NASA CONTRACTOR REPORT

NASA CR-135

(NASA-CR-135329) DEVELOPMENT OF AN EXPERIMENT FOR DETERMINING THE AUTOIGNITION CHARACTERISTICS OF AIRCRAFT-TYPE FUELS (United Technologies Research Center) 30 p
HC A03/MF A01 CSCL 21D G3/28
N78-16194
Unclas
03847

DEVELOPMENT OF AN EXPERIMENT FOR DETERMINING THE AUTOIGNITION CHARACTERISTICS OF AIRCRAFT-TYPE FUELS

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NAS3–20066

NATIONAL AERONAUTICS AND SPACE ADMINSTRATION, WASHINGTON, D.C. SEPTEMBER 197

76–10–164–1

1. Report No.
NASA CR-135329

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
DEVELOPMENT OF AN EXPERIMENT FOR DETERMINING THE AUTOIGNITION CHARACTERISTICS OF AIRCRAFT-TYPE FUELS

5. Report Date
September 1977

6. Performing Organization Code

7. Author(s)
Louis J. Spadaccini

8. Performing Organization Report No.
R78-912881-2

9. Performing Organization Name and Address
United Technologies Research Center
Silver Lane
East Hartford, CT 06108

10. Work Unit No.

11. Contract or Grant No.
NAS3-20066

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Contractor Report

14. Sponsoring Agency Code

15. Supplementary Notes
Project Manager, Cecil J. Marek, Airbreathing Engines Division, NASA Lewis Research Center, Cleveland, Ohio

16. Abstract

An experimental test apparatus was developed to determine the autoignition characteristics of aircraft-type fuels in premixing-prevaporizing passages at elevated temperatures and pressures. The experiment was designed to permit independent variation and evaluation of the experimental variables of pressure, temperature, flow rate and fuel-air ratio. A comprehensive review of the autoignition literature is presented.

Performance verification tests consisting of measurements of the ignition delay times for several lean fuel-air mixture ratios were conducted using Jet-A fuel at inlet air temperatures in the range 600 K to 900 K and pressures in the range 9 atm to 30 atm.

17. Key Words (Suggested by Author(s))
Autoignition
Ignition Delay
Premixed/Prevaporized Combustor

18. Distribution Statement
Unclassified - Unlimited

19. Security Classif. (of this report)
UNCLASSIFIED

20. Security Classif. (of this page)
UNCLASSIFIED

21. No. of Pages
30

22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev. 10-75)

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Development of an Experiment for Determining The Autoignition Characteristics of Aircraft-Type Fuels

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SUMMARY

An applied research program was undertaken to develop a critical experiment capable of determining the autoignition characteristics of aircraft-type fuels in premixing/prevaporizing passages at elevated temperatures and pressures. The program included a comprehensive review of previous autoignition research and was directed toward design of the experiment, fabrication of the test equipment, and empirical verification that variables which affect autoignition can be controlled in a manner such that quantitative results can be obtained. In particular, the experiment was designed to permit independent variation and evaluation of the experimental variables of pressure, temperature, flow rate and fuel-air ratio.

Performance verification tests consisting of measurements of the ignition delay times for several lean fuel-air mixture ratios were conducted using Jet-A fuel over ranges of inlet air temperature and pressure up to 900 K and 30 atm. The test results were used to qualify the experimental approach and apparatus for use in future parametric test programs.

INTRODUCTION

The operational characteristics of the combustors in current aircraft gas turbine engines are such that objectional quantities of air pollutants are emitted over a significant portion of the engine operating cycle. The aircraft engine exhaust emissions of primary concern are oxides of nitrogen, carbon monoxide, unburned hydrocarbons and smoke. Oxides of nitrogen (NO_x) are produced at excessive rates in combustors when elevated gas temperatures are combined with long reaction-product residence times, for example, during engine operation at high power levels.

Significant technical effort has been and is being devoted to reduction of the rates of air pollutant emissions from gas turbine engines. In most instances these efforts involve modifications of the configuration and/or operation of combustors designed according to conventional concepts. However, projected aviation advances prompt even greater emissions reductions, especially of NO_x, than are probably attainable with current combustor design technology. Therefore, it appears that, if detrimental contamination of the atmosphere is to be precluded, improvements in the state of the art of combustor design must be achieved through the development of novel combustor concepts. A promising concept involves (1) the generation of a uniformly lean, gaseous fuel-air mixture prior to combustion and (2) a combustion zone having uniformly low temperature and low species residence time, thereby achieving the necessary prerequisites to low NO_x production rates. However, the operational conditions of advanced engines are such that it is feared that autoignition of the fuel-air mixture may occur in the premixing duct prior to entrance into the combustor. Data regarding the autoignition characteristics of fuel-air mixtures at values of temperature and pressure representative of advanced engines do not exist. Moreover, the existing body of autoignition data does not permit a satisfactory quantitative description 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, and (3) experimental verification of the approach and apparatus through a limited number of tests with ASTM Jet-A fuel over ranges of inlet air temperature and pressure up to 900 K and 30 atm, respectively.

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 determines the effects of all the 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.

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 to combustion. Therefore, the very early stages of the preignition processes are probably dominated by the physical processes and the late 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.

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

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 ($T \leq 700$ K 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 900 K. 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 400 K, and may be as little as 300 K. In comparison, normal hot flame ignitions of hydrocarbon fuels yield temperature rises in excess of 1500 K. 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 discussion of the mechanisms responsible for the production of cool flames and two-stage ignition is beyond the scope of this review; however, an explanation 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 (Ref. 64) for example, 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 temperature 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 have been reported in flat-flame burners, reciprocating engine studies and in constant volume bombs (e.g., Refs. 5 and 46).

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 stea flow test apparatus (Refs. 56 through 68). However, the spontaneous ignition temperature of a combustible substance is not an absolute property of the substanc and, consequently, all spontaneous ignition data need to be interpreted carefully the light of the test apparatus and methods used for their determination. Existin experimental data are generally dependent on the particular experimental configuration employed and are, therefore, too inconsistent for universal design use. Fo example, the automotive literature contains numerous accounts of investigations of autoignition in intermittent combustion systems; however, the effects of continuou varying pressure, temperature, velocity and turbulence, and injector spray charact istics (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 c transients and permit external premixing of high-vapor-pressure fuels. However, they are not readily adaptable for use with low-vapor-pressure fuels, and transient 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 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 nonuniformitie and usually are restricted to homogeneous gaseous mixtures. In contrast, continuou 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.

