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A Photographic Study of Plasma Ignition Systems

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ABSTRACT

A photographic study was conducted using an optical-access compression-expansion machine in order to reveal the mechanism of ignition and flame propagation initiated by plasma igniters. The tests included a jet igniter with inert cavity liner (quartz), a jet igniter with reactive cavity liner (paraffin), and a J-gap spark plug. Schlieren cinematographic records were obtained for each condition along with concomitant pressure traces.

Basic features of ignition and combustion at lean limit were determined for each igniter. The spark plug permited lean operation down to an equivalence ratio of 0.7, after which mis-ignition occurred. Jet igniters provided an extension of lean limit to 0.5 in equivalence ratio. For jet igniters, these limits were imposed by either extinction of the flame or too slow burning rate, rather than by misfire.

OPERATION OF HOMOGENEOUS charge engines under dilute or lean conditions mandated the development of enhanced ignition sources capable of initiating stable combustion. A great variety of systems for this purpose were proposed and tested as outlined by Dale and Oppenheim (1)*. The successful use of plasma ignition in this connection was demonstrated by Weinberg, et al., at Imperial College, London (2,3,4,5), Dale, Smy and Clements at the Universities of Alberta and Victoria (5,6), Asik and Anderson at Ford Research (7), Dabora at the University of Connecticut (8,9), Maly, Ziegler and Wagner, at the University of Stuttgart (10,11), and Oppenheim and his associates at the University of California, Berkeley (12,13,14).

In a previous study, we investigated the performance of a number of plasma ignition systems in a CFR engine (14). We found then that, for moderately lean air-fuel mixtures with MBT timing, the power, emissions and efficiency were independent of the type of igniter. However, as the fuel content in the charge was diminished, engine operation with a conventional spark plug became limited by the onset of misfire. Plasma jet igniters on the other hand allowed lean operation to be extended past the misfire limit of the spark plug down to an equivalence ratio of 0.6. Furthermore, the nature of the lean limit for the jet igniter was distinctly different than that of the spark plug. As the relative air content was augmented, the power and efficiency of the plasma jet ignited engine decreased monotonically, approaching zero at an equivalence ratio of 0.53. This behavior led us to conclude that the lean limitation of the jet igniter was due to slow burn or extinction rather than to mis-ignition.

In addition to the nature of the lean limitation, there was a substantial difference in the ignition delay period at lean air-fuel ratios with MBT timing. We attributed this to the fundamental difference between conventional ignition systems and plasma jet ignition: the ability of the plasma jet to penetrate into the fresh mixture and impregnate a sizable portion of it with active ignition sources. Combustion then could occur very rapidly within this region, leading to a reduction in ignition delay.

The present study was conducted to attain a better understanding of the mechanism of ignition and lean limit behavior using plasma igniters. This was achieved by means of schlieren cimematography in an optical-access compression-expansion machine. The advantage of this type of apparatus is that it affords an unobstructed optical insight into the salient features of the flowfield in the direction piston motion. At the same time,

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*Numbers in parentheses designate references at end of paper.

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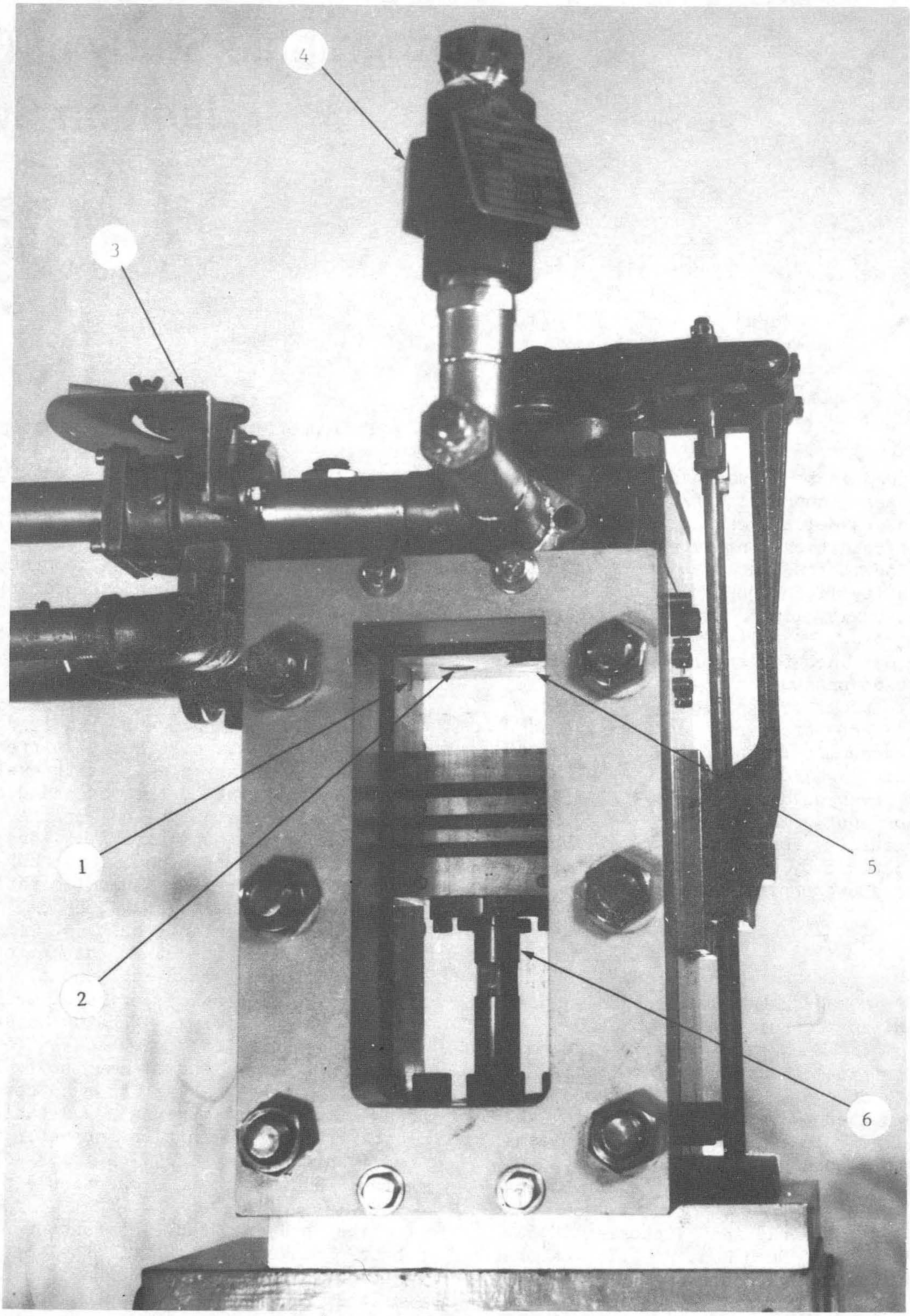

