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LITERATURE SEARCH ON THE IMPACT OF COMBUSTION CHAMBER DEPOSITS ON ENGINE PERFORMANCE

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COORDINATING RESEARCH COUNCIL, INC.
219 PERIMETER CENTER PARKWAY - ATLANTA, GEORGIA 30346

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COORDINATING RESEARCH COUNCIL
INCORPORATED
219 PERIMETER CENTER PARKWAY, SUITE 400
ATLANTA, GEORGIA USA 30346-1301
PHONE: (404) 396-3400
FAX: (404) 396-3404

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Prepared by the

Combustion Chamber Deposit Panel

of the

CRC Deposit Group

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ABSTRACT

The Coordinating Research Council (CRC) has formed a new Panel to review Combustion Chamber Deposits (CCD) because of their potential impact on engine design, customer satisfaction, and tailpipe emissions. It is generally agreed that CCD have been around as long as the spark-ignited engine and have limited engine designers on their ability to maximize squish and compression ratio. As a result, the Performance Committee assembled a subpanel of volunteers to conduct a literature search to consolidate the information on CCD to help determine the next course of action. This report discusses the findings.

The literature search was conducted by reviewing SAE, Chem Abstracts, API data bases, and selecting articles mostly after 1967. The review was non-judgmental. The literature search indicates that CCD formation is affected by a variety of factors such as fuel composition, fuel additive type, fuel additive concentrations, fuel additive composition, engine oil type and consumption, engine design and driving cycle. Also, a theory has been proposed to describe what causes CCD. It also was found that CCD contributes to octane requirement increase (ORI); however, the impact of CCD on ORI, as measured by the consumer, has eased with the widespread use of knock sensors. Most recently, the concern about the negative impact of CCD on engine performance is the issue of Combustion Chamber Deposit Interference (CCDI). Numerous references have cited a link of CCD to exhaust emissions. Most are related to an increase in engine-out hydrocarbon (HC) and oxides of nitrogen (NOx) emissions. Those data are spread out over the generation when engines had changed significantly to meet increasingly stringent emission limits. Some of the engine design changes could have minimized the effects cited in the earlier research. A limited amount of current research supports the notion that tailpipe NOx emissions are increased with CCD.

I. INTRODUCTION

It has been recognized as early as 1925 (1,2,3) that Combustion Chamber Deposits (CCD) can cause undesirable side effects in engines. Octane Requirement Increase (ORI) was one of the most considered effects during the last 20-30 years, but emissions effects of deposits were also studied. Most recently, CCD were reviewed because of their impact on Combustion Chamber Deposit Interference (CCDI) and exhaust emissions. During this time, it was also recognized that CCD could have a positive effect on fuel economy.

Octane has always been one of the prime quality features of gasoline. Refiners have gone to great lengths to increase the octane of their gasoline. Up until the mid-1970s in the US, refiners added Tetraethyllead (TEL) as an octane booster. It became clear, however, that TEL had deleterious effects and that an emerging emission control system using a catalyst could not be made to function with TEL in the fuel. During the late 1960s and early 1970s, however, the technical community was very concerned about the demise of lead. Principally, refiners were worried about how to maintain the octane levels offered at that time. Engine designers were worried about the effect that unleaded fuel deposits might have on their engines. The main concern was that the nonconductive nature of the hydrocarbon deposits might add extra insulation in the combustion chamber and raise in-cylinder temperature. The rise in in-cylinder temperatures would make knock more likely. Next, the deposits might serve as local hot spots which could cause dieseling or pre-ignition. During the 1970s it was not uncommon after 15,000 miles for vehicles to require 10 Research octane numbers (RON) higher fuel than when new.

Some researchers were concerned that deposits could trap liquid fuel and release it during the exhaust stroke and increase hydrocarbon emissions. Subsequent work was done on engine emissions and many studied these effects. During the 1980s, development of port fuel injectors, oxygen sensors, and three-way catalysts overshadowed the slight changes to engine-out emissions that many were saying were attributed to CCD.

