February 2000 • NREL/SR-540-27502

Subcontractor Report

Ignition Assist Systems for Direct-Injected, Diesel Cycle, Medium-Duty Alternative Fuel Engines

Final Report Phase I

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NREL Technical Monitor: Keith Vertin

Prepared under Subcontract No. ZAS-7-16609-01

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SUBCONTRACT NO. ZAS-7-16609-01

IGNITION ASSIST SYSTEMS FOR DI DIESEL CYCLE, MEDIUM DUTY ALTERNATIVE FUEL ENGINES

BACKGROUND

Due to the nation's continuing concern about air pollution, Congress enacted the Clean Air Act Amendments of 1990. The act's provisions will force broad changes in fuels and vehicles. For example, clean diesels, reformulated gasoline, and alternative fuels are receiving wide attention as industry struggle to comply with the act. To comply with the Clean Air Act, many ozone non-attainment areas are focusing on medium-duty and heavy-duty vehicles for their State and Federal Implementation Plans (SIPs and FIPs). Also, these vehicles constitute the major increase of US petroleum consumption in the last 10 to 15 years. Using alternative fuels in these vehicles can significantly reduce the US dependence on imported petroleum and also have the potential to greatly reduce particulate and NOx emissions. However, before the full-scale use of alternative fuel vehicles can take place, many technologies need to be developed to take full advantage of the alternative fuel's properties. These include emissions control technologies, methods for increased energy efficiency, fuel-specific engine optimization schemes, and engine and fuel system hardware development. The goal is to develop technologies that will make alternative fuel vehicles commercially competitive with diesel vehicles in terms of energy efficiency, performance, durability, cold-start ability, safety and range while having an emissions benefit.

Alternative fuels such as natural gas has a high octane number and a low cetane number, making it more suitable for light-duty, homogeneous-charge, spark-ignited (SI) Otto-cycle engines than for medium-duty and heavy-duty, direct-injection, compression-ignited (CI) Diesel-cycle engines. Multiple technologies have been investigated to design and develop medium-duty and heavy-duty natural gas engines. These technologies include spark-ignition natural gas (SING), pilot-ignition natural gas (PING), and direct-injection natural gas (DING) engines. The SING and PING engines are homogeneous-charge, Otto-cycle engines with different methods of ignition. Regardless of the ignition system, homogeneous-charge engines are limited in the highest compression ratio achievable due to combustion knock. The SING engines can burn natural gas with relatively minor modifications, but they do not generally match power density and have lower efficiency over the typical operating range as compared to CI Diesel-cycle engines, especially at light loads. In an attempt to extend the knock limit, PING engines use an injected pilot fuel to create multiple ignition sources deep in the combustion chamber, therefore shortening the total combustion time. The pilot fuel usually has a high cetane number, such as diesel. PING engines have the complexity of two fuel systems and simultaneous control of both fuels, and it may use a large amount of pilot fuel and have high particulate emissions. DING engines apparently do not have the knock limitation and the complexity of the two fuel system; therefore, they are currently being considered as the best long-term choice for duplicating diesel power and efficiency, and for providing 100% natural gas substitution.

Caterpillar has an extensive program to develop 4-stroke, single fuel, DI alternative fuel technology capable of providing power and efficiency = diesel, and emissions < diesel for fuels including natural gas[1-3]. The current technology incorporates glow plug ignition assist (GPIA). The GPIA system has performed well in laboratory, having demonstrated the capability to produce diesel power and efficiency with natural gas. Crucial to the DING engine's commercial viability is the durability and cost of the GPIA system. Although development is in process to demonstrate that durability and cost goals for the GPIA system can be met, much development is still needed. To ensure the success of DING technology, it is important to investigate alternatives to GPIA system.

Other single fuel, ignition assist options have recently been identified as having the potential for improved system durability and cost as compared to the GPIA system. These options include:

- short duration, high power (SDHP) spark
- long duration, low power (LDLP) spark
- micropilot lube oil injection

In contrast to the conventional spark system utilized in conventional SI engines, these systems have potential for creating the necessary ignition energy at the relatively high pressures that are inherent with the DI alternative fuel engine, while maintaining acceptable system durability. None of these options, however, have been evaluated in a DI alternative fuel engine. This contract will investigate and evaluate these options.

This report summarizes the results of the 1st year (Phase 1) of this NREL/Caterpillar contract, in which all feasible ignition option technologies were fully evaluated. A pressurized test chamber was constructed and used to test the SDHP and LDLP ignition assist concepts in pressures usually found in 'diesel cycle' engines. A specially designed spark plug, all potential ignition assist systems and a modified 3126 engine cylinder head have been designed and are being procured for engine testing in Phase 2.

OBJECTIVE

The objective of this work is to evaluate the potential of the following assist technologies for direct-injected alternative fuel engines vs. glow plug ignition assist:

- short-duration, high power (SDHP) spark
- long-duration, low power (LDLP) spark
- micropilot lube oil injection

The goal of this contract is to demonstrate the feasibility of an ignition system life of 10,000 hours and a system cost of less than 50% of the glow plug system while meeting or exceeding the engine thermal efficiency obtained with the glow plug system.

EXECUTIVE SUMMARY

Phase 1 has been completed. The following summarizes the results from Task 1-3 in Phase 1.

Task 1: Concept Design Ignition Assist Options

A comprehensive review of feasible ignition options for DING engines has been completed. The most promising ignition options are systems using: (i) Alternating Current (AC) and the 'SmartFire' spark, which both are long duration low power (LDLP) spark systems. (ii) the short duration high power (SDHP) spark system, (iii) the micropilot injection ignition, and (iv) the stratified charge plasma ignition. The main efforts have been concentrated on investigating the AC spark, 'SmartFire' spark, and short duration/high power spark systems. Evaluation of the micropilot injection and the stratified charge plasma ignition systems have been limited to date.

Using Caterpillar's proprietary pricing information, it is predicted that the commercial costs for the AC spark, the short duration/high power spark and 'SmartFire' spark systems will be comparable (if not less) to the glow plug system. The main difficulty is to predict the final costs of the spark plug and the glow plug, whereas ongoing research works are continuing.

Task 2: Bench Test Ignition Assist Concepts

Two bench tests were designed and performed to determine the design criteria for the ignition system and the prototype spark plug for Task 3. The two most important design criteria are: (i) the high voltage output requirement of the ignition system and (ii) the minimum electrical insulation requirement for the spark plug. Using a specially designed constant volume high pressure chamber, results from the first bench test predict that : 1) 54 kV of applied voltage is required to cause a discharge in a 0.5 mm air gap between two square end electrodes at 800 psig. 2) Breakdown voltage requirement can be lower by using different gap configuration, e.g. surface-discharge gap and electrode with sharp edges. Results from the second bench test show that in order to isolate 54 kV, a ceramic insulator with a minimum thickness of 4.8 mm is required.

A prototype micropilot ignition system has been successfully tested in a preliminary engine test. The results show that 9 mm^3 of diesel fuel injected directly in the combustion chamber of a homogenous charge natural gas engine (4.3 liter per cylinder) can cause ignition and with engine efficiency equal to a standard engine. Energy content of the 9 mm^3 of pilot diesel constitutes to about 1% fuel energy input of the engine operating at peak torque (maximum fuel consumption) condition. Since the minimum flow rate of the current injector is 9 mm^3 per injection, it is premature to conclude that this is the minimum required quantity for ignition based on the preliminary engine test. The minimum required pilot fuel may be less for a smaller size 3126 (1.2 liter per cylinder) DING engine. Review of injector designs indicate that major effort is required to design an injector which can deliver a smaller quantity of pilot fuel than 9 mm^3 per engine cycle.

Task 3: Design/Procure Best Ignition Concept for One Cylinder Engine Test

All hardware necessary for the one cylinder engine test have been designed. Hardware includes modified 3126 cylinder heads, specially designed prototype spark plugs, ignition system electronics and parts for system installation. Two 3126 cylinder heads and the 'SmartFire' ignition system have been procured. Refinements of the high frequency AC spark and the SDHP ignition systems are continuing, and will be procured for the one cylinder engine test.

SUMMARY OF PHASE 1 : IGNITION ASSIST SYSTEM DESIGN AND BENCH TESTS

Task 1: Concept Design Ignition Assist Options

Proposed Work:

The following 3 ignition assist concepts shall be "conceptually" designed for a 3116 or 3126 DI gas engine:

-short duration, high power spark (SDHP)
-long duration, low power spark (LDLP)
-micro pilot lube oil injection

Each of the ignition assist concepts shall be designed to fit into the current diesel cylinder head with minimal disruption. Initially, the ignition assist concepts shall be positioned similar to the glow plugs. The electronics for each ignition assist concept shall be identified and a predicted commercial cost for each system shall be compared to the cost of a glow plug system.

Accomplishment Summary:

A comprehensive literature review of all feasible ignition options for DING engines was conducted. Criteria used to evaluate each ignition options are: (i) stage of development, (ii) ignition delay, (iii) ignition source distribution, (iv) power/energy requirement, and (v) system durability. The review has identified four systems that warrant further investigation. They are the AC spark, Caterpillar's SDHP spark, Adrenaline's 'SmartFire' spark, and micropilot injection systems.

Using Caterpillar's proprietary pricing information, it is predicted that the commercial costs for the AC spark, the short duration/high power spark and 'SmartFire' spark systems will be comparable (if not less) to the glow plug system.

Accomplishment Details:

Table 1 shows the summary of the comprehensive literature review listing the theory of operation, advantages and disadvantages of each system. Many systems have been attempted previously, either by Caterpillar or other researchers. The merit of each system was assessed based on the theoretical performance prediction as well as the published and experimental results.

Source of Ignition Assist	Working Principle	Determinant of Ignition Delay	Est. Ign. Delay (ms)	Ignition Volume	Est. COV (Note 2)	Production Limiting Feature	Action (Note 1)
Glow Plug	Heat transfer to mixture from external hot surface	Surface temperature and local equivalence ratio	2 - 3	Medium (Layer near glow plug surface)	5	Durability requires development	1
AC Spark Plug	Long duration high frequency spark initiated early in compression stroke	Local equivalence ratio, spark duration and spark energy	1 - 2	Small (Spark plug gap)	3	Power supply and controls require development	2
SDHP Plug	Short duration high power spark	Local equivalence ratio and spark energy	1 - 2	Small (Spark plug gap)	4	Durability and electronics unproven	2
SmartFire Spark Plug	Multiple sparks with feedback control	Local equivalence ratio and spark energy	1 - 2	Small (Spark plug gap)	3	Durability and electronics unproven	2
Plasma Jet Ignitor	Plasma generated and propelled into cylinder	Plasma energy and plume volume	< 1	Large (Plasma plume volume)	2	Durability requires development	4
Heated Pre-chamber	Heat transfer to mixture from internal hot surface	Surface Temperature and local equivalence ratio	2 - 3	Medium (Layer at pre-chamber wall)	5	Durability requires development	4
Fuel Preheating	Fuel raised to ignition temperature prior to or during injection	Initial fuel temperature	< 1	Large (Injection plume)	1	Injector and power supply require development	5
Laser Excitation	Excitation of fuel molecules in laser focal volume by laser wavelength	Laser energy and local fuel concentration	1 - 2	Small (Laser focal volume)	4	Cost and component durability far from production	4
Laser Plasma	Gases in laser focal volume ionized by intense thermal heating	Laser energy and local equivalence ratio	1 - 2	Small (Laser focal volume)	4	Cost and component durability far from production	4
Inlet Air Heating	Inlet air heating and increased compression ratio of engine to induce autoignition	Inlet air temperature and compression ratio	2 - 3	Large (Injection plume)	2	Power requirement and emissions issues	5
Micropilot Injection	Small quantity of high cetane fluid injected with natural gas	Fuel pilot cetane number and quantity	1 - 2	Large (Injection plume)	2	Pilot fuel consumption issues	3
Fuel Additives	Addition of ethane to natural gas to aid autoignition	Fuel additive concentration and autoignition temperature	2 - 3	Large (Injection plume)	3	Fuel supply problems	5
Stratified Charge Plasma Ignition	Early injection of fuel through plasma jet ignitor	Plasma energy and plume volume	< 1	Large	2	Requires extensive development	4

Note 1: '1' - Continue development. '2' - Initiate development. '3' - Perform concept study. '4' - Monitor outside research. '5' - Will reevaluate if encounter new development.
Note 2: COV = Coefficient of Variation. Scale: 5 - high, 1 - low

Table 1: Direct Injection Natural Gas Engine Ignition Options Survey

The followings are the detail assessment of each ignition option:

1) **Glow Plug Ignition** [1-6]**:** The basis of glow plug ignition is the initiation of combustion by heat transfer from a high temperature surface in excess of 1200°C.

i) Stage of development - Glow plugs have been used in Diesel engines for decades as a tool of easing cold starting of the engine. Continuously activated glow plugs have been under development for use with low cetane fuels at Caterpillar since the late 1970's.

ii) Ignition Delay - The ignition delay in a DING engine using glow plug ignition depends on the fuel/air ratio and the temperature on the glow plug surface. High surface temperature and optimum fuel/air ratio will reduce the ignition delay. The current DING engine has high cycle-to-cycle variation due to fluctuation of the air/fuel mixing on the glow plug surface.

iii) Ignition source distribution - The initial ignition occurs in the thin layer on the surface of the glow plug where the fuel/air mixture has reached ignition temperature. Flame propagation starts from the surface of the glow plug. The ignition source is considered localized.

iv) Power/energy requirement - Current glow plugs used on the DING engine consume roughly 100 watts per cylinder. Future glow plug design may reduce this consumption to less than 50 watts per cylinder.

v) System durability - To develop a 2000 hours continuously activated glow plug has been a major technical challenge. Significant progress has been made at Caterpillar in the past few years, and the research is still in progress.

vi) Additional comments - Currently, glow plug ignition is the most developed technology available for the DING engine. However, all past experiences are with DING engines operated at under 2200 rpm engine speed when the real time/engine crank angle ratio is large. Since the ignition delay depends on the heat transfer from the surface of the glow plug, this delay time may be too long in engines operating in higher engine rpm when the real time/engine crank angle ratio is smaller.

2) **AC Spark Plug :** The use of spark plugs in diesel type engines has been limited by the difficulty in achieving breakdown in high cylinder pressure and the high erosion of electrodes. The AC spark plug ignition system seeks to overcome these shortcomings by initiating the spark early in the compression stroke when the cylinder pressure is low and maintain the discharge for the duration of the fuel injection. Since the sustaining voltage and current are lower than the breakdown voltage and current, the erosion rate of the electrodes is expected to be lower. The long duration spark could be produced by a high frequency (>400 Hz) and high voltage (>30 kV) source with low current (<1 A).

i) Stage of development - It is believed that this is a novel idea which has not been tested before. A simple demonstration using a Telsa coil has achieved breakdown in a 1.5 mm gap under 1500 psig of Helium. However, the voltage and the current of the Telsa coil discharged was not measured.

ii) Ignition Delay - The ignition delay in a DING engine using AC spark ignition depends on the fuel/air ratio and the power of the discharge. High discharge power and optimum fuel/air ratio will reduce the ignition delay. Long duration discharge will reduce the cycle-to-cycle variation due to fluctuation of the air/fuel mixing in the discharge volume.

iii) Ignition source distribution - The initial ignition occurs in the spark column where the fuel/air mixture has reached ignition temperature. Flame propagation starts from the surface of the spark column. The ignition source is considered localized.

iv) Power/energy requirement - No data was available; however, the power consumption of the AC spark system is expected to be somewhere between 50 watts per cylinder (glow plug) and 1 watt per cylinder (conventional spark plug @60 mJ/spark) in a 4 stroke engine running at 2000 rpm.

v) System durability - The durability of the AC spark plug is unknown, but should be better than that of conventional spark plug when used in high pressure environment. This is due to the lower sustaining current required.

3) **Short Duration/High Power Plug :** The working principle of the Caterpillar-designed short duration/high power plug system is very similar to that of the 'breakdown'[7] or the 'blast wave'[8] ignition systems used before. Energy stored in a capacitor connected in parallel with the plug gap is discharged in a very short period of time, typically less than 100 nanoseconds.

i) Stage of development - Caterpillar has been working on this ignition system for the SI gas engines for over 2 years. However, this system has yet to be demonstrated in a DING type engine. Research is still being supported internally by Caterpillar.

ii) Ignition Delay - The ignition delay in a DING engine using short duration/high power plug ignition depends on the fuel/air ratio and the power of the discharge. High discharge power and optimum fuel/air ratio will reduce the ignition delay. Due to the inherent short duration of the discharge, multiple sparks will reduce the cycle-to-cycle variation due to fluctuation of the air/fuel mixing in the discharge volume.

iii) Ignition source distribution - The initial ignition occurs in the spark column where the fuel/air mixture has reached ignition temperature. Flame propagation starts from the surface of the spark column. The ignition source is considered localized.

iv) Power/energy requirement - Optimum energy per spark required in the short duration/high power plug ignition has not been determined; however, the expected energy should be less than 100 mJ/spark.

v) System durability - It is anticipated that the short duration of the short duration/high power plug discharge will avoid the arc mode where excessive erosion rates at the cathode occur[9].

4) **SmartFire Spark Plug :** The SmartFire[10] ignition system developed by Adrenaline Research Inc.[11] minimizes the voltage and energy required to initiate combustion by using a feedback loop[12]. It has the capacity to deliver multiple sparks with increasing voltages. After the initial spark, the current in the gap is monitored to determine if a sustaining flame

kernel has been generated. If the spark fails to ignite the mixture, a second discharge is generated with a higher voltage. This process is repeated until a flame kernel is detected.

i) Stage of development - While the SmartFire ignition system is near production for SI automotive engines, there is no system designed for use in the high pressure diesel engines. Adrenaline is in the process of working with Caterpillar to develop a prototype system for the high pressure environment.

ii) Ignition Delay - The ignition delay in a DING engine using SmartFire ignition will be similar to the other spark plug ignition systems with the possibility of additional delay from the feedback system. Cycle-to-cycle variation will depend on the fluctuation of the air/fuel mixing in the discharge volume.

iii) Ignition source distribution - The ignition source is considered localized.

iv) Power/energy requirement - The energy per spark of this system may be slightly higher than that of the short duration/high power plug system due to the longer duration.

v) System durability - Since the ignition system manages the spark duration and energy, it is hoping that the required arc current is low enough to cause excessive erosion rates.

5) **Plasma Jet Ignitor**[13-17] : All sparks generate plasmas; however, usually plasma jet implies that the plasma generated is contained in a small enclosure. The high temperature causes the pressure and volume of the plasma to rise rapidly, and the plasma exits an orifice as a jet.

i) Stage of development - Plasma jet ignitors have been under development since the middle 1970's . The main thrust of the research has been to improve the cold starting, emissions, engine efficiency, and lean limit of SI engines. Substantial work has been done, and for some applications, components required to build the plasma jet ignitor and its associated electronics are both available from manufactures.

ii) Ignition Delay - Since research was mainly done on SI engines, effect on ignition delay in the DING engine can only be speculated. Results on SI engines indicate shorter ignition delay period when using plasma jet ignition over the conventional spark plug. It is believed that the effect will be similar when applied on the DING engine.

iii) Ignition source distribution - The plasma jet can penetrate deep into the combustion chamber and provide many micro pockets of plasmas; therefore, the ignition source is not localized.

iv) Power/energy requirement - The energy required for each plasma discharge is at least equal[17] but usually much higher than that of a conventional spark.

v) System durability - Past experiences have shown high erosion rates on the electrodes.

vi) Additional comments - The electronic used in the short duration/high power plug system and the plasma jet ignitor used by Gardiner[17] are very similar. The major difference is the plug design and the spark duration. The spark duration of the Gardiner system and the short duration/high power plug system are 2 ms and less than 100 nanoseconds, respectively.