Much of the early autoignition research and, in particular, investigations concerned with evaluating the minimum spontaneous ignition temperature (ignitabili 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).

$$\tau = Ke^{C/T} p^n$$

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 effect 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 pressure (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 pressures of 1 atm to 41 atm and ambient gas temperatures of 500 K to 975 K. 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.

$$\tau = Ke^{C/T} p^n \phi^D$$

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.

The use of rapid-compression machines for studying the autoignition characteristics of homogeneous 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 mixture strengths, 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 appeared 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.

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.

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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 1100 K. They suggest a possible mechanism for this phenomenon based on two-stage combustion.

Shock tubes have been widely used to investigate the high-temperature ($T > 1000$ K) 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, nitrogen, 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

$$\tau = Ke^{C/T} [Ar]^{n1} [CH_4]^{n2} [O_2]^{n3}$$

The data cover the temperature range 1100 to 2300 K 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 1700 K). 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.

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-radical 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

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

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

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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 700 K to 900 K. 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 670 K to 870 K 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 alteration 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 measurement 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 720 K to 1075 K. 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 12 msec. (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 550 K to 700 K 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 610 K and 700 K.

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., long 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.

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 (Refs. 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 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 be correlated solely on the basis of overall equivalence ratio.

Finally, ignition delay data for typical gas turbine and diesel fuels which has 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 ducumentation of fuel properties. However, differences in data reported for a particular fuel are often larger than differences measured between various grades of fuel (cf., Refs. 65 and 66). Therefore, it is likely that the major variations originate from differences in the experimental apparatus and methods.

EXPERIMENT DESIGN AND TEST PROCEDURE

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). In addition, a critical experiment should minimize flow disturbances and wall effects, and provide for a determination of the fuel-air mixture distribution and the degree of droplet vaporization. These criteria served as a basis for formulating the technical approach from which the experiment design was evolved.

The conceptual design and installation of the autoignition test apparatus which was developed 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 straightener, (3) a specially-designed premixing-type fuel injector for generating a relatively uniform fuel-air distribution, (4) a cylindrical mixer/vaporizer section comprising several flanged spool pieces to permit length (residence time) 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 at the autoignition station and a water quench, (6) a scavenger afterburner, and (7) a remotely-operated throttle value 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 relatively smooth and free of wake-producing imperfections as a result of internal machining and the use of alignment dowels. Theoretical analyses of the need for wall cooling to preclude the possibility of ignition in the boundary layer were not able to conclusively demonstrate that cooling would not be required, therefore the design provides the capability for internal wall cooling; however, this feature is optional and it should be noted that the inner wall has sufficient strength to permit uncooled operation. Uniform inlet velocity profiles are assured by flow baffles and straight sections, and the inlet temperature and pressure are measured using fixed probes.

Normal operating procedure consists of establishing a prescribed condition within the test duct and gradually increasing the air temperature or pr ssure until autoignition occurs at the exit of the mixer/vaporizer section. This continuous test procedure ensures an accurate determination of the minimum conditions for autoignition. The ignition delay time is equivalent to the residence time of the fuel-air mixture between the point of injection and the axial position of the flame, and it is computed based upon the average flow velocity. The occurrence of autoignition is determined indirectly using photodetectors and a differential pressure transducer to make simultaneous measurements of the illumination and pressure-rise delay times. Upon ignition the test is terminated abruptly by shutting off the fuel flow and thereby purging the rig with inlet air flow. This test arrangement permits infinite and independent variation of each of the important experimental variables, i.e., pressure, temperature, velocity, residence time and fuel-air ratio within a fixed range of test conditions.

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A survey of optical instrumentation suitable for detecting the presence of luminous and nonluminous flames and compatible with the test hardware resulted in the selection of EG&G Model HUV-1000B silicon photovoltaic amplifier/photodiode combinations for use in this program. The detector has a wide spectral range (2000Å to 11500 Å), high responsivity (gain), nanosecond rise time, and linearity over a wide dynamic range. Photodetectors of this type were installed in high-pressure packing gland assemblies (see Fig. 3) and located at several positions in the test rig. They were isolated from the flow within the test rig by small glass windows incorporated into the mounting assemblies. The ability of the photodetector system to detect luminous flame and provide a sufficiently high output signal (adequate gain) and sufficiently rapid response (less than 0.1 msec rise time) was verified experimentally by measuring the response characteristics of the system to illumination from a propane-fueled burner and a high-frequency flashing light source (stroboscope).

A thermocouple is located at the exit of the mixer/vaporizer to provide a backup indication of ignition, identify conditions at which exothermic chemical reaction is initiated (including cool-flame phenomena), and indicate the temperature of the mixture at the onset of autoignition. Also, provision is made to permit use of a traversing, liquid/vapor phase-discriminating sampling probe to isokinetically sample the flow. By evaluation of the hydrocarbon content of the samples, measurements of the extent of vaporization and the radial fuel-air concentration profile at the exit of the test section are obtained; thereby the mixture uniformity is evaluated. Since the facility afterburner, located in the exhaust ducting, is a continuous ignition source and because autoignition will normally be initiated at the axial location within the sudden-expansion section, the step region is deluged with water to eliminate any path by which the flame may propagate upstream from the afterburner into the mixer/vaporizer sections (e.g., via the wall boundary layer and/or the recirculation zones). As an added precaution, thermocouples and photodetectors are used to monitor the step region and identify conditions which result in flame stabilization.

The generation of a uniform mixture is a prerequisite for the evaluation of the importance of fuel-air ratio; therefore, techniques for obtaining rapid vaporization and mixing with a minimum flow disturbance were studied and a candidate fuel injector was fabricated and tested. The distributed-source injector, shown in Fig. 4, is 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 a stationary splash plate and (b) the interaction of the high-velocity airstream and the liquid film issuing from the splash plate. Rapid mixing is also anticipated as a consequence of the large number of fuel injection sites. Flow disturbance and blockage (and therefore pressure loss) are minimized by the use of small-diameter hypodermic tubing which is appropriately sized to reduce internal friction losses and is sufficiently strong to withstand the aerodynamic loading. The injector can be rotated with respect to the airflow to effect either costream or contrastream injection. When facing upstream, as shown in Fig. 4 and as used in this program, a low convective heat transfer rate to the fuel injector tubing is ensured as a result of the shielding provided by the splash plate and the backwash of fuel over its outer surface. The fuel injection temperature is continuously monitored using fine-wire thermocouples. Plugging of the injector orifices, due to fuel pyrolysis and/or coking, is avoided by flowing water during start-up and shutdown. Furthermore, the injector is designed for operation at pressure levels sufficiently high to render it insensitive to combustor pressure oscillations.