Fig. 1 - Test section of the optical-access compression-expansion machine: 1 - igniter, 2 - pressure transducer, 3 - intake throttle, 4 - safety disk, 5 - intake valve, 6 - piston/rod assem ly.

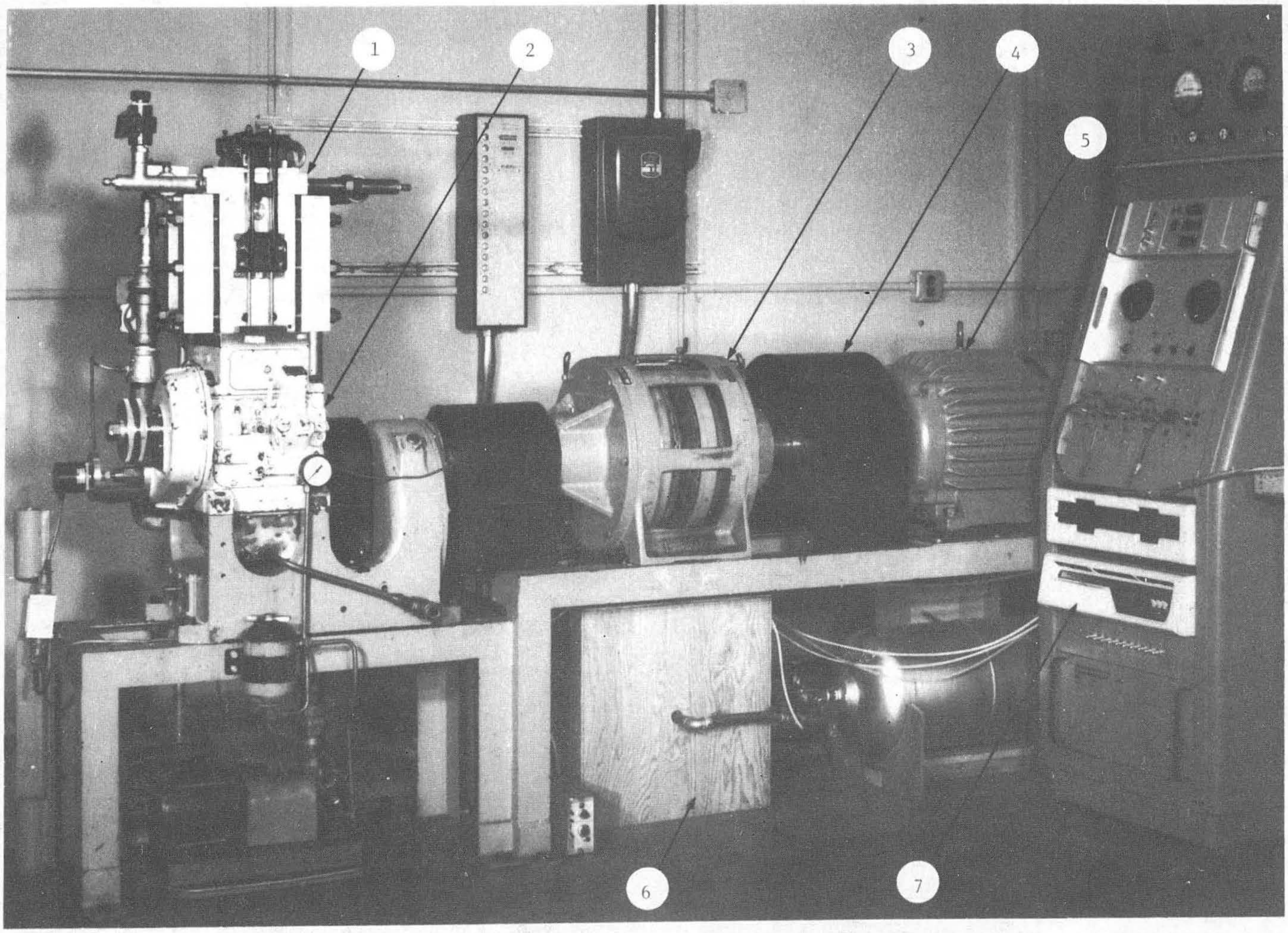

Fig. 2 - Optical-access compression- expansion machine configuration: 1 - test section, 2 - CLR crank-case, 3 - electromagnetic clutch/brake, 6 - premixed propane/air storage, 7 - computer/control electronics.

conventional overhead valve configuration can be retained, along with the concomitant effect on fluid mechanics in the combustion chamber. Disadvantages of this apparatus consist of the effect of the square cross section on the flowfield and single-cycle motored operation -- leading to combustion without the presence of exhaust residuals and greater heat losses from the flame to the cold walls of the combustion chamber.