36) **Heated Pre-chamber :** The temperature of the pre-chamber is heated to above the ignition temperature of the fuel/air mixture. Heat transfer from the internal surface of the pre-chamber causes the fuel/air mixture to autoignite.

i) Stage of development - In the late 1980's , Gas Research Institute supported research work[18] using a heated pre-chamber as a potential ignition method for DING engines. The project finished in 1989. Since then no other works has been published using this method.

ii) Ignition Delay - Since the heated pre-chamber can be considered as a big glow plug with large surface area, the ignition delay is expected to be very similar to a glow plug system.

iii) Ignition source distribution - The ignition source is localized on the internal surface of the pre-chamber.

iv) Power/energy requirement - Due to large heat capacity of the pre-chamber, the power required to heat and maintain the wall temperature of the pre-chamber is expected to be much higher than all of the spark systems.

v) System durability - Expected to be similar to the glow plug system.

vi) Additional comments - The experimental results reported on ref. 14 were significantly worse than the data obtained from the current Caterpillar's glow plug ignited DING engine. Maximum thermal efficiencies reported were around 30% with very high HC emissions.

7) **Fuel Preheating :** The fuel is heated before injecting into the combustion chamber. After mixing with air in the combustion chamber, the resulting temperature of the mixture is high enough for autoignition

i) Stage of development - In the late 1980's , GRI supported a project[19,20] using heated fuel as a potential ignition method for DING engines. The project finished in 1987. Since then no other works has been published using this method.

ii) Ignition Delay - The ignition delay can be reduced by raising the temperature of the fuel prior to injection. Hoppie[19,20] has shown that essentially no ignition delay (<0.5 ms) can be achieved when methane is heated to 1200°C prior to injection.

iii) Ignition source distribution - The ignition source distribution will depend on the fuel spray's penetration.

iv) Power/energy requirement - The power requirement of this system is high as it is necessary to heat up all coming fuel to a very high temperature. The power is expected to be over 100 watts/cylinder.

v) System durability - One of the methods used by Hoppie was to used an electrically heated fuel line to raise the temperature of the natural gas to 1200°C. Pyrolysis of the natural gas generated carbon deposits on the internal wall of the fuel line and eventually blocked the fuel passage.

vi) Additional comments - While it is not practical to heat the fuel to 1200°C, the idea of fuel preheating could be used as a supplement to other ignition methods to shorten the ignition delay.

8) **Laser Excitation :** The principle of this technique is based on the line absorption of laser light by the fuel/air mixture molecules inside the combustion chamber. The absorbed energy raises the temperature of the fuel/air mixture to autoignition.

i) Stage of development - This technique was investigated under a GRI contract[21] which consisted entirely of bench test experiments and computer modeling. No engine testing was reported and atmospheric pressure condition was used in the computer models.

ii) Ignition Delay - The ignition delay would be similar to that of spark plug ignition, as heating is concentrated in a small volume.

iii) Ignition source distribution - The ignition source is considered localized

iv) Power/energy requirement - The efficiency a typical laser is around 5%; therefore, in order to produce a 100 mJ laser pulse, 2 J of energy has to be used. In a 4 stroke engine running at 4000 rpm, this requires a power of at least 133 watts/cylinder-pulse.

v) System durability - The scientific grade, high energy, high repetition rate lasers used in this system are not designed to work in the harsh engine environment. The optical access to the combustion chamber may require frequent repair and cleaning.

vi) Additional comments - The limited experience with this system makes it difficult to conceive of it having any short term application to the DING engine development. It needs advances in laser technology to make this system viable.

9) **Laser Plasma :** Laser light is focused inside the combustion chamber. The intense high power density causes breakdown in the gaseous environment and produces plasma for ignition.

i) Stage of development - Caterpillar has limited experience using a Nd:YAG laser to induce ignition in a DI methanol engine[22].

ii) Ignition Delay - The ignition delay would be similar to that of spark plug ignition, as heating was concentrated in a small volume. Cycle-to-cycle variation will depend on the fluctuation of the air/fuel mixing in the focus of the laser light.

iii) Ignition source distribution - The ignition source is considered localized.

iv) Power/energy requirement - The efficiency a typical laser is around 5%, therefore, in order to produce a 100 mJ laser pulse, 2 J of energy has to be used. In a 4 stroke engine running at 4000 rpm, this requires a power of at least 133 watts/cylinder-pulse.

v) System durability - The scientific grade, high energy, high repetition rate lasers used in this system are not designed to work in the harsh engine environment. The optical access to the combustion chamber may require frequent repair and cleaning.

vi) Additional comments - In the Caterpillar test, the engine was not able to run past half load due to misfires. It is likely caused by two factors; the poor fuel/air mixing at the focal point and the extremely short duration (<10 nanoseconds) of the laser pulses. The limited experience with this system makes it difficult to conceive of it having any short term application to the DING engine development. It needs advances in laser technology to make this system viable.

10) **Inlet Air Heating :** This process involves heating the inlet air before compression to raise the final air temperature.

i) Stage of development - No known work was documented using this technique in natural gas engines.

ii) Ignition Delay - Autoignition of natural gas injected into air at various temperatures has been studied both experimentally and by computer modeling. The ignition delay continually decreases with increasing temperatures, reaching around 0.3 ms at 1300° C[18].

iii) Ignition source distribution - The ignition source distribution will depend on the fuel spray penetration.

iv) Power/energy requirement - The power required to heat the bulk of the inlet air to the temperature needed is expected to be high. In a turbo-charged DING engine, removing the intercooler after the air compressor can save some power. However, the volumetric efficiency of the engine will be lowered.

v) System durability - Essentially the engine will be running at an elevated compression ratio; therefore, increased cylinder head and liner stresses may cause some problems.

vi) Additional comments - In order to compress-heat the air from room temperature to 1000°C in a naturally aspirated diesel engine, the compression ratio will need to be in excess of 29:1. Therefore, this option is not considered as one of the better choices.

11) **Micropilot Injection :** This technology involves in providing flame kernels started by autoignition of small amount of injected high cetane fuel into the combustion chamber prior to the main natural gas fuel injection. Lubricating oil or diesel fuel are most likely to be used as the pilot fuel.

i) Stage of development - Pilot injection has been used in dual fuel engines where a small quantity of diesel fuel is injected into the homogeneous natural gas/air charge[24,25]. Successful demonstrations have also been reported using diesel pilot in a DING engine[26-28]. The displacement of natural gas by diesel pilot fuel in these engines typically ranges from 5% to 20% of energy input. No known work has been documented with pilot fuel using lubricating oil.

ii) Ignition Delay - The ignition delay will be similar to that of the diesel fueled engine.

iii) Ignition source distribution - The ignition source distribution will be similar to that in a diesel fueled engine.

iv) Power/energy requirement - No additional power/energy required.

v) System durability - While there is no direct experience with this system, it is expected that the durability of the engine would be no worse than that of a conventional diesel engine.

vi) Additional comments - The DING engines [26-28] have to use almost entirely diesel pilot fuel when idling. Better design of the pilot and main fuels injection systems may overcome this problem at idling. The goal of a micropilot injection system is using pilot fuel less than 1% of energy input. Using lubricating oil as pilot fuel can get rid of the routine engine oil change. However, because the cost of lubricating oil currently is about 4 times the cost of diesel fuel, the system would be more costly than using diesel fuel.

12) **Fuel Additives :** This process involves adding constituents with high cetane number to the natural gas for easy autoignition.

i) Stage of development - No known work was documented using this technique in natural gas engines.

ii) Ignition Delay - Presence of minor constituents such as ethane and propane can reduce the ignition delay[23,29].

iii) Ignition source distribution - The ignition source distribution will depend on the fuel spray's penetration.

iv) Power/energy requirement - No additional power required.

v) System durability - Same as a DING engine.

vi) Additional comments - If a gaseous constituent can be found which has the same cetane number as that of diesel fuel, no other ignition assist will be needed. Otherwise, it is likely that some form of ignition options mentioned in this survey will be needed.

13) **Stratified Charge Plasma Ignition :** This process involves fuel injected 'early' into the combustion chamber, with electrical discharge to generate plasma in the last portion of the fuel injection. Since the temperature of air in the combustion chamber is not high enough to autoignite the front portion of the fuel spray, the flame kernel can only start from the tail portion of the injected fuel.

i) Stage of development - It is believed that this is a novel idea which has not been tested before.

ii) Ignition Delay - The ignition delay is expected to be short due to the spontaneous reaction of the fuel plasma with air.

iii) Ignition source distribution - The flame kernels will be carried into the combustion chamber by the fuel spray. Therefore, it is possible to have multiple ignition sources penetrate deep into the combustion chamber.

iv) Power/energy requirement - The energy required to generated the fuel plasma will be less than a typical plasma jet because it is easier to maintain a discharge in natural gas than in air.

v) System durability - The durability of this system is not known. It should be better than a conventional plasma jet system because of the natural gas feed stock and reduced oxidation.

vi) Additional comments - Electrode erosion still remains a big technical challenge. Substantial development effort will be required to design the plasma injector/ignitor.

The design for incorporating the AC spark, Caterpillar's SDHP spark, and the Adrenaline's 'SmartFire' spark ignition systems in a 3126 DING engine has been performed in Task 3.

Task 2: Bench Test Ignition Assist Concepts

Proposed Work:

A pressurized cylindrical test chamber shall be used to test the short duration, high power (SDHP) and long duration, low power (LDLP) ignition assist concepts in an ignition-like environment. The test chamber shall incorporate a window for viewing the spark. This chamber shall be used to determine the breakdown voltage for the spark as a function of pressure and spark plug gap. Minimum insulation thickness shall be determined through testing several spark plugs with varying insulation thickness. Information on micropilot, lube oil injection shall be obtained from the Clean Air Partners demonstrations on a port injected 3176 gas engine. The information collected in Task 1 and 2 shall be used to determine the most promising system for further development. The most promising system shall be chosen for Task 3.

Subtask 2.1 - Minimum Electrical Breakdown Voltage Requirement

Objective:

Determine the minimum electrical breakdown voltage between the air gap of two electrodes as functions of air pressure, gap size, and electrode configuration. This will help to design the prototype ignition system for engine testing in Phase 2.

Accomplishment Summary:

Using a specially designed constant volume high pressure chamber (Fig. 1), minimum breakdown voltage requirements for various electrode configurations, gap lengths, air pressures, and voltage-supplying systems were investigated. Results show that as high as 54 kV is required to cause a discharge in a 0.5 mm air gap between two square end electrodes at 800 psig. Round-end electrodes require higher voltage. With pulsed or AC applied voltages, increased rate of voltage rise lowers the voltage requirement.

Accomplishment Details:

The objective is to determine the electrical breakdown voltage between the air gap of two electrodes as functions of air pressure, gap size and electrode configuration. For gas densities up to values corresponding to pressures of a few atmospheres at normal ambient temperatures, uniform-field (electric field between two infinitely large parallel plates) breakdown in most gases is in accordance with Paschen's law, that is the breakdown voltage V_s is a function of the product nd only (n being the gas number density and d the gap length). Empirical formulae were derived from experiments performed with gap lengths of 0.01 to 30 cm and is given by[30]

$$V_s = A(\rho d) + B\sqrt{\rho d} \qquad (1)$$

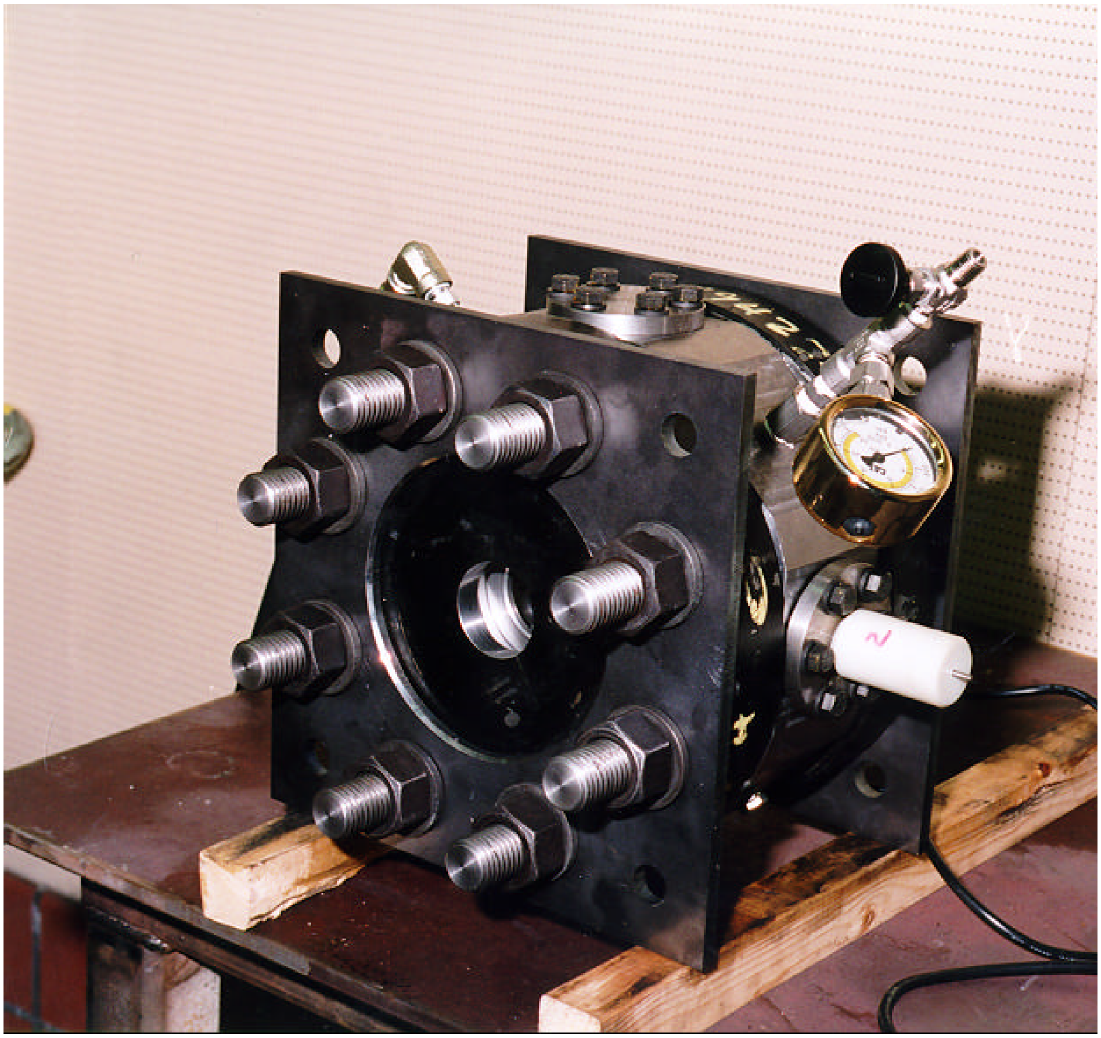

Figure 1: Constant volume high pressure chamber

where V_s is the breakdown voltage in kV, d is the gap length in cm, and

$$\rho = \frac{p}{1013} \times \frac{293}{t+273} \qquad (2)$$

is the air density relative to its value at a pressure p = 1013 mb and a temperature t = 20°C (gas number density n = 25.05 x 10^{18} cm^{-3}). A and B are constants with values between 24.4 to 25.4 and 6.53 to 7, respectively, due to effects of humidity, pressure and temperature. Using A = 24.4 and B = 6.53, Table 2 shows the predicted breakdown voltages as a function of pressure for different electrode gaps using Equation 1 to extrapolate to high pressures. Fig. 2 shows the plots of predicted breakdown voltage vs pressure. It predicts that for a 1 mm air gap under uniform field condition, the breakdown voltages are 41 kV, 95 kV, and 183 kV for pressures at 200 psig, 500 psig, and 1000 psig respectively.

Pressure (psig)	Gap Length (mm)	Pred. Vs (kV)	Gap Length (mm)	Pred. Vs (kV)	Gap Length (mm)	Pred. Vs (kV)
200	0.5	23	1.0	44	1.5	63
300	0.5	33	1.0	62	1.5	90
400	0.5	42	1.0	80	1.5	117
500	0.5	51	1.0	98	1.5	143
600	0.5	60	1.0	115	1.5	169
700	0.5	70	1.0	133	1.5	196
800	0.5	79	1.0	151	1.5	222
900	0.5	87	1.0	168	1.5	248
1000	0.5	96	1.0	186	1.5	274

Table 2: Breakdown voltage predicted by Paschen's law

Literature search revealed that work done involving pressure higher than a few atmospheres are limited. Experiments performed in dry air at high pressures using uniform field produced between two hemispherically ended rods of 30 mm diameter, showed that when the gap was set at 5 mm, the mean breakdown electric field was approximately 120 kV/mm at 1450 psig[30]. There was no significant difference between results obtained using stainless-steel electrodes and results obtained with copper electrodes. However, other researchers have performed experiments[31] at lower pressures (up to 400 psig) and have shown a difference between stainless-steel and aluminum electrodes. At the pressure of 400 psig, the mean breakdown electric fields were approximately 46 kV/mm and 30 kV/mm for stainless-steel and aluminum electrodes respectively. From a fundamental point of view, the mechanism of high-field, high-pressure breakdown is not fully understood and still remains to be investigated

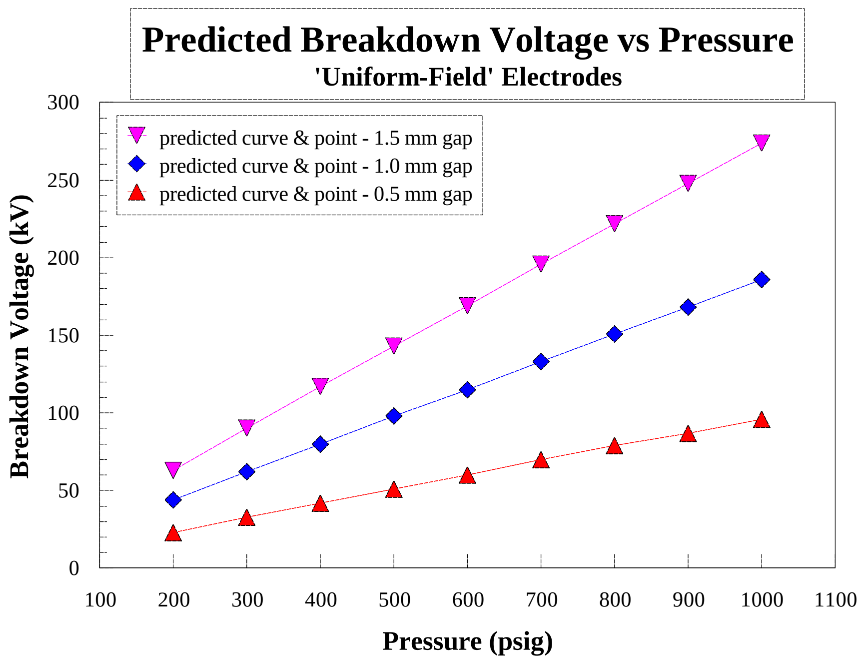

Figure 2: Predicted Breakdown Voltage vs Pressure by Paschen's law

in the whole field of study. Therefore, breakdown voltage requirements for the design of plugs in Task 3 are to be determined by experiments.

A constant volume high pressure chamber (Fig. 1) has been built and used for this test. Air was used because it is the major constituent of combustion in a DING engine. Also, it has a higher breakdown voltage requirement than methane or natural gas[30]. Therefore, the breakdown voltage in air/natural gas mixture is expected to be lower than in pure air. Different power supplies that were used in the experiments are:

1. 60 Hz AC Power Supply

It has been established that the breakdown voltage of a gap for an alternating voltage at low frequencies (≈50 Hz) is substantially the same as the for DC conditions[32]. Therefore, baseline measurements were made using a power supply (Fig. 3) capable of supplying 100 kV at 60 Hz to determine the breakdown voltage in compressed air for different gap lengths. This power supply is a 'Portable Oil Tester' (model OC90A) made by HiPotronics[33] Inc.