EXPERIMENT VERIFICATION

An experimental verification test program was conducted to demonstrate the performance capabilities of the autoignition test apparatus and to verify that the important test variables can be controlled in a manner such that quantitative results can be obtained. Tests were conducted using air flow rates up to 1.0 kg/sec, pressures up to 30 atm, and temperatures up to 900 K.

Qualification of the experimental apparatus and operating techniques was achieved by successful acquisition of data through a limited number of tests over the specified wide range of test conditions. The verification tests also served to qualify the design and operation of the distributed-source fuel injector, although further testing will be required to document the degree of mixture uniformity achieveable as a function of mixer/vaporizer section length.

Prior to initiating the test program, the uniformity of the inlet airflow was verified by radially traversing a pitot-static probe across the entrance of the mixer/vaporizer section. The maximum deviation of the local velocity from the average velocity was ± 8 percent. The results of these measurements together with an estimate of the overall experimental error suggest that the uncertainty in the determination of ignition delay time was less than 20 percent. Tests were then conducted using Jet-A fuel (see Table 2 for typical properties) over ranges of inlet air temperature and pressure up to 900 K and 30 atm, and the ignition delay times were determined for several fuel-air mixture ratios. The matrix of test conditions and the test results are summarized in Table 3. The experimental data are compared to relevant existing ignition delay data for Jet-A in Fig. 5. (Additional data reported by other investigators for other fuels and similar test conditions were presented in Fig. 1.) There is general agreement between the measured and existing data, both with respect to the magnitude of the ignition delay times and the trends with increasing pressure and temperature (i.e., ignition delay time decreases with increasing temperature and pressure). Note that in this series of verification tests several of the important experimental variables were changed simultaneously and, therefore, the data cannot be correlated by a single curve on a delay time vs pressure plot.

Measurements made at 30 atm indicate a shorter delay time than is predicted using existing data and empirical correlations (Refs. 61, 65 and 66) and suggest the

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possibility that upstream flame propagation (flashback) may have occurred at the low free-stream velocity (18 m/sec). Consequently, to reduce the likelihood of flashback, future tests will be conducted at higher free-stream velocities by increasing the minimum airflow rate to 1.0 kg/sec.

The data obtained also provide an indication that the ignition delay time may be relatively sensitive to fuel-air ratio, as was reported by Mestre and Ducourneau (Ref. 62). For example, data acquired in tests conducted at constant inlet temperature ($T = 700$ K) and with a mixer/vaporizer section length of 140 cm, (which is sufficiently long to ensure mixture homogeneity at the autoignition station) indicate that the ignition delay time measured at $P = 10$ atm and $\Phi = 0.6$ was approximately equal to the delay time measured at $P = 20$ atm and $\Phi = 0.3$. This result is contrary to the anticipated inverse proportionality of ignition delay and ambient pressure (i.e., $\tau \propto P^{-n}$). This apparent sensitivity to fuel-air ratio emphasizes the need for rapid mixing and results in the requirement that reasonably uniform fuel distributions be demonstrated in future tests.

CONCLUDING REMARKS

The design and operating features of an autoignition test apparatus which permits independent variation of mixture pressure, temperature, flow rate, fuel-air ratio and wall cooling rate have been demonstrated through tests at a limited number of operating conditions. It is anticipated that the test apparatus developed in this program will be used in subsequent programs to (1) map the autoignition characteristics of various liquid hydrocarbon fuels, including Jet-A, JP-4 and No. 2 diesel oil, and (2) determine the effect of chemical and physical properties of fuels including blends and/or pure compounds, on autoignition.

CITED REFERENCES AND BIBLIOGRAPHY OF
RELEVANT AUTOIGNITION RESEARCH

Reviews:

1. Brokaw, R. S.: Thermal Ignition, with Particular Reference to High Temperatures, Selected Combustion Problems - II. AGARD, Butterworths, London, 1956.

2. Mullins, B. P., and S. S. Penner: Explosions, Detonations, Flammability and Ignition. AGARD, Pergamon Press, New York, 1959.

3. Mullins, B. P.: Spontaneous Ignition of Liquid Fuels. AGARD, Butterworths, London, 1955.

4. Semenov, N. N.: Thermal Theory of Combustion and Explosion. NACA TM 1024, 1942.

Cool Flame Phenomena:

5. Agnew, W. G., and J. T. Agnew: Visible Emission Spectra of Two-Stage Flames of Diethyl Ether Produced in a Flat-Flame Burner. Ind. Eng. Chem., Vol. 48, 1956.

6. Barnard, J. A., and B. A. Harwood: Slow Combustion and Cool-Flame Behavior of Iso-Octane. Combustion and Flame, Vol. 21, 1973.

7. Barnard, J. A., and A. Watts: Cool-Flame Oxidation of Ketones. 12th Symposium on Combustion, The Combustion Institute, 1969.

8. Burgess, A. R., and R. G. W. Laughlin: The Cool-Flame Oxidation of N-Heptane. Part I - The Kinetic Features of the Reaction. Combustion and Flame, Vol. 19, 1972.

9. Minkoff, G. J., and C. F. H. Tipper: Chemistry of Combustion Reactions. Butterworths, London, 1962.

10. Pahnke, A. J., P. M. Cohen and B. M. Sturgis: Preflame Oxidation of Hydrocarbons in a Motored Engine. Ind. Eng. Chemistry, Vol. 46, No. 1, 1954.

11. Sheinson, R. S., F. W. Williams: Cool Flames: Use of the Term in Combustion Chemistry and Analytical Chemistry. Analytical Chemistry, Vol. 47, No. 7, 1975.

12. Voinov, A. N., and D. I. Skorodelov: Study on the Development of Preflame Processes and Ignition of Hydrocarbons of Various Structures, Part I - Induction Periods of Ignition and Cold Flames as Functions of Compressions, Temperature and Pressure. Kinetics and Catalysis, Vol. 8, 1967.

13. Voinov, A. N., and D. I. Skorodelov: A Study of the Characteristics of the Development of Pre-Ignition Processes and the Combustion of Hydrocarbons of Different Structure, Part II - The Intensity of the Cool-Flame Stage. Kinetics and Catalysis, Vol. 8, 1967.

