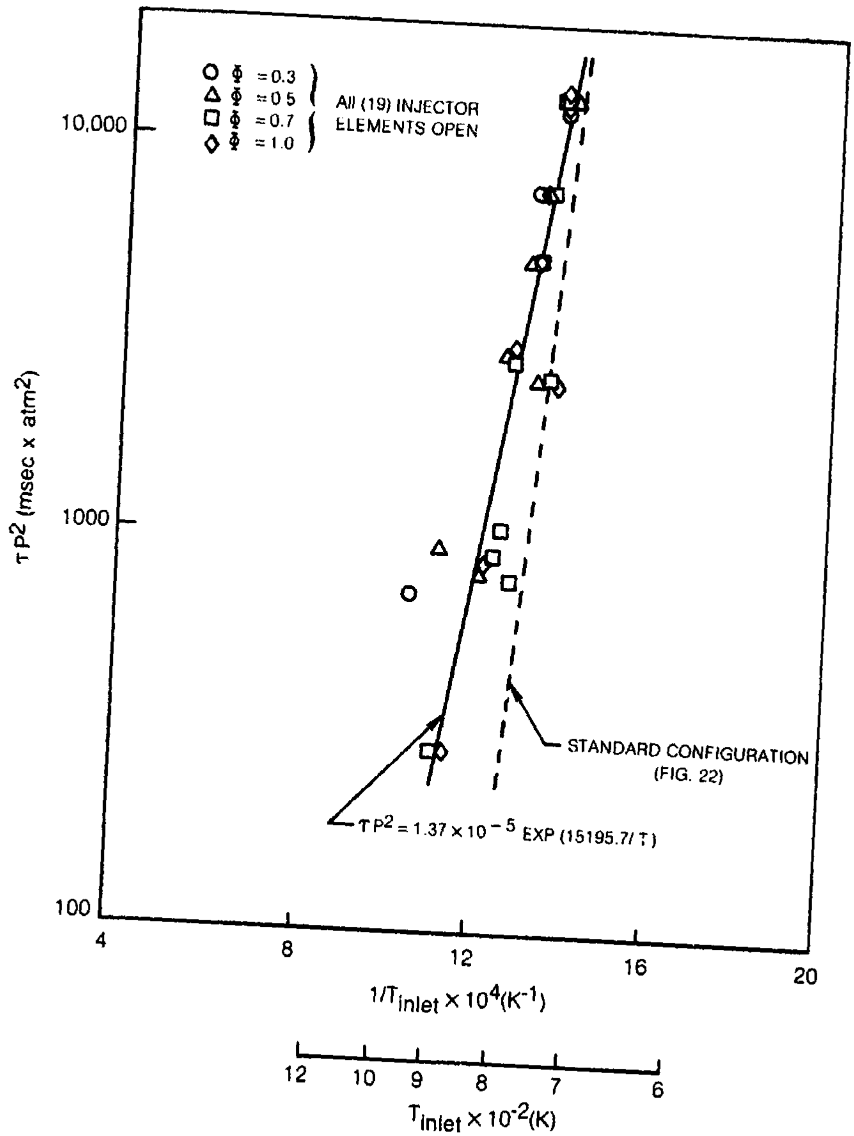

Figure 26 Effect of Injector Configuration on the Autoignition Characteristics of JP-4 in Air

80–2–36–24

APPENDIX A

TABULATED AUTOIGNITION DATA

TABLE A1

Ignition Delay Data for No. 2 Diesel Fuel in Air

$\Phi = 0.3$
$T_{fuel} = 300$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay $sec \times 10^3$	Comments
10.4	115.6	978	943	0.5	.0118	91.7	>12.6	No Autoignition
15.7	115.6	750	726	0.5	.0115	46.5	24.8	
15.4	68.6	767	742	0.5	.0125	49.1	14.0	
14.9	22.9	844	815	0.5	.0136	55.5	4.1	
15.1	7.6	976	941	0.5	.0135	64.0	> 1.2	No Autoignition
20.7	115.6	717	694	0.5	.0137	33.9	34.1	
20.7	68.6	755	730	0.5	.0117	35.7	19.2	
20.1	22.9	769	743	0.5	.0111	37.3	6.1	
20.3	7.6	778	752	0.5	.0135	37.8	2.0	
25.8	115.6	700	678	0.5	.0137	26.7	43.2	
24.7	68.6	717	694	0.5	.0107	28.5	24.1	
25.5	22.9	741	717	0.5	.0117	28.7	8.0	
25.4	7.6	731	707	0.5	.0113	28.4	2.7	
24.9	7.6	740	716	0.5	.0123	29.2	2.6	
30.2	115.6	686	664	0.5	.0137	22.0	52.6	
29.9	68.6	694	672	0.5	.0120	22.7	30.3	
29.8	22.9	715	692	0.5	.0141	23.3	9.8	