Flat-Flat Electrodes: A pair of electrodes made from 3.2 mm (1/8 inch) diameter steel drill rods with flat ends were mounted on opposite facing holes on the circumference of the pressure chamber. Using specially designed mounting fixtures, (Fig. 4) the air gap between the electrodes can easily be adjusted. A feeler gauge was used to set the gap with an accuracy of ±0.05 mm. With the electrode gap adjusted to 1 mm, voltage was applied to the electrodes. Starting from atmospheric pressure, the chamber was pressurized to 200 psig with air from a 3000 psig air cylinder. The applied voltage was increased from zero volt until breakdown occurred in the electrode gap. The power supply has an indicator showing the supplied voltage when the breakdown occurs. The breakdown voltage was also recorded with a voltage probe and a storage oscilloscope. The procedure was repeated with chamber pressure increased to 800 psig, in 100 psig intervals. When the applied voltage was increased beyond 52 kV, electrical breakdown occurred outside the electrode gap. Although the power supply indicated breakdown had occurred, no visible spark was observed. Efforts were made to remedy this problem. The chamber was rested on wooden blocks so that it was electrically 'floating'. A 1/4 inch thick Plexiglas sheet was used to isolate the metal table top from all test fixtures. High voltage putty was used to cover all electrical joints. All cables were replaced with one having a higher voltage rating. However, the problem still existed.

Since the waveform of the 60 Hz high voltage is sinusoidal, the rms (root-mean-square) voltage indicated by the power supply was converted to peak value. Table 3 shows the experimental data (peak voltage value) obtained with different gap lengths and pressures. Average breakdown voltage (Avg. V_s) was obtained from several data points. Included in the table were the high value (max. V_s) and low value (min. V_s) of the breakdown voltages, recorded for each test point. Curves were plotted for each electrode gap length using least-square fit. Since it is assumed that linear relationship

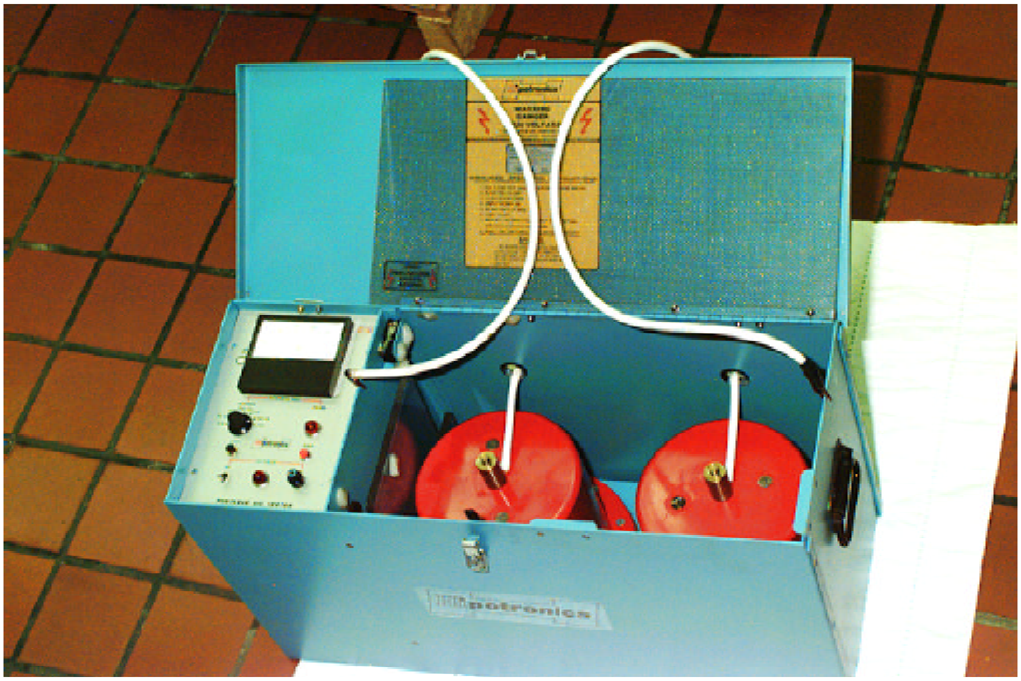

Figure 3: 60 Hz AC power supply

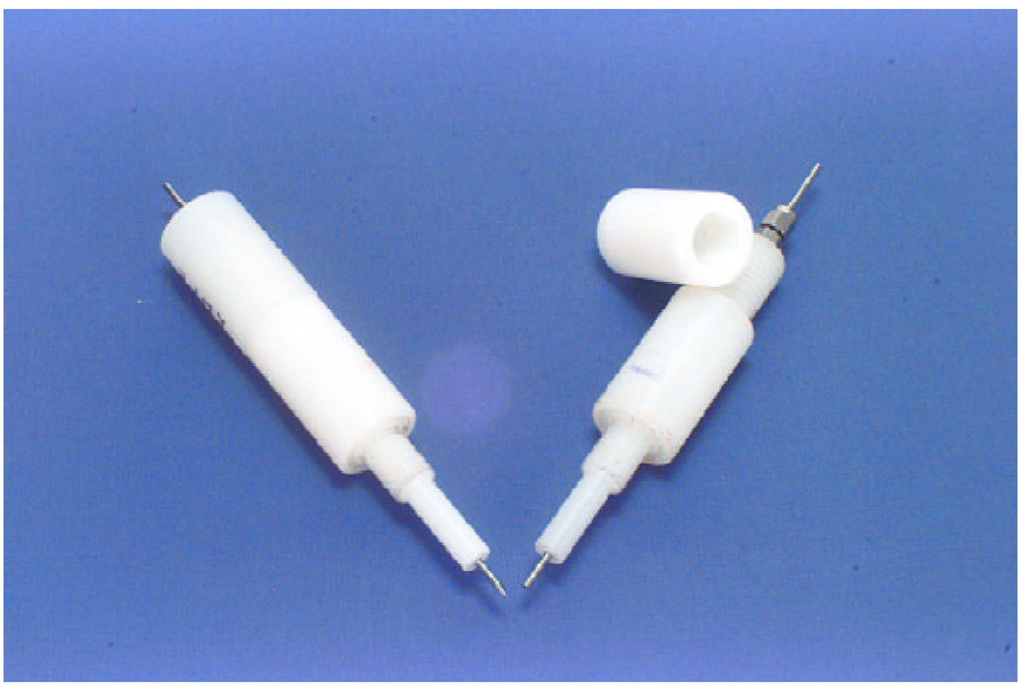

Figure 4: Electrode mounting fixture

exists between the breakdown voltage and pressure within this pressure range, straight lines were drawn (Fig. 5). Also listed in Table 3 are the estimated breakdown voltages (Est. V_s) obtained using the best-fitted curves.

For the 0.5 mm gap, the curve shows a change of gradient when the pressure is above 700 psig. This deviation has been explained in terms of a pressure dependence of the effective ionization coefficients and field emission at the cathode[30]. Since the experimental setup was voltage-limited, it was not possible to observe the same phenomena with the 1 mm and the 1.5 mm gaps. However, it is expected that the same behavior exists for the larger gaps. Notice that the measured breakdown voltages are much lower than predicted (Fig. 8 & Fig. 9). This is due to non-uniform field effect from the shape and sharp edges of the electrodes.

Pressure (psig)	Gap Length (mm)	Min. Vs (kV)	Max. Vs (kV)	Avg. Vs (kV)	Est. Vs (kV)
200	0.5	12.7	14.1	13.40	12.7
300	0.5	17.3	19.8	18.46	18.8
400	0.5	22.6	25.5	24.40	24.9
500	0.5	28.6	33.9	30.97	31.0
600	0.5	36.8	37.1	36.86	37.2
700	0.5	39.6	46.7	43.84	43.0
800	0.5	50.9	53.7	51.97	54.1
900	0.5	63.6	67.9	66.47	65.4
1000	0.5				76.7
200	1.0	27.6	31.1	29.52	29.1
300	1.0	35.4	36.8	35.99	36.9
400	1.0	41.7	46.4	44.83	44.8
500	1.0	50.9	56.6	53.67	52.7
600	1.0	58.0	62.2	60.10	60.6
700	1.0	65.1	72.1	68.48	68.5
800	1.0				76.4
900	1.0				84.2
1000	1.0				92.1
200	1.5	36.2	39.6	37.34	37.3
300	1.5	46.7	50.9	48.79	48.5
400	1.5	58.0	59.7	58.93	59.6
500	1.5	69.3	72.1	71.18	70.8
600	1.5				82.0
700	1.5				93.1
800	1.5				104.3
900	1.5				115.5
1000	1.5				126.6

Table 3: Breakdown voltage measurements for flat-flat electrodes

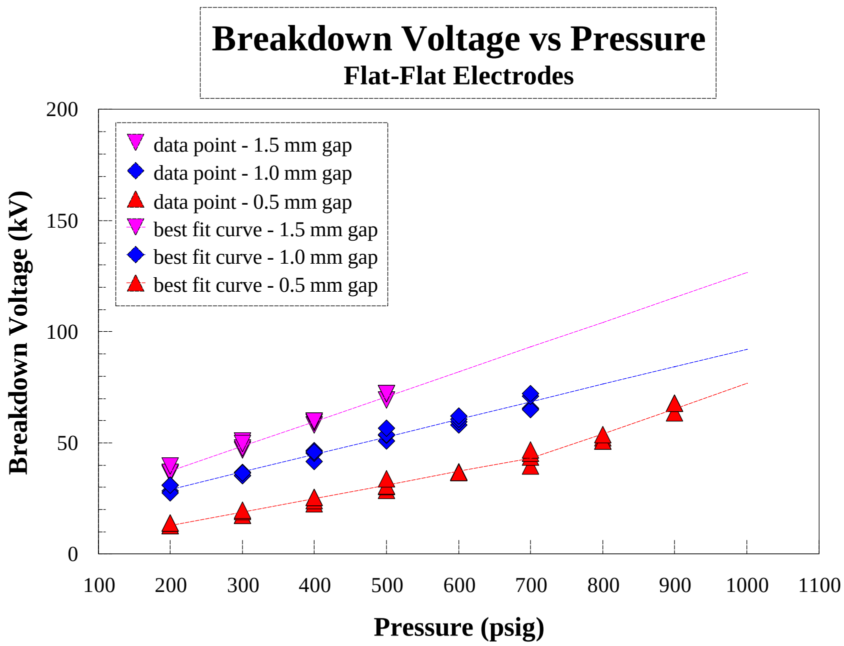

Figure 5: Breakdown Voltage vs Pressure for Flat-Flat electrodes

Flat-Round Electrodes: One way to prolong electrode life is to use a rounded-end central electrode. One of the flat-end electrodes was replaced by a rounded- end electrode with a radius of 1.6 mm. This will eliminate the edge effect from the flat end; therefore, the minimum breakdown voltage requirement is expected to be higher than the flat-flat electrode configuration. The same experiment was repeated with the electrode gap set at 0.5 mm and 1 mm. Table 4 shows the experimental data obtained. Fig. 6 shows the plots of the breakdown voltage vs pressure showing the experimental data points and the best-fit curves. The breakdown voltage requirements for the flat-round configuration were higher than the flat-flat configuration, as expected (Fig. 8 & Fig. 9). The scatter of the experimental data is larger than the flat-flat electrode case. This may be due to the reduced edge effect and lowering of the electric field intensity around the rounded end electrode.

Pressure (psig)	Gap Length (mm)	Min. Vs (kV)	Max. Vs (kV)	Avg. Vs (kV)	Est. Vs (kV)
200	0.5	17.0	22.6	21.00	20.3
300	0.5	24.9	29.3	26.98	27.0
400	0.5	31.1	39.9	37.12	33.8
500	0.5	39.6	42.9	41.30	40.5
600	0.5	41.0	45.3	43.13	47.2
700	0.5	45.7	48.4	47.55	53.9
800	0.5	53.7	65.1	60.88	60.7
900	0.5	68.6	76.4	72.83	67.4
1000	0.5				74.1
200	1.0	35.4	41.0	38.18	38.9
300	1.0	50.9	53.7	51.97	50.1
400	1.0	53.7	63.6	59.86	61.3
500	1.0	70.9	75.0	72.90	72.5
600	1.0				83.7
700	1.0				94.9
800	1.0				106.2
900	1.0				117.4
1000	1.0				128.6

Table 4: Breakdown voltage measurements for flat-round electrodes

It has been reported that in the DC conditions, the breakdown voltage characteristics of dissimilar electrodes depend on the polarity of the applied voltage[30]. With rod-plane gaps, the measured breakdown voltage was lower for an anode rod than for a cathode rod. To determine if this applies to the AC conditions with one of the electrodes grounded, the cables connected to the flat-round electrodes were switched.

No difference in the recorded breakdown voltage was observed. This agrees with results reported previously[32].

Flat-Point Electrodes: One way to lower the breakdown voltage requirement is to increase the electric field concentration at the electrode. One of the flat end electrodes was replaced by a point end electrode. This will maximize the edge effect from the point end; therefore, the minimum breakdown voltage requirement is expected to be lower than the flat-flat electrode configuration. The same experiment was repeated with the electrode gap set at 1 mm. Table 5 shows the experimental data obtained. Fig. 7 shows the plots of the breakdown voltage vs pressure showing the experimental data points and the best-fit curves. The breakdown voltage requirements for the flat-point configuration were lower than the flat-flat configuration, as expected (Fig. 5). As in the flat-round electrode case, the cables connected to the flat-point electrodes were switched. No difference in the recorded breakdown voltage was observed.

Pressure (psig)	Gap Length (mm)	Min. Vs (kV)	Max. Vs (kV)	Avg. Vs (kV)	Est. Vs (kV)
200	1.0	19.8	19.8	19.80	20.4
300	1.0	25.5	25.5	25.46	26.1
400	1.0	32.5	33.9	33.28	31.8
500	1.0	33.9	38.2	36.30	37.4
600	1.0	42.4	45.3	43.37	43.1
700	1.0	49.5	50.9	50.44	48.8
800	1.0	53.7	56.6	55.15	54.4
900	1.0	54.4	60.8	58.22	60.1
1000	1.0				65.7

Table 5: Breakdown voltage measurements for flat-point electrodes

Predicted breakdown voltages (Equation 1) and measured breakdown voltages for different electrode configurations with gaps length of 0.5 mm and 1 mm are plotted in Fig. 8 and Fig. 9 respectively. Notice the deviation from the uniform field predication is least for the flat-round case, and largest for the flat-point case.

2. High Frequency AC Power Supply

Although the breakdown voltage of a gap for an alternating voltage at low frequencies ($\approx$50 Hz) is substantially the same as the for DC conditions[34], when the frequency is raised to a value at which positive ions have insufficient time to cross the gap in half a cycle, a positive space charge is gradually built up in the gap leading to field distortion and a lowering of the breakdown voltage below the DC value. At much higher frequencies, the breakdown mechanism is further complicated as a consequence of the amplitude of oscillations of electrons in the gap

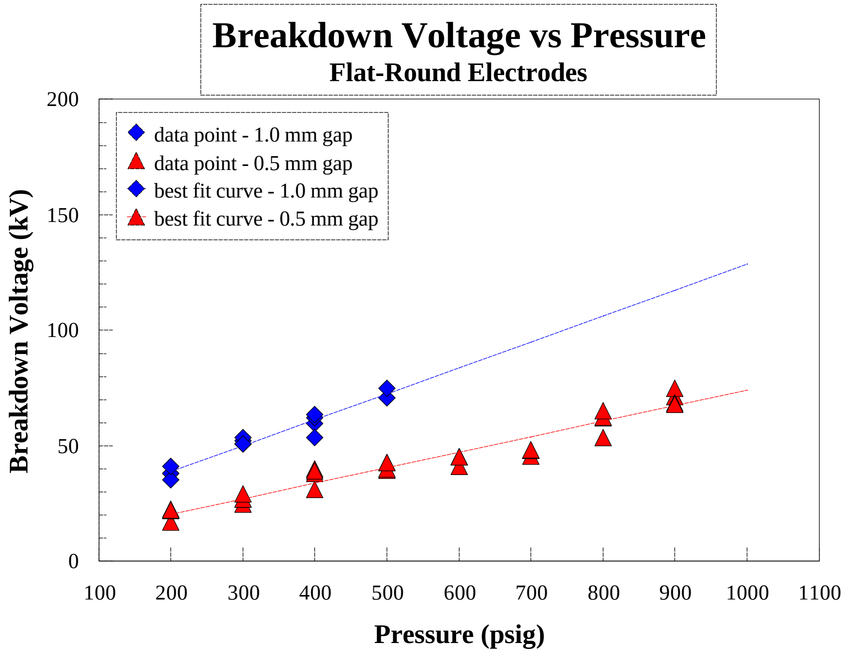

Figure 6: Breakdown Voltage vs Pressure for Flat-Round electrodes

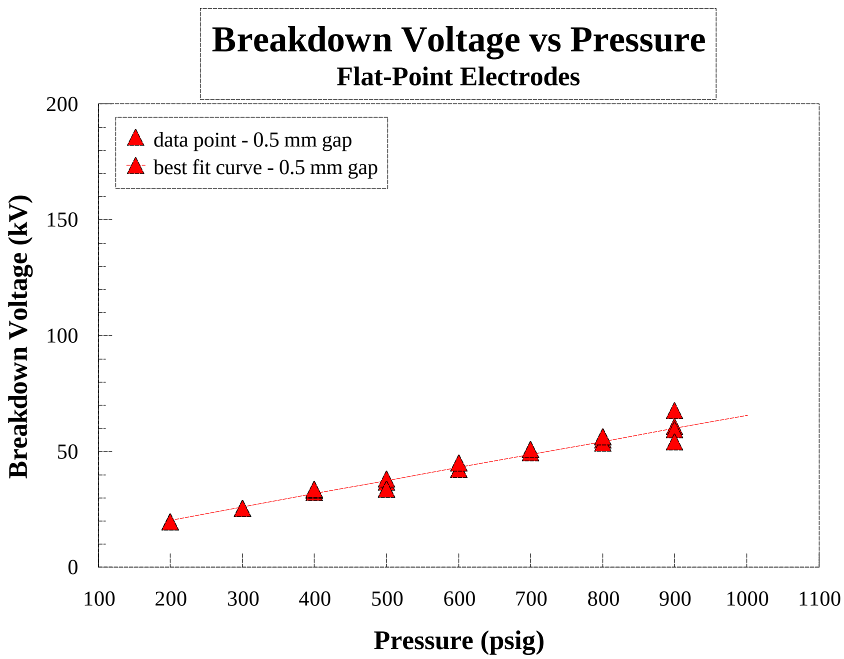

Figure 7: Breakdown Voltage vs Pressure for Flat-Point electrodes

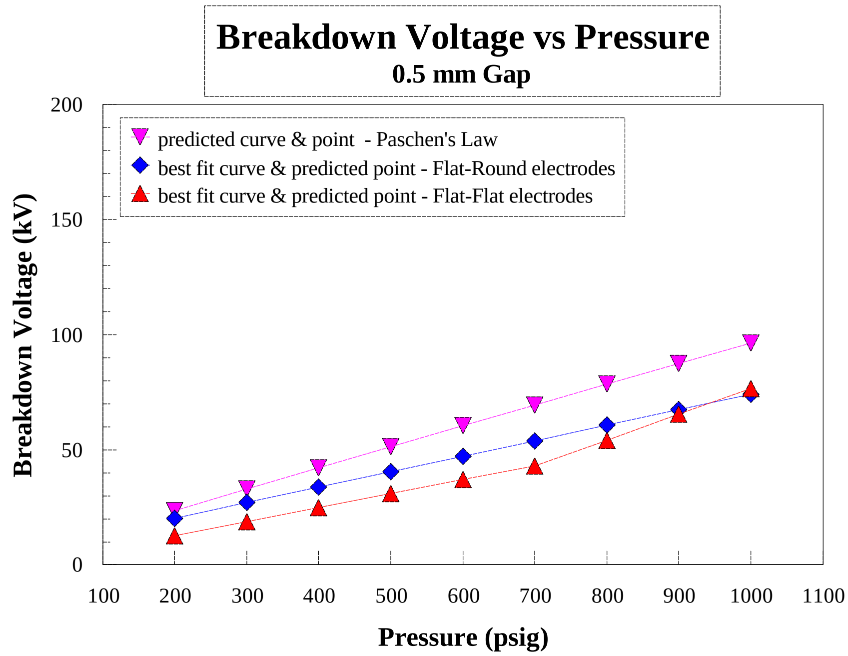

Figure 8: Comparison of breakdown voltages for a 0.5 mm gap

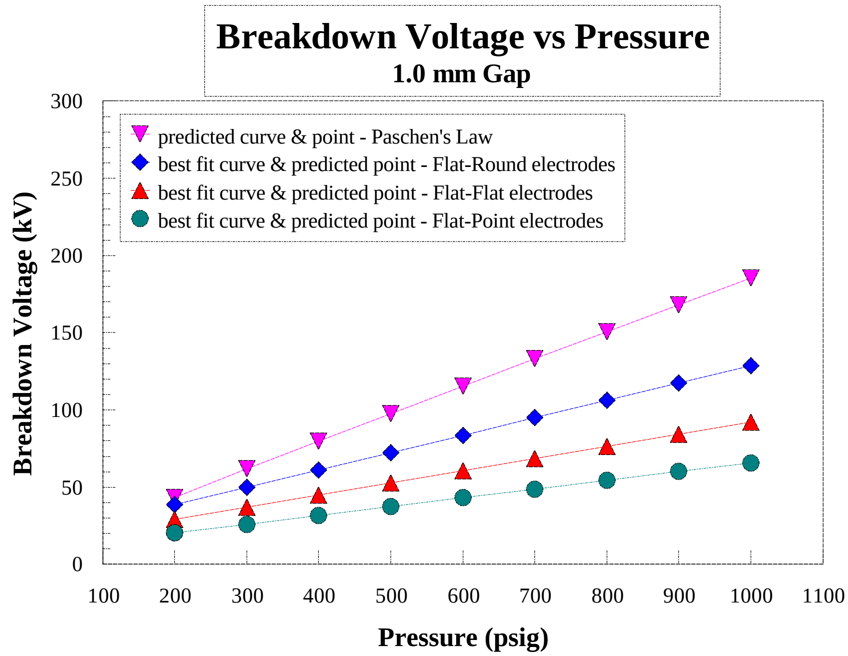

Figure 9: Comparison of breakdown voltages for a 1.0 mm gap

becoming comparable with the gap length so that cumulative ionization can be produced in the gap by an electron traveling many times the gap length in the direction of the alternating field. For example, in the case of breakdown between two plates in air with a gap of 2 mm at 147 psig, the breakdown voltage was lowered from 59 kV to 45 kV when 105 kHz AC voltage was used, as compared to DC voltage[34].

