Spark Ignition Energy Measurements in Jet A

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Abstract

Experiments have been carried out to measure the spark ignition energy of Jet A vapor in air. A range of ignition energies from 1 mJ to 100 J was examined in these tests. The test method was validated by first measuring ignition energies for lean mixtures of the fuels hexane (C_6H_6) and propane (C_3H_8) in air at normal temperature (295 K) and pressure (1 atm). These results agree with existing data and provide new results for compositions between the lean flame limit and stoichiometric mixtures. Jet A (from LAX, flashpoint 45 – 48°C) vapor mixtures with air have been tested at temperatures between 30 and 60°C at two fuel mass loadings, 3 and 200 kg/m^3, in an explosion test vessel with a volume of 1.8 liter. Tests at 40, 50, and 60°C have been performed at a mass loading of 3 kg/m^3 in an 1180-liter vessel. Experiments with Jet A have been carried out with initial conditions of 0.585 bar pressure to simulate altitude conditions appropriate to the TWA 800 explosion.

Ignition energies and peak pressures vary strongly as a function of initial temperature, but are a weak function of mass loading. The minimum ignition energy varies from less than 1 mJ at 60°C to over 100 J at 30°C. At temperatures less than 30°C, ignition was not possible with 100 J or even a neon sign transformer (continuous discharge). The peak pressure between 40 and 55°C was approximately 4 bar. Peak pressures in the 1180-liter vessel were slightly lower and the ignition energy was higher than in the 1.8-liter vessel.

The following conclusions were reached relative to the TWA 800 crash: (a) spark ignition sources with energies between 5 mJ and 1 J are sufficient to ignite Jet A vapor, resulting in a propagating flame; (b) the peak pressure rise was between 1.5 and 4 bar (20 and 60 psi). (c) a thermal ignition source consisting of a hot filament created by discharging electrical energy into a metal wire is also sufficient to ignite Jet A vapor, resulting in a propagating flame; (d) laminar burning speeds are between 15 and 45 cm/s; and (e) the limited amount of fuel available in the CWT (about 50 gal) did not significantly increase the flammability limit.

The rapid decrease in spark ignition energy with increasing temperature demonstrates that hot fuel tanks are significantly more hazardous than cool ones with respect to spark ignition sources. A systematic effort is now needed in order to utilize these results and apply spark ignition energy measurements to future analyses of fuel tank flammability. Some key issues that need to be addressed in future testing are: (a) effect of flashpoint on the ignition energy-temperature relationship; (b) ignition energy vs. temperature as a function of altitude; (c) effect of fuel weathering on ignition energy; and (d) the effect of ignition source type on ignition limits.

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1 Introduction

The purpose of the present testing is to provide basic data on ignition of mixtures of warm Jet A vapor and air. This study is part of the investigation into the crash of TWA 800 and is an extension of the previous study of Jet A properties reported in Shepherd et al. (1997). The accident investigation (NTSB 1997) has determined that the key factor in the loss of the airplane was an explosion within the center wing fuel tank (CWT). At the time of the explosion, the tank contained about 50 gallons (300 lbs) of aviation kerosene (Jet A). The fuel and air within the tank were heated by the air conditioning units (also known as the environment control system [ECS] or more simply, air packs) located directly under the center wing tank. This increased the evaporation of the liquid fuel and was a factor in creating a flammable fuel vapor-air mixture in the ullage of the tank.

The heating of the center wing tank occurs because the air packs are powered by hot (350°F) bleed air from either the main engines or the auxiliary power unit (APU). Flight testing (Bower 1997) indicates that at the time of the explosion, the temperatures in the air within the CWT ranged between 38 and 54°C (100 and 130°F), and the temperatures of the tank lower surface ranged between 38 and 60°C (100 and 140°F). Based on these temperatures, and vapor pressures measured at Caltech (Shepherd et al. 1997), the fuel vapor-air composition within the tank was estimated to be in the flammable range once the aircraft reached an altitute of 14 kft, with fuel-air mass ratios[1] between 0.040 and 0.072 (mole fractions between 0.0089 and 0.015). These estimates are corroborated by the vapor sampling of Sagebiel (1997), who measured fuel-air mass ratios between 0.048 and 0.054 (mole fractions between 0.010 and 0.012) at 14 kft. These values should be compared with a lean limit fuel-air mass ratio of 0.030 (mole fraction of 0.007) determined in previous testing (Nestor 1967; Ott 1970) on Jet A.

It is important to note that the combination of evaporation due to heating and the reduction in air pressure with increasing altitude created a flammable condition within the CWT. The finding that the fuel-vapor air mixture within the CWT was flammable at 14 kft should not be considered surprising in view of previous work (Nestor 1967; Ott 1970) on Jet A flammability. Flammability of fuel-tank ullage contents, particularly at high altitudes or with low flashpoint fuels, has long been considered unavoidable (Boeing et al. 1997). Experiments (Kosvic et al. 1971; Roth 1987) and simulations (Seibold 1987; Ural et al. 1989; Fornia 1997) indicate that commercial transport aircraft spend some portion of the flight envelope with the ullage in a flammable condition.

Aircraft manufacturers (Boeing et al. 1997) and regulatory agencies (FAA 1997) have long recognized the problem of airplane fuel-tank flammability. Extensive compilations of flammability properties of fuels (CRC 1983) and handbooks on fire and explosion (Kuchta 1985) attest to the awareness of and efforts to address this issue. Specific steps are taken to minimize the risk of fuel-tank explosions in commercial and military aviation. The commercial airplane industry practice is to provide engineering safety features such as current-limiting on the fuel quantity instrumentation system (FQIS), lightning-strike protection (Fischer and Plummer 1977), electrical bonding to prevent static buildup, anti-static (conductivity enhancing) additives for fuels

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[1] In making these computations, we have used Sagebiel's estimated Jet A vapor composition of $C_{9.58}H_{17.2}$, which has an average molar mass of 132 g/mole.

(in some countries), and active explosion suppression systems at the wing-tip vents.

Military combat aircraft use these features plus more aggressive measures (Ball 1985) such as reticulated foams within the fuel tank, "self-sealing" tank liners, inerting by reducing or removing oxygen from the ullage, and active fire suppression systems. Ignition due to projectile penetration into the fuel tank is of particular concern for combat aircraft, and many of these features are designed to enhance combat survivability. Other successful efforts to reduce fuel flammability include introducing reduced flashpoint fuels, such as the Navy's use of JP-5, the switch by the Air Force from JP-4 to JP-8 (Beery et al. 1975), elimination of Jet B and JP4 in commercial transports in favor of Jet A. There was a long-term effort to develop viscosity-modifying additives as anti-misting agents (Kleug 1985) to reduce the hazard of fires in impact-survivable crashes, although this has never been implemented in other than research airplanes.

As a consequence of these efforts, the occurrence of fuel-tank explosions and fires has been reduced to a very low rate in commercial air transport. Nevertheless, fuel-tank ullages can often be flammable, and under exceptional circumstances, accidental ignition does result in fires or explosions (FAA 1997). The TWA 800 accident may have been one of these exceptional circumstances. What is at issue in the present case is the role that elevated temperatures and the nearly empty tank may have played in increasing the relative hazard of a fuel-tank explosion. The interest in the role of temperature is due to the a strong link between fuel volatility and explosion hazard that is observed in both experiments and airplane mishaps (Beery et al. 1975). Since the volatility of a fuel (Kanury 1988) is a strongly increasing function of temperature, fuel temperature relative to the flashpoint is the most important factor in determining the explosion hazard of a specific liquid fuel.

The concept of relative hazard emphasizes the fact that flammability limits are not absolute, but depend on the type and strength of the ignition source. Previous studies on flammability limits of hydrocarbon fuels have shown that the stronger the source of the ignition stimulus, the leaner the mixture that can be ignited. Following the established practice (Kuchta 1985) in explosion hazard evaluation studies (Ural et al. 1989), we use the spark ignition energy as a measure of ignition sensitivity of the fuel vapor-air mixture within the ullage. The ignition sensitivity is expected to depend on the following factors that appear to be prominent in the TWA 800 situation:

1. Effect of higher temperatures in the CWT associated with prolonged operation of the ECS on the ground prior to takeoff.
2. Effect of limited amount of liquid fuel in the CWT.
3. Effect of "weathering," i.e., exposure of fuel to the environment during flight and subsequent loss of low-molecular-weight components.
4. Specific Jet A fuel present in the CWT.

Of all of these factors, fuel temperature is the most important since the fuel vapor is created by evaporation of a liquid fuel and the amount of vapor, as determined by the vapor pressure, depends very strongly on temperature. We have focused on the first two factors, temperature and fuel amount, in the present study.

Our study extends the previous work (Nestor 1967; Ott 1970) on Jet A flammability. Those studies used a large (10 to 20 J), fixed ignition energy and large (1/4 to 1/2-full tank) quantities (mass loading) of fuel. We have examined two mass loadings: 200 kg/m^3, corresponding to a 1/4-full tank and 3 kg/m^3, corresponding to the conditions in TWA 800. The vapor conditions were a fixed pressure of 0.6 atm and temperatures ranged between 30 and 60°C. Most importantly, we varied the energy of the ignition source over five orders of magnitude, from 1 mJ to 100 J.

This report first presents some background material on spark ignition, followed by a discussion of our experimental facilities, ranging from 1.8 to 1180 liters in capacity. Spark ignition energies over a range of 1 mJ to 100 J have been determined for several hydrocarbon fuels and Jet A. In order to validate our technique, we measured the ignition energy of two pure hydrocarbon vapors, propane and hexane, in an 11.25-liter vessel. These data extends the results of previous researchers to a much wider range of compositions, particularly approaching the lean limit. Our results show that a strong variation of ignition energy (from less than 1 mJ up to 100 J) with composition is a universal feature of hydrocarbon combustion and the minimum ignition energy values of 0.2 mJ (2×10^{-4} J) typically quoted in textbooks are inappropriate for very lean mixtures.

2 Spark Ignition

One potential source of ignition in accidental fires and explosions is an electrical discharge or spark. Other possible sources include hot surfaces or adiabatic compression of fuel-air mixtures. The origin and characterization of common ignition sources are discussed at some length in the standard literature on fire and explosions (Kuchta 1985; Kuchta and Clodfelter 1985). In the present study, we have concentrated on capacitive spark discharges as a means for characterizing the potential for ignition of Jet A vapor in the ullage of an airplane fuel tank by accidental electrical discharges. Although the motivation for this work is the TWA 800 crash, at the present time, the source of ignition within the CWT is unknown and our use of spark sources is a matter of experimental technique. However, previous studies have shown that potential sources of sparks inside fuel tanks include static buildup (Lou 1986; NFPA 1993), lightning (Fischer and Plummer 1977), or malfunctioning electrical circuits (Magison 1978).

Following Magison (1978), it is convenient to categorize electrical ignition modes as follows:

1. Sparks created across a fixed or closing gap by energy stored in a capacitive circuit.
2. Arcs created across an opening circuit by energy stored in an inductor.
3. Opening or closing contacts in a purely resistive circuit.
4. Hot metal wires, particles, or surfaces created by ohmic heating of a circuit element, such as a wire strand.

All of these possibilities have been examined extensively in the context of explosion hazard prevention (Magison 1978), but the most often studied has been the capacitive spark. The standard way to characterize capacitive discharge sparks is in terms of the quantity of stored electrical energy, measured by the Joule (J). The actual amount of energy that is deposited in the gas by the discharge is lower but difficult to quantify, particular for short duration sparks. This issue is considered in more detail in the discussion section. It is found that for mixtures of a given fuel with an oxidizer such as air, there is a minimum spark energy required to cause ignition when the mixture falls in the range of flammable compositions. In this report, this energy will be simply referred to as the ignition energy.