Research on the ORI effects of CCD lost momentum as the 1980s progressed, for several reasons. First of all, compression ratios dropped during the 1970s, and did not significantly rise again until the mid-1980s. Next, octane level at the pump started to climb as many gasoline marketers began providing very high octane premium gasolines [93 (R+M)/2]. Also, OEMs developed another new technology called the knock sensor. With the knock sensor, many consumers did not notice the effect of increasing deposits. To demonstrate this point, the CRC (who study octane requirement yearly) began finding it difficult to determine the octane requirement of new vehicles equipped with knock sensors and had to change testing procedures. Finally, in several studies conducted by the CRC (4), it appeared that ORI was trending down in recent years (Figure 1).

From 1985-1992 some gasoline marketers, the Environmental Protection Agency (EPA), and the public focused on detergents for port fuel injectors and intake valves. This all changed for automotive manufacturers and gasoline marketers in 1993 when several automotive manufacturers began to complain about a new problem of CCDI. This information was brought to the forefront at a workshop sponsored by the CRC in November 1993 which resulted in the formation of the CRC CCD Panel and subsequently this report.

Since the emergence of the CCDI issue, many have researched the effects of CCD again. Some focused on CCDI, others on ORI, and others related the deposits to increases in emissions. This literature survey will cover all three major categories after first reviewing the mechanism of CCD formation. It is felt that an understanding of the causes of CCD formation will help the panel understand that CCD are a complex phenomenon that touch on all aspects of the collective industries.

On the positive side, several investigators have shown that CCD can improve fuel economy of an engine by reducing the cooling loss. Improvement of between 1 and 13 percent has been reported. If CCD could be eliminated, engine designers are confident that they can design for higher fuel economy by raising compression ratios.

One can best visualize the effects of CCD by reviewing each of the four strokes of the four-stroke engine. Shown in Figure 2 is the "Intake Stroke" during which fuel is drawn into the combustion chamber. Depending on engine conditions (i.e., driving cycle), fuel volatility (particularly the amount of fuel with the highest boiling point), and fuel delivery system employed (e.g.,carbureted or port fuel injected) some fuel enters the combustion chamber in liquid form. During the "Compression Stroke" (Figure 3), pressure and temperatures rise and most of the liquid fuel is vaporized. In some recent engine designs, if deposit level exceeds the clearances between the piston top at top dead center and the cylinder head, it is possible that the piston and cylinder head will strike causing a mechanical knocking sound to be heard. This is most likely when the engine is cold. Next, during the "Power Stroke" (Figure 4), a flame front is started at the spark plug and travels in the direction of the approaching piston top across the combustion chamber. In a new engine with no deposits and the proper octane, this flame propagation goes uninterrupted. As the vehicle ages, however, carbon deposits can form, particularly on the piston top and cylinder head. These deposits are hot because they can retain heat from the previous cycle; consequently, they can start a second ignition called a surface ignition (surface ignition can also be preignition). Also, the deposits on the cylinder head can reduce heat flow to the coolant and subsequently raise the in-cylinder temperature. At these higher temperatures, the fuel-air mixture can auto-ignite before the normal flame front arrives. When autoignition occurs, the whole unburned mixture in the end-gas region will be consumed in a very short time period, which will produce a pressure oscillation in the combustion chamber. The resulting "pinging" noise is the so-called "engine-knock." During the "Exhaust Stroke" (Figure 5), hydrocarbons leave the engine from several sources including unburned fuel, fuel desorbed from the oil film or the crevices (particularly in the piston top land area) for a new engine. For an engine with deposits, unburned hydrocarbons also can be desorbed from the deposit. In addition, the insulation effect of the deposit raises the in-cylinder gas temperatures and changes the chemical reaction associated with combustion. This literature survey shows that this rise in gas temperature may increase NOx emissions.