In light of these differences between the optical-access apparatus and a conventional engine, performance of the plasma ignition systems was recorded by schlieren photography and pressure histories, rather than mass burning rate and concomitant engine performance parameters. For this type of information the reader may consult our previous publication (14) where the performance of various ignition systems has been quantified in a CFR engine.

PROCEDURE

Schlieren cinematographic records were obtained of the ignition process in a square piston optical-access machine. The test section of the apparatus is displayed in Figure 1. The piston is 86mm on a side and runs unlubricated between two stainless steel walls and two quartz walls. Compression sealing is provided by three graphite ring assemblies mounted in the piston. The piston area and stroke, as well as clearance height, are identical to those of a CFR engine. Overhead intake and exhaust valves, driven by a camshaft, are employed. Ports are provided for a piezoelectric pressure transducer, as well as for the plasma igniters.

The test cell was mounted on the base of a

CLR engine, as depicted in Fig. 2*, furnishing the crank and connecting rod for piston motion, as well as cams for operation of the valves. Coupled to the CLR is an electromagnetic clutch/brake unit allowing the crankshaft to be driven by a synchronous motor and flywheel. Data aquisition and apparatus control were accomplished by means of a DEC PDP 11/03 minicomputer and a programmable digital timer. Synchronization of the crankshaft with control electronics was achieved by the use of an optical shaft encoder providing information on piston position at intervals of 1/2 crank angle degree.

The apparatus was operated under conditions similar to those of the CFR engine used in our previous study (14). The compression ratio and speed were fixed at 8:1 and 1800 RPM respectively, while the inlet manifold was held at atmospheric pressure. Spark timing was set according to the MBT conditions established in the CFR engine.

Since the major purpose of the apparatus was to elucidate the mechanism of ignition by cinematography, it was operated in a pulsed mode. When the clutch was engaged, the motor/flywheel accelerated the crankshaft to 1800 RPM in three revolutions. Two additional revolutions were allowed to pass before firing the igniter and taking data. The clutch was released and the brake activated, bringing the crankshaft to rest after approximately ten revolutions. Premixed propane/air was allowed to flow through the combustion chamber prior to operation, while the intake stream was drawn from a neoprene bladder enclosed in a pressure vessel. Use of the bladder ensured that the mixture pressure was held constant regardless of the amount withdrawn during the test.

High speed movies were taken using a "Z" configuration for schlieren photography, as shown in Fig. 3. Light from a Xenon arc lamp was collimated by a spherical mirror and passed through the test cell. The refracted light was re-focused by a second mirror through a circular schlieren aperture and imaged onto the film plane of a high speed movie camera. Photographs were taken at 10,500 frames per second with a shutter speed of 4 microseconds per exposure. For conditions used in the present study, this framing rate corresponded to approximately one frame per crank angle degree.

Cylinder pressure was recorded simultaneously with the movies at intervals of 1/2 crank angle degree. The piezoelectric transducer and charge amplifier signal was, for this purpose, digitized by a 12-bit analog to digital converter and stored on a floppy disk.

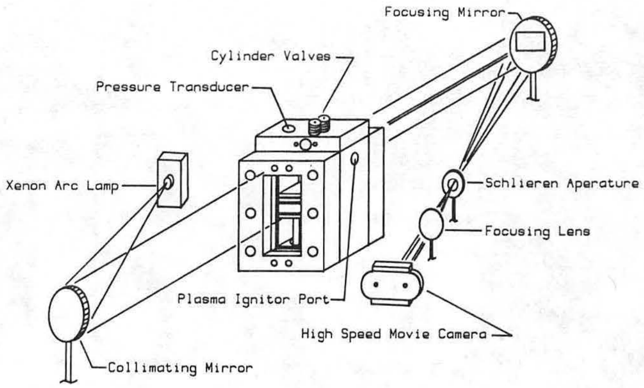

Fig. 3 - Instrumentation and optical arrangement for pressure measurement and schlieren cinematography.

IGNITERS

Tests were conducted using two types of igniters. The first, providing a pulsed jet of plasma, was tested with an inert (quartz) as well as reactive (paraffin) cavity liner (Fig. 4). The quartz-lined plasma jet igniter was constructed according to the optimum geometric configuration established by our previous study. Cavity length and diameter were fixed at 3mm and a non-restricting (3mm) orifice was used. In tests where a reactive plasma medium was required, the quartz liner was replaced by a paraffin sleeve of the same geometry. The electrical pulse discharge for both cases was a slightly underdamped RLC half-wave, 100 microseconds in duration, with a total stored energy of 3 Joules. A schematic diagram of the discharge circuit used, as well as voltage, current and power waveforms, may be found in our previous publication (14).

The second type of igniter was a J-gap spark plug. The gap was set at 1.6mm to allow formation of a large ignition kernel and reduce losses of heat and radicals to the electrodes. The latter were extended 5mm into the combustion chamber to minimize any heat losses from the flame kernel to the wall. In order to provide an optimum spark, a 120mJ capacitive discharge was used. This configuration was designed to provide a "conventional" spark discharge at its best performance, against which the plasma jet igniter would be compared.

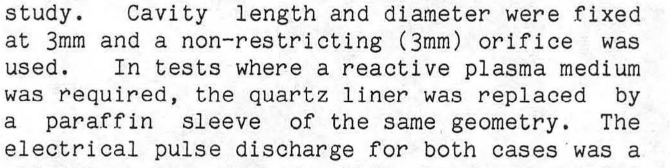

Fig. 4 - Design of the plasma jet igniter.

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*The authors wish to express their appreciation to Chevron Research Company for the donation of this engine and, in particular, to Dr. H. Newhall who made this possible.