Beginning with the work of Guest at the Bureau of Mines in the 1940s and continued by Blanc et al. (1947), an extensive series of tests (summarized in Lewis and von Elbe 1961) was carried out to determine ignition energy in hydrocarbon-air vapors. Ignition energy was found to be a function of fuel type and composition. For a given fuel, the ignition energy is a U-shaped function of composition with the vertical portions of the "U" occurring at the flammability limits and bottom of the "U" at some intermediate composition (see Fig. 1). The ignition energy for the most sensitive mixture is known as the Minimum Ignition Energy, or MIE. For both leaner and richer mixtures, the ignition energy increases sharply from the MIE. The MIE for hydrocarbon fuels in air has been measured for many common substances (Lewis and von Elbe 1961; Calcote et al. 1952) and is known to be on the order of 0.2 mJ and usually occurs for a rich composition. Examples of measured minimum ignition energy (Lewis and von Elbe 1961) are shown in Fig. 1. Based on these results, the MIE for all petroleum-based fuels, including aviation kerosene is assumed to be on the order of 0.2 mJ.

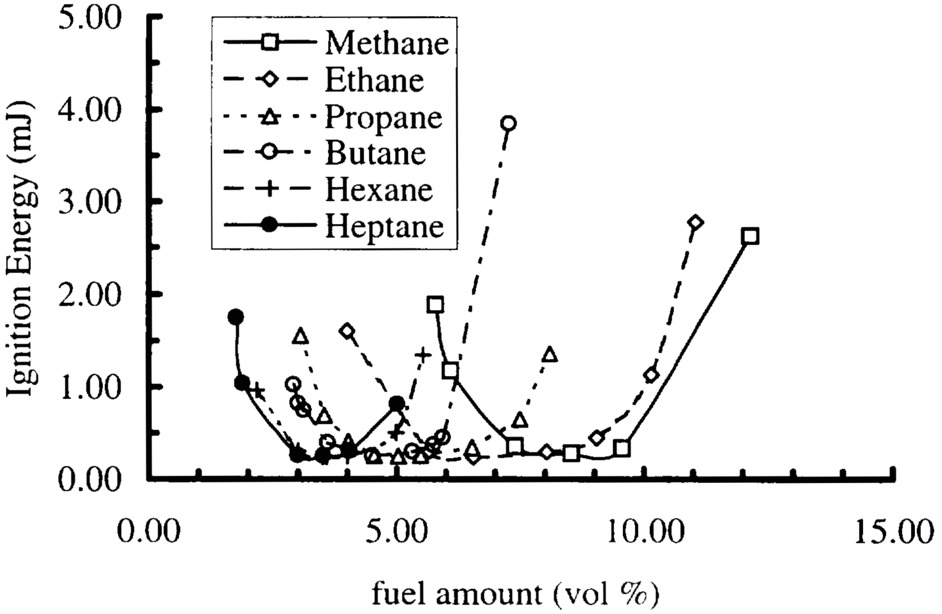

Figure 1: Classical results on ignition energy by Lewis and von Elbe (1961).

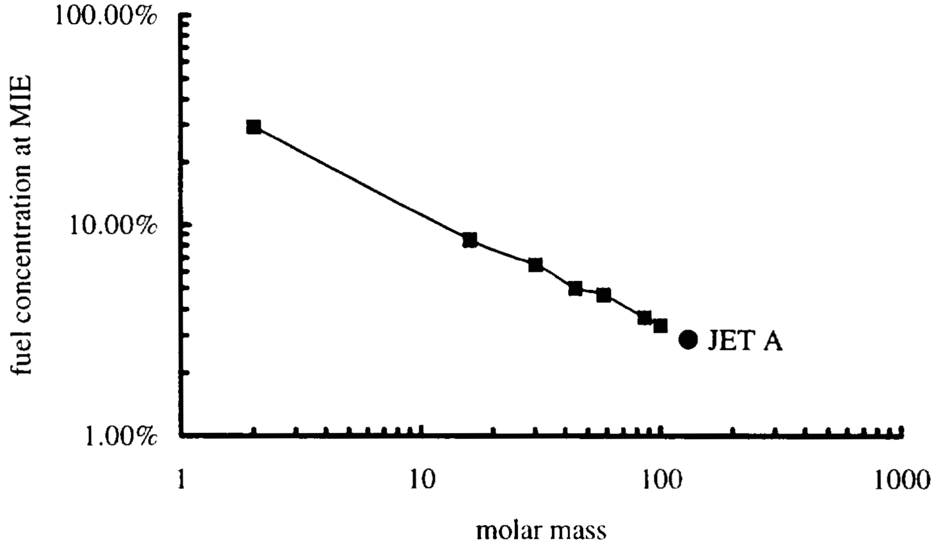

Figure 2: Dependence of composition at MIE (minimum ignition energy) on the molar mass of fuel. Based on the data of Lewis and von Elbe (1961) and following the treatment of (Ural, Zalosh, and Tamanini 1989).

As well as showing the strong dependence of the ignition energy on mixture composition, these results also indicate that the MIE occurs at increasingly rich concentrations (Fig. 2) as the size of the fuel molecule (number of carbon atoms) increases. The results of Fig. 1 hint that the MIE increases as the fuel concentration is varied from the minimum ignition point. However, only a limited range of concentrations has been examined in the previous studies and these results conceal the very strong variation in ignition energy as the lean limit is approached.

The problem of ignition energy and flammability are closely related. Loosely speaking, flammability is the sensitivity of fuel-oxidizer mixture to ignition. A limiting concentration of fuel that will just result in ignition or flame propagation is referred to as the flammability limit. Traditional evaluations of explosion hazards rely on comparing the fuel concentration to the measured flammability limit.

However, the flammability limit depends on the choice of ignition method. Consequently, different methods of measuring the flammability have been devised such as the flashpoint test (ASTM D56 1988), spark ignition (ASTM E582 1988), temperature limit method (ASTM E1232 1991), and concentration limit method (ASTM E681 1985). Each of these uses different ignition methods: an open pilot flame in the flashpoint test; a capacitive spark in the spark ignition test; an electrically heated fuse-wire in the temperature limit test; and either a fuse wire or an electric arc in the concentration limit method. The most commonly used method of all, the flammability limit tube developed at the Bureau of Mines (Coward and Jones 1952; Zabetakis 1965; Zabetakis et al. 1951), has never been standardized. This method uses various ignition sources; one commonly employed is a quasi-continuous arc produced by a neon-sign transformer (20 kV, 30 mA) across a 0.25-in gap. Experience at Caltech with this type of source indicates that this is at least equivalent to a 100-J capacitive spark. Not surprisingly, all of these methods yield different results. This is illustrated for propane in Fig. 13. Since there is no fundamental theory of ignition or flammability limits, it is not possible to reconcile these various techniques.

2.1 Jet A Ignition Experiments

There are few reported values of Jet A vapor ignition energy in the open literature, but the MIE value of 0.2 mJ for hydrocarbon fuels is suggested in (CRC 1983) as being applicable to aviation fuels. The flammability limit measurements of Nestor (1967) and Ott (1970) use sparks with energies between 4 and 20 J. These values were used to create the standard flammability limit plots reported in most handbooks (CRC 1983); the results of Nestor (1967) are reproduced in Fig. 3.

We have not been able to identify any openly published data other than the Nestor and Ott data sets. However, after our initial experimental work was completed, we learned of experiments carried out in 1992 (Plummer 1992) with both propane and JP-8. The JP-8 was heated, vaporized, and mixed with air at temperatures between 150 and 190°F. The composition of the mixture was adjusted by varying the ratio of fuel-to-air flow rate and carrying out comparisons to a propane-air mixture. However, because not all of the fuel was vaporized and a mass balance was not carried out, the actual composition of the fuel-air mixture could not be determined.

The JP-8 experimental results were compared to a propane mixture had a concentration of

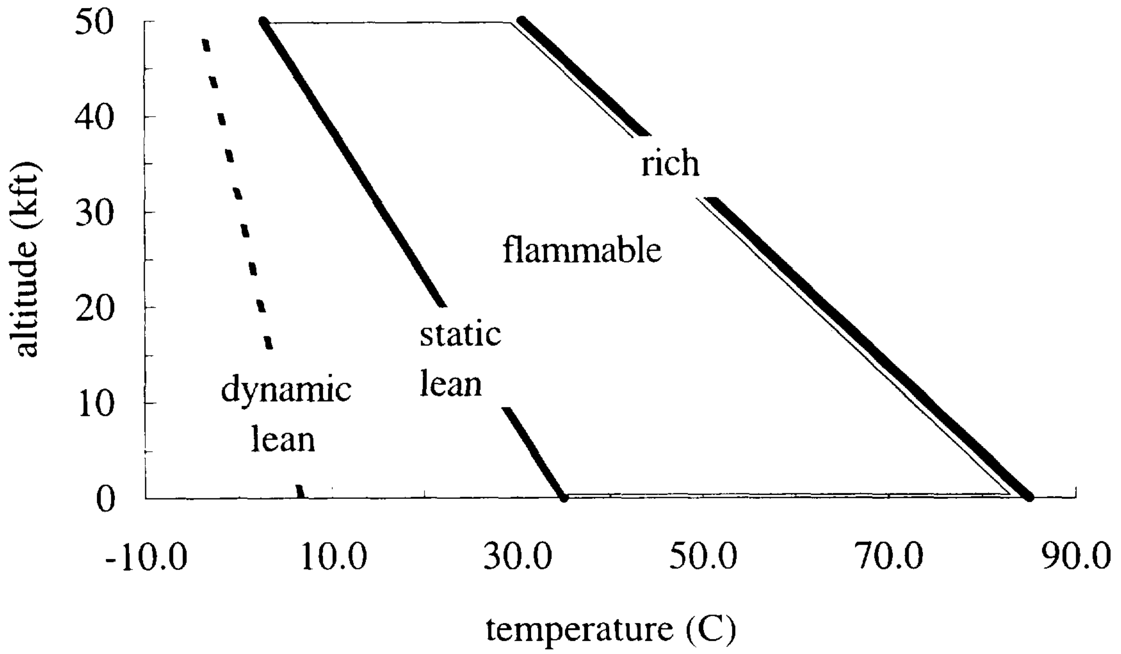

Figure 3: Flammability limits of Jet A in air in the standard representation of temperature vs. altitude (CRC 1983) based on Nestor (1967) measurements with a 20-J spark.

1.2 times stoichiometric, or approximately 4.8% fuel by volume. This is the composition at which the minimum ignition energy is observed and is frequently used as a test standard in military fuel-tank tests. By adjusting the JP-8/air mixture to have a similar ignition sensitivity as the reference propane mixture, it was assumed that the resulting JP-8/air mixture corresponded to the most sensitive mixture for spark ignition. The probability of ignition for a given energy was evaluated through multiple tests and found to vary from less than 5% at 400 μJ to 100% at 900 μJ for both the reference and JP-8 mixtures. The energy was computed from the capacitance and the charging voltage. The spark was created across a 2-mm gap with a secondary corona discharge to promote breakdown.

One other set of "data" deserves comment here. There is a published report (Frechou 1975) from the Concorde development team of ignition energy for both JP-4 and fuels characterized as "JP-1 and JP-5." This report provides a detailed, quantitative contour plot of ignition energy as a function of temperature and altitude. However, no information is given about the experimental technique or properties of the fuels. Further investigation reveals that these results were derived from estimates created by BAC (BAC 1972) using the Lewis and von Elbe data on propane shown in Fig. 1, and in fact consists of an estimated vapor pressure curve and some simple scaling ideas. There are a number of factors that make the analysis invalid:

1. The assumption that ignition-energy dependence on equivalence ratio is the same for propane as for Jet A or any other aviation fuel is incorrect.

2. The vapor pressures used in that analysis are a factor of three higher than Caltech mea-

surements and CRC reported values. The BAC memorandum refers to the vapor pressure as being appropriate for both Jet A and Jet B, although it is known that the vapor pressure of Jet B is substantially higher than Jet A.

3. The basic propane data are valid only up to 2 – 3 mJ but is extrapolated over three orders of magnitude, up to 25 J.
4. The scaling ideas are "believed to have been extracted from an FAA paper." There is no other justification or validation of the scaling.

