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Technical Report

Characterization of a Heavy-Duty Diesel Engine Modified for Operation on Neat Methanol

By

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Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air, Noise and Radiation
U. S. Environmental Protection Agency

I. Introduction

Because of the increased interest in methanol as a motor vehicle fuel, EPA's Office of Mobile Source Air Pollution Control (OMSAPC) has initiated a vehicle and engine testing program to characterize the emissions and performance of the most likely methanol applications. In one study an International Harvester DT-466B heavy-duty diesel engine was modified and subsequently tested on diesel fuel and on neat methanol. This report describes the conductance and results of the study.

II. Background

The growing dependence of many countries on unstable supplies of imported petroleum has created a need to evaluate the use of alternative fuels. One of the most promising and extensively studied alternate fuels is methanol.

Methanol is well suited for use in the fuel-inducted, spark-ignition (SI) engine and much research and attention has been concentrated in this area. Methanol has been generally disregarded for use in the fuel-injected, compression-ignition (CI) engine, because its low cetane properties make it difficult to compression-ignite. However, if an ignition source is provided, methanol's combustion properties are such that it can be used in the traditional CI engine and potentially result in environmental benefits when compared to diesel fuel or other alternate fuels.

Methanol's high octane rating allows for the higher compression ratios, hence higher thermal efficiencies, of SI engines. Methanol use in the CI engine would take advantage of the inherently better efficiency of unthrottled operation. Methanol's ability to burn at lower flame temperatures contribute to better efficiency and lower NOx emissions. The organic emissions from methanol combustion are primarily unburned fuel and aldehydes, which are controllable with standard oxidation catalysts. Since methanol fuel contains no catalyst-poisoning heavy metal or sulfur compounds, unburned fuel and organic emissions may perhaps be controlled with a base metal catalyst instead of the more expensive noble metal catalysts currently in use. Methanol also burns free of carbonaceous particulates, a major emission problem of diesel engines today. In short, methanol use offers the potential to achieve comparable performance and engine efficiency as diesel fuel with significantly lower exhaust gas and particulate emissions.

The most common methods to accomplish ignition of methanol in a diesel type engine, so far, have been the use of cetane improving additives to the fuel,[1,2,3,4] diesel-fuel pilot-injection systems,[5,6,7] or an electrical ignition system.[8,9,10,11,12] The use of cetane improvers has resulted in acceptable performance but to date has proven otherwise undesirable because of increased emissions, cost, and safety concerns. Diesel-fuel pilot-injection systems have also been demonstrated with acceptable performance and emissions, but the additional cost and complexity of a second injection system is a major drawback to this type of system.

Electrical ignition sources have been used successfully in several test projects to achieve methanol combustion in CI engines. In a project conducted in Brazil,[10] glow plugs were used in a small diesel engine to burn methanol, resulting in comparable performance and emissions as diesel fuel. Spark ignition systems have also been used successfully to assist combustion of alcohol fuels in standard diesel engines as well as in multiple fuel engines such as the MAN-FM[11] and White/Texaco stratified charge engine.[12]

Because of the demonstrated success and feasibility of the test projects which utilized electrical ignition, OMSAPC investigated this method to obtain methanol combustion in a common, domestic diesel engine. In addition, three combustion concepts represented by the Brazil project and the MAN-FM engines were investigated. The combustion concepts and test program are discussed next.

III. Test Program

A. Engine Concepts Investigated

This project centered on the investigation of three combustion concepts for the use of neat methanol in a CI engine. These concepts were:

1. Glow Plug "Torch" Ignition - This configuration consisted of the addition of a glow plug directly into the combustion chamber, and modification of the injector nozzle to concentrate the fuel spray near the glow plug. The glow plug provides a source of ignition as the concentrated spray is introduced. This system is based on the Brazil project and approximates the White-TCCS lean-burn, stratified charge combustion.

2. Spark Plug "Torch" Ignition - This configuration is similar to the glow plug ignition concept except a spark is used to initiate combustion. The fuel spray is concentrated near the ignition source, and, thus also approximates the White-TCCS stratified charge combustion.

3. Fuel Deposition, Spark Ignition - This concept is based on the MAN-FM process where fuel is deposited on the piston bowl, combustion is initiated with a spark and sustained by continued evaporation of the fuel into the hot rotating air. The heat for

vaporization is theoretically supplied by flame radiation, therefore, the rate of mixture formation is proportional to the intensity of combustion. This functional segregation of the fuel and air provides the stratified charge necessary for combustion in an unthrottled engine.

With these combustion concepts and the required modifications for engine optimization in mind, a set of criteria were developed to select the best engine possible for testing. The engine selection is discussed next.

B. Engine Selection

This engine was chosen after a careful review of the technical specifications and design parameters of all domestic heavy-duty diesel engines certified for 1981. The following criteria were used to select the engine.

The engine should be/have:

1. A small heavy-duty engine (150-220 rated HP).

2. Adequate space in the head and combustion chamber for the addition of a glow plug or spark plug and sleeve in each cylinder.