TABLE A2

Ignition Delay Data for No. 2 Diesel Fuel in Air

$\phi = 0.5$
$T_{fuel} = 300$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times10^3$	Comments
10.4	115.6	769	729	0.5	.0174	72.4	16.0	
10.1	115.6	802	759	0.5	.0177	77.4	15.0	
10.3	68.6	978	924	0.5	.0183	92.5	> 7.4	No Autoignition
10.2	22.9	961	908	0.5	.0182	92.8	> 2.5	No Autoignition
15.2	115.6	733	695	0.5	.0175	46.9	24.6	
15.3	68.6	739	701	0.5	.0172	47.5	14.4	
15.1	22.9	781	740	0.5	.0170	50.9	4.5	
14.8	7.6	875	827	0.5	.0175	58.3	1.3	
20.3	115.6	705	669	0.5	.0169	33.9	34.1	
20.4	115.6	709	673	0.5	.0173	34.1	33.9	
20.9	68.6	718	681	0.5	.0170	33.6	20.4	
19.8	22.9	761	721	0.5	.0171	37.3	6.1	
19.6	22.9	755	715	0.5	.0173	37.4	6.1	
20.6	7.6	756	716	0.5	.0164	36.1	2.1	
19.8	7.6	778	737	0.5	.0170	38.6	2.0	
25.4	115.6	689	654	0.5	.0166	26.5	43.6	
24.9	68.6	711	675	0.5	.0170	28.0	24.5	
25.4	22.9	728	691	0.5	.0168	28.3	8.1	
25.1	7.6	736	698	0.5	.0176	28.7	2.7	
29.8	68.6	701	666	0.5	.0172	22.9	29.9	
30.1	22.9	722	685	0.5	.0169	23.6	9.7	
30.1	7.6	725	688	0.5	.0170	23.4	3.3	

TABLE A3

Ignition Delay Data for No. 2 Diesel Fuel in Air

$\Phi = 0.7$
$T_{fuel} = 300$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times 10^3$	Comments
10.3	115.6	764	710	0.5	.0237	72.1	16.0	
10.4	68.6	803	746	0.5	.0244	75.4	9.1	
10.0	22.9	1005	929	0.5	.0240	99.5	> 2.3	No Autoignition
15.1	115.6	725	675	0.5	.0240	46.8	24.7	
15.2	68.6	750	698	0.5	.0235	48.4	14.2	
15.4	22.9	780	724	0.5	.0244	49.9	4.6	
15.4	7.6	797	740	0.5	.0239	51.0	1.5	
15.4	7.6	789	733	0.5	.0237	50.8	1.5	
19.7	115.6	708	659	0.5	.0230	35.0	33.0	
20.3	68.6	725	675	0.5	.0243	34.9	19.7	
20.0	22.9	758	705	0.5	.0239	36.6	6.2	
20.3	22.9	758	705	0.5	.0239	35.3	6.5	
19.8	7.6	761	708	0.5	.0235	37.8	2.0	
20.5	7.6	759	706	0.5	.0233	36.4	2.1	
25.6	115.6	692	645	0.5	.0238	26.5	43.9	
25.1	68.6	717	668	0.5	.0239	28.1	24.4	
25.3	22.9	742	690	0.5	.0235	28.6	8.0	
24.7	7.6	742	690	0.5	.0239	29.5	2.6	

TABLE A4

Ignition Delay Data for No. 2 Diesel Fuel in Air

$\phi = 1.0$

$T_{fuel} = 300$ K

Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times 10^3$	Comments
10.2	115.6	764	690	0.5	.0349	73.0	15.8	
10.3	68.6	800	722	0.5	.0338	75.6	9.1	
10.6	22.9	875	787	0.5	.0350	81.6	2.8	
10.0	7.6	978	878	0.5	.0332	96.1	> 0.8	No Autoignition
15.1	115.6	730	661	0.5	.0343	46.9	24.6	
15.3	68.6	758	685	0.5	.0348	45.7	14.1	
15.5	22.9	794	716	0.5	.0339	50.1	4.6	
15.4	22.9	794	716	0.5	.0336	50.9	4.5	
15.4	7.6	806	727	0.5	.0335	51.6	1.5	
20.3	115.6	711	644	0.5	.0345	34.2	33.8	
20.2	68.6	737	667	0.5	.0342	35.6	19.2	
20.2	22.9	767	693	0.5	.0344	36.1	6.3	
20.5	7.6	769	695	0.5	.0326	37.0	2.1	

TABLE A5

Ignition Delay Data for ERBS Fuel in Air

$\Phi = 0.3$
$T_{fuel} = 300$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay $sec\times10^3$	Comments
10.3	115.6	997	961	0.5	.0135	95.5	> 12.0	No Autoignition
10.4	68.6	983	948	0.5	.0121	93.7	> 7.3	No Autoignition
15.1	115.6	752	727	0.5	.0124	49.6	23.0	
14.7	115.6	772	746	0.5	.0113	51.7	22.1	
15.4	68.6	781	755	0.5	.0128	50.1	13.7	
15.4	22.9	814	787	0.5	.0137	52.1	4.4	
15.2	22.9	783	757	0.5	.0141	50.2	4.6	
20.4	115.6	699	677	0.5	.0113	33.9	33.7	
20.7	68.6	750	725	0.5	.0121	35.9	19.1	
20.7	22.9	753	728	0.5	.0139	35.9	6.4	
19.8	22.9	756	731	0.5	.0141	37.5	6.1	
20.0	7.6	828	800	0.5	.0107	40.0	1.9	
25.3	115.6	711	688	0.5	.0104	27.8	41.1	
25.1	68.6	733	709	0.5	.0107	28.9	23.7	
25.4	22.9	744	720	0.5	.0110	28.4	8.0	
25.3	7.6	752	727	0.5	.0135	29.0	2.6	
30.1	115.6	681	659	0.5	.0130	22.3	51.4	
29.8	68.6	718	695	0.5	.0127	23.9	28.7	
30.0	22.9	736	712	0.5	.0110	23.9	9.6	
30.4	7.6	742	717	0.5	.0121	24.1	3.2	