The original 1972 BAC memorandum clearly identifies some of the limitations inherent in the original analysis, but these limitations have been disregarded in subequent applications to aircraft design.

The origin of these "data" has been further confused over the years since the label "JP-4" was substituted for "Jet B" and "JP-1 and JP-5" for "Jet A" when Frechou replotted the original estimates as a function of altitude instead of pressure. This plot has resurfaced recently (see Clodfelter 1997), and is now labeled as being characteristic of JP-8 with a 100°F flashpoint.

The only other published data are values of ignition energy measured by Kuchta et al. (1971) for mists (spray) of Jet A sprayed directly on electrodes (see Fig. 4). In discussing these data, the confusing and incorrect statement is made in the Handbook of Aviation Fuel Properties (CRC 1983, p. 74): "Likewise, if the fuel is present in the form of a mist or spray as opposed to a vapor, the ignition energy requirements will increase." However, this is clearly incorrect since spray ignition energies of 10 – 50 mJ are shown at conditions (1 atm, $-15 < T < +20$°C) for which the vapor cannot even be ignited with energies as high as 20 J. Studies of spray ignition (see discussions in Chapter 7 of Lefebvre 1983) have shown that when hydrocarbon fuel sprays are directly impinging on igniter electrodes, ignition can be obtained for much lower energies — or even for situations for which it is impossible to ignite the pure vapor phase created by equilibrium with the liquid. These data are clearly irrelevant to the problem of spark ignition energy in the pure vapor phase.

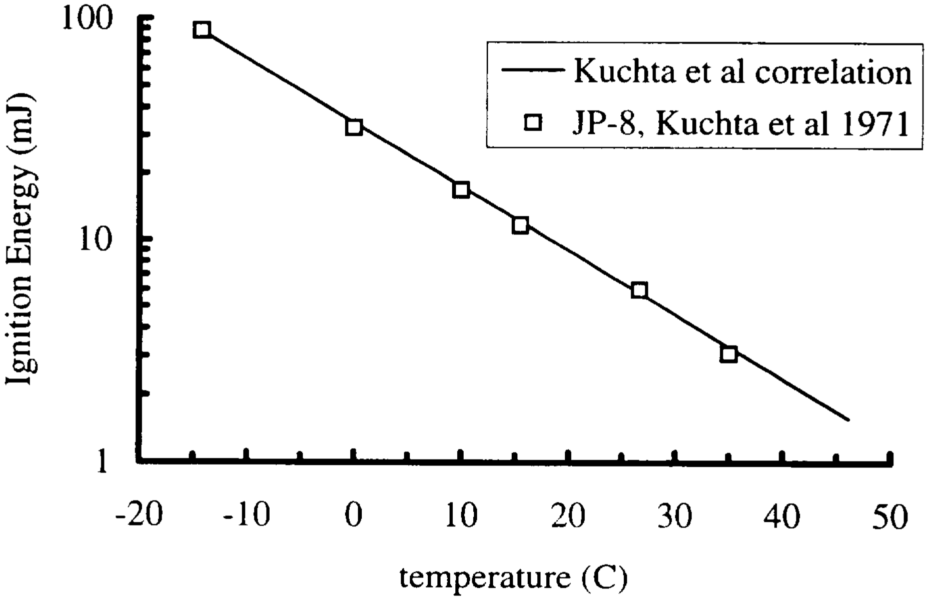

Figure 4: Dependence of ignition energy for Jet A sprays on fuel temperature (Kuchta et al. 1971).

3 Experimental Apparatus

Ignition energy measurements were performed in two different vessels with common electrical ignition and gas supply systems. For experiments conducted at ambient temperature with a purely gaseous mixture, an unheated 11.25-liter vessel was used. This vessel was used for initial calibration measurements with propane-air and hexane-air mixtures. For tests with Jet A in which the initial temperature of the system had to be precisely controlled, a heated 1.84-liter ignition vessel was used.

3.1 Gas Ignition Vessel

Ignition energy measurements on purely gaseous mixtures such as hexane-air and propane-air were performed in the gas ignition vessel. These tests were conducted primarily for verification of the ignition system and of the procedures used for flammability testing of Jet A.

3.1.1 Vessel

The gas ignition vessel consists of an 11.25-liter steel vessel with an approximately cubic interior of dimensions 19.0 cm × 20.3 cm × 30.5 cm as shown in Fig. 5. The vessel contains two circular windows on the front and back walls; this allows video documentation of the combustion phenomenon. A mixing fan inside the vessel ensures the homogeneity of the gaseous mixture. Liquid fuel such as hexane was introduced into the vessel under vacuum through the septum connected to the tank. The pressure history was recorded with a Kulite XT-190 gauge; the temperature history was recorded with a K-type thermocouple located about 5 cm from the vessel ceiling, near the center of the chamber. A high-precision Heise diaphragm pressure transducer was used to determine the initial pressure in the vessel.

The combustion process was captured using a color schlieren system. The schlieren images were recorded on video, allowing one to observe the details of the ignition process and flame propagation as well as infer flame speeds. The optical set-up is shown in Fig. 6. The light source is a mercury vapor lamp, and a mirror and lens system is used to obtain a parallel beam suitable for schlieren photography of the combustion event in the vessel. A three-color stop is used to provide the color schlieren effect, and the image is recorded using a CCD camera and a standard video recorder.

3.1.2 Gas-Feed System

The gaseous mixture in the vessel is controlled through the gas feed system shown in Fig. 7. The pneumatic valves of the system are activated from an external control panel such that the entire gas-loading procedure can be performed remotely. Gases can be evacuated through the vacuum pump, and various gases can be selected to fill the vessel. The mixture composition is determined by introducing the desired quantity of each gas through the method of partial pressures. In the case of hexane-air mixtures, liquid hexane was introduced into the evacuated vessel by a syringe through a septum located on the side of the vessel.

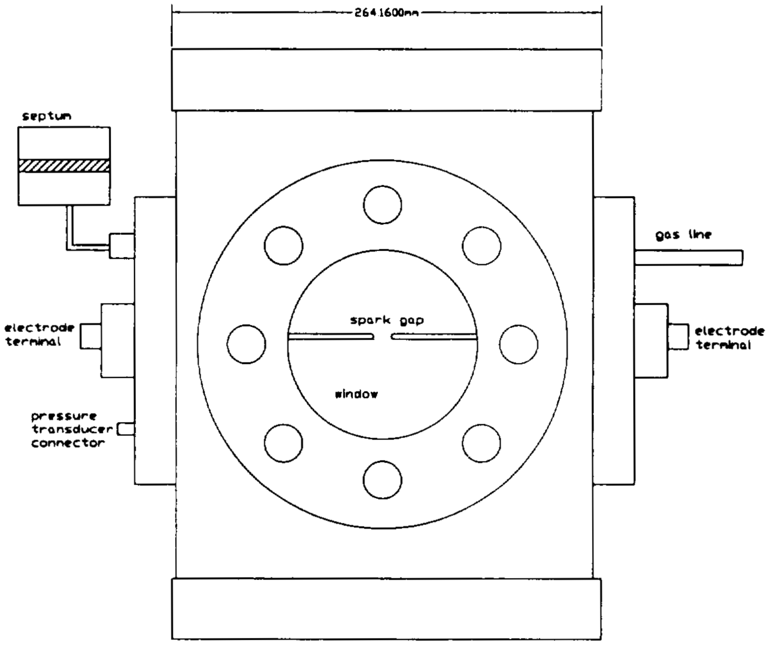
264.1600mm
septum
gas line
electrode terminal
spark gap
electrode terminal
window
pressure transducer connector

Figure 5: Schematic of the 11.25-liter vessel used for ignition energy measurements of hexane and propane with air.

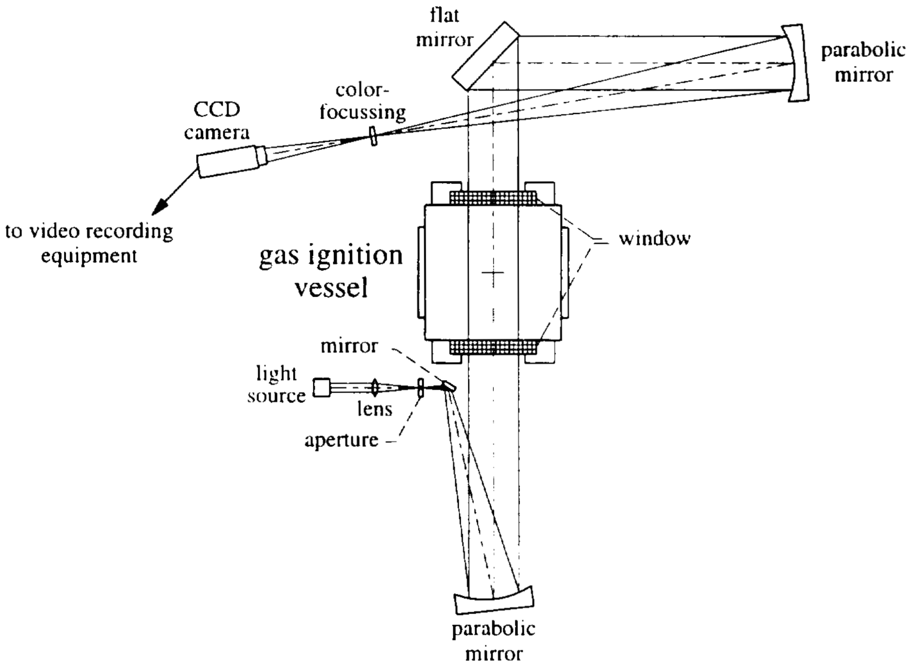
flat mirror
parabolic mirror
color-focussing
CCD camera
to video recording equipment
window
gas ignition vessel
mirror
light source
lens
aperture
parabolic mirror

Figure 6: Schematic of optical arrangement used for color schlieren video recording of the combustion phenomena (shown with the 11.25-liter vessel).

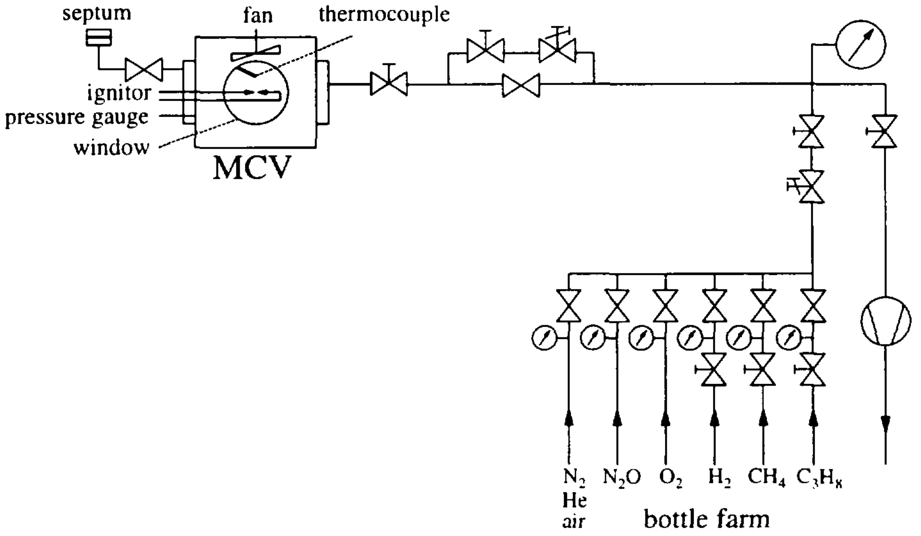

Figure 7: Schematic of the gas-feed system (shown here connected to the 11.25-liter vessel, labeled MCV).

3.1.3 Electrodes

The electrodes used for spark ignition of the gaseous mixture consisted of two 3.2-mm diameter stainless-steel rods inserted into opposite sides of the chamber such that the spark gap was located at the center of the chamber. The rods were insulated from the chamber wall with Teflon plugs and the electrode tips were rounded.