3. The capacity for a two-fold increase in fuel delivery volume since methanol's energy density is roughly half that of diesel fuel.

4. Direct fuel injected with easily controlled injection parameters such as timing, opening pressure, spray pattern, and spray direction.

5. A high swirl, mexican hat type piston.

6. As few engine cylinders as possible to lessen the modification effort.

The turbocharged IHC DT-466B was one of four engines which best met the above criteria for selection for the project. International Harvester generously agreed to donate the test engine to the project, and engine selection was complete.

IV. Test Operation and Results

A. Diesel Baseline

The engine was first tested, as received, to determine baseline performance and emissions levels on diesel fuel for comparison to operation on neat methanol. The following test sequence was observed:

1. Two fine-fuel maps - These consisted of measurements of output power, fuel flow, and air flow over a 90 point speed-load matrix, i.e., ten power points from 10-100 percent load at each speed increment of 200 rpm from 1,000-2,600 rpm.

2. Also performed were 13-mode steady-state emissions tests.

3. Three transient emissions tests over the 1984 Heavy-Duty Federal Test Procedure with two additional hot-start tests were also performed.

4. Results - This engine exhibited emissions and brake thermal efficiency results typical for its size and class. The transient emissions results are summarized in Table 1 and an engine efficiency map is shown in Figure 1.

B. <u>Glow Plug "Torch" Ignition</u>

Several modifications were first performed in order to operate the engine on pure methanol with glow plug ignition. These modifications are listed below.

1. A second cylinder head was procured and fitted with steel sleeves through the water jacket to hold the glow plug (and spark plugs for later configurations). Because of space limitations the glow/spark plug could only be placed in one location, near the edge of the piston cup on the exhaust valve side (see Figure 2).

2. Several standard and also blank, unhardened nozzle tips were procured from their manufacturer for machining of four different spray patterns. These consisted of:

a. A set with a single spray hole twice the area of a standard hole directed towards the ignition source;

b. A set with a single spray hole four times the area of a standard hole directed towards the ignition source;

c. A set with four standard size spray holes arranged in a 135° quadrant directed towards the ignition source;

d. A set of standard nozzles with an extra spray hole pointed directly at the ignition source.

3. To increase the fuel delivery capacity, the rotary head assembly on the injection pump was replaced by one with a larger plunger bore and zero retraction delivery valve.

4. A system was devised to quickly change the static injection timing in 11° increments by rotating gear teeth on the main drive of the injection pump.

Table 1

Diesel Baseline Transient Test Results

Composite FTP Emissions Results

Number	HC (g/BBP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	Fuel (#/BHP-hr)	Particulate (g/BHP-hr)
3	1.31	3.55	9.29	.49	-
	.12	.08	.40	.02	-