14. Yantovskii, S. Ya.: Two-Stage Combustion of Explosive Mixtures, Part III - Kinetic Zones of Autoignition of Iso-Octane-Air Mixtures Under High Pressures. Kinetics and Catalysis, 1966.

Constant Volume Bomb Studies:

15. Affens, W. A., J. E. Johnson and H. W. Carhart: Effect of Chemical Structure on Spontaneous Ignition of Hydrocarbons. Jl. of Chem. and Engr. Data, Vol. 6, No. 4, 1961.

16. Affens, W. A., and H. W. Carhart: Ignition Studies. Part VII. The Determination of Autoignition Temperatures of Hydrocarbon Fuels. Naval Research Laboratory Report No. 7665, 1974.

17. Barnard, J. A., and B. A. Harwood: Physical Factors in the Study of the Spontaneous Ignition of Hydrocarbons in Static Systems. Combustion and Flame, Vol. 22, 1974.

18. Barnard, J. A., and B. A. Harwood: The Spontaneous Combustion of N-Heptane. Combustion and Flame, Vol. 21, 1973.

19. Faeth, G. M., and D. R. Olsen: The Ignition of Hydrocarbon Fuel Droplets in Air. SAE Paper No. 680465, 1968.

20. Hurn, R. W., and K. J. Hughes: Combustion Characteristics of Diesel Fuels as Measured in a Constant-Volume Bomb. SAE Trans., Vol. 6, pp. 24-35, 1952.

21. Hurn, R. W., J. O. Chase, C. F. Ellis, and K. J. Hughes: Fuel Heat Gain and Release in Bomb Ignition. SAE Trans., Vol. 64, pp. 703-711, 1956.

22. Johnson, J. E., J. W. Crellin, and H. W. Carhart: Autoignition Properties of Certain Diesel Fuels. Ind. Eng. Chemistry, Vol. 44, No. 7, 1952.

23. Johnson, J. E., J. W. Crellin, and H. W. Carhart: Ignition Behavior of the Hexanes. Ind. Eng. Chemistry, Vol. 46, No. 7, 1954.

24. Johnson, J. E., J. W. Crellin, and H. W. Carhart: Spontaneous Ignition Properties of Fuels and Hydrocarbons. Ind. Eng. Chemistry, Vol. 45, No. 8, 1953.

25. Kadota, T., H. Hiroyasu, and H. Oya: Spontaneous Ignition Delay of a Fuel Droplet in High Pressure and High Temperature Gaseous Environments. Bulletin of the JSME, Vol. 19, No. 130, April 1976.

26. Kuchta, J. M., A. Bartkowiak, and M. G. Zabetakis: Autoignition Characteristics of JP-6 Jet Fuel, AFASD-62-615, 1962.

27. Kuchta, J. M.: Summary of Ignition Properties of Jet Fuels and Other Aircraft Combustible Fluids. AFAPL-TR-75-70, 1975.

28. Kuchta, J. M., R. J. Cato, G. H. Martindill, and W. H. Gilbert: Ignition Characteristics of Fuels and Lubricants. AFAPL-TR-66-21, 1966.

29. Starkman, E.: Ignition Delay in Diesel Engines, Trans. of AIChE, Vol. 42, pp. 107-120, 1946.

30. Wolfer, H. H.: Ignition Lag in the Diesel Engine. Trans. by R.A.E., No. 358, 1950.

31. Wood, B. J., and W. A. Rosser: An Experimental Study of Fuel Droplet Ignition. AIAA Journal, Vol. 7, 1969.

32. Zabetakis, M. G., A. L. Furno, and G. W. Jones: Minimum Spontaneous Ignition Temperatures of Combustibles in Air. Industrial and Engineering Chemistry, Vol. 46, No. 10, 1954.

Rapid Compression Methods:

33. Falk, K. G.: Ignition Temperatures of Hydrogen-Oxygen Mixtures. Journal of the ACS, Vol. 28, pp. 1517-1534, 1906.

34. Halstead, M. P., L. J. Kirsch, A. Prothero, and C. P. Quinn: A Mathematical Model for Hydrocarbon Autoignition at High Pressures. Proc. R. Soc. Lond., A. 346, 1975.

35. Jost, W., and A. Martinengo: Recent Investigations of Reaction Processes by Means of Adiabatic Compression. SAE Trans., Vol. 75, 1967.

36. Livengood, J. C., and P. C. Wu: Correlation of Autoignition Phenomena in Internal Combustion Engines and Rapid Compression Machines. Fifth Symposium (International) on Combustion, The Combustion Institute, 1955.

ORIGINAL PAGE IS
OF POOR QUALITY

37. Rifkin, E. B., and C. Walcutt: A Basis for Understanding Antiknock Action. SAE Trans., Vol. 65, pp. 552-566, 1957.

38. Taylor, C. F., E. S. Taylor, J. C. Livengood, W. A. Russell, and W. A. Leary: Ignition of Fuels by Rapid Compression. SAE Quarterly Trans., Vol. 4, 1950.

Reciprocating Engine Studies:

39. El Wakil, M. M., P. S. Meyers, and O. A. Uyehara: Fuel Vaporization and Ignition Lag in Diesel Combustion. SAE Trans., Vol. 64, pp. 712-729, 1956.

40. Garner, F. H., F. Morton, J. B. Saunby, and G. H. Grigg: Preflame Reactions in Diesel Engines. Jl. of the Inst. of Petroleum, Vol. 43, pp. 124-130, 1957.

41. Garner, F. H., F. Morton, and J. B. Saunby: Preflame Reactions in Diesel Engines, Part V. Jl. of the Inst. of Petroleum, Vol. 47, pp. 175-193, 1961.

42. Henein, N. A., and J. A. Bolt: Ignition Delay in Diesel Engines. SAE Paper No. 670007, 1967.

43. Henein, N. A., and J. A. Bolt: Kinetic Considerations in the Autoignition and Combustion of Fuel Sprays in Swirling Air. ASME Paper No. 72-DGP-8, 1972.

44. Henein, N. A., and J. A. Bolt: Correlation of Air Charge Temperature and Ignition Delay for Several Fuels in a Diesel Engine. SAE Paper No. 690252, 1969.

45. Lyn, W. T., and E. Valdmanis: The Effects of Physical Factors on Ignition Delay. Proc. Auto. Div., Institution of Mechanical Engineers, 181 (Pt. 2A), 34, 1966-67.