RESULTS

Schlieren photographs of combustion initiated by spark plug and plasma jet igniter are shown in Plates 1 and 2 for a stoichiometric propane-air mixture at MBT timing. Concomitant pressure histories are displayed on the accompanying diagram, the motoring and firing pressures being denoted by Pm and Pf respectively. The difference between the two curves at any time provides a measure of the exothermic energy evolved in the combustion process. The photographic sequences depict the flame initiation and travel over a 50 degree interval immediately following the igniter discharge. From these records it became apparent that the plasma jet initiated combustion much more rapidly than the standard spark. This was due to entrainment of a portion of the mixture into the turbulent plasma plume. The mixture thus inducted became seeded with ignition sources and therefore reacted quite rapidly. As a consequence, in the case of jet ignition, the flame propagated through half of the chamber in 20 crank angle degrees while in the case of spark ignition as much as 27 degrees was required for this purpose. Similarly, the combustion process was faster with the use of the plasma jet, requiring only 25 degrees to complete combustion from the point of half flame propagation, while the corresponding time interval for the spark plug was 30 crank angle degrees.

Similar results were obtained at 0.7 equivalence ratio. Shown in Plates 3 and 4 are the photographic sequences and concomitant pressure transducer records for the 70 crank angle degrees following ignition. At this mixture strength significant differences appear between the two igniter systems. The time required for the spark-ignited flame to propagate to the half way point increased to 36 degrees while that for a plasma jet ignited flame was 25 degrees. Correspondingly, the time for completion of combustion from the half way point was 35 degrees for the spark plug, and 28 degrees for the jet igniter.

As apparent from the above, the most prominent effect of plasma jet ignition is in reducing ignition delay. Plate 5 provides a graphic display of the plasma jet and spark plug flame kernel behavior during the ignition delay period (1-10 crank angle degrees after discharge, 0.7 equivalence ratio, MBT timing). The spark plug initiated a flame kernel in the electrode gap which slowly grew and developed into a flame front. The plasma jet created a much larger intial flame kernel by the mechanism of turbulent entrainment. As a consequence, the spark-ignited flame kernel was developing for ten crank angle degrees before it achieved a volume comparable to that attained by the plasma jet after only 2 degrees of development time.

The lean limit for spark ignition occurred at an equivalence ratio of 0.6. As displayed in Plate 6, the flame kernel formed in the electrode region was too weak to produce a self-sustained flame front. The accompanying pressure trace is devoid of any exothermic effect. This is the condition of classical misfire, which could be referred to, more appropriately, as the mis-ignition limit. On the other hand, the plasma jet ignited flame was not subjected to this limitation, as displayed in Plate 7, demonstrating that a plasma plume could, at the same equivalence ratio, initiate a flame which was able to burn the charge completely.

The lean limitation of the jet igniter was encountered at an equivalence ratio of 0.5 (vid. Plate 8). The plume was formed and began to develop but was destroyed before the evolution of a significant amount of exothermic energy. In our previous studies (14), the leanest equivalence ratio at which a significant amount of energy evolution was detected using a jet igniter was 0.53, in essential agreement with the observations illustrated by Plate 8.

A question often arises as to what effect the high energy level of the jet igniter would have if it were deposited in a conventional spark gap. This question has not be settled because of the onset of pre-ignition when using high energy sparks with a J-gap igniter in an engine. In our previous study we attempted to address this question by utilizing a high energy surface discharge igniter, providing a configuration similar to that of the spark gap but devoid of the pre-ignition problem. We found that the high energy surface discharge behaved similarly to the standard spark, permitting only a modest extension of lean operation before misfire. These results were not surprising as the initial flame is established in close proximity to the cold wall of the combustion chamber when using this type of igniter. In the present study we address this question directly since operation of the optical-access compression-expansion machine in a single firing mode permited the use of a high energy discharge in a J-gap spark plug without the problem of pre-ignition. Plate 9 presents the results when the energy in the gap was boosted to 3 Joules. A mixture at 0.6 equivalence ratio was ignited by the high energy spark, just as in the case of the jet igniter. At leaner mixtures however, the high energy spark plug was impaired by the lean limit in a fashion similar to the inert cavity plasma jet igniter.

These results demonstrate the benefits one can derive for ignition by changing only one parameter: the discharge energy. As demonstrated by Weinberg and his associates (3), additional benefits can be obtained by altering the chemical kinetic and fluid dynamic features of ignition through the use of an appropriate feedstock to form the plasma. Towards this end, following the suggestion of Weinberg, the quartz cavity liner of the jet igniter was replaced by a paraffin sleeve.

During the electrical discharge the long chain hydrocarbon, typically $C_{36}H_{74}$, was sublimated from the cavity wall, dissociated, and ionized to form a plasma plume rich in hydrocarbon derived radicals.

Plates 10 and 11 are photographic sequences recorded with the paraffin-lined jet igniter at equivalence ratios of 0.7 and 0.6, respectively. The ignition process was quite similar to that of the quartz lined plasma cavity (vid. Plates 10 and 11), however the initial volume of the plume was substantially larger -- a direct result of the addition of the feedstock. At 0.5 equivalence ratio -- a condition at which neither the high energy spark plug nor the quartz lined jet igniter could ensure complete combustion -- the paraffin-lined jet igniter was capable of igniting and inflaming the combustion chamber in its entirety (Plate 12), although most of the burning took place in the course of the expansion stroke.

The capability of the paraffin plasma jet to ignite mixtures at 0.5 equivalence ratio prompted us to observe the ignition process with this igniter at an equivalence ratio of 0.4. The results are displayed in Plate 13. Both the photographic records and the pressure trace demonstrate that the igniter is able to initiate combustion, but the flame was extinguished in the turbulent environment near top dead center.