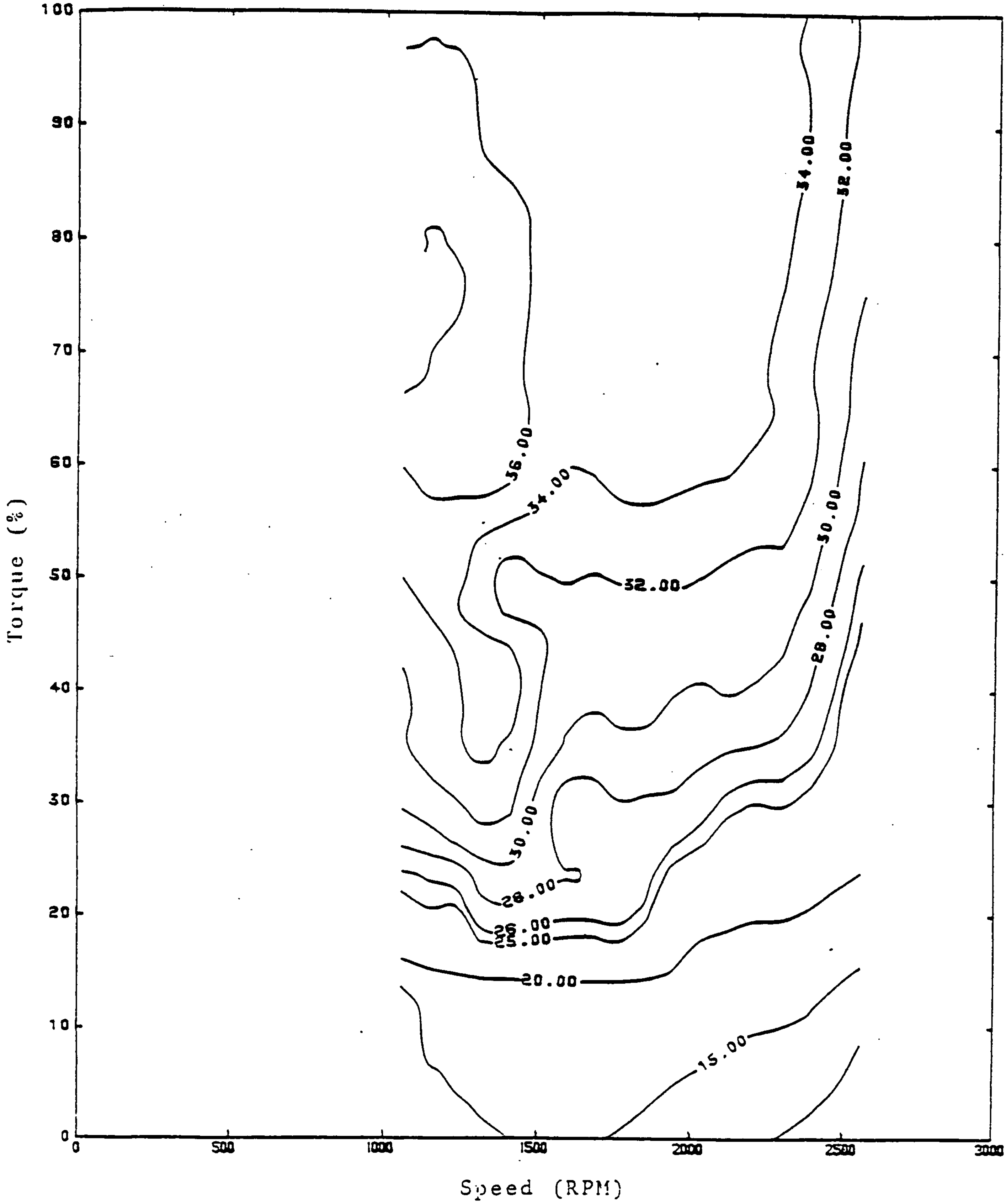
Composite Cold-Start Emissions Results

Number	HC (g/BBP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	Fuel (#/BHP-hr)	Particulate (g/BHP-hr)
3	1.43	3.73	9.29	.49	-
	.21	.17	.36	.003	-

Composite Hot-Start Emissions Results

Number	HC (g/BBP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	Fuel (#/BHP-hr)	Particulate (g/BHP-hr)
5	1.36	3.50	9.32	.49	-
	.13	.09	.35	.02	-