46. Rassweiler, G. M., and L. L. Withrow: Spectrographic Detection of Formaldehyde in an Engine Prior to Knock. Ind. and Eng. Chem., Vol. 25, pp. 1359-1366, 1933.

47. Schmidt, F. A. F.: Theoretical and Experimental Study of Ignition Lag and Engine Knock. NACA TM 891, 1939.

48. Sunn Pedersen, P., and B. Qvale: A Model for the Physical Part of the Ignition Delay in a Diesel Engine. SAE Paper No. 740716, 1974.

49. Wentzel, W.: Ignition Process in Diesel Engines. NACA TM 979, 1936.

Shock-Tube Studies:

50. Burcat, A.: Calculation of the Ignition Delay Times for Methane-Oxygen-Nitrogen Dioxide-Argon-Mixtures. Technion-Israel Inst. of Tech., 1975.

51. Lifshitz, A., K. Scheller, and G. B. Skinner: Shock-Tube Investigation of Ignition in Methane-Oxygen-Argon Mixtures. Combustion and Flame, Vol. 16, pp. 311-321, 1971.

52. Myers, B. F., and E. R. Barth: Reaction and Ignition Delay Times in the Oxidation of Propane. AIAA Journal, Vol. 7, No. 10, pp. 1862-1869, 1969.

53. Skinner, G. B., A. Lifshitz, K. Scheller, and A. Burcat: Kinetics of Methane Oxidation. Jl. of Chem. Phys., Vol. 56, No. 8, pp. 3853-3861, 1972.

54. Steinberg, M., and W. E. Kaskan: The Ignition of Combustible Mixtures by Shock Waves. Fifth Symposium (International) on Combustion. The Combustion Institute, 1955.

55. Vermeer, D. J., J. W. Meyer, and A. K. Oppenheim: Autoignition of Hydrocarbons Behind Reflected Shock Waves. Combustion and Flame, Vol. 18, pp. 327-336, 1972.

Continuous Flow Methods:

56. Brokaw, R. S., and J. L. Jackson: Effect of Temperature, Pressure and Composition on Ignition Delays for Propane Flames. Fifth Symposium (International) on Combustion, The Combustion Institute, 1955.

57. Burwell, W. G., and D. R. Olsen: The Spontaneous Ignition of Iso-Octane Air Mixtures under Steady Flow Conditions. SAE Paper No. 650610, 1965.

58. Ducourneau, F.: Inflammation Spontanee de Melanges Riches Air-Kerosene. Entropie, N°59, 1974.

59. Ingebo, R. D., and C. T. Norgren: Spontaneous-Ignition Temperature Limits of Jet A Fuel in Research-Combustor Segment. NASA TM-X-3146, 1975.

60. Jackson, J. L., and R. S. Brokaw: Flow Apparatus for Determination of Spontaneous Ignition Delays. Industrial and Engineering Chemistry, Vol. 46, No. 12, 1954.

61. Marek, C. J., L. Papathakos, and P. Verbulecz: Preliminary Studies of Autoignition and Flashback in a Premixing-Prevaporizing Flame Tube Using Jet-A Fuel at Lean Equivalence Ratios. NASA TM X-3526, May 1977.

62. Mestre, A., and F. Ducourneau: Recent Studies of the Spontaneous Ignition of Rich Air-Kerosene Mixtures. O.N.E.R.A., 1973.

63. Mullins, B. P.: Studies on the Spontaneous Ignition of Fuels Injected into a Hot Airstream. Parts I - VIII, Fuel, Vol. 32, 1953.

64. Mullins, B. P.: The Spontaneous Combustion of Fuels Injected into a Hot Gas Stream. Third Symposium on Combustion, Flame and Explosion Phenomena, The Combustion Institute, 1949.

65. Spadaccini, L. J.: Autoignition Characteristics of Hydrocarbon Fuels at Elevated Temperatures and Pressures. Journal of Engineering for Power, Trans. ASME, Vol. 99, Series A, January 1977; also ASME Paper No. 76-GT-3.

66. Stringer, F. W., A. E. Clarke, and J. S. Clarke: The Spontaneous Ignition of Hydrocarbon Fuels in a Flowing System. Proc. Auto. Div., Institution of Mechanical Engineers, 1970.

67. Subba Rao, H. N., and A. H. Lefebvre: Ignition of Kerosene Fuel Sprays in a Flowing Airstream. Combustion Science and Technology, Vol. 8, 1973.

68. Taback, E. D.: The Autoignition Characteristics of JP-4 at High Temperature and Pressure. P&WA TDM-2284, 1971.

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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 velocities and low turbulence levels • Physical delay time [illegible] to spray-type combustion systems • Configuration and material [illegible]
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

TYPICAL PROPERTIES OF LIQUID ASTM JET-A FUEL

Specific Gravity	0.809 (311 K)
Avg. Hydrogen/Carbon Ratio	1.98
Viscosity	1.7 x 10^{-6} m^2/sec (311 K)
Surface Tension	21.9 dynes/cm (311 K)
Initial Boiling Pt.	420 K
Final Boiling Pt.	561 K
Flash Pt.	329 K
Heating Value	43,000 kJ/kg
Avg. Molecular Wgt.	170
Stoichiometric Ratio (by wgt).	0.068
Critical Pressure	18 atm
Critical Temperature	656 K
Specific Heat at Constant Pressure	2.13 kJ/kg C (311 K)

TABLE 3

EXPERIMENTAL VERIFICATION TEST RESULTS

Jet-A Fuel

P atm	T_{air} deg. K	Fuel-Air Ratio	Equivalence Ratio	Airflow Rate kg/sec	V_{air} m/sec	Mixer/ Vaporizer Length cm	Ignition Delay sec x 10^3	Comments
20.0	700	0.022	0.32	0.96	66	140	21.2	Determine minimum equivalence ratio for autoignition
9.3	733	0.042	0.61	0.50	77	140	18.2	Determine minimum auto-ignition temperature
9.9	705	0.044	0.65	0.49	68	140	20.5	
17.8	876	0.054	0.79	0.81	78	18	2.3	
30.3	606	0.045	0.65	0.46	18	18	10.0	