3.1.4 Experimental Procedure

In the first series of experiments, propane-air and hexane-air mixtures were tested. The tests with these mixtures were all conducted at approximately 22°C and an initial pressure of 1 bar. The propane used in the tests was commercial grade. The mixing fan was turned off during the tests so that the mixture was quiescent at the time of ignition.

The vessel was first evacuated, then filled to the desired fuel pressure. In the case of hexane, an appropriate quantity of liquid hexane was introduced into vessel through the septum. To ensure that no liquid residue remained, the hexane was limited to quantities such that the fuel partial pressure was always less than the vapor pressure. The chamber was left at low pressure with the mixing fan on for several minutes to allow the hexane to evaporate completely. Air was then added until the total pressure of the mixture in the vessel reached 1 bar. The mixture was stirred for several minutes with the fan before proceeding with the test.

The capacitor was charged to an energy between 1 mJ and 100 J and discharged across a 3.3-mm gap to create the igniting spark. If the mixture failed to ignite, the stored energy was increased until a flame was initiated. Since, in the case of ignition failure, the small amount of mixture burnt by the spark can contaminate the unburnt gases and influence the ignition limit of the mixture, a limited number of tests were performed with the same mixture. For tests at low ignition energies (between 1 mJ and 500 mJ) for which only a small volume of mixture was burnt by the initiating spark, up to five tests were performed with the same mixture to find the ignition limit. For high-ignition-energy tests (between 1 J and 100 J), for which a larger volume of the mixture was burnt by the spark, no more than two tests were performed in succession without changing the mixture in the vessel. Ignition was determined by visual inspection of the video recording and by the recorded pressure signal.

3.2 Heated Ignition Vessel

3.2.1 Vessel

A 1.84-liter heated vessel was used for ignition energy measurements on the Jet A vapor and air mixture. This apparatus was designed to test the flammability of a combustible mixture created when fuel at the bottom of a partially-filled tank evaporates and mixes with the air in the space above (the ullage). Since the amount of Jet A vapor in the mixture depends primarily on the liquid fuel temperature, the initial temperature of the system was precisely controlled.

The heated ignition vessel is shown in Fig. 8. The vessel has an approximately cubic interior with a dimension of about 14 cm. A magnetic stirring rod ensures proper mixing of the liquid inside the chamber. The front and back walls of the vessel have circular windows through which the combustion process can be observed. We used the same color schlieren and video-recording system as the gas ignition vessel. The pressure history was recorded with a Kulite XT-190 gauge and the temperature history was recorded with a K-type thermocouple inserted from the top of the vessel into the gaseous section of the vessel above the liquid surface. An additional Baratron MKS diaphragm pressure transducer was used to determine the initial pressure in the vessel. The temperature of the vessel and its contents are controlled using 5-W/in^2 heating pads attached to the outside surface of the vessel. Power to the heating pads is supplied by a temperature controller unit which can monitor the vessel temperature through thermocouples on the top and bottom exterior surfaces as well as inside the vessel, at a point approximately 2 cm from the side walls. To maintain the vessel at the desired temperature during long periods of time, the entire vessel is placed inside a cubic wooden box with a dimension of about 25 cm. Natural convection in the air between the vessel and the box walls ensures thermal equilibration within 60 to 90 minutes.

3.2.2 Gas and Liquid Supply System

Liquid jet fuel is introduced into the vessel with a pipet through one of the inlets on top. The gas-feed system used for controlling the pressure in the vessel and evacuating the combustion products was the same as the one shown in Fig. 7 for the MCV vessel.

3.2.3 Electrodes

Two electrodes protrude into the vessel to provide a spark gap in the center of the chamber. The electrodes were made of 3.2-mm diameter stainless-steel rods with rounded tips. The gap

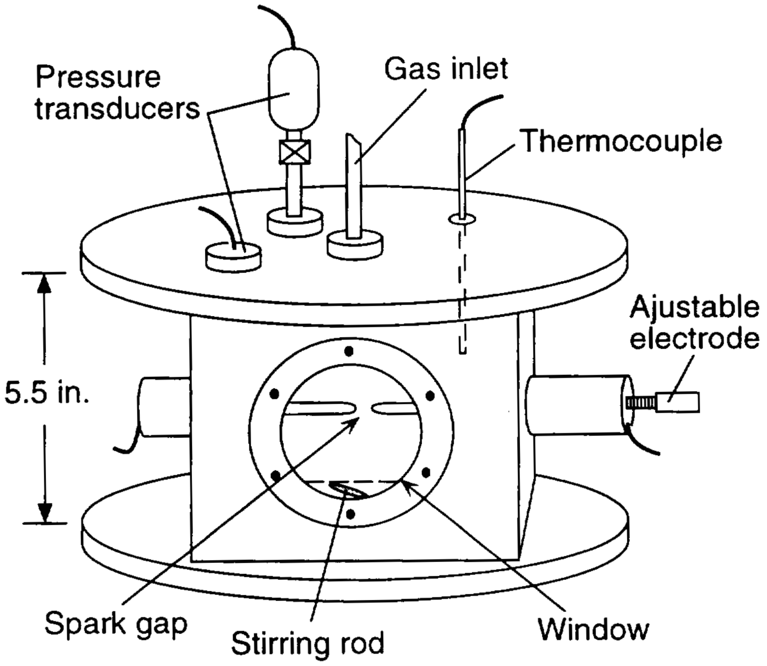
Pressure transducers
Gas inlet
Thermocouple
Ajustable electrode
5.5 in.
Spark gap
Stirring rod
Window

Figure 8: Schematic of the heated ignition vessel used for ignition energy measurements of Jet A vapor with air.

size determined by the electrode tip separation can be adjusted with a micrometer screw on one of the electrodes. The details of the electrode construction are shown in Fig. 9.

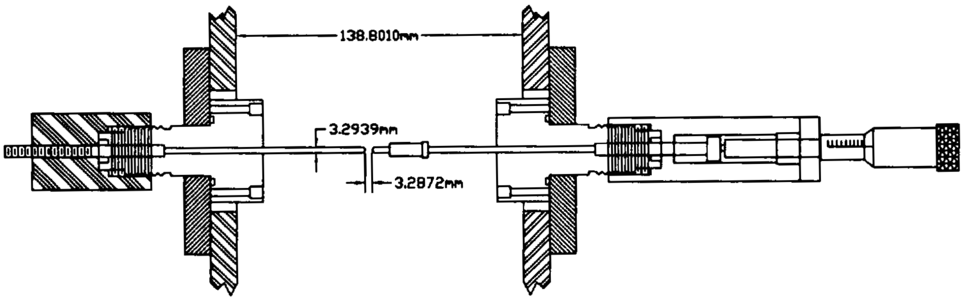
138.8010mm
3.2939mm
3.2872mm

Figure 9: Schematic diagram of the adjustable gap electrodes used in the heated ignition vessel.

3.2.4 Experimental Procedure

The ignition energy was measured for commercial Jet A fuel obtained from local airports. Tests were done for two mass-to-volume ratios in the vessel: 3 kg/m^3, corresponding to 6.9 ml of fuel; and 200 kg/m^3, corresponding to 460 ml of fuel. The initial temperature of the mixture in the chamber was varied from 25°C to 55°C, and all tests were conducted at a pressure of 0.585 bar to match the atmospheric pressure at 13.8 kft.

For the tests at 3 kg/m^3, the empty vessel was first heated and allowed to stabilize at the desired temperature. The appropriate amount of fuel (6.9 ml) was then poured in carefully to avoid splashing onto the windows. After sealing the vessel, gas was evacuated until a pressure of 0.585 bar was reached. The magnetic stirring rod was turned on and the system was allowed to equilibrate over a period of about 30 minutes to 1 hour. During equilibration, the pressure rose due to the evolution of dissolved air and evaporation of the fuel. The vessel was periodically evacuated to reduce the pressure back to 0.585 bar. We proceeded with the ignition test when the pressure and temperature stabilized. The vessel was emptied and cleaned between each test.

A similar procedure was followed for tests at 200 kg/m^3, except that the same fuel was used for an entire series of tests over the temperature range 25°C to 55°C. The total amount of liquid fuel in the vessel was 460 ml. Between each test, the products of the previous combustion event were evacuated to approximately 6 mbar for a duration of several seconds. Fresh air was subsequently introduced into the chamber until the desired pressure of 0.585 bar was attained. The windows were cleaned between tests by heating the outside surfaces until the liquid droplets on the inside surface evaporated.

The fuel-air mixture in the vessel above the liquid layer was ignited using sparks created by discharging capacitors with stored energy between 10^{-3} J to 10^{2} J across a 3.3-mm gap. This gap size was chosen to match the gap size used in previous ignition experiments done with hexane and propane. As in the gas-ignition vessel tests, the ignition limit was found by increasing the spark energy until ignition occurred for a given mixture. To minimize the influence of mixture contamination by spark-generated combustion products, no more than five successive tests (two for high spark energies) were performed with the same mixture. Inspection of the video recordings and pressure data was used to determine if a propagating flame was produced.

3.3 The 1180-Liter Vessel

Preliminary ignition energy tests were performed in a heated 1180-liter (1.18 m^3) vessel. The general features of this facility have been reported in Shepherd et al. (1997). This vessel was modified to use spark ignition. Due to its larger volume, the effects of vessel size on flame propagation rate and peak pressure could be investigated.

A schematic of the vessel is shown in Fig. 10. Previous experiments (Shepherd et al. 1997) were carried out with a jet ignition system. For the present study, the jet ignition was replaced by spark ignition, with the spark gap attached at the location where the jet nozzle was formerly attached. Only a limited number of tests were carried with propane, hexane, and Jet A to confirm the results obtained in the smaller vessels. Jet A tests were only carried out at a mass loading of 3 kg/m^3 due to the difficulty of handling and disposing of the large amounts of Jet A that would be required at higher mass loadings.

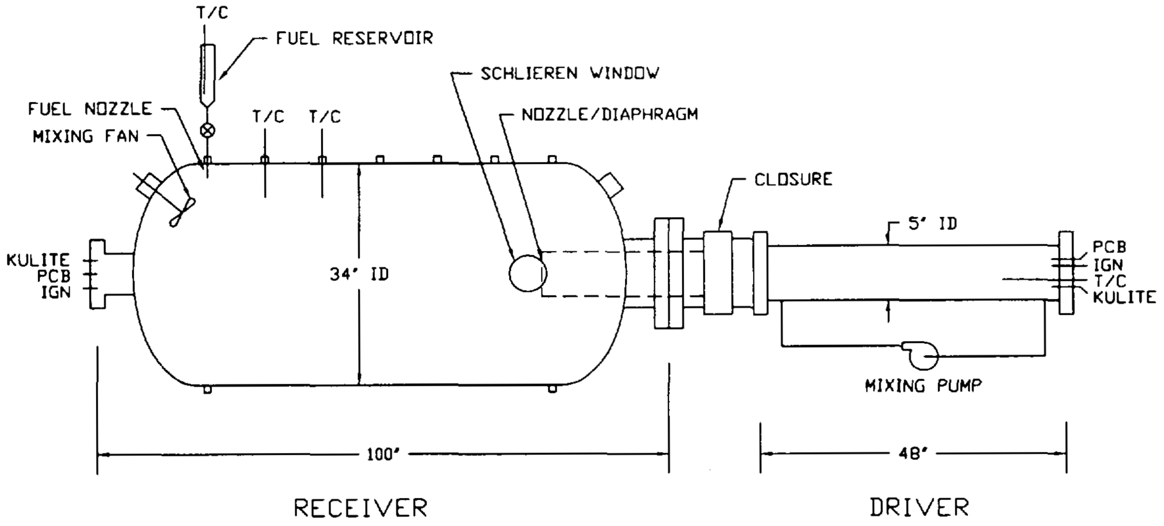

Figure 10: Schematic of the 1180-liter vessel.