TABLE A6

Ignition Delay Data For ERBS Fuel in Air

$\Phi = 0.5$
$T_{fuel} = 300$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times 10^3$	Comments
10.2	115.6	814	771	0.5	.0169	79.0	14.5	
10.3	68.6	994	948	0.5	.0162	95.3	> 7.2	No Autoignition
14.9	115.6	731	692	0.5	.0165	48.5	23.5	
15.1	68.6	769	728	0.5	.0167	50.5	13.6	
15.4	22.9	778	737	0.5	.0168	49.4	4.6	
15.1	7.6	978	924	0.5	.0160	63.4	> 1.2	No Autoignition
14.9	7.6	956	903	0.5	.0174	62.8	> 1.2	No Autoignition
20.4	115.6	713	677	0.5	.0170	34.6	33.0	
19.7	68.6	739	701	0.5	.0172	37.0	18.5	
20.2	22.9	747	708	0.5	.0176	36.9	6.2	
20.0	7.6	794	752	0.5	.0150	38.8	2.0	
20.0	7.6	778	737	0.5	.0172	38.2	2.0	
25.6	115.6	696	661	0.5	.0159	26.9	42.5	
25.4	68.6	736	698	0.5	.0183	28.6	24.0	
25.2	22.9	733	695	0.5	.0174	28.2	8.1	
25.6	7.6	747	708	0.5	.0165	28.5	2.7	
30.0	115.6	678	644	0.5	.0165	22.4	51.4	
30.2	68.6	708	672	0.5	.0158	23.2	29.5	
30.5	22.9	725	688	0.5	.0170	23.0	9.9	
30.2	7.6	728	691	0.5	.0171	23.5	3.2	

TABLE A7

Ignition Delay for ERBS Fuel in Air

$\Phi = 0.7$

$T_{fuel} = 300$ K

Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay $sec \times 10^3$	Comments
10.4	115.6	767	713	0.5	.0231	73.0	15.7	
10.3	68.6	803	746	0.5	.0226	77.0	8.9	
10.1	22.9	992	917	0.5	.0236	96.0	> 2.4	No Autoignition
10.2	7.6	978	905	0.5	.0236	94.3	> 0.8	No Autoignition
15.1	115.6	714	665	0.5	.0228	46.8	24.4	
14.9	68.6	758	705	0.5	.0231	50.2	13.7	
15.2	22.9	775	725	0.5	.0237	49.7	4.6	
15.2	7.6	811	753	0.5	.0230	52.4	1.5	
15.2	7.6	800	743	0.5	.0235	51.6	1.5	
20.1	115.6	699	652	0.5	.0232	34.4	33.0	
20.0	68.6	733	682	0.5	.0226	36.2	18.9	
19.9	22.9	750	697	0.5	.0235	36.8	6.2	
20.0	7.6	767	713	0.5	.0234	40.0	1.9	
25.4	115.6	689	642	0.5	.0226	26.8	42.7	
25.3	68.6	723	673	0.5	.0233	28.2	24.3	
25.5	22.9	740	688	0.5	.0234	28.2	8.1	
24.6	7.6	747	695	0.5	.0238	29.8	2.6	
29.4	115.6	675	629	0.5	.0228	22.0	50.1	
30.5	68.6	711	668	0.5	.0228	23.0	29.8	
30.4	22.9	731	680	0.5	.0233	23.7	9.6	
29.8	7.6	738	686	0.5	.0232	24.6	3.1	

TABLE A8

Ignition Delay for ERBS Fuel in Air

$\Phi = 1.0$
$T_{fuel} = 300$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times 10^3$	Comments
10.3	115.6	767	693	0.5	.0332	73.4	15.6	
10.2	68.6	814	734	0.5	.0335	79.1	8.7	
10.3	22.9	869	781	0.5	.0336	82.3	2.8	
10.3	7.6	978	878	0.5	.0338	93.0	> 0.8	No Autoignition
15.2	115.6	724	655	0.5	.0333	47.0	24.3	
14.9	68.6	764	690	0.5	.0339	50.6	13.6	
15.5	22.9	789	712	0.5	.0339	49.8	4.6	
15.2	7.6	825	744	0.5	.0335	53.3	1.4	
20.4	115.6	707	640	0.5	.0334	30.3	33.3	
20.0	68.6	744	672	0.5	.0331	36.8	18.6	
20.4	22.9	767	693	0.5	.0338	36.8	6.2	
20.0	7.6	789	712	0.5	.0334	38.6	2.0	

TABLE A9

Ignition Delay Data for Jet-A Fuel in Air

$\Phi = 0.3$

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	T_{fuel} K	Ignition Delay sec$\times10^3$	Comments	
15.2	99.1	717	694	0.5	.0102	44.2	300	22.4	Streamline	Injector
20.1	83.8	706	683	0.5	.0104	33.3	300	25.2	"	"
20.3	53.8	740	716	0.5	.0104	34.7	300	15.4	"	"
20.3	22.9	783	756	0.5	.0104	36.2	300	6.3	"	"
20.7	22.9	800	773	1.0	.0201	71.9	300	3.2	"	"
20.2	6.4	794	766	0.5	.0104	36.9	300	1.7	"	"
25.2	22.9	739	715	0.5	.0109	27.8	300	8.2	"	"
25.1	22.9	744	720	1.0	.0201	55.6	300	4.1	"	"
25.5	6.4	761	736	0.5	.0104	28.3	300	2.2	"	"
25.5	6.4	772	746	1.0	.0211	59.3	300	1.1	"	"
31.0	6.4	722	699	0.5	.0100	22.2	300	2.9	"	"