Caterpillar has specially designed a voltage generator capable of delivering an AC voltage with several frequency ranges covering 1 kHz to 400 kHz (Fig. 10). Fig. 11 shows the schematic diagram of the circuitry. The function of each component 'blocks' is briefly described in the following:

DC Power Supply - A power source for the electronics package. Able to supply 15 to 20 volts @ 20 amp DC power to two voltage regulators and a 108 volt DC supply.

5 Volt Regulator - A linear voltage regulator IC (integrated circuit) with 1 amp capacity. Able to provide powers to low voltage IC components including the *High Frequency Generator*, the *Spark Duration Control*, and the *Spark Repetition Rate Control.*

12 Volt Regulator - A linear voltage regulator IC (integrated circuit) with 1 amp capacity. Able to provide powers to moderate voltage IC components.

108 Volt supply - A regulated power supply with 17 amp surge capacity. Able to provide power to the *'H' Bridge Circuitry.*

Adjustable High Frequency Generator - A precision, adjustable frequency generator which provides the operating frequency for the AC spark. It has a frequency range of 1 kHz to 400 kHz.

Adjustable Spark Duration Control - An adjustable timer control which sets the duration of the AC pulses sent to the *Ignition Coil.*

Adjustable Spark Repetition Rate Control - An adjustable timer control which sets the time duration between each AC pulse sent to the *Ignition Coil.*

Enable/Disable Switch - An interruption switch which stops the spark pulses sent to the *Ignition Coil.*

Low Voltage Logic to High Voltage Circuit Interface - This circuitry provides signals to drive the *'H' Bridge Circuity.*

'H' Bridge Circuity - A high voltage switching circuitry generates 108 volt (peak-to-peak) square-wave AC pulses with 17 amp peak current to the primary side of the *Ignition Coil.*

Ignition Coil - A high turn ratio power transformer which converts the 108 volt AC pulses to 40 kV (peak-to-peak) AC pulses.

External Single spark Control - An external electronic circuitry which allows the ignition system to produce a single spark event.

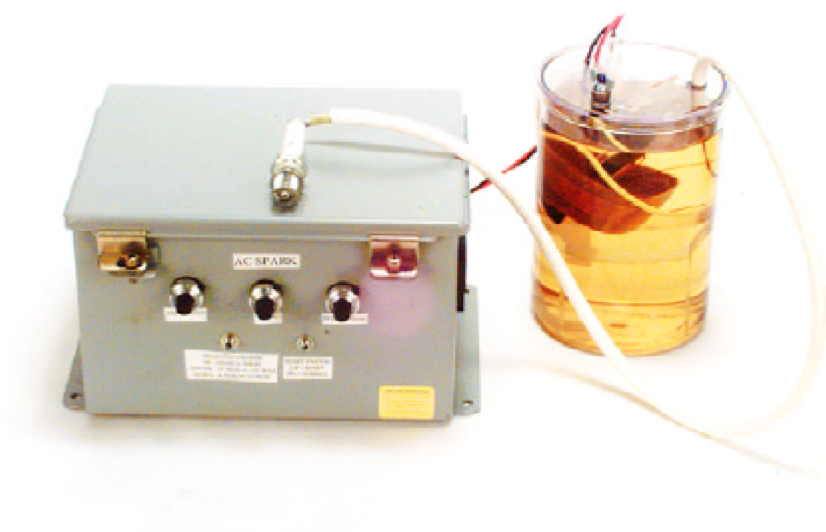

Figure 10: High frequency AC power supply

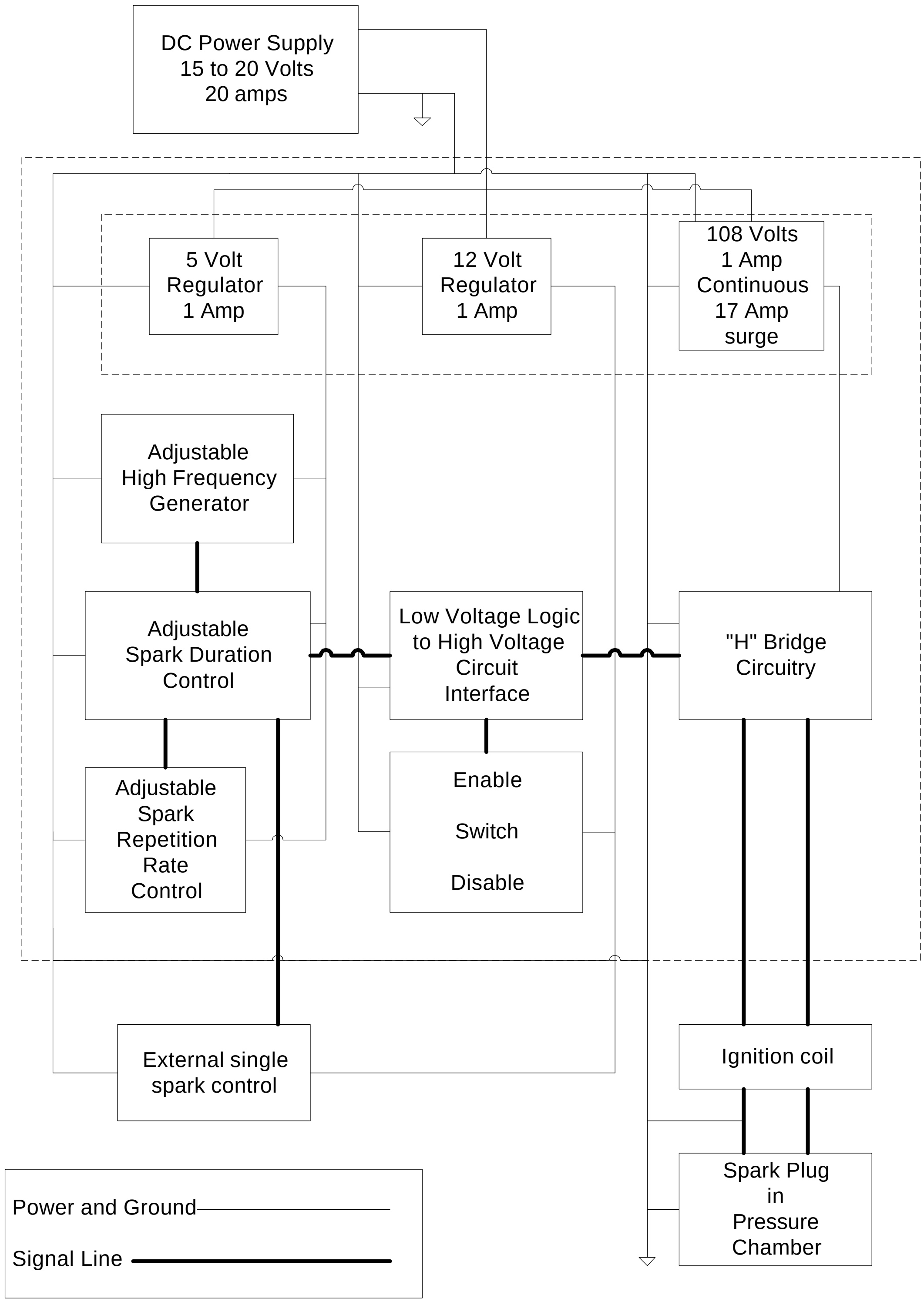

Figure 11: Schematic diagram of the high frequency AC power supply

For the high pressure chamber test, the voltage generator was adjusted to provide 3.3 ms duration, 108 volts AC pulses ranging from 8.7 kHz 10 kHz to the ignition coil. The ignition coil is a custom designed high efficiency voltage transform supplied by Coast Magnetics Corp[35]. The spark plug used was a J-gap type plug made by Champion Spark Plug Co[36]., with a gap of 0.28 mm. The pressure in the chamber was increased from 150 psig to 1000 psig. The observation of the spark under different pressures are as follows:

@ 150 psig - Consistent spark was observed with frequencies 8.7 kHz to 10 kHz.

@ 250 psig - Consistent spark was observed with frequencies 8.7 kHz to 10 kHz.

@ 500 psig - Consistent spark was observed with frequency at 8.7 kHz. Occasional misfires occurred when frequency was higher than 9.3 kHz.

@ 600 psig - Spark was observed with frequency at 8.7 kHz with occasional misfires. No spark was observed with higher frequencies.

@ 1000 psig - Spark was observed occasional with frequency at 8.7 kHz.

In an attempt to explain the result observed, the high voltage output from the ignition coil was measured using a spark-gap-peak-voltage calibrator. Table 6 shows the 'peak-to-peak' voltage output (Vout) from the ignition coil as a function of input signal frequency. Frequency response test was also performed on the coil showing that above 20 kHz, the output voltage dropped rapidly. The coil has the characteristic behavior of a bandpass filter with the peak response at 4.3 kHz. Factors which limit the high frequency performance of a transformer are the 'leakage' inductance and the intrinsic capacitance of the secondary winding. The high frequency response limit can be extended with changes in the winding design.

Frequency (kHz)	**Vout (kV)**
8.7	**48**
12.0	**40**
17.9	**38**
18.9	**30**
20.9	**28**
22.3	**26**
21.0	**12**

Table 6: Voltage output of the ignition coil as a function of input signal frequency

With a spark gap of 0.28 mm, 48 kV should cause breakdown at 1000 psig consistently as predicted from plots shown in Fig. 8. The problem may be caused by the capacitance of the spark plug. A spark plug consisting a central electrode and an outer electrode separated by a ceramic body constitute a capacitor. Since the impedance of an capacitor is given by $1/(\omega C)$, where ω is the voltage frequency and C is the capacitance, the impedance decreases with increase in ω. Therefore, even at 8.7 kHz, the 'leakage' current from the ceramic body may be high enough to cause the voltage to drop before breakdown can occur in the air gap. In order to overcome this problem, the capacitance of the spark plug must be reduced by redesigning the spark plug.

Caterpillar is currently working on the refinement of the electronics. The coil supplier and Champion Spark Plug Co.[36] are also involved in improving the coil and the plug design.

3. Caterpillar's Electronic Ignition System (EIS)

Caterpillar has developed and is using a proprietary electronic ignition system (EIS) in their SI natural gas engines. The EIS (Fig. 12) is based on the working principle of the transistorized coil ignition (TCI) system. In a typical TCI system, current normally flows from the battery or alternator through the primary winding of the high voltage coil, producing a strong magnetic field for energy storage. At the ignition point, the current in the primary winding is interrupted by an electronic switch, the magnetic field in the coil collapses and the high voltage is induced in the secondary winding. The rise time of the high voltage pulse in a typical TCI system is usually around 100 kV/ms and the duration of the current discharge in a spark is usually in the order of millisecond. The EIS also uses the 'coil on plug' design which allows the whole assembly to be situated under the valve cover. The integrated electronic control is a separate unit usually mounted on the side of the engine. The 'open circuit voltage' of the current EIS was 35 kV when tested with a 50 pF capacitor[37]. A typical spark plug used with the EIS is a J-gap type plug, with a gap of 0.28 mm. The EIS was tested in the high pressure chamber to determine its pressure breakdown capability. Starting from atmospheric pressure, sparks were initiated. Pressure in the chamber was gradually increased until sparks disappeared. The experiment was repeated with plug gap adjusted to 0.46 mm and 0.15 mm. During the experiment, the brightness of the spark increased with rising pressure. This is due to increase in spark energy in the gap. Table 7 summarizes the highest pressure breakdown capability obtained for each gap length.

Gap Length (mm)	Pressure (psig)
0.46	525
0.28	925
0.15	1500

Table 7: Pressure breakdown capability for each gap length

As the data have shown, the breakdown voltage of the EIS with a 0.46 mm gap at 525 psig is very similar to that of the flat-flat electrode configuration (Fig. 5). The EIS is also capable of causing breakdown in 1500 psig with a 0.15 mm gap. If a larger gap is desirable, the secondary voltage has to be made higher by increasing the turn ratio of the high voltage coil. More turns in the secondary winding means higher self-inductance which results in longer current discharge time. If the stored energy is unchanged, the instantaneous power is therefore lower. A TCI system stores energy in the high voltage coil according to :

$$W_m = \frac{1}{2} L_p I^2 \qquad (3)$$

where W_m is the magnetic energy, L_p is the self-inductance of the primary winding and I is the current. In order to increase W_m, L_p has to be larger which means more turns in the primary winding. Therefore, size limitation may be a major factor in designing an ultra high voltage coil in a TCI system with the Caterpillar EIS system.

4. Caterpillar's SDHP (short duration high power) Ignition System

In contrast to the TCI system, a capacitor discharge ignition (CDI) system operates on a different principle. The essential feature of a CDI system is that the energy is stored in the electric field of a capacitor which is in parallel with the primary winding of the high voltage coil. The capacitor normally is fully charged by the battery or the alternator to full working voltage. At the ignition point, an electronic switch causes the capacitor to discharge. The high voltage coil transforms the primary voltage generated by the discharge of the capacitor to the required high voltage in the secondary winding. The voltage rise rate of the high voltage pulse in a CDI system is usually around 1000 kV/ms and the duration of the current discharge in a spark is usually less than a millisecond. The SDHP ignition system shown in Figure 13 is a modified CDI system, whereas the energy-storing capacitor is in the high voltage side in parallel with the secondary winding. At the ignition point, current is allowed to flow in the primary winding generating a voltage in the secondary winding to charge the capacitor. The voltage continue to rise with the capacitor acquiring charges. When the voltage is high enough to cause breakdown across the spark plug gap, the energy stored in the capacitor is dumped into the spark. Since the connection between the capacitor and the plug can be made with minimal resistance and inductance, the duration of the discharge pulse will be very short. The SDHP system is capable of delivering a breakdown pulse of 10 nano-seconds with a peak power in the order of 1000 MW.

As part of Caterpillar's internal research, a spark plug has been designed for use with this ignition system. Initial testing of this system in the high pressure chamber exposed the problem with high EMI (electromagnetic interference). The EMI induced by the high power pulse was severe enough to interrupt the working of the EIS electronic control unit which was used to drive the SDHP system. Working is in process to solve this problem.

Bench durability tests on the EIS and the SDHP ignition system have recently been completed. A standard EIS, using a Champion spark plug and the SDHP ignition system using the specially designed spark plug, were both tested in a chamber filled with 15 psig of SF_6 gas. SF_6 is an electrically insulating gas commonly used to test high voltage properties of electrical components. A 15 psig of SF_6 will have the equivalent dielectric strength of 100 psig of air[31]. Since the SDHP system was tested in this low pressure, the EMI was not severe enough to cause problems. After 98,000,000 cycles of firing, the spark plugs in both systems showed signs of electrode erosion. The spark gap in the EIS/Champion system has increased from 0.3 mm to 1.2 mm, the spark gap in the SDHP system had increased from 1.5 mm to 2.5 mm. Although the rates of electrode erosion (1mm in 98,000,000 firings) are similar in both systems, since the EIS started with a smaller gap which implies that the breakdown voltage requirement is less than the SDHP system, this concludes that the relative rates of electrode erosion with the long duration, low power EIS/Champion system (300% gap increase) is greater than with the SDHP (40% gap increase). This tends to support the hypothesis that the short duration system, by staying out of the "Arc Phase", would result in less electrode erosion[9].

Conclusion:

Although not all bench testing has been completed, the following conclusions can be made based on results obtained:

1) The electrodes shape and the characteristics of the high voltage source can effect the breakdown voltage requirement.
2) The edge effect from the electrode shape can lower the breakdown voltage requirement.
3) The capacitance of the spark plug can cause significant 'leakage current' due to low impedance when using high voltage source with high frequencies. This increases the power demand from the voltage source.

From the results of the bench tests, valuable information has been obtained, and problems have been identified. Efforts to improve the high frequency AC and the SDHP systems are continuing. Effects due to high voltage rise rate and high signal frequency will be fully realized with the bench testing of the refined high frequency AC and the SDHP systems.