3.4 Spark Discharge and Electrode Issues

Previous studies on spark ignition have shown that there is variability in results due to the dependence of ignition energy on the electrode construction and discharge circuit design. Quantifying the strength of a short-duration, low-energy capacitive spark ignition source has been found to be difficult (Strid 1973); thus a standard for spark energy has not been developed. The ASTM ignition energy test (ASTM E582 1988) follows the practice started by Lewis and von Elbe (1961) of reporting the stored energy rather than measuring the energy discharged into the spark. Some test procedures require flanges to be used on electrodes (ASTM E582 1988), while other researchers (Calcote et al. 1952; Crouch 1994) do not use flanges and find comparable ignition energies to studies done with flanges.

In the present study, we have reported the "energy stored" as the ignition energy and used unflanged electrodes. Some of the issues connected with these choices are explored in the next two sections. Ultimately, the validation of these choices and our experimental protocol was confirmed by doing control experiments with propane and hexane. Our values of ignition energy compare favorably with those of previous researchers for the overlapping ranges near the MIE, and interpolate smoothly between the lean limit and the MIE values.

3.4.1 Spark Energy

In the present study, the ignition energy reported is actually the energy stored in the capacitor used to create the electrical discharge. The stored energy was varied by using different combinations of capacitors and different charging voltages from 1 kV to 15 kV. Voltage was measured as the capacitor was charged, and the spark was triggered when the desired charging voltage was reached and stabilized. The energy stored in the capacitor was computed from the standard relationship

$$E = \frac{1}{2}CV^2 \tag{1}$$

where E is the stored energy (J), C is the capacitance (F), and V is the charging voltage (V). With a fixed gap size (3.3 mm) and a constant pressure (0.585 bar), a minimum voltage of about 6 to 8 kV is needed to cause spontaneous electrical breakdown across the gap. This necessitated using various sizes of capacitors, ranging from 30 pF to 1 μF, for tests at different energy ranges (see Table 1).

Table 1: Discharge capacitor types.

Capacitance (nF)	Voltage (kV)	Type
500	15	Oil dielectric (2)
5	30	Mylar dielectric
0.0581	6	59 cm of RG-8A/U coaxial cable
0.0317	6	31 cm of RG-8A/U coaxial cable

In our arrangement, the residual energy remaining in the capacitor after the discharge was less than 1%. However, due to the finite impedance of the circuit and the complex nature of electrical arcs, it is not possible to draw any conclusions about the amount of energy deposited into the arc. In order to do that, it would be necessary to determine the actual energy dissipated within the arc

$$E_{arc} = \int_0^\infty v(t)i(t)\mathrm{d}t \tag{2}$$

which requires measuring the voltage $v(t)$ across the arc and current $i(t)$ through the arc as a function of time. Various arrangements have been proposed to do that; a review is given by Strid (1973). However, a short-duration (less than 1 μs) spark created by discharge of a small capacitor directly into an air gap is difficult to quantify in this fashion. The capacitance and resistance introduced by the measuring circuit can be substantial. Since the spark is of very short duration, careful circuit design is needed to eliminate the effects of the frequency response (phase shifts) introduced by the measurement circuit. Finally, the efficiency for converting electrical energy into work on the surrounding gas is known to have a strong dependence on spark duration but quantitative details are unknown.

It is possible to measure the energy dissipated by a spark directly if the spark energy is high enough and a pulse-shaping circuit is used to substantially increase the duration of the discharge. Recent studies (Ronney and Wachman 1985; Kono et al. 1976; Ballal and Lefebvre 1975) have used more sophisticated circuits to lengthen and measure the electrical pulse in order to report measured (Eq. 2) rather than stored (Eq. 1) energy. Critics (Grenich and Tolle 1983) of the "energy stored" method suggest that as little as 10% of the stored energy gets into the spark, but they were unsuccessful at actually measuring the energy deposited by short-duration sparks. Other researchers (Eckhoff 1975) have found that a substantial fraction of the stored energy is deposited into the gas by a long-duration spark. Parker (1985) examined the effect of pulse duration and discharge circuitry on igniting a 2.7% propane-in-air mixture. A short-duration, constant-power pulse circuit was able to ignite this mixture using a 4-mm gap with a minimum energy of 0.3 mJ. This is about an order of magnitude lower than Lewis and von Elbe (1961) found with a capacitive circuit. Parker speculated that this difference was due to the much greater efficiency of coupling electrical to thermal energy for the pulse circuit as compared to straight capacitive discharge systems. However, if resistance elements are added to a capacitive discharge circuit, Parker suggests that the electrical-to-thermal conversion efficiency is increased. Resistance elements in series with capacitive discharges are used by one flammability testing organization in the USA (Dahn 1998). This is primarily to create an overdamped circuit in order to use conventional probe techniques and slow data acquisition systems to record the voltage-current characteristics used for computing energy. A recent project (Crouch 1994) to construct a standard test rig for lightning protection studies did not attempt to directly measure the spark energy but relied on the "energy stored" concept with a purely capacitive discharge circuit.

Direct measurements of a voltage and current of the spark were performed by Eckhoff (1975) using a circuit similar to our "trigger spark" device. The resulting measured energies were compared to the calculated estimate using stored capacitor energy (Eq. 1). For a calculated spark energy of 0.1 mJ, the measured energy was ten times higher (1 mJ). This is due to the energy of a trigger spark circuit. The difference between the two decreases as the spark energy increases, and at energies between 10 mJ and 100 mJ, the calculated and measured energies are the same. Above 100 mJ, the measured energy is lower than the calculated energy and is about a factor two lower for a calculated energy of 10 J.

3.4.2 High-Voltage Switching

In our experiments, the spark was triggered by one of two methods: a mechanical switch consisting of contacts closed by a metallic bar, or a 30-kV trigger spark provided by a TM-11A trigger module. The circuit for the mechanical switch is shown in Fig. 11. When the switch is in the normal position, the capacitor charges through the 1.9-MΩ resistor. When the switch is pressed, the capacitor discharges through the spark gap. This circuit was generally used

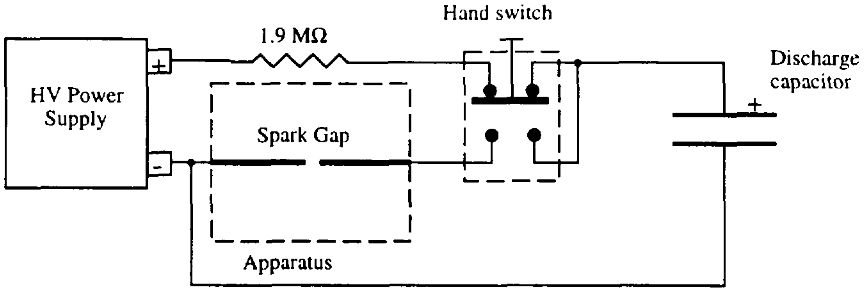

Figure 11: Circuit diagram for the high-voltage mechanical switch spark system.

for spark energies less than 1 J. For higher spark energies, the trigger spark system (shown in Fig. 12) was used. In this system, the breakdown across the electrode gap is initiated by a low-energy (40 mJ), high-voltage (30 kV) spark from the TM-11A trigger module. Just before firing, the capacitor is charged by increasing the high-voltage power supply to the desired voltage through the 2-MΩ resistor. Ignition-energy measurements with 450-mJ sparks were performed on propane-air mixtures for both the mechanical switch and the trigger spark systems. For the mechanical switch system, a mixture of 2.6% propane ignited while a 2.5% propane mixture did not (Fig. 13). For the trigger spark system, the ignition limit was found to be slightly richer, as a mixture of 2.7% propane ignited while a 2.6% propane mixture did not. This discrepancy is well within the accuracy of the Kulite pressure gauge used to measure the composition of the mixture. We therefore conclude that the two spark generation systems are equivalent within the experimental error of the experiment.

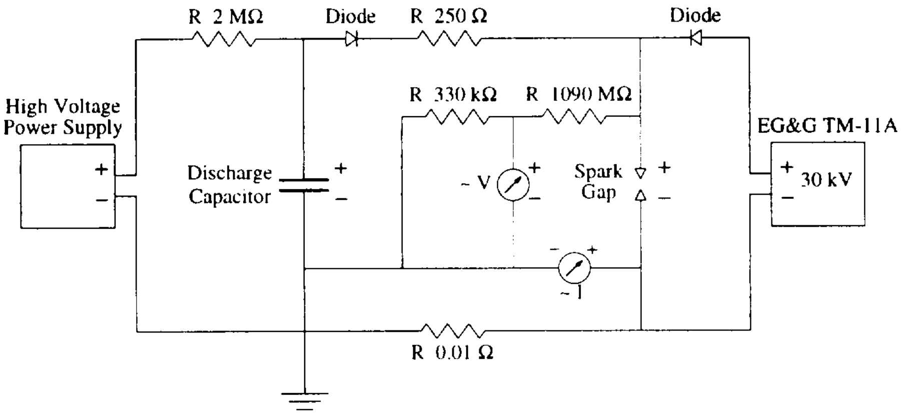

Figure 12: Circuit diagram for the trigger spark system.

3.4.3 Circuit Reactance

Stray circuit reactance in the discharge circuit and in the electrodes can have an effect on the time constant of the spark. Specifically, the reactance consists of resistance in the wires and contacts, stray capacitance in the electrodes, and inductance in various parts of the circuit. The reactance can change the rate of energy deposition or power as well as the spark duration. An underdamped discharge circuit can lead to an oscillatory spark energy release while an overdamped circuit can result in a lower-power, but longer-duration spark. Inductance is generally found to have little influence on the measured spark ignition energy (Magison 1978), but the series resistance on the electrodes is sometimes used to change the spark power (Ronney 1985).

The circuit inductance for the experimental arrangement used in this work was found to be approximately 1.5 μH. The resistance was a few ohms for the case of the mechanical switch. A resistance of 250 Ω was deliberately added to the spark trigger circuit in order to increase the duration of the discharge. Preliminary measurements of the spark duration showed it to be less than 5 μs. Previous work by Kono et al. (1976) showed that for propane-air mixtures at concentrations between 3.0% and 3.5%, the ignition energy varies by less than 1 mJ for spark durations less than 50 μs. Hence stray reactance is likely to have a negligible influence on ignition energy measurements with the present discharge circuit.

At low spark energies however, smaller discharge capacitors are used, and the stray capacitance cannot be neglected. We measured the capacitance of our circuit and found values of approximately 20 pF to 40 pF, which is comparable to the lowest capacitor sizes (Table 1). At a spark voltage of 6 kV, however, the stray capacitance may produce a variation in the spark energy of up to 7 mJ. The present circuit is therefore not well suited for low ignition energy measurements.

3.4.4 Electrode Type

The electrodes used in this study were not of the flanged type described by the ASTM standard (ASTM E582 1988). When the electrodes are flanged, the flame kernel generated by the spark can be quenched by the flanges. This phenomenon was investigated by Calcote et al. (1952) and Lewis and von Elbe (1961) who found that the minimum ignition energy is generally higher with flanged electrodes. For flanged electrodes, the ignition energy was found to increase sharply as the spark gap was decreased to within 0.2 mm of the quenching distance of the combustible mixture; and the mixture was not ignitable at all if the gap was less than the quenching distance. Without flanges, the ignition energy increases a modest amount with decreasing gap size. By using unflanged electrodes, we were able to carry out tests over a large range of compositions without having to continuously adjust the gap size in order to stay above the so-called quenching distance.

The main advantage of this is that the voltage needed to breakdown the gap and produce a spark is relatively fixed and the energy input can be adjusted by simply changing the amount of capacitance. For a given dielectric, the breakdown voltage is proportional to the product of gap distance and pressure (Paschen's Law), so that the spark trigger voltage has to be increased with increasing gap distance. The drawback of working with a fixed gap distance is that the losses to the electrodes increase as the stored energy and consequently the flame kernel size increase. This results in ignition energies that are higher than the minimum value for the highest values of stored energy, which are encountered near the lean flammability limit. Further study is needed to quantify the magnitude of this effect.