TABLE A10

Ignition Delay Data for Jet-A Fuel in Air

$\Phi = 0.5$

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	T_{fuel} K	Ignition Delay $sec \times 10^3$	Comments
10.2	129.5	761	721	0.5	.0172	73.0	300	17.2	Streamline Injector
10.1	116.9	722	685	0.5	.0171	69.5	300	16.8	Conical Injector
10.5	116.9	722	685	0.5	.0173	67.2	300	17.2	" "
10.6	116.9	694	659	0.5	.0170	65.0	402	18.0	" "
10.4	115.6	756	716	0.5	.0170	71.1	300	16.3	" "
10.2	99.1	733	695	0.5	.0172	67.5	300	14.7	Streamline Injector
10.5	83.8	740	701	0.5	.0174	66.6	300	12.6	" "
10.6	69.9	753	714	0.5	.0172	70.0	300	9.9	Conical Injector
9.8	69.9	831	786	0.5	.0173	81.8	300	8.5	" "
10.2	69.9	772	731	0.5	.0170	74.6	413	9.3	" "
10.0	68.6	808	765	0.5	.0172	79.2	300	8.7	" "
10.4	53.3	806	763	0.5	.0172	73.5	300	7.3	Streamline Injector
10.2	24.2	951	898	0.5	.0170	90.9	300	>2.7	Conical Injector, No Autoignition
15.2	99.1	694	659	0.5	.0172	43.3	300	22.9	Streamline Injector
15.3	83.8	715	678	0.5	.0172	44.4	300	18.9	" "
15.2	53.3	744	705	0.5	.0177	46.6	300	11.5	" "
15.7	22.9	790	747	0.5	.0172	47.7	300	4.8	" "
15.0	22.9	793	750	1.0	.0354	103.3	300	2.2	" "
15.2	6.4	794	751	0.5	.0170	49.7	300	1.3	" "
20.3	115.6	705	669	0.5	.0171	34.0	300	34.0	Conical Injector
20.4	115.6	702	666	0.5	.0176	33.6	300	34.4	" "
20.1	83.8	707	671	0.5	.0170	33.3	300	25.2	Streamline Injector
20.3	68.6	722	685	0.5	.0175	35.1	300	19.5	Conical Injector
20.2	68.6	717	680	0.5	.0177	34.9	300	19.6	" "
20.3	24.2	736	698	0.5	.0170	35.4	300	6.8	" "
20.1	24.2	750	711	0.5	.0174	36.1	300	6.7	" "
20.3	24.2	753	714	0.5	.0175	35.3	300	6.5	" "
19.0	8.9	731	694	0.5	.0165	36.9	300	2.4	Streamline Injector
20.3	6.4	778	737	1.0	.0333	74.0	300	0.9	" "
23.8	53.3	706	670	0.5	.0170	28.1	300	19.0	" "
25.4	6.4	733	696	0.5	.0166	27.4	300	2.3	" "

TABLE A11

Ignition Delay Data for Jet-A Fuel in Air

$\phi = 0.7$

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	T_{fuel} K	Ignition Delay sec$\times10^3$	Comments
10.0	116.9	739	688	0.5	.0239	72.5	300	16.1	Conical Injector
10.9	116.9	724	674	0.5	.0235	64.9	300	18.0	" "
10.5	116.9	700	652	0.5	.0235	65.9	402	17.7	" "
11.1	116.9	705	657	0.5	.0241	62.0	402	18.9	" "
10.3	115.6	742	690	0.5	.0238	70.2	300	16.5	" "
10.2	99.1	729	679	0.5	.0236	69.9	300	13.6	Streamline Injector
10.5	99.1	717	668	0.5	.0236	64.9	300	15.3	" "
10.2	83.8	747	694	0.5	.0232	69.9	300	12.1	" "
10.0	69.9	750	697	0.5	.0243	67.1	300	10.4	Conical Injector
10.1	69.9	778	722	0.5	.0238	74.6	300	9.3	" "
10.5	69.9	756	703	0.5	.0252	70.4	400	9.8	" "
10.5	53.3	789	733	0.5	.0232	71.5	300	7.5	Streamline Injector
11.1	24.2	803	746	0.5	.0245	68.2	300	3.6	Conical Injector
10.2	24.2	914	846	0.5	.0245	87.2	403	2.7	" "
10.5	22.9	850	788	0.5	.0232	77.0	300	3.0	Streamline Injector
10.1	8.9	986	913	0.5	.0241	94.1	300	>0.95	Conical Injector, No Autoignition
15.2	83.8	722	672	0.5	.0236	45.2	300	18.6	Streamline Injector
15.1	53.3	752	700	0.5	.0232	47.3	300	11.3	" "
15.4	22.9	783	727	0.5	.0232	48.2	300	4.8	" "
15.0	6.4	794	737	0.5	.0232	50.2	300	1.3	" "
20.0	115.6	698	650	0.5	.0240	34.0	300	33.9	Conical Injector
20.3	115.6	694	646	0.5	.0233	33.4	300	34.6	" "
19.5	69.9	712	663	0.5	.0238	35.4	300	19.7	" "
20.2	68.6	716	667	0.5	.0235	34.9	300	19.7	" "
19.9	68.6	711	662	0.5	.0238	35.2	300	19.5	" "
20.3	24.2	722	672	0.5	.0235	34.4	300	7.0	" "
20.3	8.9	711	662	0.5	.0226	33.7	300	2.6	" "
20.3	8.9	711	662	0.5	.0221	33.7	300	2.6	" "