It is of interest to note that extremely small quantities of paraffin were actually consumed in each discharge of the igniter. Figure 5 shows the paraffin mass consumption rate of the igniter when fired repeatedly at a stored energy of 3 Joules. Since all of our tests were conducted with less than 50 firings of the igniter, the rate of paraffin erosion was in the range of 10 to 100 micrograms per firing. This quantity is three orders of magnitude less than the 20 milligrams of fuel contained in the charge at an equivalence ratio of 0.6. However, the mass of paraffin consumed is of the same order as the mass of gas contained in the cavity at the time of discharge. The net effect of paraffin addition is then twofold in that: 1 - the chemical activity of the jet is enhanced by the presence of the hydrocarbon feedstock, 2 - the mass of the plume is increased, leading to formation of a larger ignition kernel than that which is obtainable by utilization of the in-cavity gases alone.

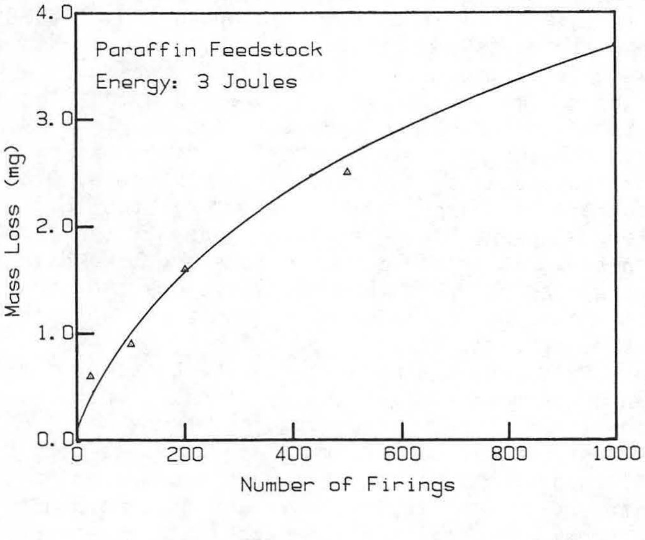

Fig. 5 - Mass consumption rate of paraffin feedstock by the plasma jet igniter at 3 Joules stored energy.

CONCLUSIONS

High speed schlieren cinematography, combined with pressure transducer records, revealed some interesting features of the basic mechanism of plasma jet ignition. Specifically:

(1) The primary effect of the plasma jet is in providing a large plume into which the combustible mixture is entrained, becoming thereby seeded with a multitude of ignition sources.

(2) As a consequence, the induction period of plasma jet ignition is significantly shorter than that of conventional spark ignition.

(3) The lean operating limit of an engine may be extended to 0.6 in equivalence ratio with the use of an inert cavity plasma jet igniter, and although at lower equivalence ratios the mixture can be ignited, it does not promote complete combustion of the charge.

(4) The high energy spark plug is capable of furnishing the same advantages as the plasma jet igniter; however, this type of igniter cannot be used in an engine because of the pre-ignition problem.

(5) A plasma jet igniter, exploiting a heavy hydrocarbon (paraffin) feedstock, was instrumental in extending the lean operating limit over that of the inert cavity jet igniter. Measurable levels of exothermicity were obtained even at an equivalence ratio of 0.4.

(6) The specific nature of the lean limitation for each of the igniters was revealed. The J-gap spark plug was limited by mis-ignition. The plasma jet is limited either by extinction of the flame or by inadequate time for the completion of combustion.

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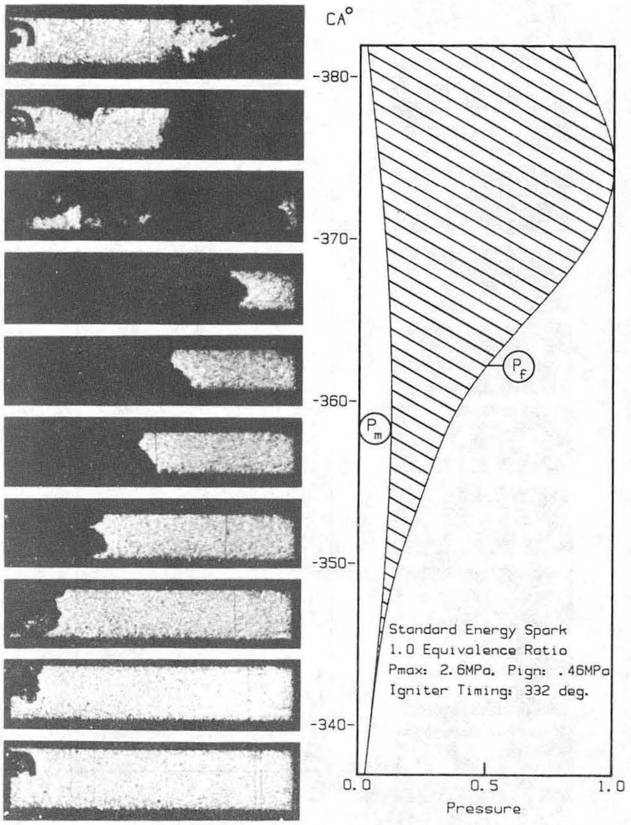

Plate 1 - Photographic sequence and pressure traces for standard spark plug (Ø = 1).