4 Validation Tests

4.1 Propane Combustion

The first set of validation tests was carried out with propane-air mixtures. The propane used was from a small commercial cylinder of the type supplied for a hand-held plumbing torch. The exact composition is not known, but the HD-5 fuel specification is for at least 95% propane with the balance being lighter compounds such as propylene and butane. The initial conditions and key results are given in Table 5 of Appendix A.

4.1.1 Ignition Energy

Our ignition energy results for propane-air mixtures are shown in Fig. 13 along with previously reported data. The present data extend from 2.2% propane (LFL) up to 3.5% propane. The minimum ignition energy of approximately 0.2 mJ occurs at 5% propane as determined by Lewis and von Elbe (1961) and Calcote et al. (1952). The ignition energy increases continuously by a factor of 10^5 as the concentration is decreased from stoichiometric to the lean limit of 2.1% propane. Mixtures with less than 2% propane cannot be ignited even with a 20 J spark. The present data are consistent with the previously measured ignition limit between 2.1% and 2.3% propane given by Kuchta (1975) and Coward and Jones (1952).

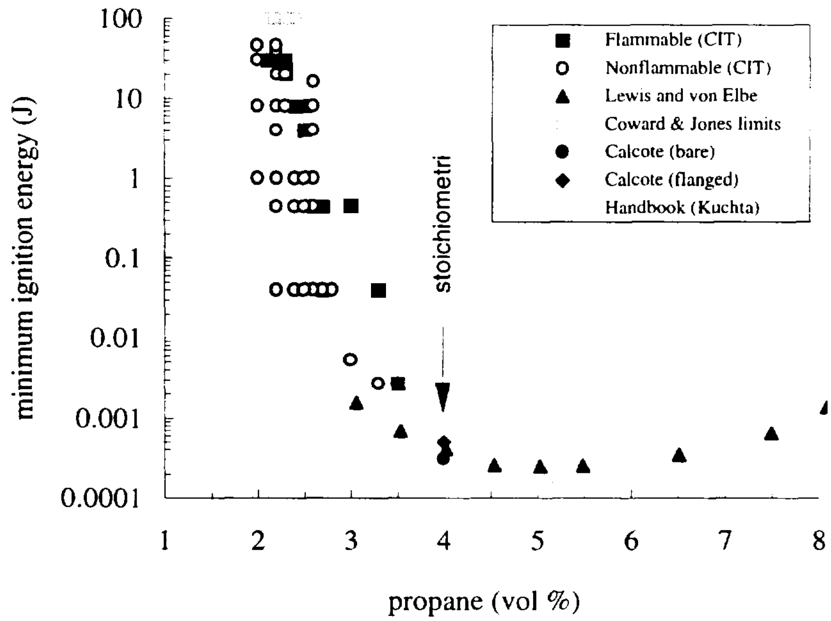

Figure 13: Measured ignition energy for propane-air mixtures, initial pressure 1 atm, initial temperature 295 K.

4.1.2 Combustion Pressure

The pressure-time histories were also recorded to confirm that the mixture had been ignited and burned. Selected results (Fig. 14) show that the leaner the mixtures, the slower the pressure rise. This agrees with the known dependence of burning speed on mixture strength. The burning speed S_u and the pressure rise coefficient K_g were calculated from the pressure-time profiles by the techniques discussed in (Shepherd et al. 1997). These values are shown in Table 5 of Appendix A.

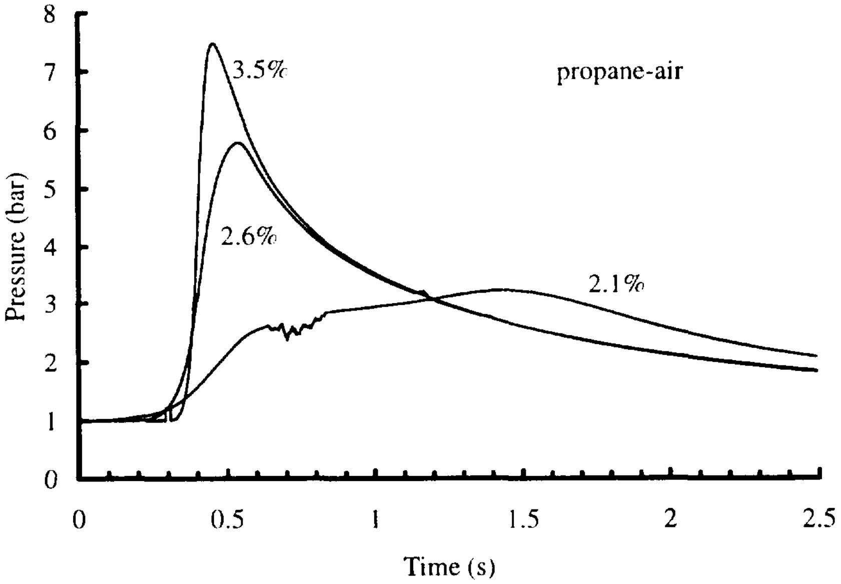

Figure 14: Measured pressure histories for propane-air combustion, initial pressure 1 atm, initial temperature 295 K.

The peak pressures for the various mixtures are shown in Fig. 15 along with the calculated maximum pressure for adiabatic, constant-volume combustion (AICC). The measured pressures are lower than the calculated values due to energy losses caused by radiative and convective heat transfer during the burn. This effect is stronger for leaner mixtures, for which the burning speed is lower. For very lean mixtures, less than about 2.6% propane, buoyancy prevents the flame from burning downward and the discrepancy between computed (AICC) peak pressure and measured peak pressure becomes even larger. This can also be observed qualitatively in the 2.1% propane case shown in Fig. 14. The pressure history in this near-limit case has a plateau between 0.6 and 1.5 s, which corresponds to a very slow combustion process in the upper portion of the vessel (this can be observed on the schlieren system). Contrast this with the 2.6 and 3.5% propane cases, which correspond to flame propagation throughout the vessel with a minimum buoyancy effect. Data from the 1180-liter vessel is also shown in Fig. 15. The peak pressures obtained in the two facilities are essentially identical, given the spread observed from repeat testing at the same concentration in a given facility.

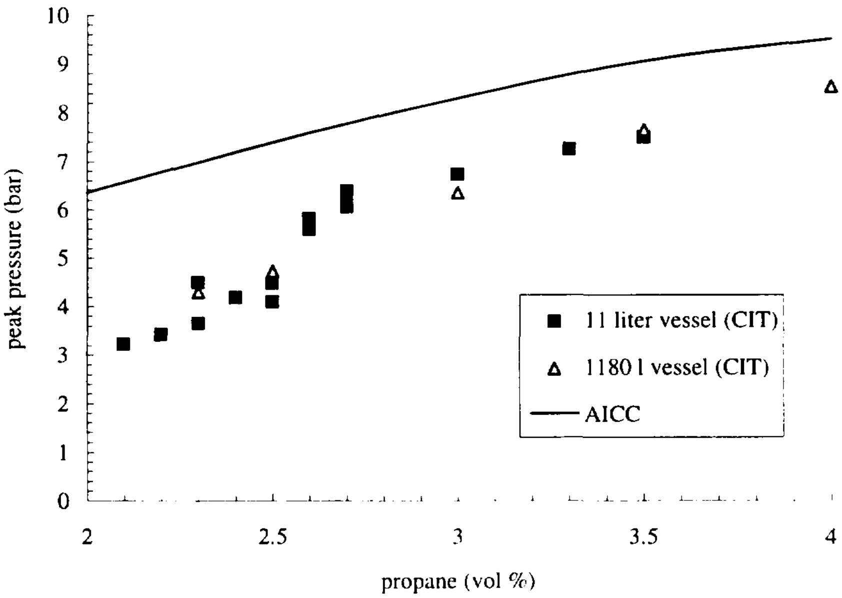

Figure 15: Measured peak pressure for propane-air mixtures, initial pressure 1 atm, initial temperature 295 K.

4.1.3 Flame Speeds

The burning speeds (Fig. 16) for the propane experiments were computed by the "t^3" pressure-trace analysis method described by Shepherd et al. (1997). We have compared our values with the previous measurements of Metghalchi and Keck (1980), Gibbs and Calcote (1959) and the computations of Göttgens et al. (1992). The present data are about 5 cm/s higher than the results of Metghalchi and Keck (1980) and in good agreement with both the computations of Göttgens et al. (1992) and the older data of Gibbs and Calcote (1959).

4.2 Hexane Combustion

Further ignition energy tests were conducted with hexane-air mixtures. The hexane used was UV grade (99.99%) hexane as supplied by Burdick and Jackson. The test conditions and key results are given in in Table 6 of Appendix A.

4.2.1 Ignition Energy

The results of the ignition trials are shown in Fig. 17 together with previously reported data. The present data covers the range of 1 to 2.2% hexane. As in the case of the propane-air mixtures, our results agree with previous studies at the lowest and highest energy levels tested. The studies of Lewis and von Elbe (1961) and Calcote et al. (1952) obtained the minimum ignition energy for mixtures of about 3.5% hexane. Our measured ignition limit of 1.2% hexane

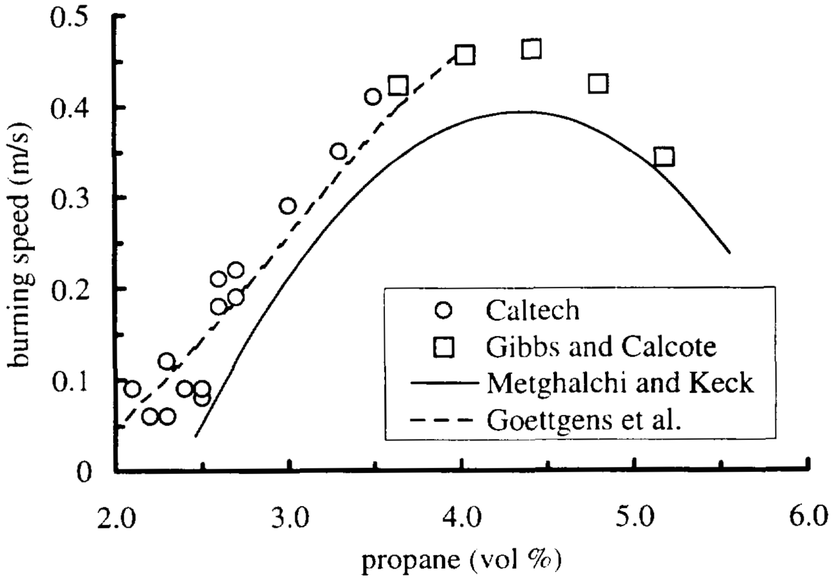

Figure 16: Effective burning speeds estimated from the pressure-time histories for propane-air mixtures, initial pressure 1 atm, initial temperature 295 K. Present measurements (Caltech) compared with previous data (Gibbs and Calcote 1959; Metghalchi and Keck 1980) and computations (Göttgens et al. 1992)

is in agreement with the values between 1.1% and 1.3% propane given by Kuchta (1975) and Coward and Jones (1952).

4.2.2 Combustion Pressure

The pressure-time curves (Fig. 18) are qualitatively similar to those for the propane-air case. The burning speed S_u and the pressure rise coefficient K_g were calculated from the pressure-time profiles by using the techniques discussed by Shepherd et al. (1997). The values are shown in Table 6 of Appendix A. The effect of buoyancy on the near-limit case (1.2% hexane) is not quite as dramatic as in the propane case, but the results have a lot of variability near the limits. This can be observed from the large spread in peak pressure values for the 1.2 and 1.5% cases shown in Fig. 19.

A few data points from the 1180-liter vessel are included on Fig. 19. Two of those experiments were carried out with the mixing fan running during the ignition event; the effect of convection and turbulence within the vessel can be observed to result in slightly higher peak pressure.