TABLE A12

Ignition Delay Data for JP-4 Fuel in Air

$\phi = 0.3$
$T_{fuel} = 300$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times 10^3$	Comments
10.8	115.6	994	958	0.5	.0131	89.7	>12.9	No Autoignition
10.3	68.6	964	930	0.5	.0103	91.5	> 7.5	No Autoignition
15.1	115.6	783	756	0.5	.0100	51.3	22.3	
15.7	115.6	744	720	0.5	.0112	46.3	25.0	
14.9	69.9	757	732	0.5	.0100	49.2	14.2	
14.9	69.9	778	752	0.5	.0107	50.2	13.9	
15.3	24.2	792	765	0.5	.0103	50.2	4.8	
14.9	24.2	769	744	0.5	.0109	49.9	4.8	
15.2	22.9	856	826	0.5	.0128	54.8	4.2	
15.5	7.6	978	943	0.5	.0117	62.0	> 1.2	No Autoignition
20.5	115.6	736	712	0.5	.0096	35.4	32.3	
20.3	115.6	717	694	0.5	.0122	34.4	33.5	
20.0	69.9	736	712	0.5	.0105	35.6	19.7	
19.4	68.6	759	734	0.5	.0124	38.5	17.8	
20.0	24.2	756	731	0.5	.0110	36.7	6.6	
20.7	7.6	747	722	0.5	.0113	35.2	2.2	
20.7	7.6	814	787	0.5	.0113	39.5	1.9	
25.4	115.6	711	688	0.5	.0131	27.3	42.2	
24.8	115.6	725	702	0.5	.0091	28.6	40.4	
25.2	69.9	714	691	0.5	.0110	27.4	25.5	
26.4	69.9	712	689	0.5	.0109	26.1	26.8	
25.1	7.6	736	712	0.5	.0106	28.5	2.7	
24.6	7.6	728	705	0.5	.0113	28.2	2.7	
25.2	7.6	780	754	1.0	.0208	61.4	1.4	
30.0	7.6	717	694	0.5	.0106	23.2	3.3	
28.8	7.6	764	738	1.0	.0212	52.7	1.4	

TABLE A13

Ignition Delay Data for JP-4 Fuel in Air

$\phi = 0.5$
$T_{fuel} = 300$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times10^3$	Comments
10.1	116.9	793	751	0.5	.0172	75.6	15.5	
10.5	115.6	775	734	0.5	.0177	71.7	16.1	
10.2	69.9	824	779	0.5	.0170	78.2	8.9	
10.1	69.9	797	754	0.5	.0169	75.9	9.2	
10.0	69.9	808	765	0.5	.0171	77.7	9.0	
15.5	116.9	724	687	0.5	.0180	45.1	25.9	
15.2	116.9	734	696	0.5	.0178	46.8	25.0	
15.3	115.6	729	692	0.5	.0176	47.1	24.2	
15.2	69.9	731	694	0.5	.0172	46.4	15.1	
15.2	69.9	728	691	0.5	.0171	46.2	15.1	
15.1	68.6	781	740	0.5	.0169	50.9	13.5	
15.3	24.2	744	705	0.5	.0176	47.0	5.1	
15.0	24.2	767	727	0.5	.0177	49.3	4.9	
14.9	22.9	786	744	0.5	.0173	51.5	4.4	
14.9	8.9	837	792	0.5	.0168	54.3	1.6	
15.3	7.6	767	726	0.5	.0168	48.6	1.6	
15.4	7.6	806	763	0.5	.0181	51.3	1.5	
20.8	116.9	711	675	0.5	.0168	33.1	35.3	
20.3	115.6	725	688	0.5	.0174	35.3	32.3	
20.3	69.9	703	667	0.5	.0171	33.4	20.9	
20.0	68.6	747	702	0.5	.0168	36.7	18.7	
20.3	24.2	729	692	0.5	.0168	34.9	6.9	
20.0	22.9	736	698	0.5	.0186	35.8	6.4	
20.3	7.6	731	694	0.5	.0152	35.0	2.2	
19.8	7.6	731	694	0.5	.0163	35.7	2.1	
19.6	7.6	731	694	0.5	.0177	36.3	2.1	
20.1	7.6	761	721	0.5	.0168	37.0	2.1	
24.8	115.6	706	670	0.5	.0173	27.7	41.8	
25.4	69.9	711	675	0.5	.0177	27.1	25.8	
25.5	68.6	722	685	0.5	.0171	27.6	24.9	
25.8	7.6	706	670	0.5	.0171	26.5	2.9	
25.2	7.6	711	675	0.5	.0170	27.4	2.8	
30.0	68.6	708	672	0.5	.0160	22.9	29.9	
29.9	7.6	702	666	0.5	.0181	22.8	3.3	