Figure 1
Engine Thermal Efficiency Map
IHC DT-466B Diesel Baseline



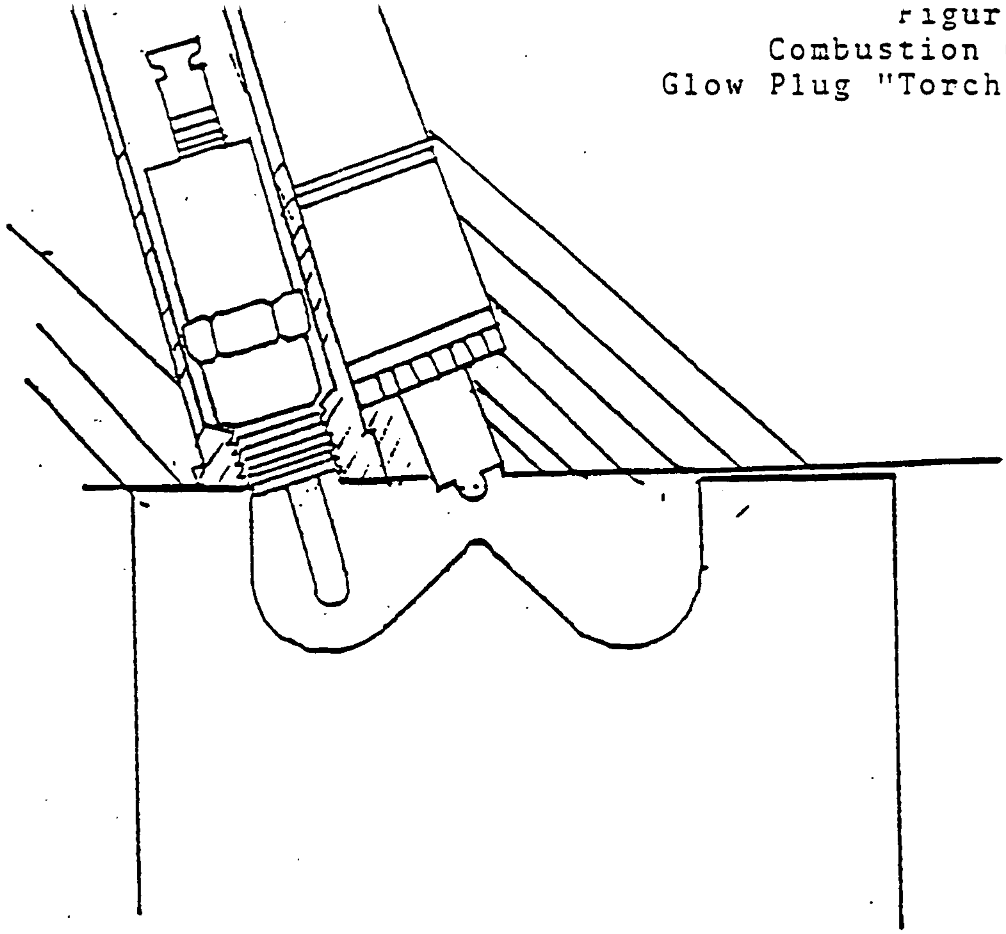


Figure 2
Combustion Chamber
Glow Plug "Torch" Ignition

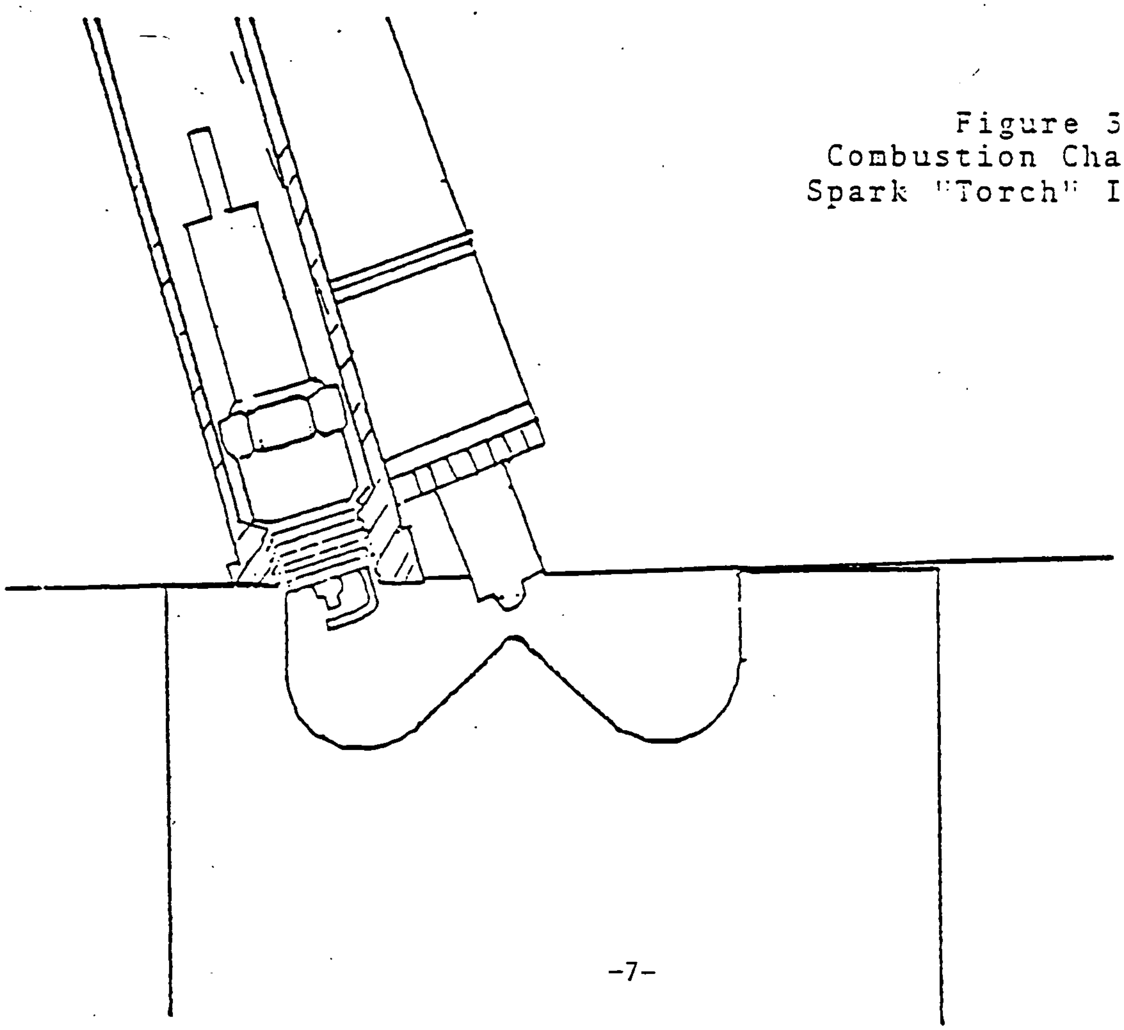


Figure 3
Combustion Chamber
Spark "Torch" Ignition

5. A system was devised to rotate the injectors so the spray could be directed to any location in the combustion chamber.

6. Test Matrix - A test matrix was conceived to determine the optimum operating configuration by varying several control parameters. The parameter variations and speed sequence which comprised the test matrix are listed in Table 2. The testing was conducted such that nearly all possible combinations of parameter adjustments were evaluated. The performance measure was simply maximum torque at given speeds.

When an optimum configuration was obtained, the engine was to be tested over fine-fuel maps, steady-state emissions tests and transient emissions tests. However, as will be discussed later, no configuration proved to be acceptable for emissions testing.