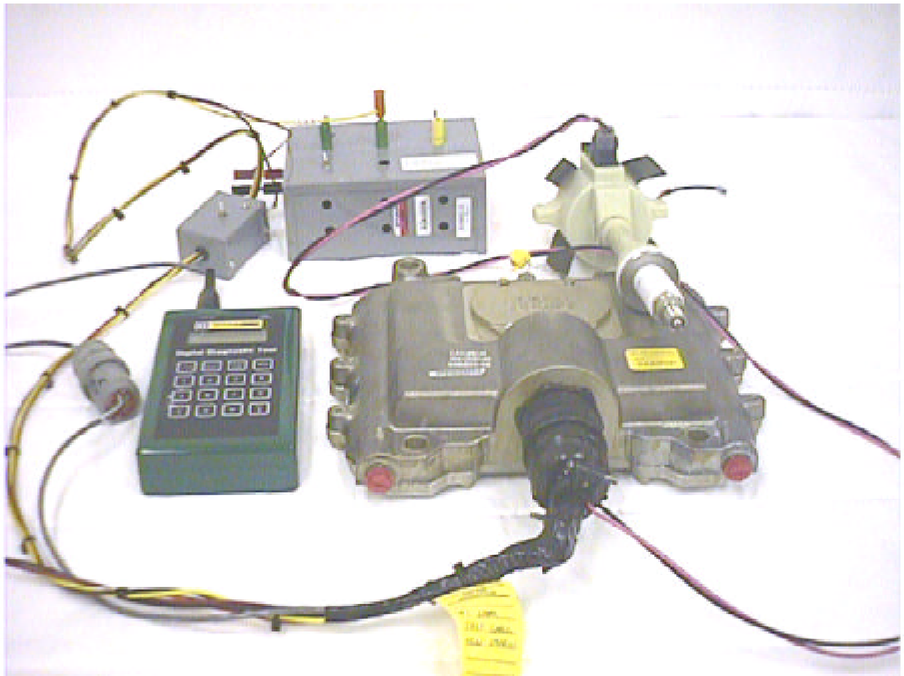

Figure 12: EIS (electronic ignition system)

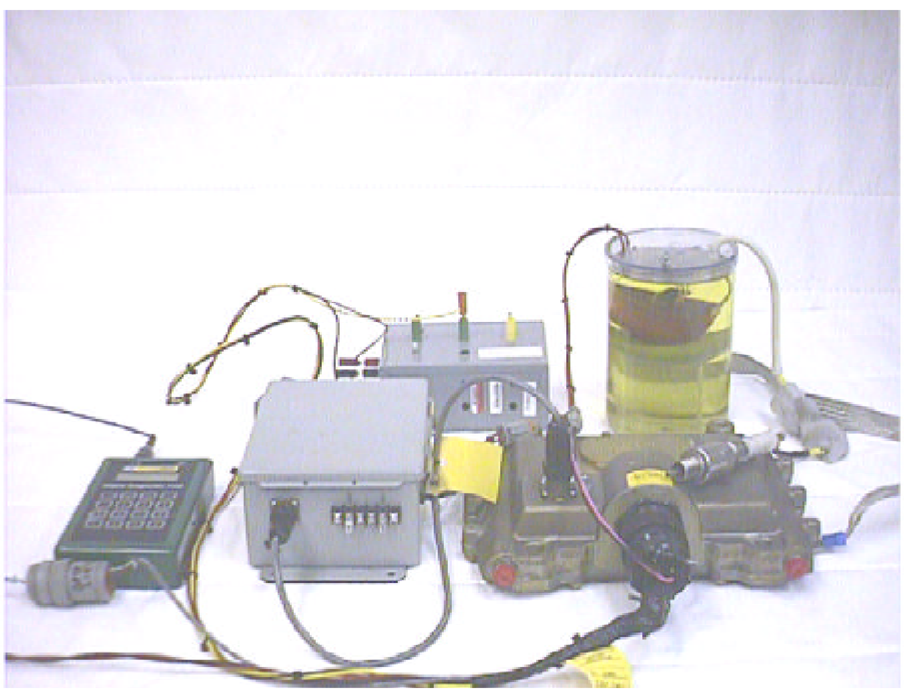

Figure 13: SDHP (short duration high power) ignition system

Subtask 2.2 - SmartFire Ignition System Evaluation

Objective:

Evaluate Adrenaline Research Inc.'s "SmartFire" ignition system's high pressure breakdown capability in air.

Accomplishment Summary:

An agreement was signed with Adrenaline Research Inc. to lease their 'SmartFire' ignition system for evaluation. They also provided engineering and technical support for the design of the high voltage coil and spark plugs which were tested in the high pressure chamber. A specially designed high voltage coil capable of supplying 40 kV was able to cause breakdown in 1000 psig of air using a specially designed spark plug having a 0.46 mm gap. The lower than expected breakdown voltage requirement was mainly due to the high rate of voltage rise which was estimated at about 3.5 kV/μs and the high frequency of the voltage pulse at 25 kHz. The specially designed spark plugs were made by Champion Spark Plug Co. and showed severe ceramic erosion after a short time (> 1 min) of testing. The conclusion from this bench test has shown that the "SmartFire' electronics can supply the voltage and power to achieve breakdown in high pressure, but more work is needed on the spark plug design. Adrenaline is in the process of improving the spark plug design and will use better ceramic material.

Accomplishment Details

An agreement has been signed with Adrenaline Research Inc. to provide a demonstration system to be tested in the high pressure chamber and in a single cylinder test engine. Their patented 'SmartFire' ignition system[10] is a dual energy system able to provide high voltage spark and high current arc. An initial high voltage spark is generated in the spark gap, using an ionization detection feedback loop to determine if ignition has occurred. A secondary spark with higher current arc could be generated to sustain the flame kernel[12]. Their electronic ignition system incorporates a microprocessor which can control the duration of the secondary current pulse and provides multiple spark capability. These two features make this system very attractive to the DING engine. Long duration spark and multiple sparks will ensure ignition and reduce misfire.

Adrenaline has designed and built the electronic ignition system for the high pressure chamber bench test. The high voltage coil was specially designed for Caterpillar. The 'open circuit voltage' of the coil was 41.5 kV when tested with a 50 pF capacitor[37] (Fig. 14). The spark plugs (Fig. 15) were designed by Adrenaline and made by Champion. The 'SmartFire' system was tested in the high pressure chamber to determine its high pressure breakdown capability. Fig. 16 shows the 'SmartFire' ignition system and the specially designed high voltage coil. Using a plug with 0.46 mm (0.018 inch) gap, the spark was initiated at atmospheric pressure. The pressure inside the chamber was increased gradually to 1100 psig when the sparks disappeared. Strong sparks were still observed at 1000 psig. However, damage must have been

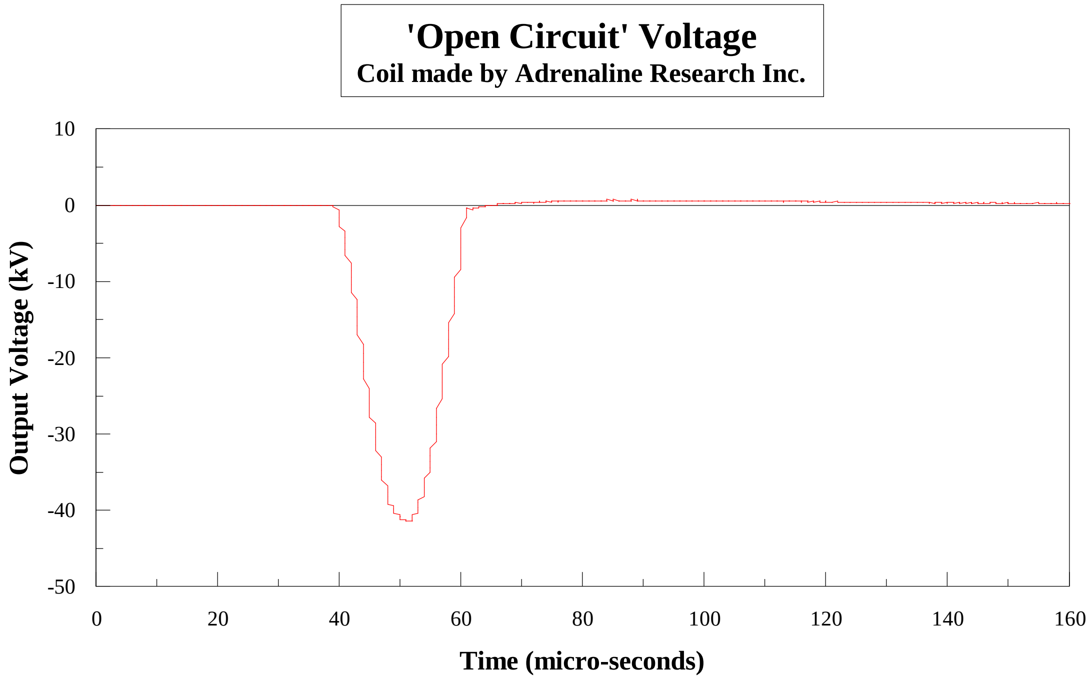

Figure 14: Voltage Output vs Time

Figure 15: Adrenaline plugs made by Champion

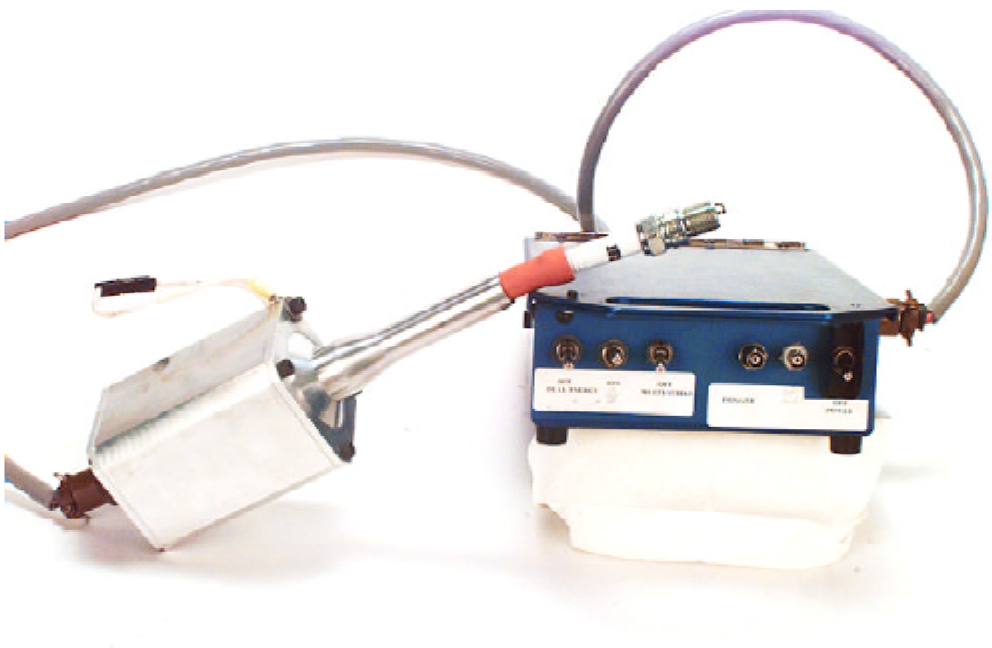

Figure 16: `S martFire' ignition system

done to the plug because it was no longer able to repeat the high pressure performance. Close examination shows that the ceramic insulator in the plug suffered severe damage (Fig. 17). A second plug with a 0.51 mm (0.020 inch) gap was able to sustain a spark at 900 psig and failed at 1000 psig. Damage to the ceramic was again observed (Fig. 18). Increasing the gap to 1.02 mm (0.040 inch) in the third plug enabled the pressure to reach 800 psig. Damage to the ceramic was also observed (Fig. 19). Inferior ceramic material used in the plugs was suspected as the reason for the damage. For comparison purpose, a fourth plug was tested under conditions used by Adrenaline. The plug was gaped at 1.27 mm (0.050 inch) and was continuously tested for 70 minutes under 100 psig pressure. According to past experience at Adrenaline with plugs made by Allied Signal Inc., the ceramic insulator should survive the test without noticeable damage. However, the plug made by Champion showed grooves in the ceramic tip (Fig. 20). When this plug was again subjected to the high pressure test, 500 psig was the highest pressure achievable with good sparks. Table 8 summarizes the highest pressure breakdown capability obtained for each gap length. Since four different plugs were used in the bench test and because differences in the plugs can greatly affect the pressure ratings, Table 8 should only be used as a general guide for the breakdown pressure for each gap length.

Gap Length (mm)	Pressure (psig)
1.27	500
1.02	800
0.51	900
0.46	1000

Table 8: Pressure breakdown capability for each gap length for Adrenaline system

Conclusion:

The 'SmartFire' system's electronics can provide high voltage pulse capable of causing breakdown in 1000 psig with 0.46 mm gap, but the spark plug requires better ceramic material. The lower-than-expected breakdown voltage requirement was mainly due to the high rate of voltage rise, which was estimated at about 3.5 kV/μs. Since the duration of the voltage pulse is about 24 μs, this has an equivalent frequency of 21 kHz. The high frequency factor may also help to lower the breakdown voltage requirement.

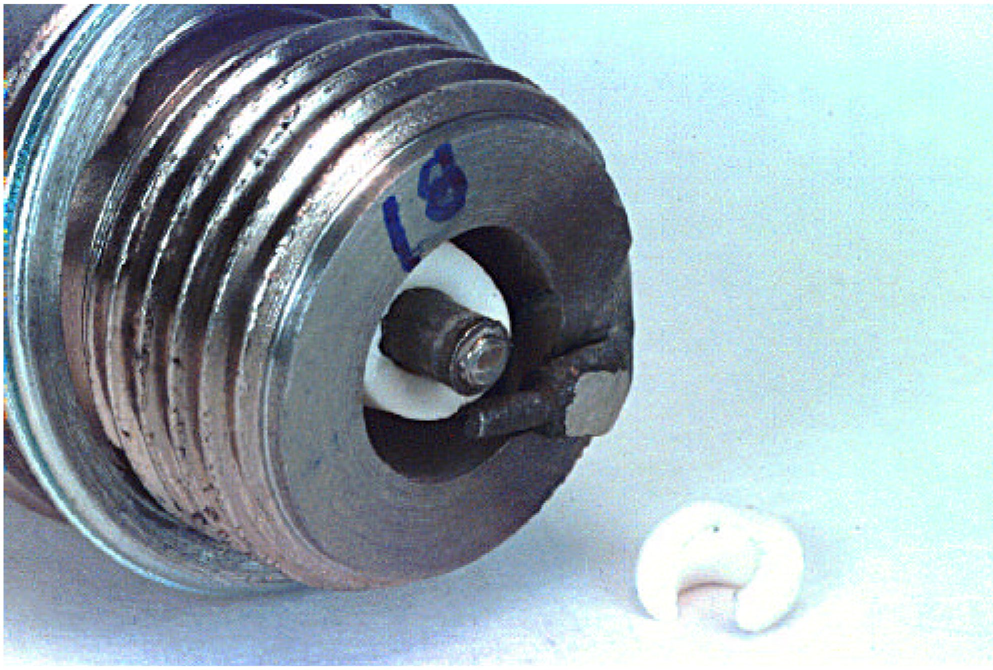

Figure 17: Spark plug after bench testing with the Adrenaline System (0.46 mm gap)

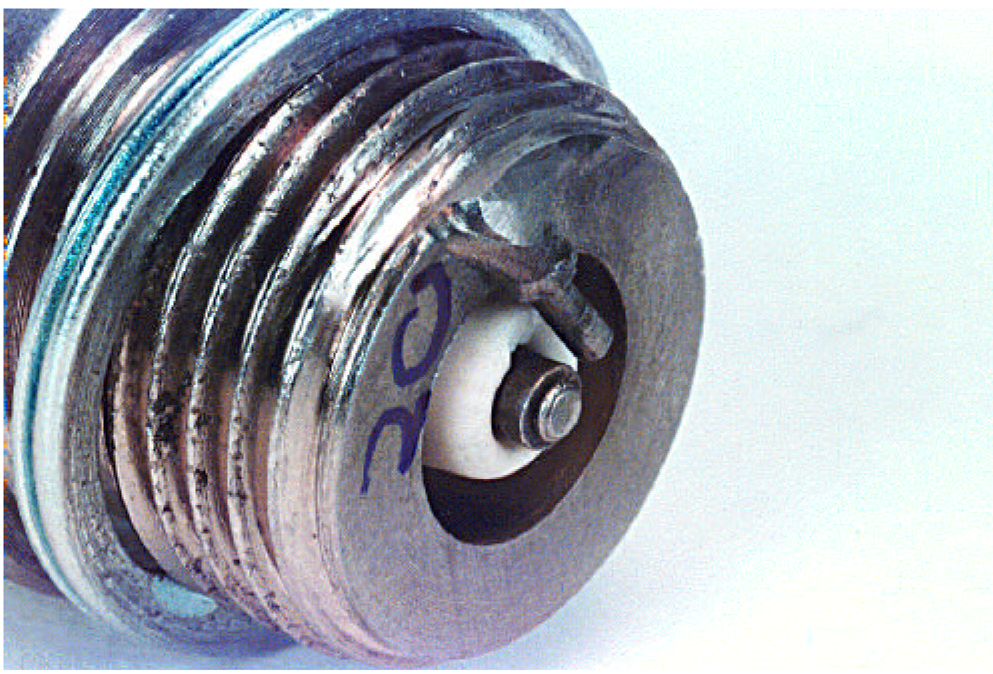

Figure 18: Spark plug after bench testing with the Adrenaline System (0.51 mm gap)

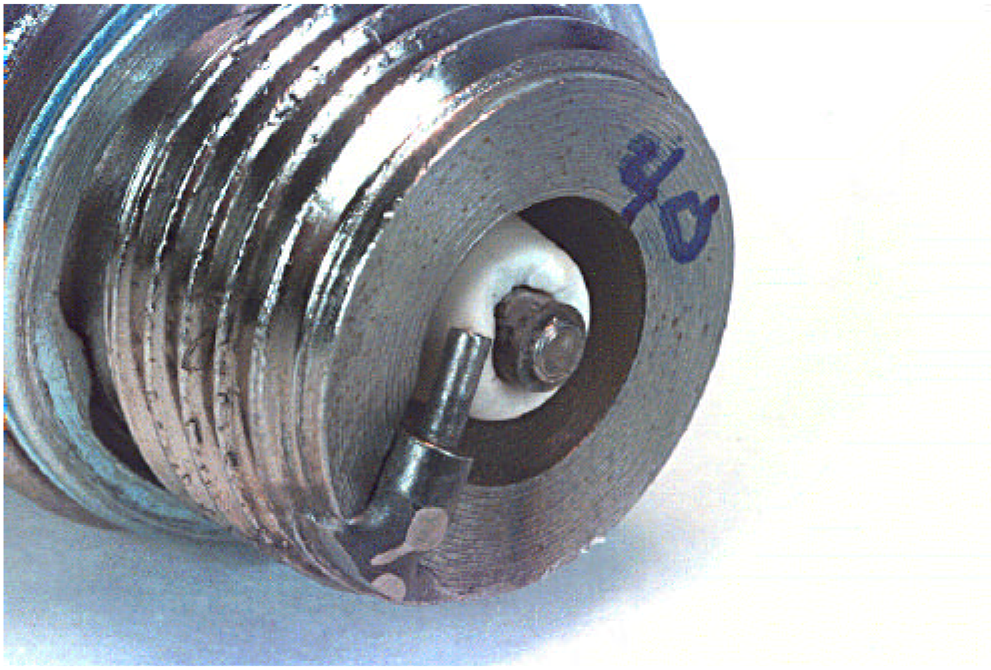

Figure 19: Spark plug after bench testing with the Adrenaline System (1.02 mm gap)

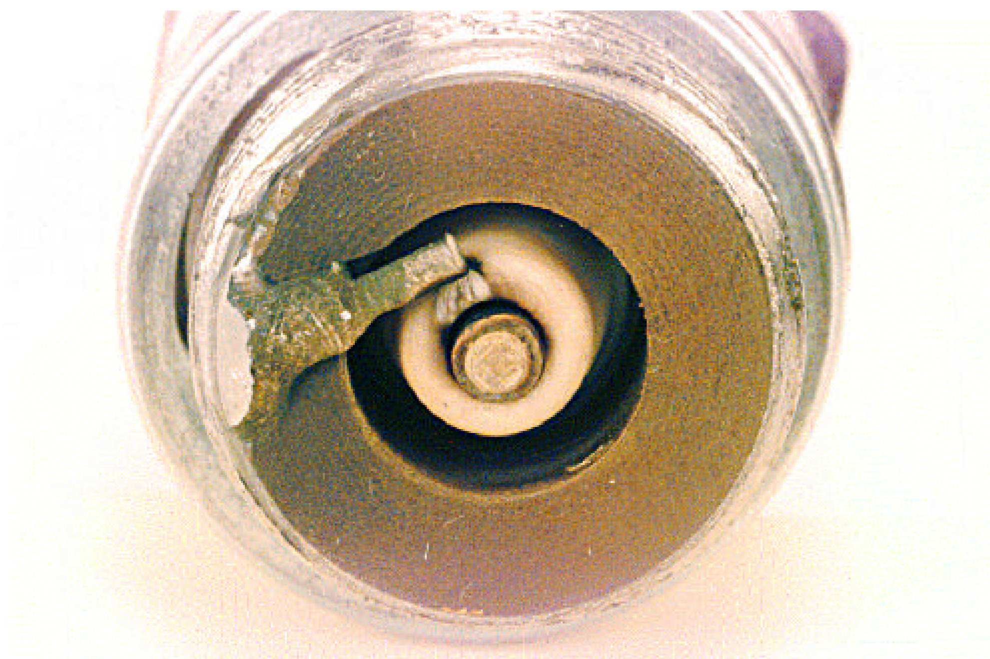

Figure 20: Spark plug after bench testing with the Adrenaline System (1.27 mm gap)

Subtask 2.3 - Minimum Electrical Insulation Requirement

Objective:

Determine the minimum thickness of electrical insulation between electrodes required for the prototype ignition system. This will help to design the prototype spark plug to be tested in Phase 2.