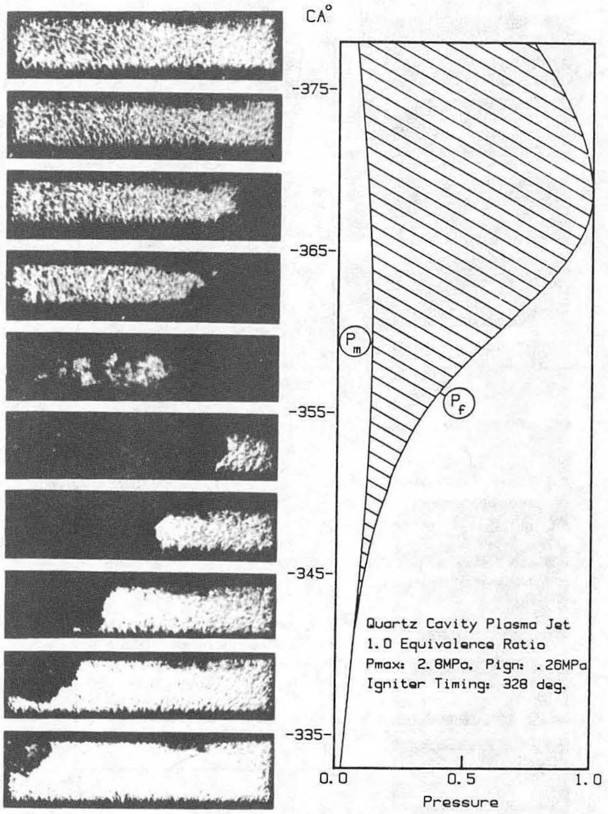

Plate 2 - Photographic sequence and pressure traces for quartz-lined jet igniter (Ø = 1).

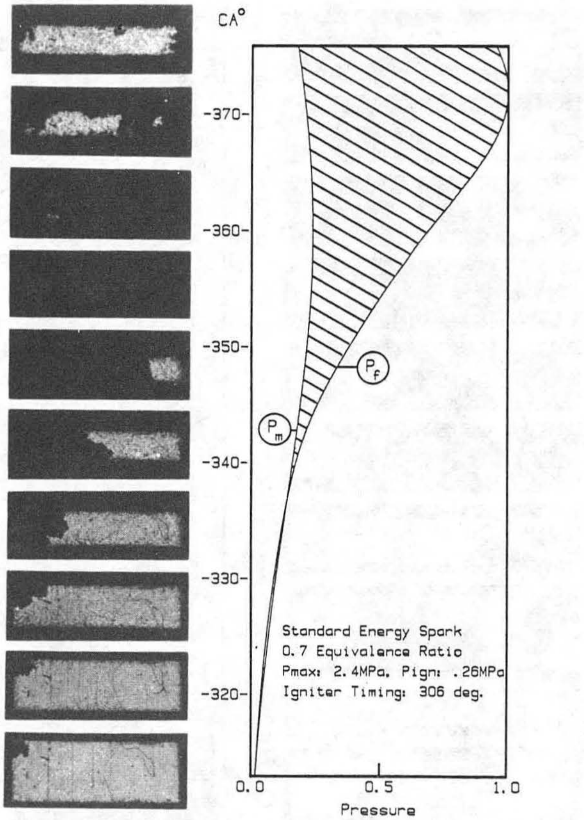

Plate 3 - Photographic sequence and pressure traces for standard spark plug (Ø = 0.7).

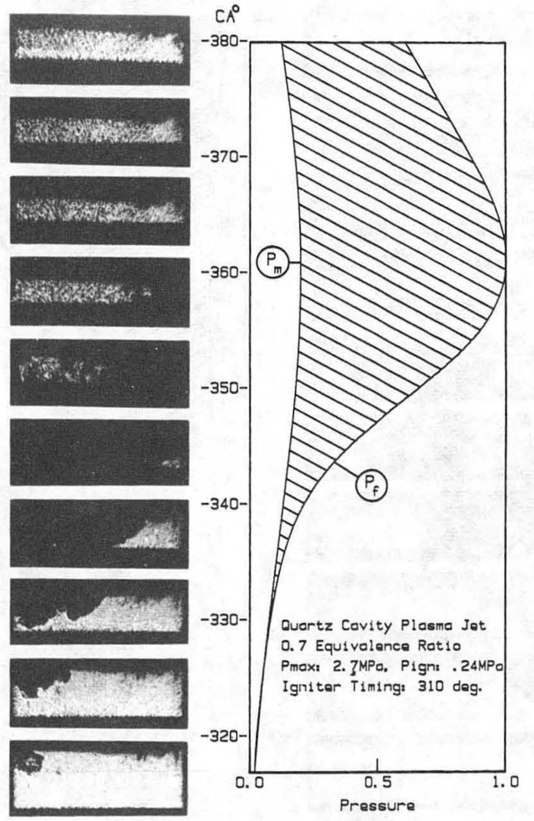

Plate 4 - Photographic sequence and pressure traces for quartz-lined jet igniter (Ø = 0.7).

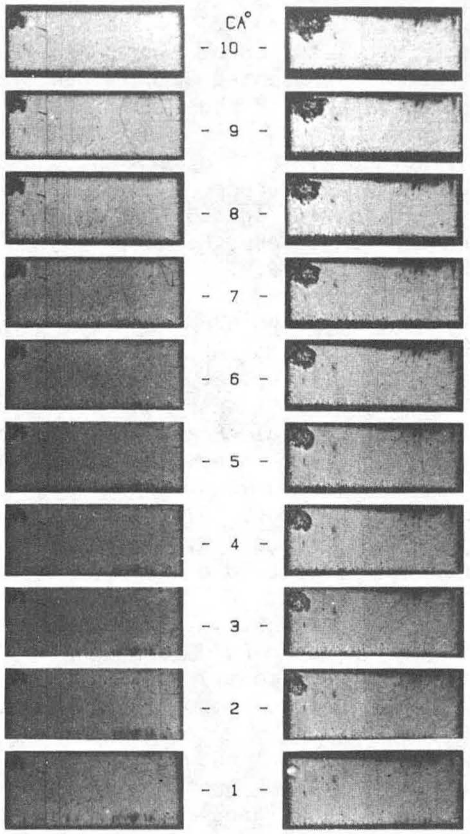

Plate 5 - Comparison of early flame development for spark plug and jet igniter (Ø = 0.7).