7. Results - The performance and efficiency results of the best configurations are shown in Table 5. The best performance obtained was 246 ft/lbs at 1800 rpm and best efficiency 28 percent brake thermal efficiency at 1400 rpm. The best power obtained is 48 percent and best efficiency 84 percent of corresponding diesel operation. This relatively poor performance on methanol may be attributed to several factors. Methanol's high heat of vaporization, hence long ignition delay, necessitated early fuel injection (as much as 91° BTDC) to achieve best performance. This early injection combined with the high swirl and typically lean diesel operation probably resulted in a nearly homogeneous mixture far too lean to sustain complete combustion. Analysis of raw exhaust revealed that large amounts (6,000 ppm) of unburned fuel were present, indicating that incomplete combustion was occurring. The poor results are likely indicative of the tradeoff between an early injection allowing methanol to become combustible, and an early injection allowing the charge to be more thoroughly dissipated. Ignition delays probably were too large and flame propagation too inadequate to permit late injection. Also, the location of the ignition source in the combustion chamber may not have been ideal, but could not be changed because of space limitations.

Because of the poor performance, this engine combustion concept was not subjected to fine-fuel maps and emissions tests.

C. <u>Spark "Torch" Ignition</u>

The operation and optimization of this engine with spark assistance required, in addition to the modifications listed previously for glow plug ignition, the following changes:

1. Installation of spark plugs (see Figure 3).

2. Mountings were fabricated and electronic controls assembled so two different ignition systems could be used: a high energy ignition and a multiple spark discharge ignition.

Table 2

Parameters Varied for Methanol Glow Plug Ignition

Sequence Speed	Injection Nozzles	Nozzle Rotation	Glow Plug Depth	Static Injection Timing (BTDC)
800	5-hole	Stock	3/4" into chamber, 5/8",1/2", 3/8",1/4",1/8"	16°,27°,38°, 49°,60°,71°, 82°
1,000	1 hole, 2x area	45° CCW from stock (upswirl)		
1,200	1 hole, 4x area	45° CW from stock (downswirl)		
1,400	quadrant			
1,800				
2,200				
2,600				

Table 3

Parameters Varied for Methanol Spark Ignition

Sequence Speed	Injection Nozzles	Nozzle Rotation	Spark Plug Depth	Ignition System	Ignition Timing	Static Injection Timing (BTDC)
800	5-hole	Stock	1/4"	High Energy, Multiple Spark	MBT	16°,27°
1,000	1 hole, 2x area	45° CCW	1/2"			38°,49°
1,200	1 hole, 4x area	90° CCW	9/10" into chamber			82°,60°,
1,400	quadrant	45° CCW				
1,800		90° CCW				
2,200		180° CCW				
2,600						

Table 4

Parameters Varied for Methanol Fuel Deposition

Sequence Speed	Injection Nozzles	Nozzle Rotation	Piston Type	Spark Plug	Ignition System	Ignition Timing	Static Injection Timing (BTDC)
800	Pintle	Stock	"Bowl"	1/4"	High Energy,	MBT	16°,27°,
1,000	Tube	45° CCW	"Dam"	1/2"	Multiple Spark,		38°,49°,
1,200		45° CCW		9/10"	Glow Plug		60°,71°,
1,400							338°,349°,
1,800							360°,371°

Table 5

Best Performance Configurations with Glow Plug Ignition

Speed	Torque	Brake Horsepower	Fuel (lb/hr)	Air/Fuel Ratio	Thermal Efficiency	Nozzle Type	Rotation	Injection Timing
1000	169	32.18	37.20	16.6	25.6%	2x area	Stock	60° BTDC
1400	203	54.11	57.41	16.4	28.02%	2x area	Stock	60° BTDC
1800	246	84.31	139.40	9.8	18.1%	2x area	Stock	60° BTDC
2000	235	89.49	160.00	9.8	16.6%	2x area	Stock	60° BTDC

3. A device was installed to change ignition timing electronically.

4. Extended electrode spark plugs, specifically designed for this project, were procured. Three different electrode length sets were used; one extending 1/4" into the combustion chamber, one extending 1/2" into the chamber with the ground electrode parallel to the center electrode, and one extending 9/10" into the chamber, (see Figure 6).

5. Test Matrix - The optimization test matrix for the spark ignition configuration was performed in the same manner as for glow plug ignition. Nearly all combinations of the parameter adjustments and speed sequence listed in Table 3 were evaluated.

6. Results - The performance and efficiency results of the best spark, ignition configurations are shown in Table 6. The best performance obtained was 230 ft/lbs. at 1800 rpm which is 46 percent of diesel baseline levels, and best brake thermal efficiency, estimated at 30 percent at 1400 rpm, is 84 percent of diesel baseline.

These results were very similar to those obtained with glow plug ignition. The relatively poor performance may be attributed to the same factors discussed previously for glow plug ignition combustion, namely methanol's high heat of vaporization necessitating early injection, high swirl precluding a stratified charge at early injection timings, and non-optimum ignition source placement. Even throttling the intake air could not achieve better performance.

D. Fuel Deposition

The additional modificatons required for the Fuel Deposition Concept testing are listed below.