Fuel temperature = 304 K

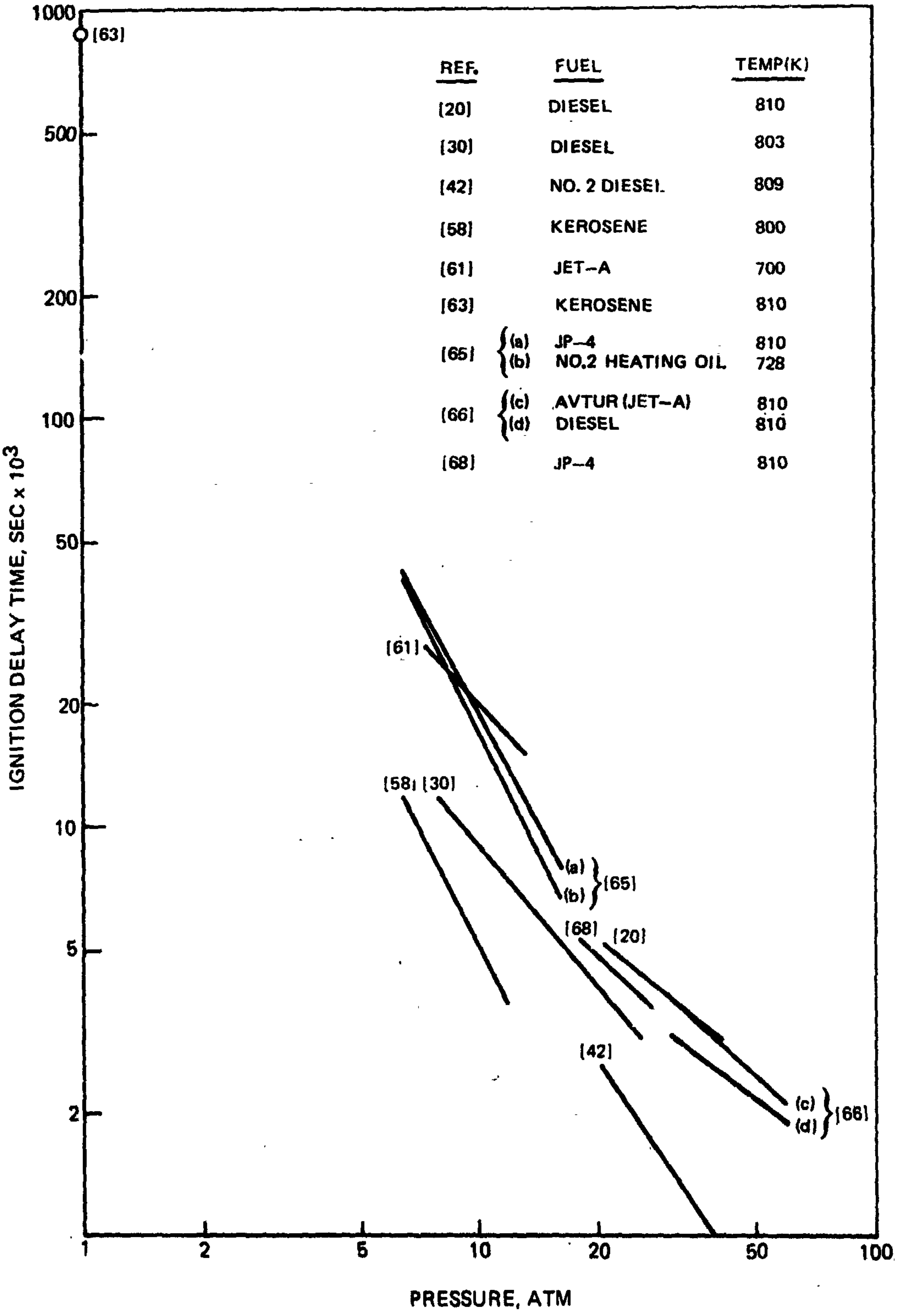

Figure 1 - Correlation of Ignition Delay Data

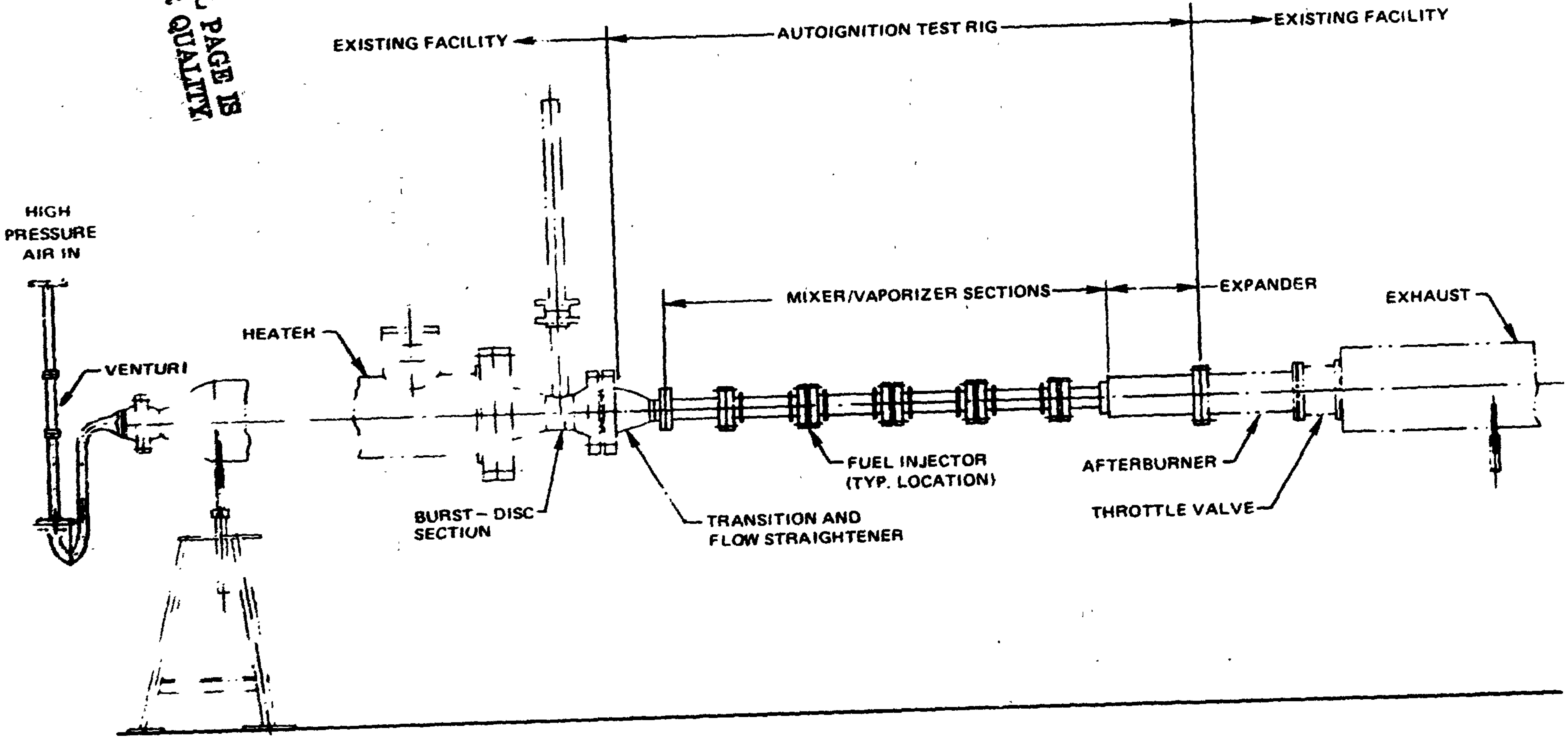