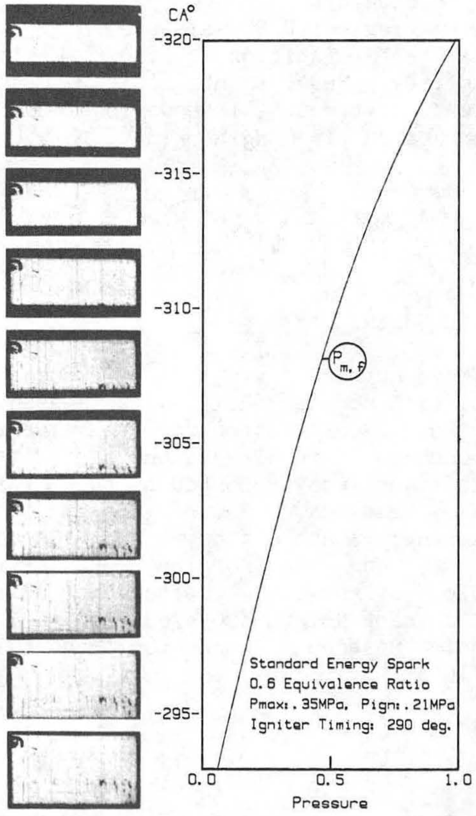

Plate 6 - Photographic sequence and pressure traces for standard spark plug (Ø = 0.6).

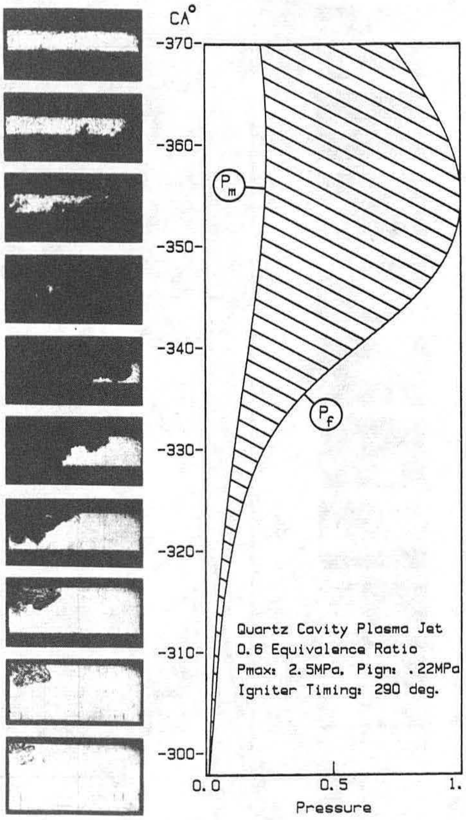

Plate 7 - Photographic sequence and pressure traces for quartz-lined jet igniter (Ø = 0.6).

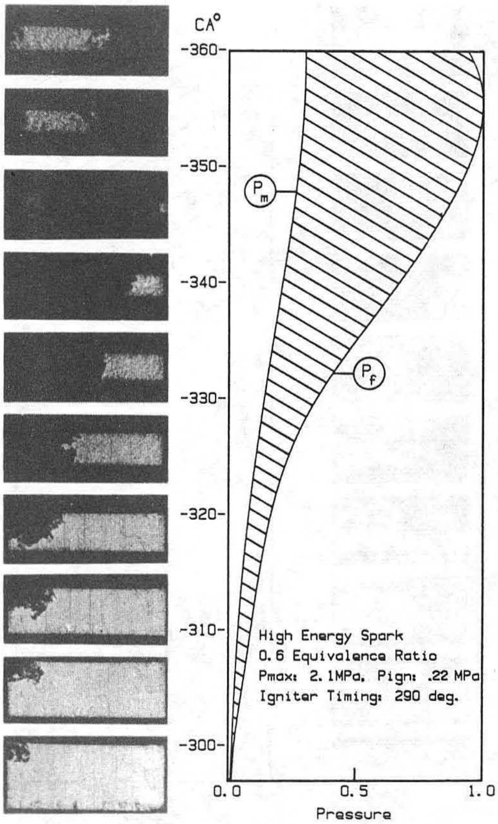

Plate 9 - Photographic sequence and pressure traces for high energy spark plug (Ø = 0.6).

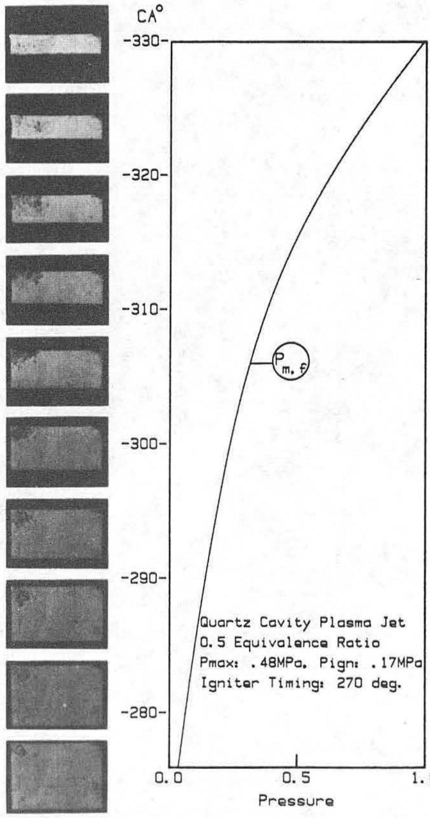

Plate 8 - Photographic sequence and pressure traces for quartz-lined jet igniter (Ø = 0.5).