In the sections that follow, the mechanism and causes of CCD are first discussed, followed by their subsequent effects on:

- ORI
- Fuel consumption
- CCDI
- Exhaust emissions

II. MECHANISM AND POTENTIAL CAUSES OF CCD

Several researchers (1,5,6,7,8) have cited factors that they believe influence CCD formation which can be summarized with the following list:

- Engine design
- Driving cycle
- Lubricant
- Gasoline composition
- Additive type formulation, composition, and treat rate
- Surface material
- Coolant temperature

A. *Engine Design and Its Effects on CCD*

Engine design is a factor in the formation of CCD. Design differences which have been shown to affect deposit formation include:

- Oil consumption
- Coolant system
- Air charge temperature system
- Materials of construction
- Fuel delivery system
- Hardware design of combustion chamber

It is expected that within a single engine, variability also could exist among cylinders due to slight differences in temperature or fuel delivery. Finally, two of the same engines could produce varied deposit levels due to slight changes in manufacturing tolerances off the assembly line.

Engines that have high oil consumption have been shown to have high levels of CCD; however, in most engines with good oil control, this does not seem to be the dominant factor. In many areas of research (1,6,7,9), it appears that coolant and/or surface temperature is the most important variable, and this may relate to some equilibrium temperature and CCD formation.

"Investigation (1) using a temperature controlled probe revealed that surface temperature is a dominant factor in the deposit forming process. Within the temperature range of 98°C to 256°C, there is an inverse relationship between the amount of deposit accumulated and the surface temperature. The critical surface temperature for deposit formation is near 310°C, above which no deposit is expected to form."

Cheng (6) showed that inlet charge temperature (over a range of temperatures from 26°C to 100°C) had little effect on CCD mass, but also showed (1,6) that lowering coolant or surface temperature increased deposits.

Nippon Oil (7) showed that coolant temperature had a larger effect on CCD formation than other variables. A coolant temperature of 50°C produced about 20 percent more deposits than a more normal 80°C coolant temperature. Finally, Cheng (6) showed that changing materials of construction also significantly altered deposits. For example, changing from steel to ceramic had a five-fold decrease on deposit formation.

No evidence was uncovered relating CCD to fuel delivery systems; however, there has been research (10) which shows that fuel delivery can affect IVD. It is possible that some fuel delivery systems might allow more liquid fuel to enter the combustion chamber than others. More liquid fuel should increase deposits, but this effect may be confounded with driving cycle changes listed below.

B. ***<u>Driving Cycle and CCD Formation:</u>***

"City type driving involving a great deal of starting and stopping tends to lay down more deposits than high speed driving" (5). It should be noted that at low speed driving, the engine operates cooler since it is doing less work. This reduced temperature forms a basis for condensation of the fuel-air mixture. Also, engine-soaks or shut-off can affect deposits. As engines are restarted, the temperatures are lower than equilibrium running temperatures.

Other recent work, (11,12) clearly shows the influence of operating conditions on CCD. Basically, at low speed/load conditions, CCD on either the piston top or combustion chamber (cylinder head) are much greater than at the high speed/load conditions.

Finally, during low speed/load operations, a high engine vacuum exists which can tend to draw more oil into the combustion chamber causing an increase in deposits.

C. *Lubricants and Their Effects on CCD:*

As discussed in a previous section, engine oil consumption can influence CCD formation; however, it has been pointed out that engine oil composition (6,13) also affects CCD. The effects of different base stocks and different lubricant additives were studied as well as differences in commercially-available fully-formulated oils.

Cheng pointed out (6,13) that oils can have a significant effect on CCD. In this study, formulated oil packages were added to fuel and the levels of deposits were measured. The conclusions were that heavier oils produced more deposits than lighter ones, and that certain viscosity improvers produced more CCD than others.

As previously stated, the level of combustion chamber deposits varies with oil consumption. In older-type engines, in which oil consumption was high [typically 1 quart of oil every 150 miles (3)], it could be shown quite clearly that the lubricant was a major contributor to combustion chamber deposits (3,14). Prior to 1930, the lubricants had few, if any, additives and it could be shown (15) that the amount of deposit in the combustion chamber of an engine correlated with the amount of residue after distillation of the lubricant [the Conradson Carbon Residue (CCR)]. In their work, Yonekawa et al., (16) also found a relationship between ORI and CCR of the lubricant, without apparently being aware of the earlier work of Parish (15). Yonekawa et al., however, were measuring the CCR of a formulated lubricant so that detergent additives, polymeric additives, and the basestock were all making a contribution to the CCR.