Accomplishment Summary:

Ceramic material type AD-94 (supplied by Coors Ceramic Co.[38]) and titanium oxide were tested using a commercially available oil tester. Results show that a minimum thickness of 4.8 mm is required to insulate 54 kV. Also observed was that the dielectric strength per unit thickness (kV/mm) of the ceramic material is a function of the thickness and varies with the manufacturing process.

Accomplishment Details

In order to determine the minimum thickness requirement of the insulator in the prototype spark plug, ceramics disks of different thickness (4 mm, 5 mm and 6 mm) were made. These disks were machined from a 3/4 inch diameter ceramic rod made of material type AD-94 (nom. 94% Al_2O_3) supplied by Coors Ceramic Co.[38] and from a 1 inch diameter titanium oxide (TiO_2) rod supplied by Kyocera Industrial Ceramics Corp.[39] Opposite faces of the disk were coated with a thin layer of gold by vacuum sputtering to ensure good electrical contact with the ceramic. Using the 'Portable Oil Tester'[32], the ceramics disks were subjected to a test similar to the ASTM D149 test method[40]. The ceramic disk was sandwiched between two semi-spherical electrodes (Fig. 21) and submerged in an oil bath (Fig. 22). Diala AX[41] oil was used, which is a mineral oil with high dielectric breakdown voltage. Voltage was gradually increased until breakdown occurred. Since the breakdown destroyed the disk, a new test specimen was used for each test. Initially the gold plating was applied to the entire disk surface (Fig. 23); however, surface discharge across the ceramic disk surfaces was observed at the rim of the ceramic disk. A second set of samples were made with gold plating the central area (Fig. 24). This stopped the surface discharge. Disks with thickness of 4 mm, 5 mm and 6 mm were tested. Tables 9 and 10 show the experimental data obtained with AD-94 and TiO_2 respectively. The rms (root-mean-square) values were converted to the peak values which were the actual voltage differences across the disk surfaces. Tables 9 and 10 also show the dielectric strength in units of kV/mm. With the ceramic disk removed, the electrode gap was adjusted to 4 mm, 5 mm and 6 mm to test the breakdown voltage of the oil at different gaps (Table 11).

Fig. 25 is a plot of breakdown voltage vs disk thickness for different materials. The data scatter obtained from the two ceramic materials is mainly due to the non uniformity of the ceramic resulting from the manufacturing process. The data shows that the dielectric strength of the two ceramic materials are very similar, with an average value of about 11 kV/mm. Information from Coors[38] states that the dielectric strengths of AD-94 are 8.7 kV/mm and 11.8 kV/mm for a 6.35 mm and a 3.18 mm test specimens, respectively. Apparently the dielectric strength of ceramic materials depends on the thickness of the test specimen, with higher kV/mm values for thinner insulators.

Thickness (mm)	Vs (rms) (kV)	Vs (peak) (kV)	Dielectric Strength (kV/mm)
3.93	22	31	7.9
4.03	29	41	10.2
4.13	37	52	12.7
4.18	31	44	10.5
4.96	44	62	12.6
5.05	48	68	13.4
5.25	43	61	11.6
5.30	40	57	10.7
5.30	46	65	12.3
5.90	43	61	10.3
5.91	50	71	12.0
6.08	51	72	11.9
6.16	50	71	11.5
6.20	45	64	10.3

Table 9: Breakdown voltage measurement for different thickness of Al_2O_3

Thickness (mm)	Vs (rms) (kV)	Vs (peak) (kV)	Dielectric Strength (kV/mm)
4.04	40	57	14.0
4.04	36	51	12.6
5.02	45	64	12.7
5.03	46	65	12.9
5.03	39	55	11.0
6.03	43	61	10.1
6.03	45	64	10.5
6.03	46	65	10.8
6.04	44	62	10.3
6.04	46	65	10.8
6.04	46	65	10.8

Table 10: Breakdown voltage measurement for different thickness of TiO_2

Gap (mm)	Vs (rms) (kV)	Vs (peak) (kV)	Dielectric Strength (kV/mm)
4.04	49	69	17.2
5.02	54	76	15.2
6.04	58	82	13.6

Table 11: Breakdown voltage measurement for gaps filled with Diala oil

Conclusion:

The conclusion from the bench testing is as following:

1. The dielectric strength of the two ceramic materials (AD-94 & TiO_2) are very similar, with an average value of about 11 kV/mm.

2. The dielectric strength (kV/mm) of ceramic materials depend on the thickness of the material, with higher values for thinner insulators. For a given thickness, the overall insulating strength of an insulator can be increased by using more than a single layer of ceramics with thinner thickness.

3. For a single layer ceramic insulator made of AD-94 or TiO_2, 4.8 mm is the thickness requirement in order to insulate 54 kV.

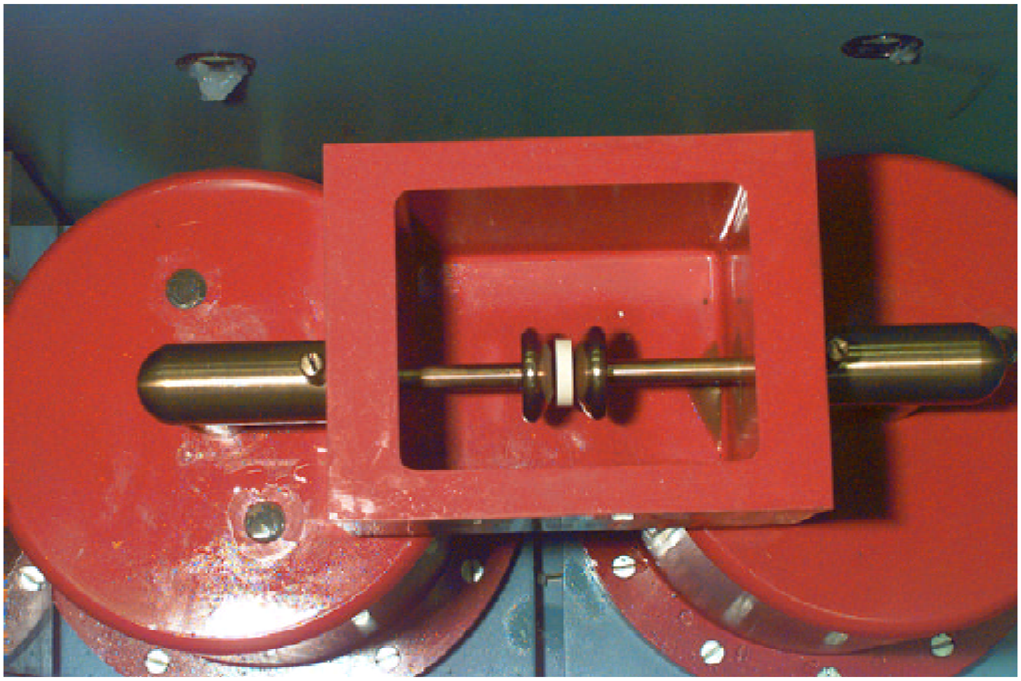

Figure 21: Ceramic disk sandwiched in the portable oil tester

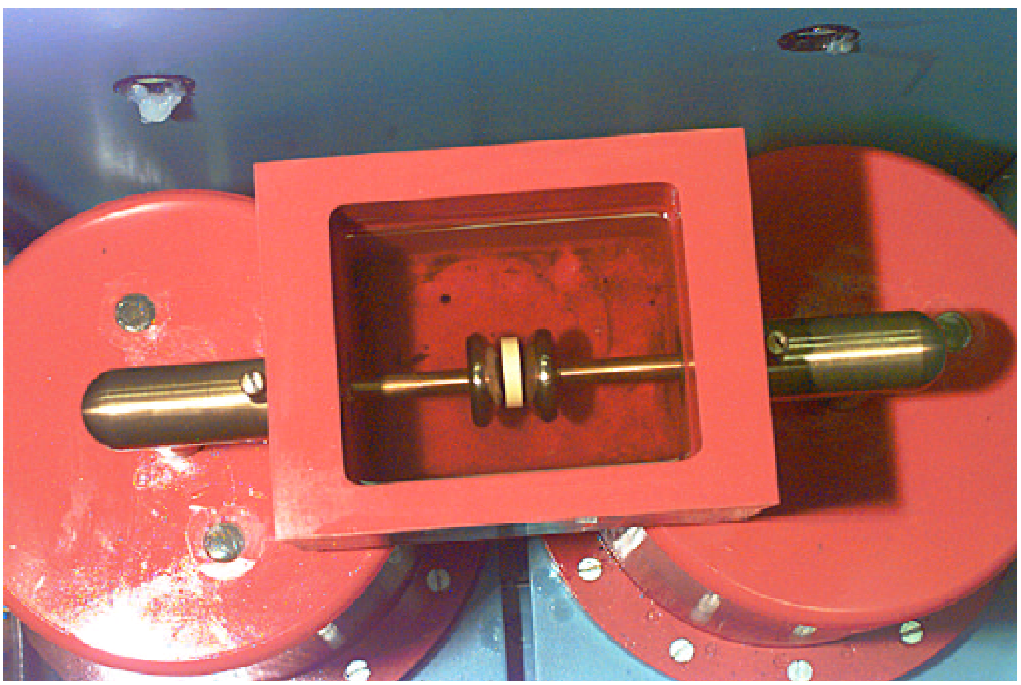

Figure 22: Ceramic disk sandwiched in the portable oil tester submerged the oil bath

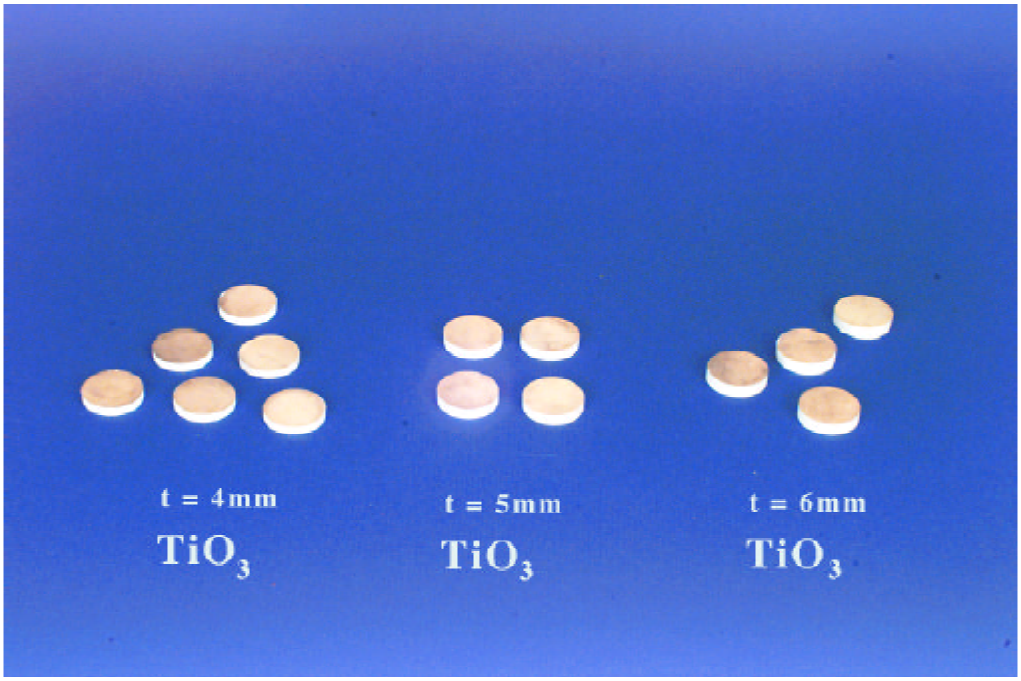

Figure 23: Disks showing original coatings

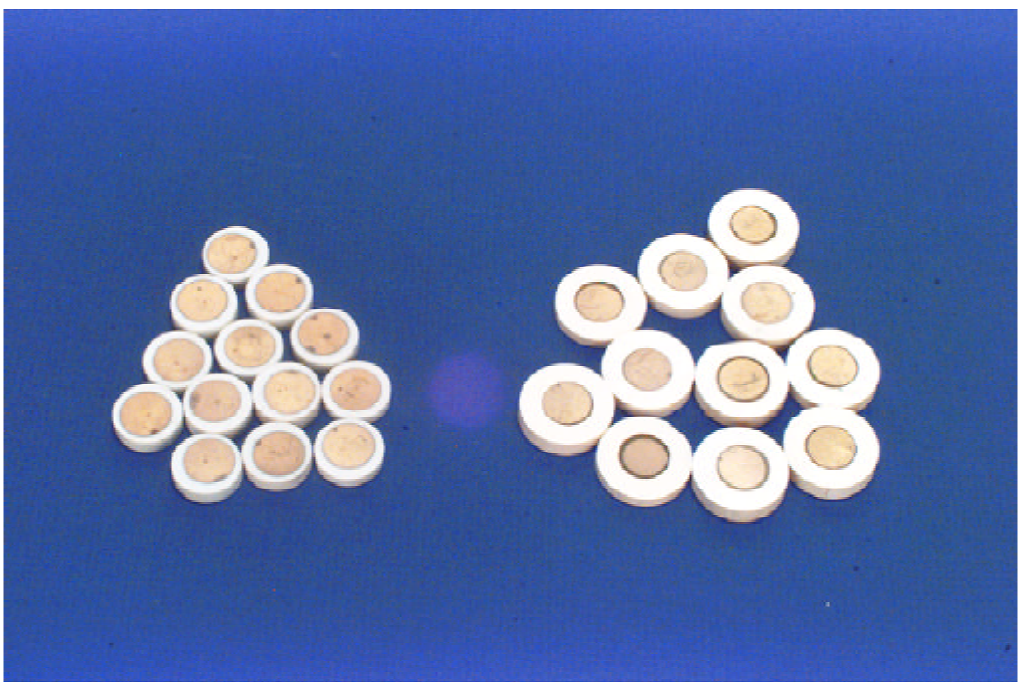

Figure 24: Disks showing modified coatings

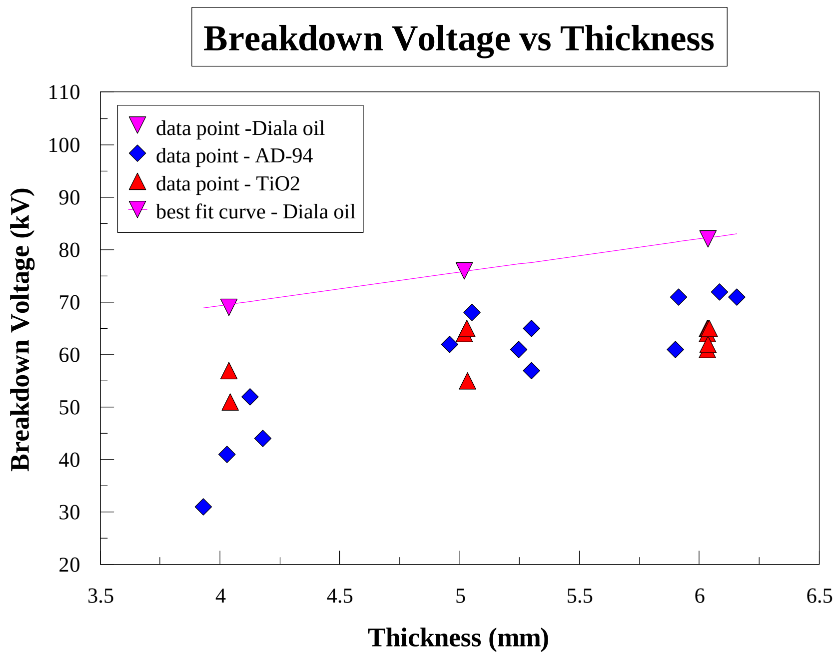

Figure 25: Breakdown Voltage vs Insulator Thickness

Subtask 2.4 - Micropilot Concept Evaluation

Objective:

Determine the feasibility of micropilot ignition with pilot fuel quantity containing less than 1% of the maximum fuel energy, by evaluating its effect on the engine performance.

Accomplishment Summary:

Tests in a Caterpillar's 3501 test engine (1 cylinder, 4.3 liter), indicate that a premixed open chamber natural gas engine can operate at the 2020 kPa BMEP (brake mean effective pressure) peak torque condition with diesel pilot containing 1% of the total fuel energy. Comparable brake efficiency was also achieved with improved NOx emissions over the standard SI engine using the electronic ignition system (EIS). The results provide a good indication to the feasibility of using this technology in the DING engine.

Accomplishment Details

A conventional Caterpillar 3501 natural gas engine was used to investigate the feasibility of using pilot fuel for ignition. The spark plug and the standard ignition system in a 3501 natural gas engine were replaced with a Caterpillar production diesel fuel injector (model HI90). The minimum delivery rate of the HI90 injector is about 9 mm^3/stroke of diesel fuel at 14000 kPa supply pressure. A specially designed adapter allowed the injector to be mounted in the cylinder head. Natural gas was injected into a mixing chamber mounted between the intake manifold and the cylinder head. Actual mass flow rates of the diesel pilot and the natural gas were measured in the engine tests.

With the engine operating at peak torque condition (2020 kPa @ 1300 RPM), intake air temperature at 49°C, and volumetric air-fuel (A/F) ratio of 18.7, pilot diesel quantity was decreased from 7% to approximately 1%. The 1% pilot quantity corresponds to a diesel delivery of approximately 9 mm^3 per each firing cycle. Table 12 shows the operating and measured engine parameters. As data indicate in Table 12, decreasing the pilot fuel from 7% to 1% resulted in a 2% increase in BSFC (brake specific fuel consumption) but reduced the BSNOx by a factor of ten.

Pilot Diesel Qty (%)	Pilot Diesel Flow (g/min)	Pilot Injection Timing (BTDC)	Natural Gas Flow (g/min)	Exhaust Temperature (C)	Brake Efficiency (%)	BSFC (BTU/hp-hr)	NOx (PPM)	BSNOx (g/hp-hr)
6.5	20.0	20	278.3	460	40.1	6342	357	2.01
3.8	11.6	20	288.0	465	39.8	6390	246	1.39
2.0	5.0	25	297.0	461	39.6	6427	120	0.68
1.0	<5.0	25	302.0	469	39.2	6487	34	0.19

Table 12: Engine test results @ peak torque condition with varying pilot fuel quantity

With the engine operating at peak torque condition (2020 kPa @ 1300 RPM), intake air temperature at 49°C, minimum (1%) pilot diesel quantity and pilot injection timing of 25 degree BTDC, the A/F ratio was varied between engine lean misfire and detonation limits. Table 13 shows the operating and measured engine parameters from A/F ratios of 18.6 to 14.4. Engine misfire occurred with an A/F ratio of 18.6 while mild detonation occurred with an A/F ratio of 14.4.

Volumetric A/F Ratio	Excess Air Ratio	Natural Gas Flow (g/min)	Exhaust Temperature (C)	Brake Efficiency (%)	BSFC (BTU/hp-hr)	NOx (PPM)	BSNOx (g/hp-hr)
18.6	1.83	302.0	469	39.2	6487	34	0.19
18.7	1.81	293.0	469	39.9	6383	55	0.31
15.8	1.53	283.6	551	41.2	6169	245	1.13
16.2	1.56	278.6	531	42.0	6062	337	1.57
14.4	1.39	272.2	564	42.7	5951		

Table 13: Engine test results @ peak torque condition with varying A/F ratio

With the engine operating at rated power condition (1700 kPa @ 1750 RPM), intake air temperature at 49°C, the 9 mm^3 pilot diesel quantity was equal to 1.5% of the total energy of the fuel intake. With the pilot injection timing set at 28 degree BTDC, Table 14 shows the operating and measured engine parameters when the A/F ratio was varied between engine lean misfire and detonation limits. Engine misfire occurred with an A/F ratio of 16.7, while mild detonation occurred with an A/F ratio of 13.3.