Figure 2 - Autoignition Test Assembly

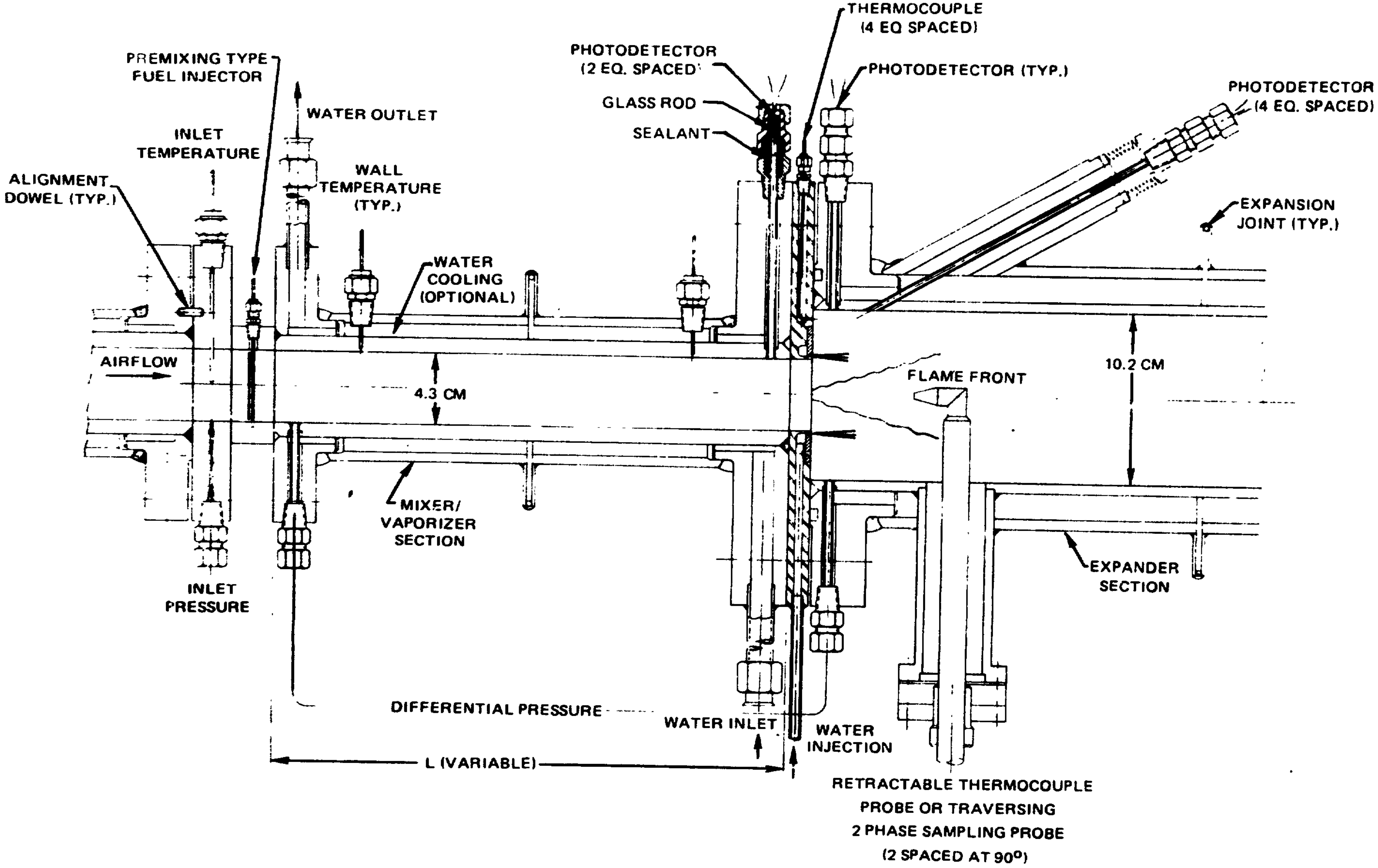

Figure 3 - Mixer/Vaporizer and Expander Assembly

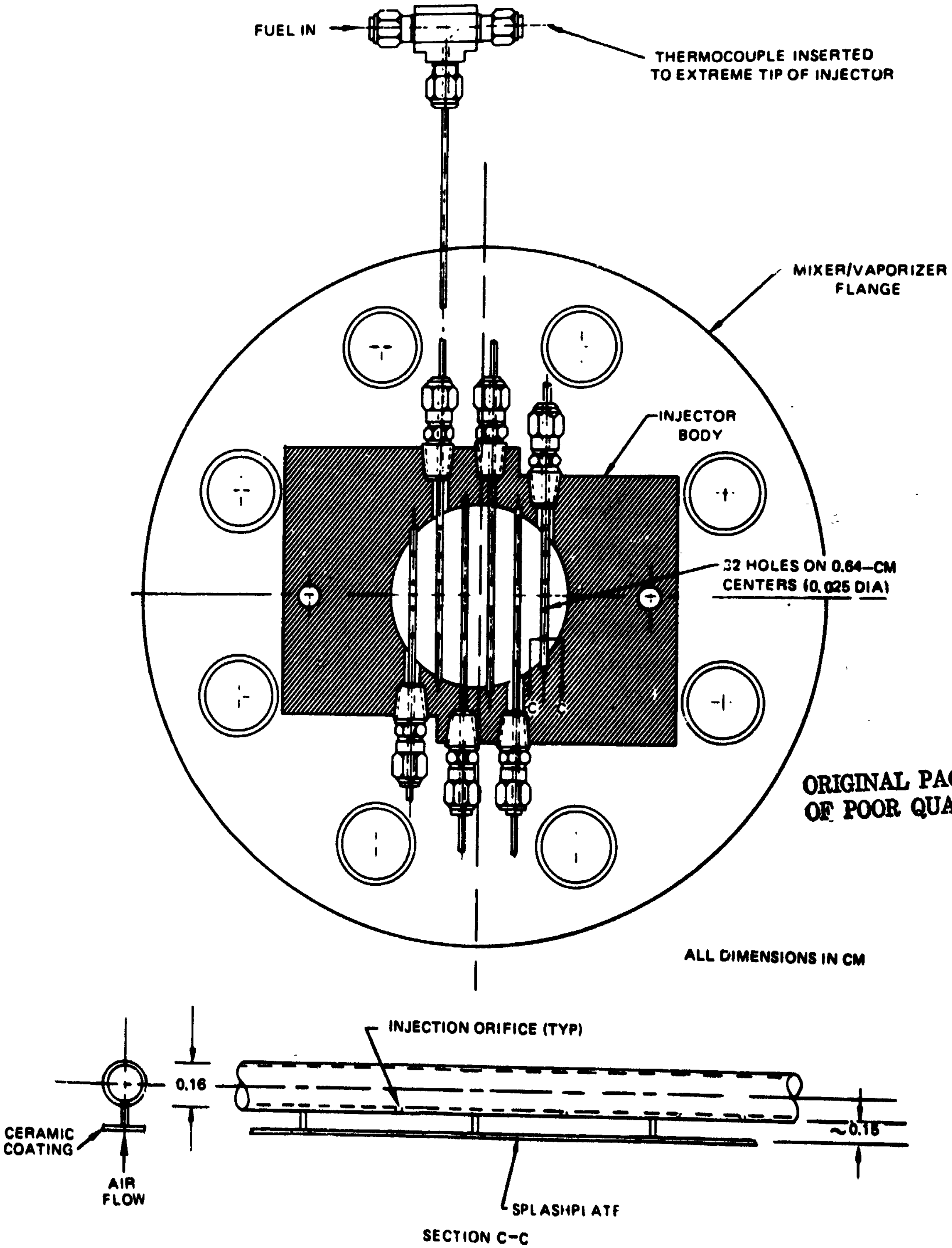