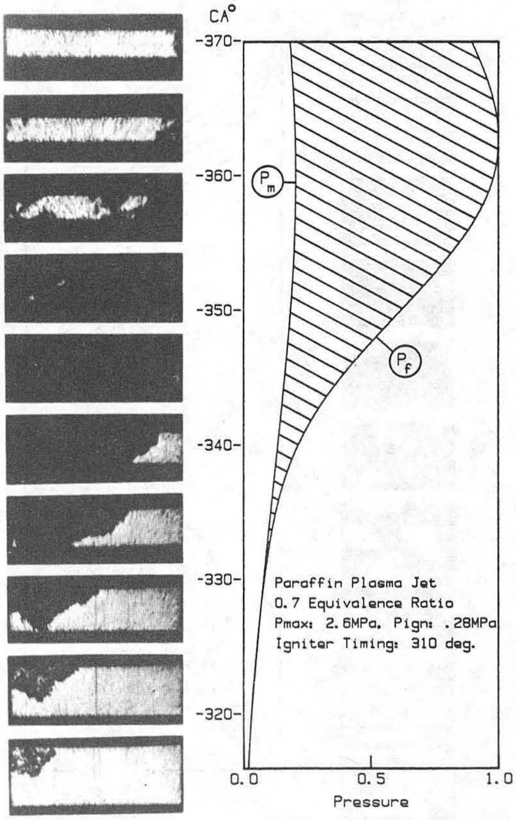

Plate 10 - Paraffin-lined plasma jet igniter records for Ø = 0.7.

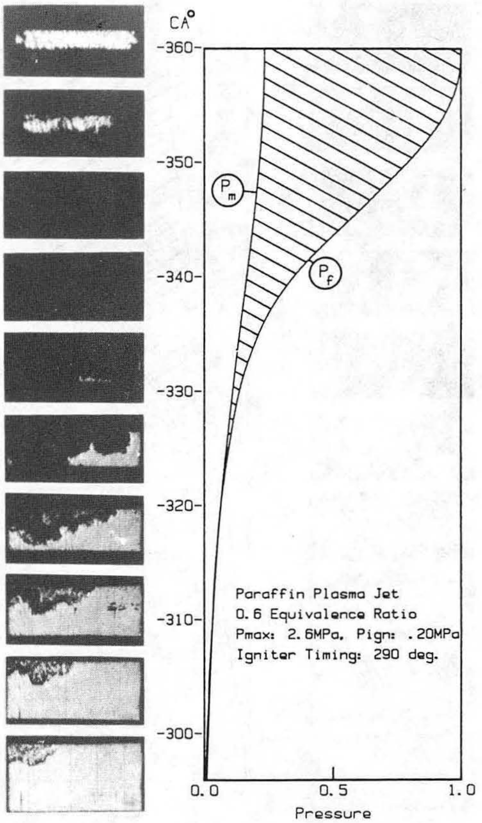

Plate 11 - Paraffin-lined plasma jet igniter records for Ø = 0.6.

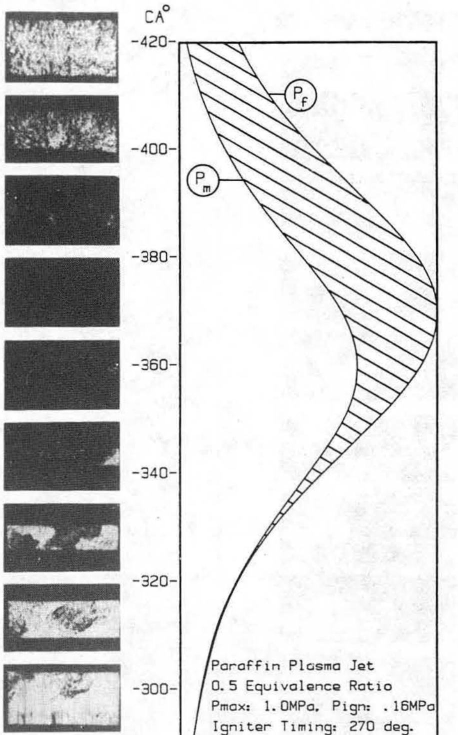

Plate 12 - Paraffin-lined plasma jet igniter records for Ø = 0.5.

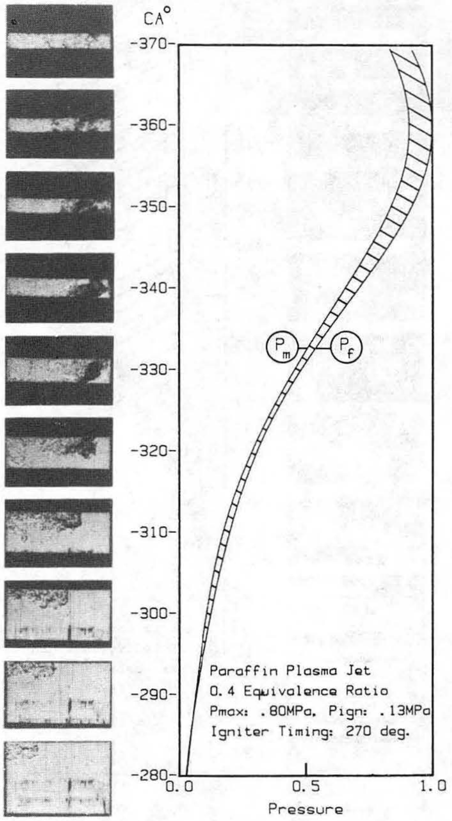

Plate 13 - Paraffin-lined plasma jet igniter records for Ø = 0.5.

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