Volumetric A/F Ratio	Excess Air Ratio	Natural Gas Flow (g/min)	Exhaust Temperature (C)	Brake Efficiency (%)	BSFC (BTU/hp-hr)	NOx (PPM)	BSNOx (g/hp-hr)
16.7	1.62	356.0	577	37.6	6766	72	0.38
16.8	1.64	346.3	572	38.8	6560	110	0.57
15.8	1.59	337.8	574	39.9	6376	165	0.80
15.3	1.48	336.3	607	39.9	6380	320	1.46
13.3	1.29	328.0	635	41.0	6200	2200	8.50

Table 14: Engine test results @ rated power condition with varying A/F ratio

For comparison, the engine was operated at the baseline condition of the standard SI mode (1400 kPa @1500 RPM) with the 9 mm^3 (minimum) pilot fuel. Table 15 shows the comparison of the operating and measured engine parameters using the micropilot vs the EIS as the ignition sources. Note that the 'initiation' timing for the micropilot system is defined as the pilot injection timing, while it is defined as the spark timing in the EIS system. The data indicates that when operating at similar engine efficiency, the micropilot ignition system provides slightly less NOx emission and cooler exhaust temperature than when using the standard EIS.

System	'Initiation' Timing (BTDC)	Natural Gas Flow (g/min)	Volumetric A/F Ratio	Exhaust Temperature (C)	Brake Efficiency (%)	BSFC (BTU/hp-hr)	NOx (PPM)	BSNOx (g/hp-hr)
Micropilot	28	234.8	16.8	509	39.9	6374	125	0.63
EIS	26	242.6	16.5	543	39.4	6460	142	0.73

Table 15: Engine test results with EIS and micropilot ignition systems

Conclusion:

9 mm^3 of diesel fuel injected directly in the combustion chamber of a homogenous charge natural gas engine (4.3 liter per cylinder) can cause ignition and with engine efficiency equal to a standard engine. Energy content of the 9 mm^3 of pilot diesel constitutes to about 1% fuel energy input of the engine operating at peak torque (maximum fuel consumption) condition. The energy percentage will increase with other engine operating conditions, reaching to the maximum at engine idle. Since the minimum flow rate of the current injector is 9 mm^3 per injection, it is premature to conclude that this is the minimum required quantity for ignition based on the preliminary engine test. Review of injector designs indicate that major effort is required to design an injector which can deliver a smaller quantity of pilot fuel than 9 mm^3 per engine cycle.

Although this is different from the DING engine, it has provided a good indication to the feasibility of using the micropilot as a source of ignition in the DING engine. The results warrant further research for application to the DING engine.

Task 3: Design/Procure Best Ignition Concept for One Cylinder Engine Test

Proposed Work:

Hardware shall be designed and procured to develop a complete system for testing the most promising system from the evaluation in Task 1 and 2. This shall include a spark plug system (or oil injection) and a modified cylinder head for testing on one cylinder of a 3116 DI propane or gasoline engine.

Accomplishment Summary:

A 3126 DING engine, instead of the 3116 DI propane or gasoline engine has been selected for the one-cylinder demonstration. All hardware necessary for one cylinder engine test have been designed. Hardware includes modified cylinder heads, specially designed prototype spark plugs, ignition system electronics and parts for system installation. Two 3126 cylinder heads, the EIS and the 'SmartFire' ignition systems have been procured. Refinements of the high frequency AC spark and the SDHP ignition systems are continuing, and will be procured for the one cylinder engine test.

Accomplishment Details:

One cylinder of a 3126 DING engine (6 cylinders, 1.2 liters per cylinder) will be used for the test. The 3126 (diesel) engine is currently used for pickup/delivery trucks and for buses, and will be suited for eventual transportation sector field demonstration. The following hardware have been designed and are being procured for the 3126 DING engine.

Gas Retainer/Ground Electrode

Past experiences with Caterpillar's DING engines with glow plug ignition system indicates that a glow plug shield (Fig. 26) is required to enhance ignition. The function of the shield is to increase residence time of the air/fuel mixture around the hot surface of the glow plug. The benefits due to the increase in residence time are less engine misfires due to more stable ignition and longer glow plug life due to lowering the glow plug temperature requirement. The shape of the glow plug shield and orientation in the cylinder head were derived from past engine test experiences. A new 'gas retainer' has been designed which is a larger version of the glow plug shield. It also serves the purpose of providing the ground electrode for one of the prototype spark plugs (Fig. 39). The shield is being made of Inconel 625.

Spark Plug

Due to the location of the glow plug hole, material available in the cylinder head, and other installed engine components such as valves and rockers, there is a size restriction for the spark plug. From information obtained in Task 2.3, a solid layer

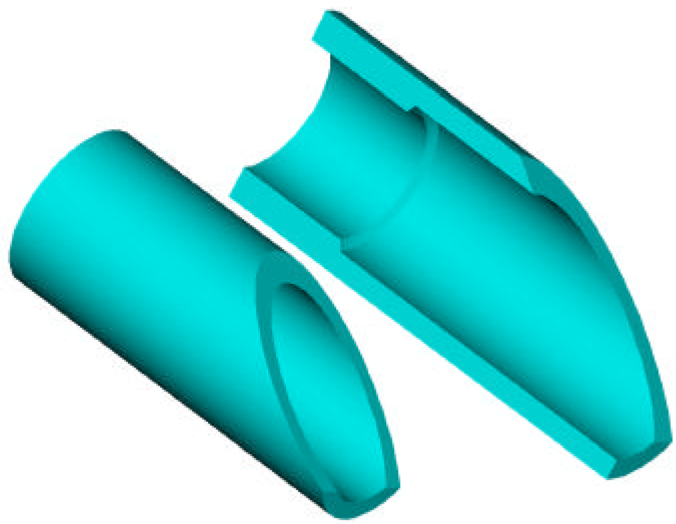

Figure 26: Glow plug shield

ceramic insulator should have at least 4 mm in thickness in order to shield 44 kV, which is the target voltage output of all ignition systems to be used in the engine test. Fig. 27 shows the prototype insulator body design. The overall length of the insulator body is about 200 mm. The outside diameter of the long body is 12.4 mm and the inside cavity diameter is 5 mm. The purpose of the inside cavity is to aid in making the long insulator body, as well as to accommodate the central electrode. If the thickness of the ceramic is not adequate to isolate the high voltage central electrode from the surrounding ground, a ceramic sleeve may be used . Therefore, the central electrode is essentially being shielded by two layers of ceramic. This configuration is to increase the dielectric strength of the insulator body (see Task 2.3). Fig. 28 shows the assembled spark plug assembly. Usually the ground electrode is an integral part of the spark plug, but this prototype design will have the ground electrode separated from the insulator body, but mounted in the cylinder head (Fig. 36). This design uses the traditional air-gap discharge mode of operation.

A second prototype design was proposed which uses the surface-discharge mode of operation. The major advantage of a surface-discharge ignitor over a traditional air-gap ignitor is its lower breakdown voltage increase with pressure. Fig. 29 shows the second prototype insulator body design. It has a rib-like feature which will provide a surface discharge path between the central electrode and the ground electrode. Fig. 30 shows the assembled spark plug assembly. This design has an integral ground electrode which is part of the plug assembly.

Fig. 31 and Fig. 32 show the two prototype central electrode designs. The diameter of the electrodes is about 1 mm with an overall length of about 200 mm. The size of the disks at the end of the electrodes determine the spark gap length of the spark plugs (Fig. 39 & Fig. 43). Input from Champion[36] will help to decide the material used.

Both designs are currently at the concept design stage. The shape and form of the prototype plugs will be finalized with design and manufacturing input from Champion[36] who will be making the plugs.

Cylinder Head

Although the 3126 cylinder head has provision for glow plug installation, the glow plug hole has to be enlarged and modified for a specially designed spark plug. Fig. 33 and Fig. 34 show the modified cylinder head. Fig. 35 shows the sectional view of the glow plug and the air-gap spark plug holes. The glow plug hole is enlarged to 13 mm in diameter, with an inside groove machined near the bottom of the cylinder head. This groove is needed to install the 'gas retainer/ground electrode' for the air-gap spark plug (Fig. 36). Limited by the amount of the material that can be removed from the cylinder head, 13 mm probably is the maximum size for the spark plug hole. O-ring with high temperature capability will be used to achieve gas sealing. A 45 degree chamfer is machined at the opening of the plug hole. The chamfer surface will provide a sealing surface for the O-ring. Fig. 37 and Fig. 38 show the air-gap spark plug

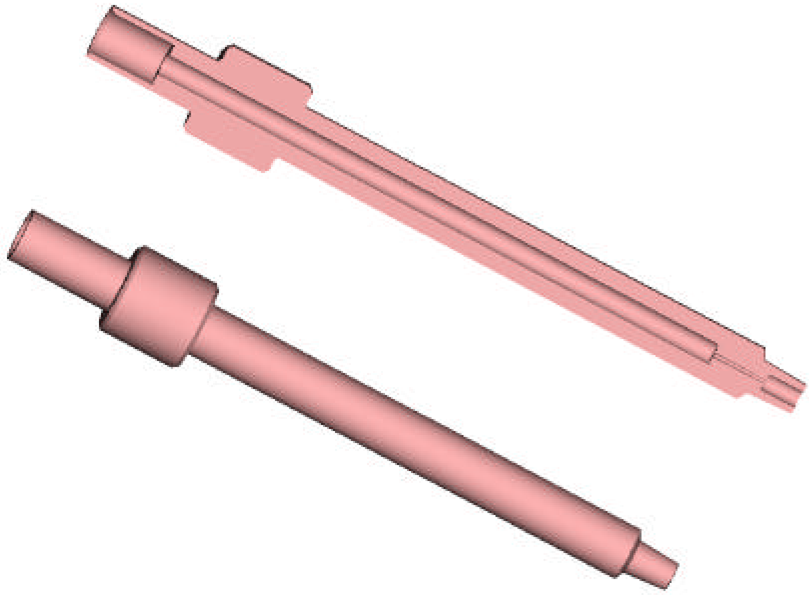

Figure 27: Prototype ceramic insulator body

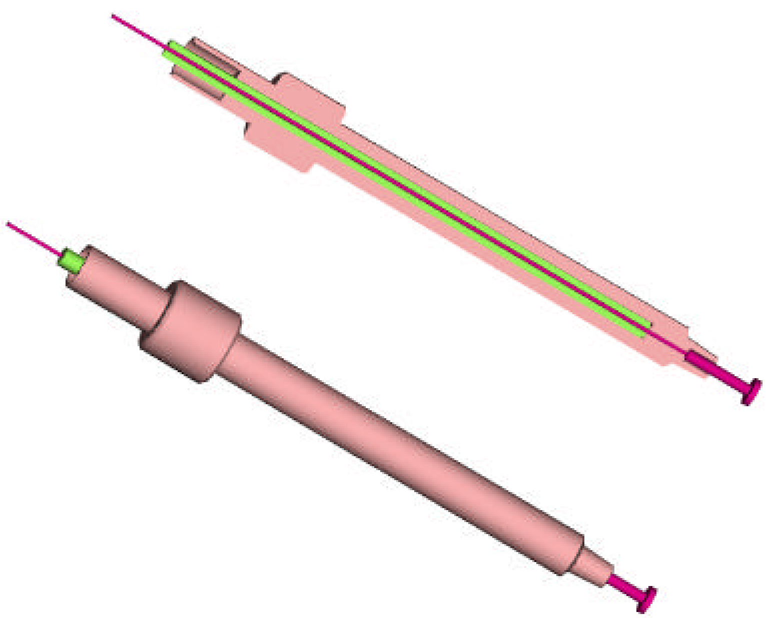

Figure 28: Prototype spark plug assembly

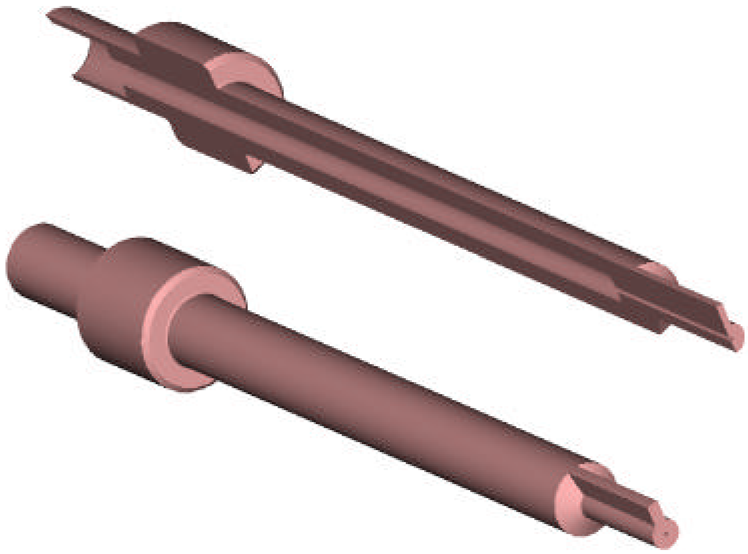

Figure 29: Prototype ceramic insulator body for surface-discharge plug

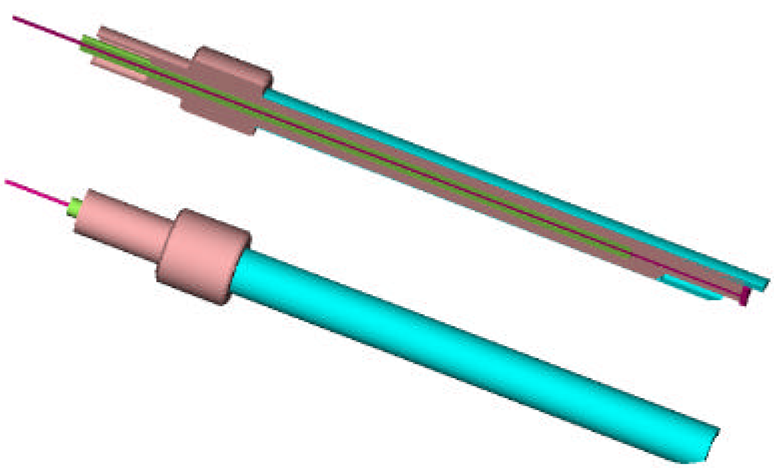

Figure 30: Prototype surface-discharge spark plug assembly

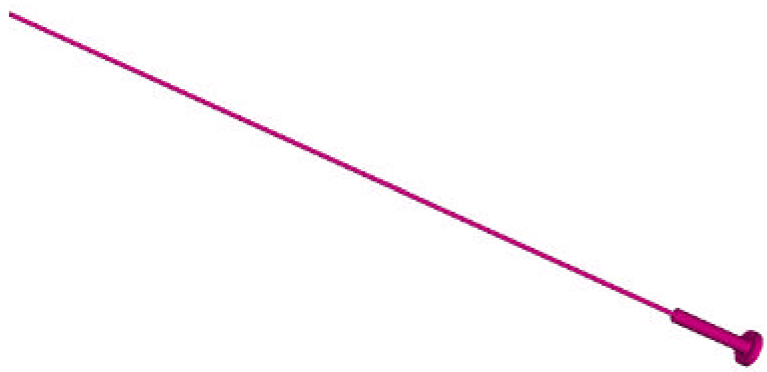

Figure 31: Central electrode for the air-gap spark plug

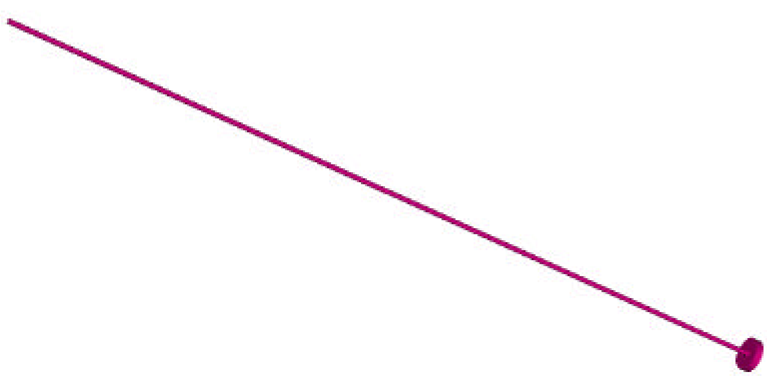

Figure 32: Central electrode for the surface-discharge spark plug

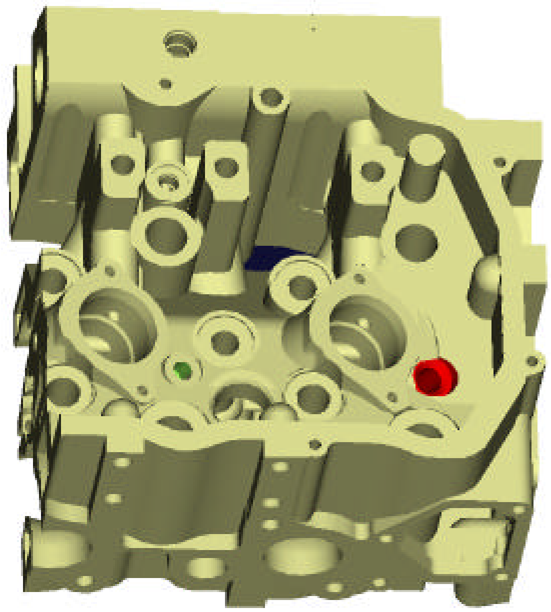

Figure 33: Modified 3126 DING cylinder head

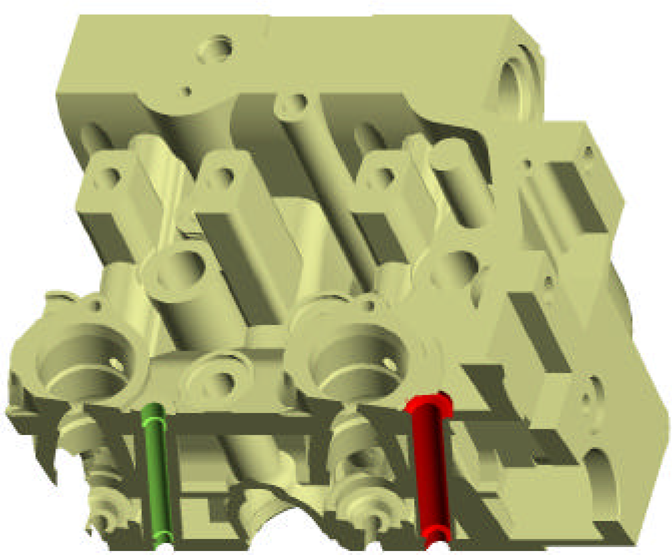

Figure 34: Cutout view showing the glow plug and the spark plug hole

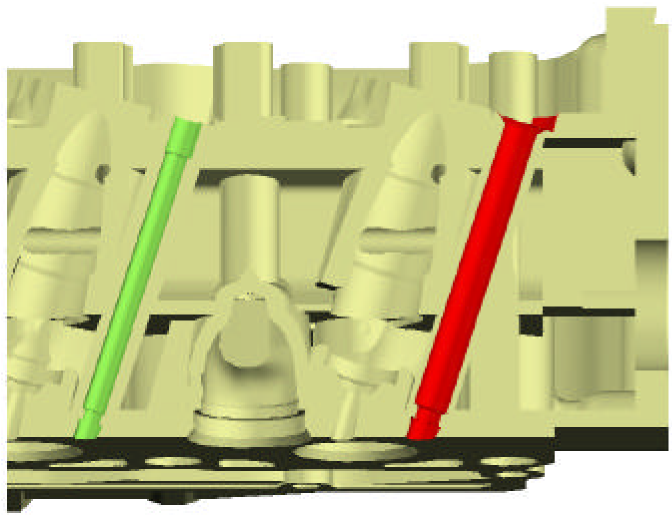

Figure 35: Sectional view of the glow plug and the air-gap spark plug holes

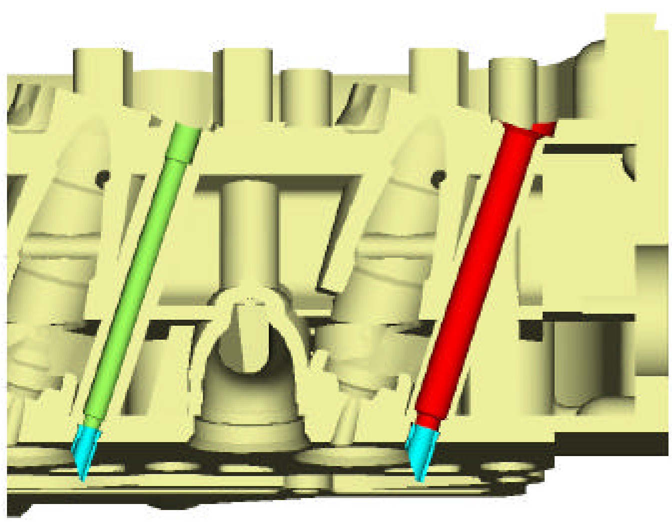

Figure 36: Sectional view showing the 'gas retainer/ground electrode'