TABLE A14

Ignition Delay Data for JP-4 Fuel in Air

$\phi = 0.7$

$T_{fuel} = 300$ K

Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times 10^3$	Comments
10.3	116.9	782	726	0.5	.0246	73.4	15.9	
10.3	69.9	781	725	0.5	.0243	73.3	9.5	
10.1	69.9	792	735	0.5	.0241	75.78	9.2	
10.2	69.9	792	735	0.5	.0240	70.9	9.9	
10.4	24.2	888	823	0.5	.0241	83.0	>2.9	No Autoignition
14.9	116.9	733	682	0.5	.0242	47.7	24.5	
15.0	115.6	731	680	0.5	.0247	48.1	23.8	
14.7	68.6	758	705	0.5	.0242	50.2	13.7	
15.1	68.6	769	715	0.5	.0247	50.0	13.7	
14.6	68.6	767	713	0.5	.0252	50.5	13.6	
15.3	22.9	772	717	0.5	.0254	49.6	4.6	
15.2	8.9	778	723	0.5	.0233	49.5	1.8	
15.2	8.9	764	710	0.5	.0235	48.7	1.8	
15.3	7.6	814	756	0.5	.0254	52.3	1.5	
15.3	7.6	822	763	0.5	.0247	52.9	1.4	
20.0	116.9	706	658	0.5	.0246	34.2	34.2	
20.0	115.6	719	670	0.5	.0239	35.5	32.2	
19.7	68.6	733	682	0.5	.0246	36.1	19.0	
20.4	68.6	744	692	0.5	.0247	35.8	19.2	
20.3	22.9	739	688	0.5	.0247	35.5	6.4	
19.9	7.6	733	682	0.5	.0247	35.7	2.1	
20.6	7.6	767	713	0.5	.0251	36.4	2.1	
20.3	7.6	764	711	0.5	.0248	36.9	2.1	
25.9	115.6	700	652	0.5	.0250	26.3	43.9	
25.4	68.6	717	668	0.5	.0244	27.4	25.0	
25.2	7.6	717	668	0.5	.0238	27.6	2.8	
25.1	7.6	728	678	0.5	.0238	28.7	2.7	
29.4	7.6	713	664	0.5	.0235	23.6	3.2	

TABLE A15

Ignition Delay Data for JP-4 Fuel in Air

$\phi = 1.0$
$T_{fuel} = 300$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay $sec \times 10^3$	Comments
9.9	116.9	783	707	0.5	.0348	76.3	15.3	
10.2	69.9	808	729	0.5	.0343	76.6	9.1	
10.1	8.9	972	878	0.5	.0328	93.8	> 0.95	No Autoignition
15.3	115.6	747	675	0.5	.0327	48.4	23.6	
15.1	115.6	739	668	0.5	.0326	48.2	23.7	
15.2	68.6	758	685	0.5	.0340	48.5	14.1	
15.3	68.6	783	707	0.5	.0331	50.4	13.6	
14.9	68.6	775	700	0.5	.0338	51.0	13.4	
15.0	22.9	778	703	0.5	.0321	51.3	4.6	
15.1	8.9	794	716	0.5	.0325	50.9	1.7	
15.5	7.6	794	716	0.5	.0341	49.9	1.5	
15.1	7.6	822	741	0.5	.0326	53.6	1.4	
20.3	115.6	711	644	0.5	.0331	34.6	33.1	
20.7	68.6	736	666	0.5	.0336	34.7	19.8	
20.4	68.6	750	678	0.5	.0328	36.0	19.0	
20.7	7.6	761	688	0.5	.0349	35.6	2.1	
24.8	7.6	747	675	0.5	.0358	29.3	2.6	

TABLE A16

Ignition Delay for Cetane Fuel in Air

$\phi = 0.3$
$T_{fuel} = 305$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times 10^3$	Comments
10.7	115.6	731	703	0.5	.0104	67.6	16.9	
10.2	68.6	758	727	0.5	.0098	73.5	9.3	
10.3	22.9	978	930	0.5	.0122	94.0	> 2.4	No Autoignition
10.1	7.6	978	930	0.5	.0123	95.1	> 0.8	No Autoignition
15.4	115.6	675	651	0.5	.0100	43.4	26.3	
15.6	68.6	711	685	0.5	.0098	45.0	15.2	
15.2	22.9	719	693	0.5	.0107	46.6	4.8	
15.1	7.6	784	752	0.5	.0090	51.0	1.5	
20.3	115.6	663	640	0.5	.0093	32.0	35.4	
20.3	68.6	686	661	0.5	.0099	33.2	20.7	
20.7	22.9	708	682	0.5	.0091	34.1	6.7	
20.2	7.6	714	687	0.5	.0093	34.7	2.2	
25.8	115.6	657	635	0.5	.0098	25.1	45.5	
25.8	68.6	671	647	0.5	.0105	25.5	26.9	
25.8	22.9	689	664	0.5	.0093	26.0	8.8	
25.2	7.6	700	674	0.5	.0098	27.1	2.8	
30.5	115.6	643	619	0.5	.0093	20.8	55.1	
30.1	69.6	666	642	0.5	.0095	21.7	31.6	
30.0	22.9	669	645	0.5	.0094	21.9	10.4	
30.1	7.6	681	656	0.5	.0093	21.9	3.5	