1. A set of pistons with a bowl shape cavity and a lip to aid fuel retention was machined. (See Figure 4)

2. A set of pistons with two dams welded to form a 90° quadrant directly beneath the ignition source for fuel retention was machined. (See Figure 5)

3. A set of pintle nozzles was procured.

4. A set of fuel nozzles with a fuel passage extension brazed onto the tip and a threaded tube extending to just beneath the ignition source was machined. (See Figure 7)

5. A set of spark plugs with three extended ground electrodes was procured and machined to fit the sleeves.

Table 6

Best Performance Configurations with Spark Ignition

Speed	Torque	Brake Horsepower	Fuel (lb/hr)	Air/Fuel Ratio	Thermal Efficiency	Nozzle Type	Rotation	Injection Timing	Ignition Timing	Spark Plug
1000	183	34.84	-	-	-	Quad	Stock	71° BTDC	32° BTDC	1/4" into chamber
1400	220	58.64	-	-	Est. 30%	Quad	Stock	71° BTDC	32° BTDC	1/4" into chamber
1800	230	78.82	129.41	9.4	18.11%	Quad	Stock	71° BTDC	32° BTDC	1/4" into chamber
2000	184	77.07	-	-	-	Quad	Stock	71° BTDC	32° BTDC	1/4" into chamber
1000	110	20.94	43.86	12.3	14.16%	5-hole	Stock	71° BTDC	41° BTDC	1/4" into chamber
1400	100	26.66	61.81	12.5	12.81%	5-hole	Stock	71° BTDC	35° BTDC	1/4" into chamber
1800	150	51.41	83.75	13.6	18.24%	5-hole	Stock	71° BTDC	28° BTDC	1/4" into chamber
2000	110	46.08	108.22	13.6	12.65%	5-hole	Stock	71° BTDC	16° BTDC	1/4" into chamber