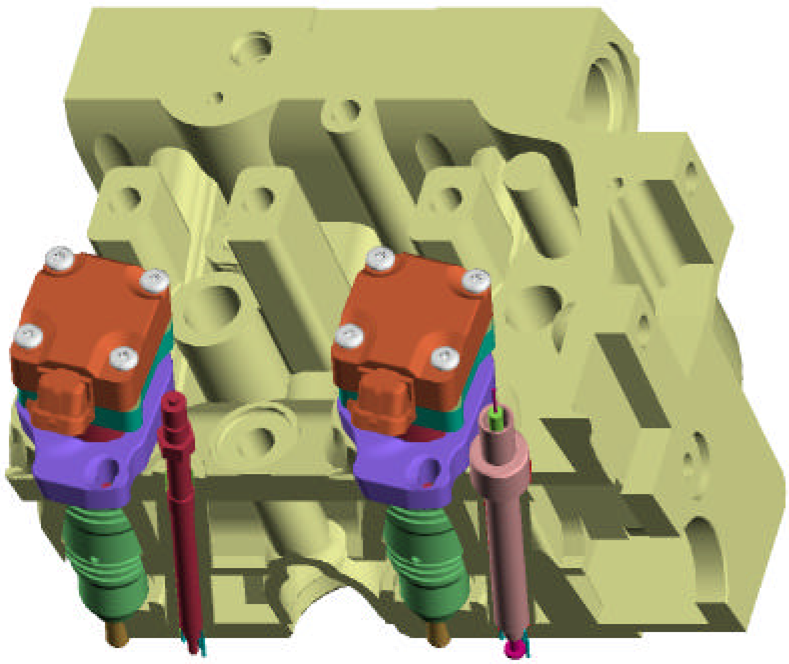

Figure 37: Air-gap plug in the cylinder head

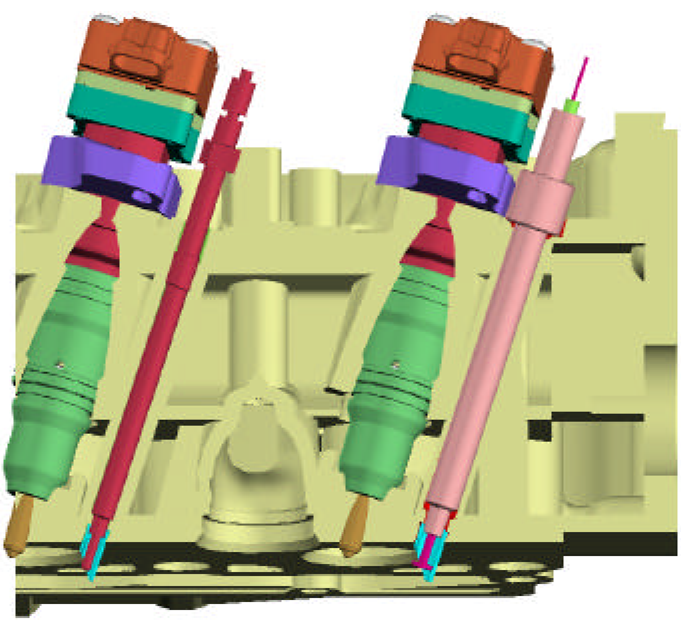

Figure 38: Sectional view of the air-gap plug in the cylinder head

mounted in the cylinder head. Fig. 39 shows the spark gap between the central electrode and the ground electrode.

A second cylinder head will be modified to accept the surface-discharge spark plug. The glow plug hole is also enlarged to 13 mm in diameter but with the bottom groove removed (Fig. 40). This allows the ground electrode of the surface-discharge spark plug to protrude beneath the cylinder head. Fig. 41 and Fig. 42 show the surface-discharge spark plug mounted in the cylinder head. Fig. 43 shows the surface spark gap between the central electrode and the ground electrode.

Mounting Hardware

Since there is not possible to machine a mounting thread in the cylinder head for the spark plug, other provision has to be made to keep the plug in the cylinder head during engine operation. Fig. 44 shows the clamp specially designed to hold the spark plug in the cylinder head. Matching clamp to each spark plug will be made since the angle and the distance between the two contacting surfaces on the clamp must be machined accurately according to the finished dimension of each plug. This is to ensure that the clamp will exert enough clamping force to squeeze the O-ring, but not large enough to crush the ceramic insulator. A cylinder head mounting bolt is drilled and tapped with a 5/16 inch thread to secure the clamp. Fig. 45 and Fig. 46 show the spark plug installed in the cylinder head with the mounting clamp.

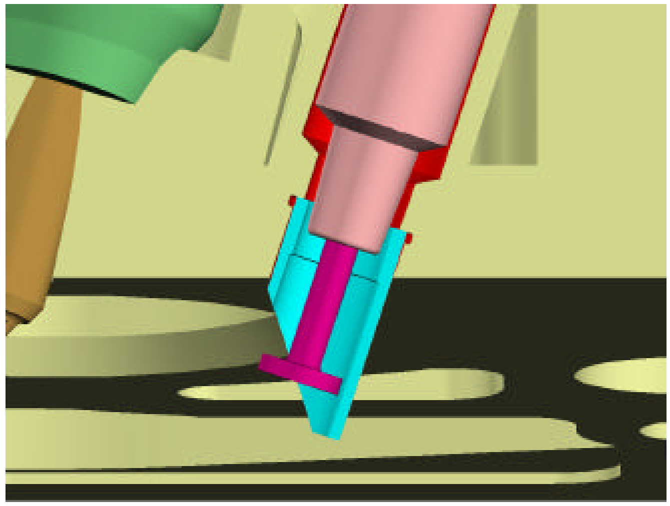

Figure 39: Spark gap between the central electrode and the ground electrode

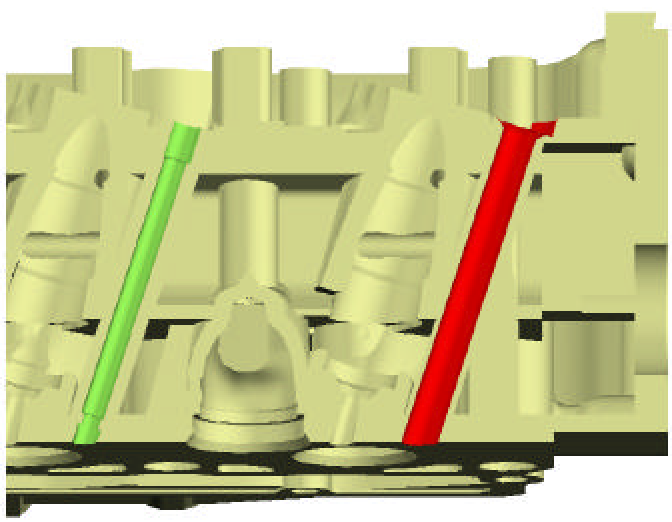

Figure 40: Sectional view of the glow plug and the surface-discharge spark plug holes

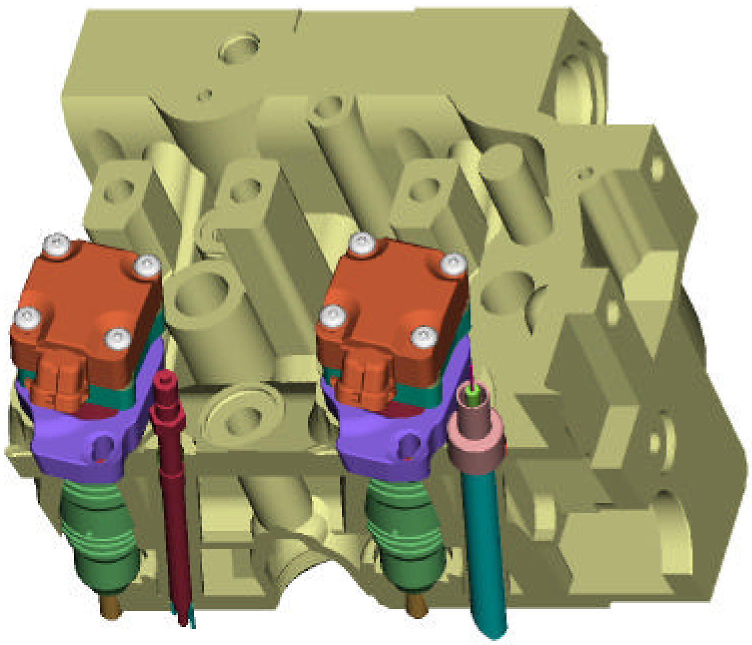

Figure 41: Surface-discharge plug in the cylinder head

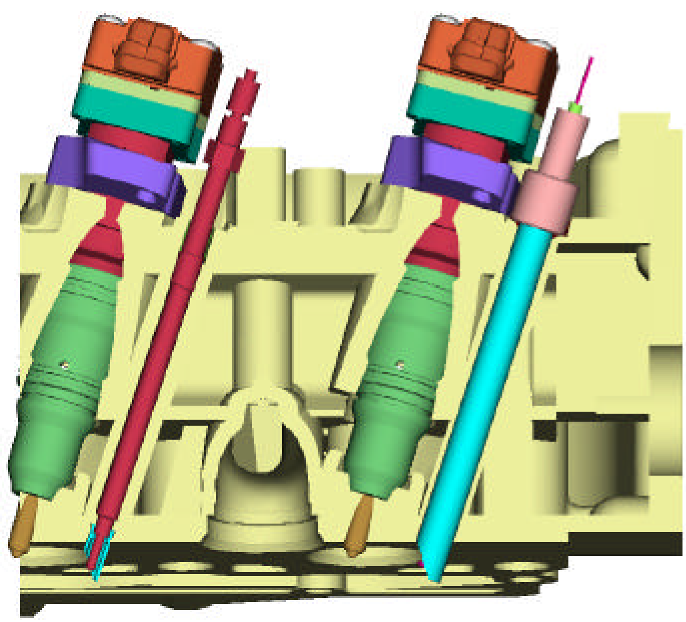

Figure 42: Sectional view of the surface-discharge plug in the cylinder head

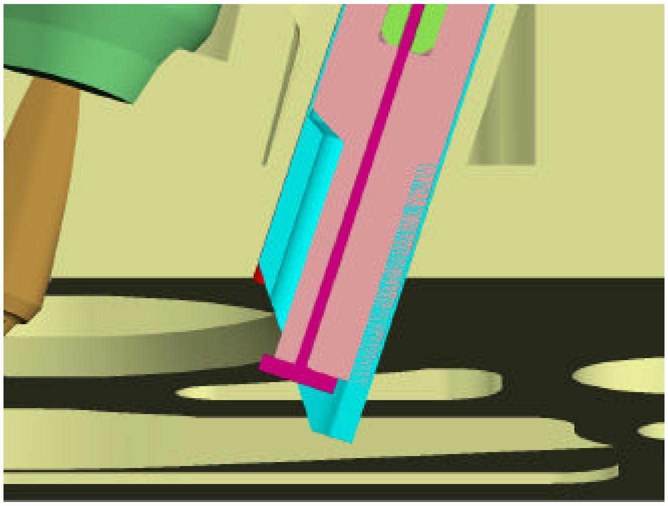

Figure 43: Surface spark gap between the central electrode and the ground electrode

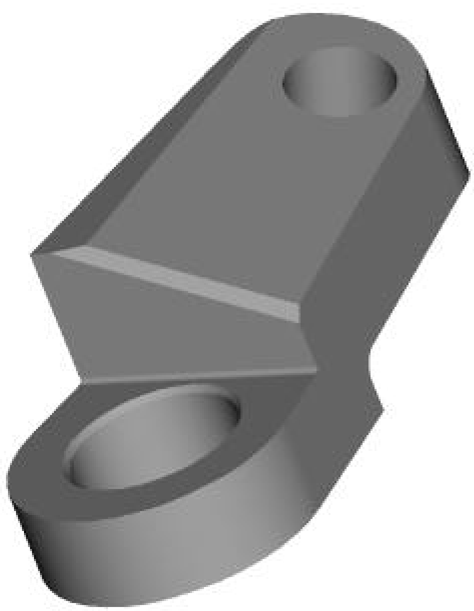

Figure 44: Mounting clamp

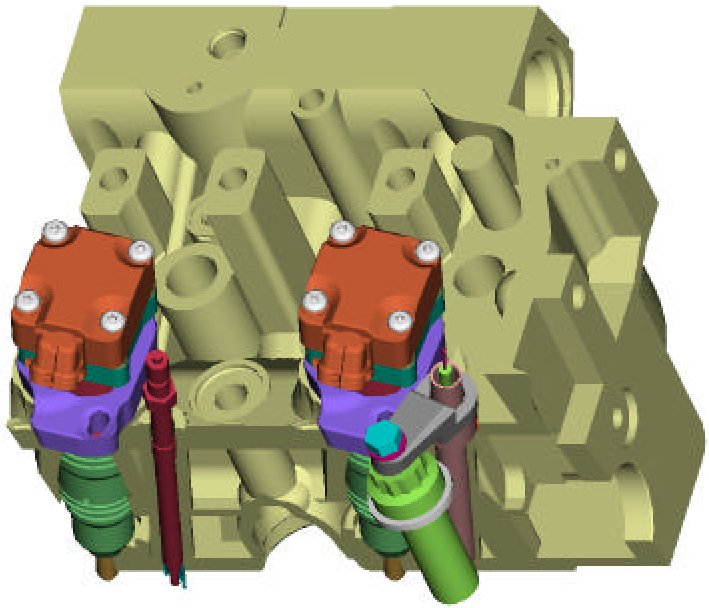

Figure 45: Plug in cylinder head with mounting clamp

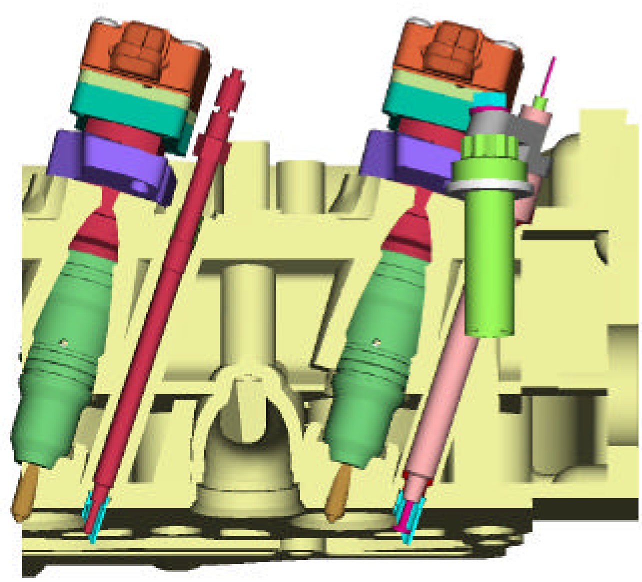

Figure 46: Side view of plug in cylinder head with mounting clamp

PHASE 2 PLANS

The plan for Phase 2 will be similar to that in the original proposal, with minor modifications. Refinement of the ignition systems identified in Phase 2 will be continued. Further high pressure chamber bench test is expected.

Task 4: Demo Ignition Concepts in 1 Cylinder of 3126 DI Gas Engine

Instead of choosing only one ignition option system, Caterpillar will procure several promising ignition option systems for the engine demonstration. A 3126 engine will be used instead of the 3116 engine stated in the proposal, since Caterpillar is replacing it with the 3126 engine. Utilizing hardware from Task 3, this task provides for a brief demonstration of the ignition options in one cylinder of a 3126 DING engine. The remaining five cylinders will incorporate the "standard" glow plug ignition. Instrumentation will record pertinent parameters such as ignition timing and cylinder pressure in comparison with the "baseline" glow plug system. The purpose of this test is to demonstrate that the concept can provide suitable ignition before investing in procurement of an entire 6 cylinder ignition system.

Task 5: Procure Hardware for 6 Cylinder Demonstration in 3126 DING Engine

Based on the conclusions derived from Task 4, the best performing ignition system will be chosen for Task 5. This task provides for designing/procuring necessary hardware to demonstrate the chosen ignition concept in all 6 cylinders of a 3126 DING engine. It is assumed that some minor system improvements will be identified in Task 4, which will be incorporated into the 6 cylinder system.

Task 6: Demonstrate 3126 DING Engine with Best Ignition Concept

This task provides for assembling a 3126 DING engine with hardware procured in Task 5 and for performing the necessary tests to evaluate the ignition concept and compare it to the glow plug ignition system. Initial testing will be performed with the "conventional" glow plug ignition system to establish baseline performance (goal: power and efficiency = diesel). DING technology from the NREL/Caterpillar "Development of a Direct Injected natural Gas Engine System for Heavy-Duty Vehicles" program will help facilitate this demonstration. The engine will then be converted to incorporate the ignition concept (hardware from Task 5), and performance tests will be performed (goal: power and efficiency = diesel). Following performance demonstration with the ignition concept, a brief durability test will be conducted to assess ignition system durability. The system will be compared to the glow plug ignition system. An assessment of whether the ignition concept is a better ignition assist system for the direct injected, single fuel, ignition assist (DISFIA) alternative fuel engines will be made.

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13. ABSTRACT *(Maximum 200 words)*

This report is a summary of the results of Phase 1 of this contract. The objective was to evaluate the potential of assist technologies for direct-injected alternative fuel engines vs. glow plug ignition assist. The goal was to demonstrate the feasibility of an ignition system life of 10,000 hours and a system cost of less than 50% of the glow plug system, while meeting or exceeding the engine thermal efficiency obtained with the glow plug system. There were three tasks in Phase 1. Under Task 1, a comprehensive review of feasible ignition options for DING engines was completed. The most promising options are: 1) AC and the “SmartFire” spark, which are both long-duration, low-power (LDLP) spark systems; 2) the short-duration, high-power (SDHP) spark system; 3) the micropilot injection ignition; and 4) the stratified charge plasma ignition. Efforts concentrated on investigating the AC spark, “SmartFire” spark, and short-duration/high-power spark systems. Using our proprietary pricing information, we predicted that the commercial costs for the AC spark, the short-duration/high-power spark and “SmartFire” spark systems will be comparable (if not less) to the glow plug system. Task 2 involved designing and performing bench tests to determine the criteria for the ignition system and the prototype spark plug for Task 3. The two most important design criteria are the high voltage output requirement of the ignition system and the minimum electrical insulation requirement for the spark plug. Under Task 3, all the necessary hardware for the one-cylinder engine test was designed. The hardware includes modified 3126 cylinder heads, specially designed prototype spark plugs, ignition system electronics, and parts for the system installation. Two 3126 cylinder heads and the “SmartFire” ignition system were procured, and testing will begin in Phase 2 of this subcontract.

14. SUBJECT TERMS
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