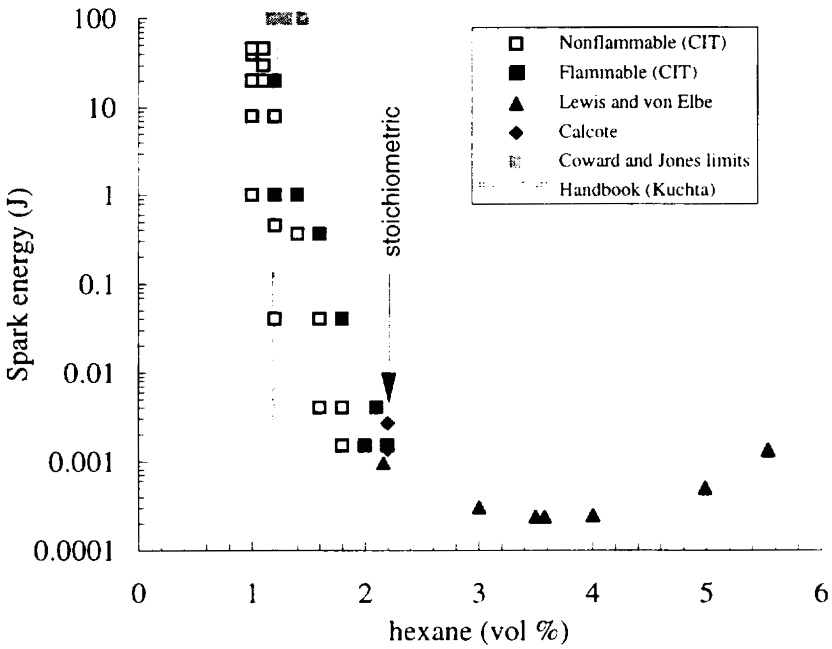

Figure 17: Measured ignition energy for hexane-air mixtures, initial pressure 1 atm, initial temperature 295 K.

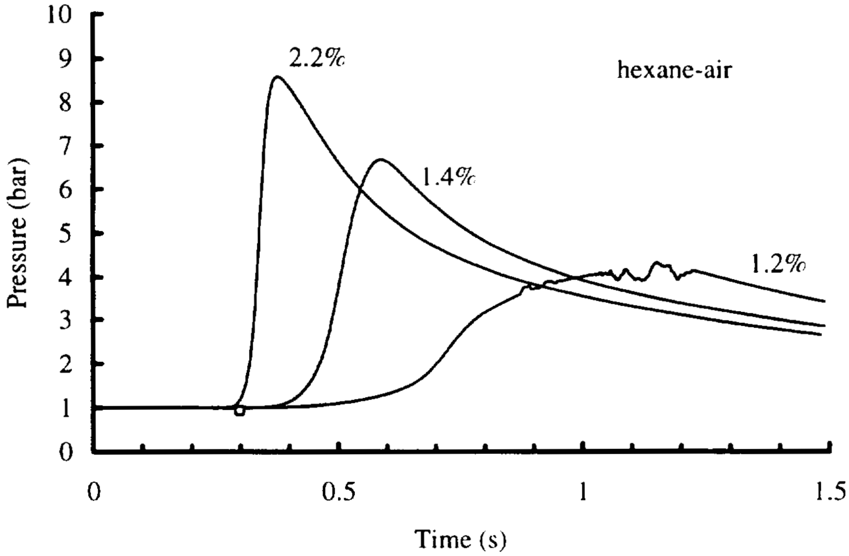

Figure 18: Measured pressure histories for hexane-air combustion, initial pressure 1 atm, initial temperature 295 K.

4.2.3 Flame Speeds

The burning speeds (Fig. 20) for the hexane experiments were also computed by the "t^3" pressure-trace analysis method described by Shepherd et al. (1997). There are no values

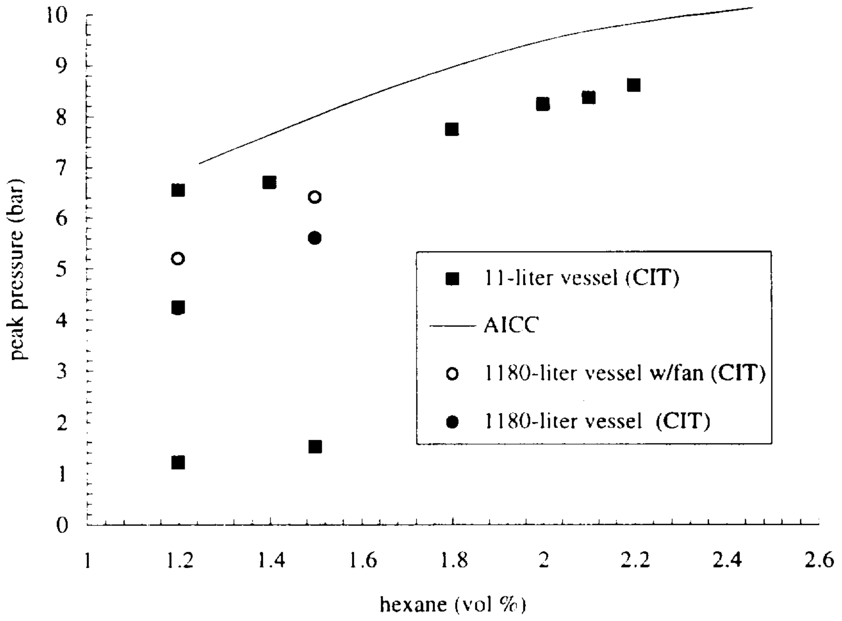

Figure 19: Measured peak pressure for hexane-air mixtures, initial pressure 1 atm, initial temperature 295 K.

for hexane-air burning speeds available in the open literature. However, the range of speeds is similar in magnitude to the range observed for propane, and varies with fuel concentration in a consistent manner. These speeds are comparable to those obtained for similar hydrocarbons like heptane (Gibbs and Calcote 1959; Gerstein et al. 1951).

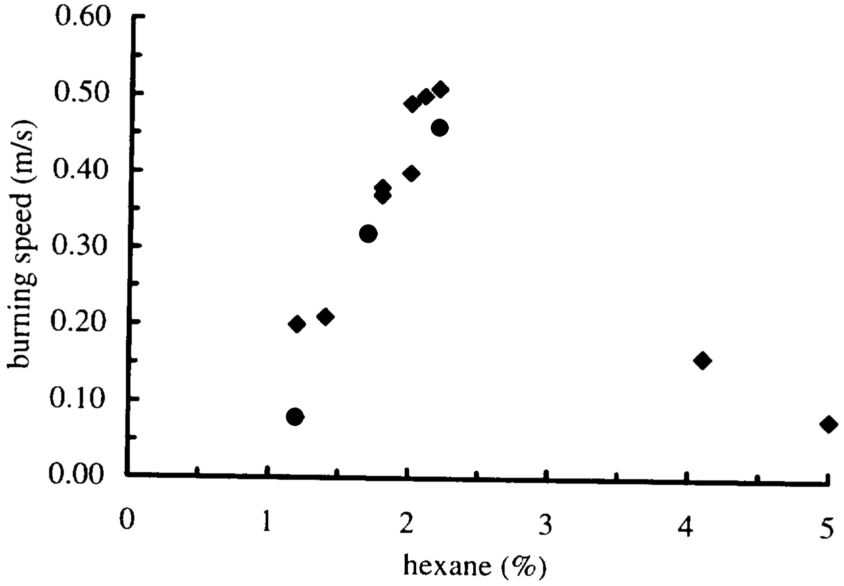

Figure 20: Effective burning speeds estimated from the pressure-time histories for hexane-air mixtures, initial pressure 1 atm, initial temperature 295 K.

5 Jet A Combustion

Following the validation testing with the hexane-air and propane-air mixtures, tests with Jet A were carried out. All these tests were carried out in the 1.84-liter vessel, with the exception of six tests performed in the 1180-liter vessel. The ignition energy was measured at two mass loadings, 3 kg/m^3 and 200 kg/m^3, for temperatures between 25 and 60°C. The initial conditions and key results are given in Tables 7 and 9 of Appendix A.

5.1 Flashpoint Measurements

In order to characterize the Jet A used in this study, we measured the flashpoint with a Tag closed-cup tester using the ASTM D56 (1988) method. These tests were conducted at an ambient pressure of about 99 kPa, and the flashpoints were corrected to an atmospheric pressure of 101.3 kPa as required by the method. Several other fuels, including hardware-store kerosene and single-component hydrocarbons were also measured in order to validate our procedures. The results of these tests and NTSB results on a Jet A sample from Athens, Greece are shown in Table 2.

Ignition energy tests were primarily performed with Jet A fuel obtained from Los Angeles International Airport (LAX). The fuel was stored at 20°C in a closed gas container to minimize the effects of fuel weathering, namely the loss of the low-molecular-weight components in the fuel. A single batch of fuel was used over a period of 3 to 4 months. Preliminary tests were also performed with Jet A fuel from El Monte airport. These tests were numbers 30, 31, and 31b shown in Table 7 of Appendix A. The results of these tests indicate that the El Monte fuel is indistinguishable from the LAX fuel in terms of ignition energy.

The El Monte and LAX fuel flashpoints ranged between 45 and 48°C, essentially identical given the intrinsic variability of the measurement technique. These values can be compared to the minimum flashpoint given in the specification (ASTM D1655 1997) of 38°C (100°F), which is chosen to coincide with the division between flammable and combustible liquids (Benedetti 1996). The NMAB report (NRC 1997) suggests that the processing used to refine and blend Jet A is often shared with the production of home heating oil (No. 2 Fuel Oil) which has a minimum flashpoint of 49°C (120°F). As a consequence, some Jet A flashpoints are similar to or greater than this value (see p. 7 of the NMAB report, NRC 1997). Surveys of the U.S. and world supply of Jet A indicate that the extremes range from flashpoint values of 100°F to 150°F.

The flashpoint is the standard (Benedetti 1996) figure-of-merit to classify the fire and explosion hazard of liquid fuels. For pure substances (Affens 1966) and simple mixtures, e.g., alkanes (Affens and McLaren 1972), the flashpoint can be uniquely related to the flammability limit of the vapor through the vapor pressure dependence on temperature. The flashpoint is found to be correlated closely to the temperature at which the vapor concentration reaches the lower flammability limit value. In terms of the fuel-air mass ratio f, this is

$$f_{LFL} \approx \frac{W_{fuel}}{W_{air}} \frac{P_{\sigma}(T_{flash})}{P_a} \tag{3}$$

Table 2: Flashpoints of different fuels.

Fuel	Flashpoint (°C)	Flashpoint (corrected) (°C)	Description
Jet A (sample 1)	47	48	LAX
Jet A (sample 2)	44	45	LAX
Jet A (sample 3)	47	47	LAX
Jet A	47	48	El Monte
Jet A	–	45	Athens
kerosene	56	57	commercial (1-K)
octane	13	14	technical grade
dodecane	80	80	technical grade

where W_{fuel} is the average molar mass of fuel vapor, about 130 g/mole, W_{air} is the molar mass of air, 29 g/mole, P_σ the vapor pressure of the fuel, and P_a is the ambient pressure.

For complex mixtures like Jet A, the flashpoint test only provides an indication of the relative flammability between different fuels. In the case of Jet A, ignition measurements with spark sources indicate that ignition can be obtained at temperatures that are lower than the flashpoint (Nestor 1967; Ott 1970). This has been ascribed variously as due to the method of ignition, the procedure used in the flashpoint test, lack of adequate mixing between fuel vapor and air, and the difference between upward and downward propagation of flames. It appears that the complex nature of the chemical composition must play a role in this effect since simple mixtures obey the relationship expressed in Eq. 3 (Affens and McLaren 1972).