TABLE A17

Ignition Delay for Cetane Fuel in Air

$\Phi = 0.5$
$T_{fuel} = 305$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times 10^3$	Comments
10.1	115.6	689	652	0.5	.0170	67.3	17.0	
10.2	68.6	719	679	0.5	.0171	69.7	9.8	
10.2	22.9	739	697	0.5	.0171	71.5	3.2	
10.0	7.6	772	726	0.5	.0171	75.8	1.0	
15.2	115.6	671	635	0.5	.0169	43.5	26.3	
15.1	68.6	692	655	0.5	.0171	45.1	15.2	
15.1	22.9	708	669	0.5	.0171	46.3	4.9	
15.0	7.6	715	675	0.5	.0171	46.8	1.6	
20.0	115.6	658	624	0.5	.0165	32.5	35.2	
20.0	68.6	677	641	0.5	.0168	32.9	20.8	
20.3	22.9	689	652	0.5	.0174	33.9	6.7	
20.1	7.6	702	664	0.5	.0175	34.4	2.2	
25.6	115.6	647	613	0.5	.0173	25.0	45.6	
24.6	68.6	666	631	0.5	.0174	25.7	26.6	
25.5	22.9	683	646	0.5	.0171	26.1	8.8	
25.7	7.6	689	652	0.5	.0172	26.2	2.9	
29.8	115.6	641	608	0.5	.0168	21.3	53.7	
29.8	68.6	661	626	0.5	.0172	21.8	31.4	
30.0	68.6	657	622	0.5	.0174	21.5	32.0	
30.0	22.9	674	638	0.5	.0177	22.0	10.4	
29.6	7.6	683	646	0.5	.0170	22.4	3.4	

TABLE A18

Ignition Delay for Cetane Fuel in Air

$\phi = 0.7$
$T_{fuel} = 305$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay secx10^3	Comments
10.2	115.6	691	641	0.5	.0240	66.9	17.1	
10.3	68.6	719	666	0.5	.0240	68.6	10.0	
10.4	22.9	744	688	0.5	.0238	70.7	3.2	
10.2	7.6	761	702	0.5	.0240	73.5	1.0	
15.1	115.6	672	624	0.5	.0239	44.0	26.0	
15.0	68.6	686	636	0.5	.0234	45.0	15.2	
15.2	22.9	708	656	0.5	.0236	45.9	5.0	
15.4	7.6	722	668	0.5	.0239	46.3	1.6	
20.3	115.6	656	609	0.5	.0236	32.0	35.7	
20.0	68.6	678	629	0.5	.0238	33.2	20.6	
20.3	22.9	697	646	0.5	.0236	34.1	6.7	
20.3	7.6	708	656	0.5	.0239	34.4	2.2	
25.4	115.6	650	604	0.5	.0237	25.3	45.2	
25.4	68.6	667	620	0.5	.0245	25.7	26.6	
25.8	22.9	686	636	0.5	.0240	25.8	8.9	
25.6	7.6	697	646	0.5	.0244	26.6	2.9	
30.7	115.6	644	599	0.5	.0235	20.7	55.2	
29.9	68.6	663	616	0.5	.0236	21.8	31.5	
29.9	22.9	678	629	0.5	.0236	22.2	10.3	
29.9	7.6	689	649	0.5	.0244	22.4	3.4	

TABLE A19

Ignition Delay for Cetane Fuel in Air

$\Phi = 1.0$
$T_{fuel} = 305$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times 10^3$	Comments
10.1	115.6	697	627	0.5	.0343	68.0	16.8	
10.3	68.6	724	650	0.5	.0348	69.8	9.8	
10.2	22.9	747	669	0.5	.0344	72.2	3.2	
10.3	7.6	772	690	0.5	.0347	74.2	1.0	
15.1	115.6	678	611	0.5	.0334	44.2	25.8	
14.9	68.6	700	630	0.5	.0343	46.2	14.8	
15.4	22.9	716	643	0.5	.0334	45.7	5.0	
15.1	7.6	725	651	0.5	.0338	47.3	1.6	
19.7	115.6	662	597	0.5	.0316	33.2	34.5	
19.8	68.6	686	617	0.5	.0326	33.9	20.2	
19.5	22.9	706	634	0.5	.0325	35.9	6.4	
19.8	7.6	711	639	0.5	.0346	35.1	2.2	

TABLE A20

Ignition Delay for JP-4 Fuel in Air

$\Phi = 0.3$
$T_{fuel} = 300$ K
Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times10^3$	Comments*
15.1	115.6	783	756	0.5	.0100	51.3	22.3	6 elements
15.2	22.9	856	826	0.5	.0128	54.8	4.2	6 elements
14.9	22.9	978	943	0.5	.0113	64.6	>3.5	All elements, No Autoignition
15.5	7.6	978	943	0.5	.0117	62.0	>1.2	6 elements, No Autoignition
20.5	115.6	736	712	0.5	.0096	35.4	32.3	6 elements
19.6	115.6	740	716	0.5	.0113	37.1	30.8	All elements
20.3	68.6	800	773	0.5	.0101	38.9	17.6	All elements
19.4	68.6	759	734	0.5	.0124	38.5	17.8	6 elements
20.2	7.6	814	787	0.5	.0113	39.5	1.9	6 elements
20.9	7.6	972	938	0.5	.0121	45.5	1.7	All elements

* Center and outer injector elements capped = 6 elements
All injector elements open = All elements