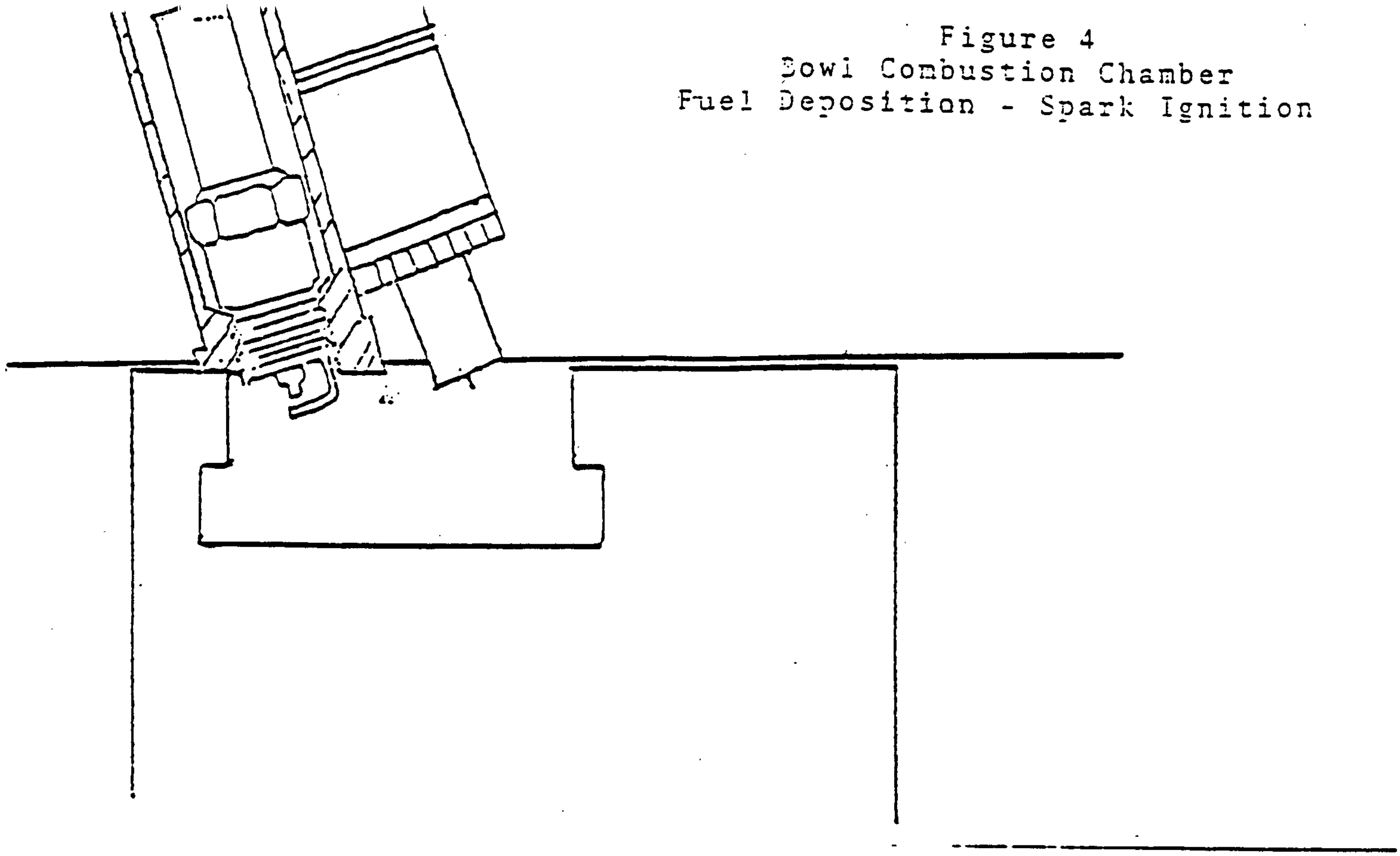


Figure 4
Bowl Combustion Chamber
Fuel Deposition - Spark Ignition

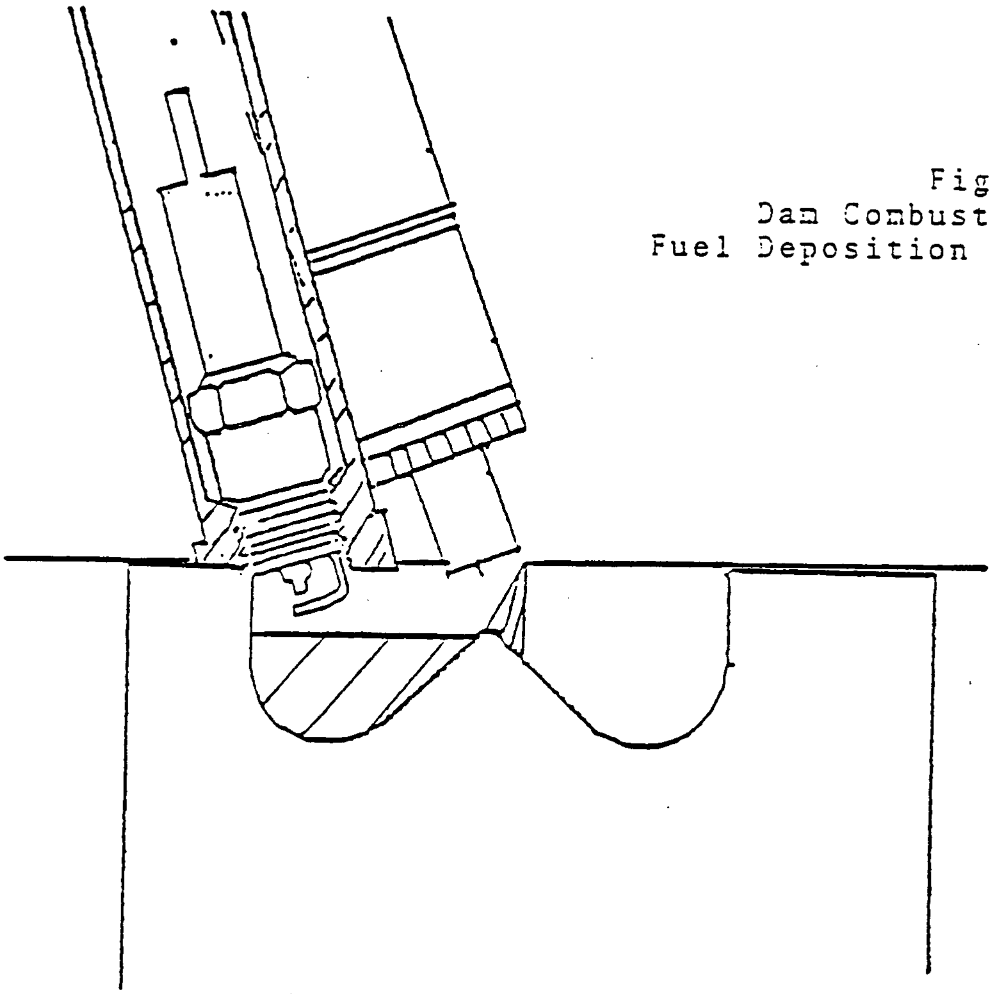


Figure 5
Dam Combustion Chamber
Fuel Deposition - Spark Ignition

Figure 6
Extended Electrode Spark Plugs

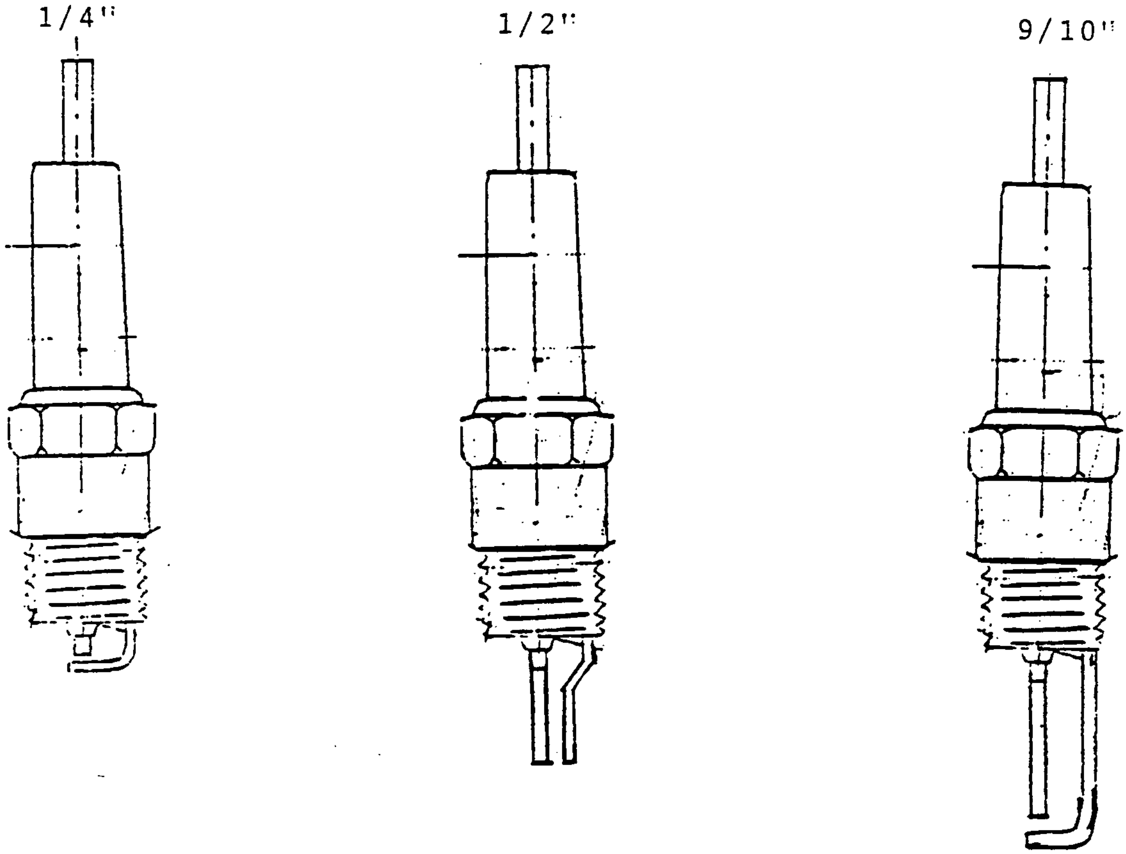
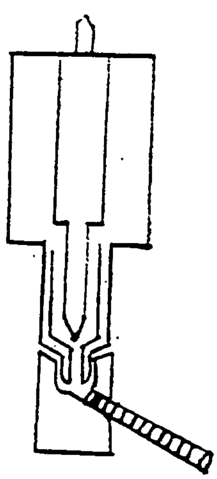


Figure 7
Fuel Deposition Tube Nozzles



6. Test Matrix - The optimization test matrix for the fuel deposition combustion concept was performed first with the "bowl" pistons and then with the dam pistons. Two sets of injector nozzles capable of depositing fuel on the piston cup surface were evaluated. The first set, the Bosch pintle nozzles, had good deposition characteristics with a mid-pressure, concentrated fuel stream formed by injection. A major drawback to these nozzles was that the spray direction could not be varied, and the resulting injection was directly opposite the ignition source (see Figure 4). The second set of nozzles, the machined tube nozzles, had good fuel location with the stream directed just beneath the ignition source, however they possessed a large sac volume resulting in some "dribbling" of the fuel and a more disperse spray. A combinations of these two nozzles would have been preferable, although not practically possible. Also investigated with this combustion concept was the injection of fuel at the beginning of the intake stroke. The parameters varied for the test matrix are listed in Table 4.