A test of the relationship between flashpoint and vapor pressure is shown in Fig. 21 using the vapor pressure measurements and flashpoint measurements for Jet A carried out at Caltech (Shepherd et al. 1997). The vapor pressure used in this comparison was obtained at a high mass loading (400 kg/m^3) and is representative of what might be obtained in a flashpoint-type test, but not for a nearly empty fuel tank such as in TWA 800. Shown in this figure are two curves, one representing the fuel-air mass ratio at sea level and the other at 14 kft. The usual rule-of-thumb for flammability is that $f_{LFL} \approx 0.030$ to 0.035; it is plotted as the shaded bar.

Note that the flashpoint of 47°C is slightly higher than the intercept of the standard flammability limit range of $f = .030$ to .035. The reduction in the flashpoint and flammability limit temperature with increasing altitude is clearly illustrated by the 14 kft curve. This simple estimate indicates that at 14 kft, the mixture should be flammable for any temperature higher than about 30°C. This is roughly in accord with the observations discussed in the next section and the previous studies on Jet A (Nestor 1967; Ott 1970).

5.2 Ignition Energy Results

As demonstrated by the results for propane and hexane, the key factor in determining ignition energy is the composition and concentration of fuel vapor. The concentration of fuel vapor in

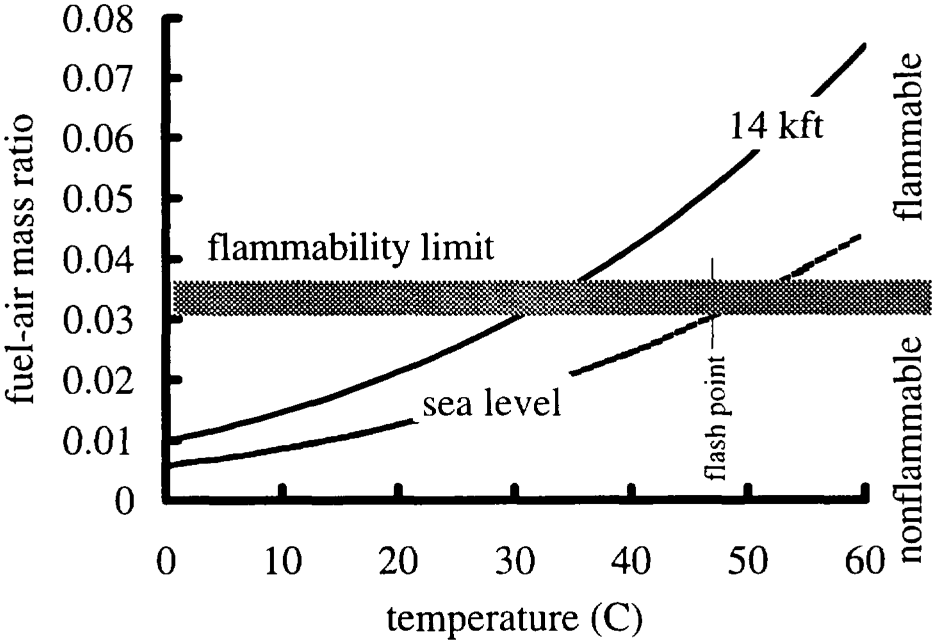

Figure 21: Fuel-air mass ratios estimated from Caltech 3-kg/m^3 vapor pressure measurements using a fuel-vapor molar mass of 130 g/mole.

equilibrium with a liquid fuel is proportional to the fuel vapor pressure $P_{\sigma,fuel}$ and inversely proportional to the ambient pressure P_a

$$X_{fuel} = \frac{P_\sigma(T_{fuel})}{P_a} . \tag{4}$$

The vapor pressure of fuel will in turn (Shepherd et al. 1997) depend primarily on the fuel liquid temperature T_{fuel} and secondarily on the amount of liquid and the history of handling. In previous flammability experiments (Nestor 1967; Ott 1970), the vapor pressure and the fuel concentration were not measured. Instead, with Eq. 4 in mind, the results of these experiments were simply presented as a function of temperature. We follow that practice here in the presentation of the data. The possibility of combined ignition and vapor pressure measurements to present the data in terms of concentration is discussed in the following section. In addition to examining the temperature dependence, we have studied the dependence on fuel loading by testing two situations, one with a 1/4-full tank (200 kg/m^3) and the other with a nearly empty tank (3 kg/m^3).

Quarter-full tank (200 kg/m^3) The ignition energy (Fig. 22) was measured for temperatures between 30°C and 60°C at a pressure of 0.585 bar and a mass-to-volume ratio of 200 kg/m^3. The pressure corresponded to the ambient pressure at 14 kft, and the mass-to-volume ratio corresponded to a tank 1/4-full of liquid, similar to previous experiments. In the 1.8-liter vessel, this was about 450 ml of liquid fuel, which formed a layer about 3 mm deep on the bottom of the vessel. Below 30°C, the ullage mixture cannot be ignited even with spark energies of up to 100 J. The ignition energy decreases rapidly as the temperature increases. Above 50°C, the mixture can be ignited with spark energies on the order of 1 to 10 mJ. Typical pressure histories for tests at different temperatures are shown in Fig. 24.

Nearly empty tank (3 kg/m^3) One significant factor for TWA 800 was the very small mass of fuel in the CWT. At low mass-to-volume ratios, Jet A vapor pressure decreases due to depletion of the more volatile components in the fuel (Shepherd et al. 1997). This results in leaner fuel-air mixtures in the ullage and possibly, higher ignition energies. In order to examine this possibility, ignition energy (Fig. 23) was also measured for a mass-to-volume ratio of 3 kg/m^3 and temperatures between 30°C and 60°C at a pressure of 0.585 bar. This condition corresponds to that estimated for TWA 800 at the explosion altitude of 14 kft. In the 1.8-liter vessel, this was about 7 ml of liquid fuel, which formed a layer that just wetted the bottom of the vessel.

The results of our ignition energy tests with this mixture are shown in Fig. 23, and indicate a dependence on temperature very similar to the 200 kg/m^3 case (Fig. 22). The expected mass-loading effect is not obvious. Below 30°C, the ullage mixture cannot be ignited even with spark energies of up to 100 J. The ignition energy decreases rapidly as the temperature increases. Above 50°C, the mixture can be ignited with spark energies on the order of 1 to 10 mJ. Typical pressure histories for tests at different temperatures are shown in Fig. 24.

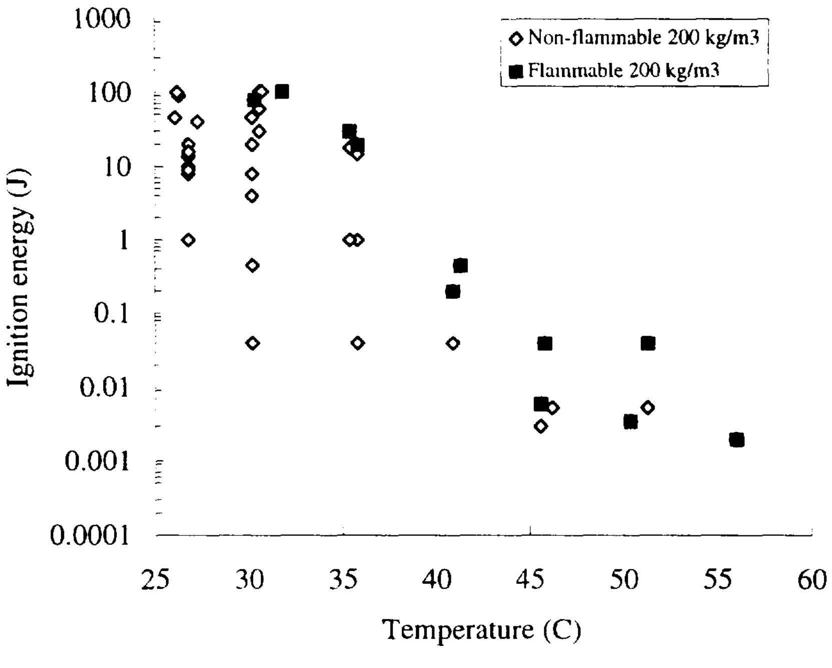

Figure 22: Measured ignition energy for Jet A vapor-air mixtures, mass loading of 200 kg/m^3 and an initial pressure 0.585 bar.

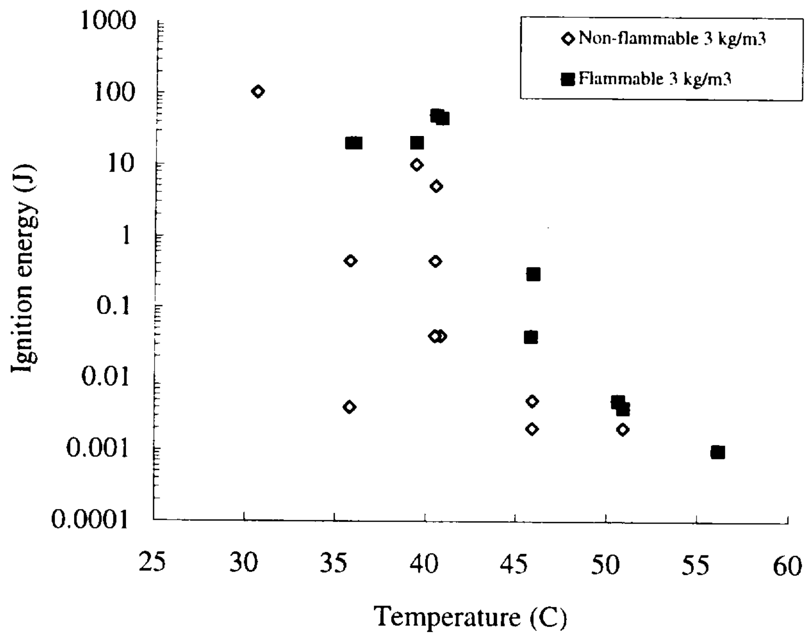

Figure 23: Measured ignition energy for Jet A vapor-air mixtures, mass loading of 3 kg/m^3 and an initial pressure 0.585 bar.

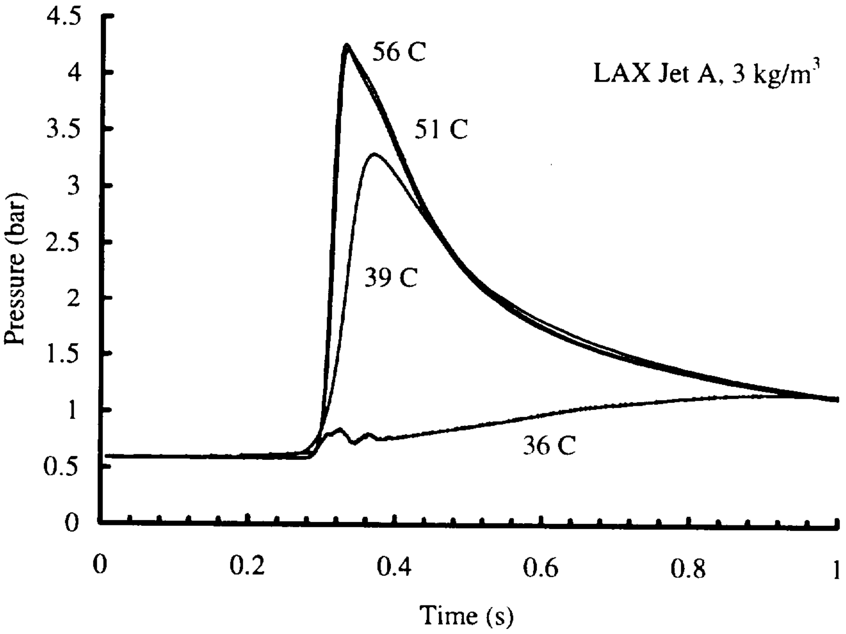

Figure 24: Pressure histories for Jet A-air mixtures (3 kg/m^3) in the 1.8-liter vessel.

5.3 Peak Combustion Pressure

The peak pressure rise data (maximum measured pressure minus the initial pressure) for the current Jet A combustion tests are shown in Fig. 26. The values of peak pressure rise ranged