TABLE A21

Ignition Delay for JP-4 Fuel in Air

$\Phi = 0.5$

$T_{fuel} = 300$ K

Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times10^3$	Comments*
15.1	115.6	781	740	0.5	.0175	50.9	22.5	All elements
15.3	115.6	729	692	0.5	.0176	47.1	24.2	6 elements
15.1	68.6	814	771	0.5	.0174	53.0	12.9	All elements
15.1	68.6	781	740	0.5	.0169	50.9	13.5	6 elements
15.4	68.6	919	868	0.5	.0173	58.6	3.9	All elements
14.9	22.9	786	744	0.5	.0173	51.5	4.4	6 elements
15.4	22.9	806	763	0.5	.0181	51.3	1.5	6 elements
15.1	22.9	978	924	0.5	.0178	63.3	>1.2	All elements, No Autoignition
20.3	115.6	725	688	0.5	.0174	35.3	32.3	6 elements
19.6	115.6	722	685	0.5	.0181	36.2	31.6	All elements
20.0	68.6	767	726	0.5	.0170	37.7	18.2	All elements
20.0	68.6	747	702	0.5	.0168	36.7	18.7	6 elements
20.3	22.9	772	732	0.5	.0173	37.3	6.1	All elements
20.0	22.9	736	698	0.5	.0186	35.8	6.4	6 elements
20.1	7.6	761	721	0.5	.0168	37.0	2.1	6 elements
20.7	7.6	842	796	0.5	.0175	39.8	1.9	All elements

* Center and outer injector elements capped = 6 elements
All injector elements open = All elements

TABLE A22

Ignition Delay for JP-4 Fuel in Air

$\phi = 0.7$

$T_{fuel} = 300$ K

Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times 10^3$	Comments*
15.0	115.6	731	680	0.5	.0247	48.1	23.8	6 elements
14.9	115.6	769	715	0.5	.0251	50.6	22.6	All elements
15.1	68.6	769	715	0.5	.0247	50.0	13.7	6 elements
14.8	68.6	797	740	0.5	.0250	53.1	12.9	All elements
14.9	68.6	767	713	0.5	.0252	50.5	13.6	6 elements
15.7	22.9	814	756	0.5	.0243	53.1	4.3	All elements
14.7	22.9	822	763	0.5	.0241	54.8	4.2	All elements
15.3	22.9	772	717	0.5	.0254	49.6	4.6	6 elements
15.3	7.6	814	756	0.5	.0254	52.3	1.5	6 elements
15.1	7.6	925	857	0.5	.0252	59.6	1.3	All elements
15.3	7.6	978	905	0.5	.0247	63.0	>1.2	All elements, No Autoignition
20.0	115.6	719	670	0.5	.0239	35.5	32.2	6 elements
20.0	115.6	747	604	0.5	.0241	36.8	31.1	All elements
20.0	115.6	739	688	0.5	.0241	35.9	31.8	All elements
20.4	68.6	744	692	0.5	.0247	35.8	19.2	6 elements
20.1	68.6	753	700	0.5	.0254	36.9	18.6	All elements
20.1	22.9	758	705	0.5	.0245	36.9	6.2	All elements
20.3	22.9	739	688	0.5	.0247	35.5	6.4	6 elements
20.3	7.6	764	711	0.5	.0248	36.9	2.1	6 elements
20.6	7.6	767	713	0.5	.0251	36.4	2.1	6 elements
20.0	7.6	794	737	0.5	.0247	38.3	2.0	All elements

* Center and outer injector elements capped = 6 elements
All injector elements open = All elements

TABLE A23

Ignition Delay for JP-4 Fuel in Air

$\Phi = 1.0$

$T_{fuel} = 300$ K

Conical Injector

P atm	L cm	T_{air} K	T_{mix} K	Airflow Rate kg/sec	Fuel Flow Rate kg/sec	V_{air} m/sec	Ignition Delay sec$\times 10^3$	Comments*
15.3	115.6	747	675	0.5	.0327	48.4	23.6	6 elements
15.1	115.6	739	668	0.5	.0326	48.2	23.7	6 elements
15.0	115.6	772	697	0.5	.0331	50.6	22.6	All elements
15.1	68.6	794	716	0.5	.0335	52.0	13.2	All elements
15.3	68.6	783	707	0.5	.0331	50.4	13.6	6 elements
14.9	68.6	775	700	0.5	.0338	51.0	13.4	6 elements
14.7	22.9	828	746	0.5	.0331	55.2	4.1	All elements
15.0	22.9	778	703	0.5	.0321	51.3	4.6	6 elements
15.2	7.6	892	801	0.5	.0323	57.3	1.3	All elements
15.1	7.6	822	741	0.5	.0326	53.6	1.4	6 elements
20.3	115.6	711	644	0.5	.0331	34.6	33.1	6 elements
19.9	115.6	744	673	0.5	.0326	36.8	31.0	All elements
20.3	115 6	742	671	0.5	.0333	36.0	31.7	All elements
20.0	68.6	767	693	0.5	.0341	38.0	18.1	All elements
20.0	68.6	767	693	0.5	.0328	37.7	18.2	All elements
20.4	68.6	750	678	0.5	.0328	36.0	19.0	6 elements
19.9	22.9	742	671	0.5	.0336	36.5	6.3	All elements

* Center and outer injector elements capped = 6 elements
All injector elements open = All elements