7. Results - No detectable combustion was achieved with any of the deposition test configurations. The fuel deposition type of operation demonstrated by the MAN engine was not achievable with this engine and the particular fuel injection, ignition, and air flow characteristics. The major contributing factor was probably the inability to present the spark to a region of combustible vapors above the fuel pool in the piston. Whether sufficient vaporization existed to create a combustible mixture at any location in the piston cup is open for question. Other contributing factors were: non-optimum fuel injection characteristics, non-optimum spark location, and potentially a failure to cold-start (a warmed-up engine may have enhanced combustion by providing heat for initial fuel vaporization).

V. Summary

1. Combustion of neat methanol was achieved in a common heavy-duty diesel engine, an IHC DT-466B, using glow plugs and spark plugs as ignition sources.

2. Three combustion concepts for operation on neat methanol were attempted with this engine: glow plug "torch" ignition, spark "torch" ignition, and fuel deposition-spark ignition. For each concept, several engine parameters were varied to obtain optimum performance.

3. Results for glow and spark "torch" ignition were comparable. The best performance obtained was 246 ft-lbs at 1800 rpm and best brake thermal efficiency 30 percent at 1400 rpm. This was 48 percent (power) and 84 percent (efficiency) of corresponding diesel baseline operation.

4. No combustion was achieved with the fuel deposition concepts.

5. Combustion of neat methanol in the engine was very sensitive to the engine operational parameters, and was probably inhibited by the limitation on ignition source location, high swirl in the combustion chamber, and very lean air-fuel mixtures.

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