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Figure 4 - Distributed Source Injector

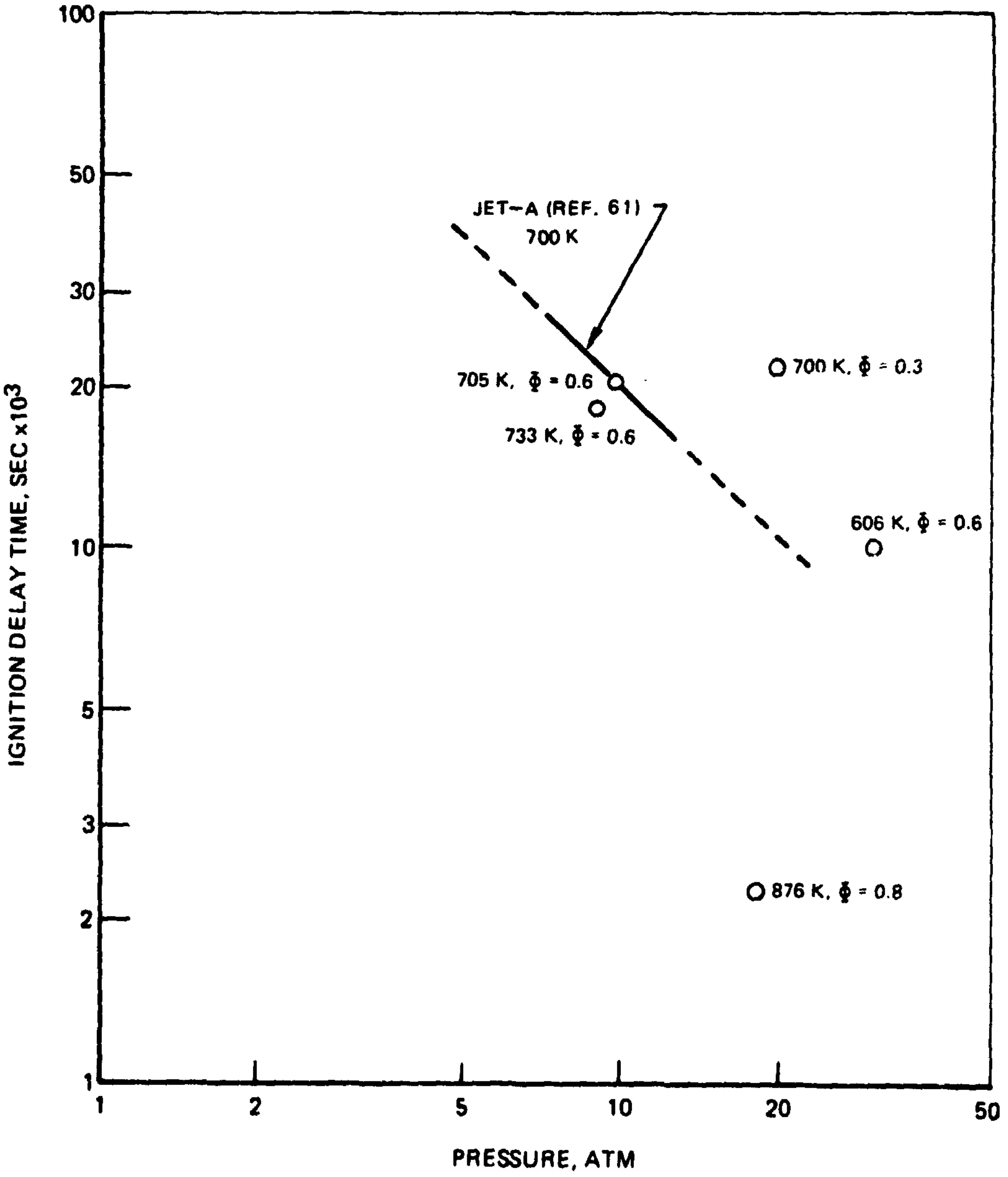

Figure 5 - Ignition Delay of Jet-A Fuel in Air