More recent work has concentrated on the effect of lubricant additives on ORI. The results are mixed. Lee and Thomas (17) have shown that there is a fairly good relationship between the ORI of an engine and the sulfated ash of the oil used to lubricate the engine. Maficante and Chiampo (18), and Barber et al., (19) have all produced results to show that additives in the engine oil will increase combustion chamber deposits and contribute to ORI. In contrast, Benson (20) and Keller et al., (21) show that the lubricant does not affect ORI. Thus, in engines with relatively high levels of oil consumption, the lubricant and lubricant additives are the major contributor to deposits, which subsequently affect ORI. If, however, oil consumption is relatively low, the fuel is the major contributor to deposits and the effect of additives in the lubricant is not as readily detected.

D. *Gasoline Composition and Its Effects on CCD:*

Many researchers (6,9,22,23,24,25) have identified heavy aromatics as the principal agent in gasoline responsible for CCD. In one paper, Texaco (22) used a single-cylinder engine with a window and several analytical methods to determine the chemical nature of the deposit. It was found that deposits were generally comprised of condensed aromatic clusters of very high molecular weight. The research then compared the deposits formed by base gasoline, alkylate, and reformate. The reformate CCD had the largest group of aromatic clusters, leading them to conclude that aromatic content of fuel correlates with the aromatics content of the deposit.

This reference (22) joins a previous paper from Choate (23) et al., and demonstrates that the chemical nature of the deposit varies with the type of fuel. An example is given showing a very complex aromatic structure when using reformate fuel. A figure in this paper (23) clearly shows that CCD weight increases linearly with fuel aromatics level. This research shows that the number of intact bridges (connectors between aromatic clusters) also increases with increasing fuel aromatic content.

Along those lines, Cheng (6) demonstrated that deposits from toluene fuel produced more CCD than 100 percent Indolene, 30 percent toluene/70 percent isooctane, and 100 percent isooctane. Alternately, the same increase of CCD by switching from Indolene to toluene was obtained by spiking 10 percent naphthalene into Indolene. The CCD effect of olefins was also checked, but there was not much of an effect. He also looked at other fuel effects on CCD formation which are of interest. For example, he (1) showed that higher aromatic levels raised CCD. At 8 hours of operation, a 100 percent change in aromatics level raised deposit levels by a factor of 7, while a change from a 30 percent aromatic fuel to 100 percent aromatic fuel increased deposits from 825 micrograms/coupon to 1400 micrograms/coupon, respectively. This would suggest that the greatest impact of aromatics content is in the first 10-30 percent (Figure 6).

At the CCD Workshop, Gibbs (26) showed that both ORI and CCD were related and were influenced by fuel refinery streams. The highest CCD levels were obtained from Heavy Cat Cracked Naphtha followed by Whole Reformate. Other refinery streams were less prone to form CCD than those two streams. In another set of data, the presentation showed that saturates and C7/C8 aromatics resulted in average amounts of ORI/CCD, but it was clearly shown that C9+ aromatics were very detrimental to deposits and ORI as follows:

	ORI Effect	CCD Effect
C9+ aromatics	*High*	*High*
Olefins	*Average*	*Average*
C7/C8 aromatics	*<Average*	*<Average*
Saturates	*Low*	*Low*

In general, when the experimental conditions are such that the fuel is the major contributor to combustion chamber deposits, then research has shown that:

- As the boiling point of a hydrocarbon increases, so does its tendency to form combustion chamber deposits (27,28). This may explain why the lubricant has such a major effect on deposits when oil consumption is high, since the lubricant is so much less volatile than the fuel.
- For hydrocarbons with a given boiling point, aromatics form more deposits than saturates with olefins holding an intermediate position (27,28) .
- In a full-boiling range fuel, the least volatile fraction of the fuel contributes most to deposits. It has been shown (28), for example, that the bottom 1.7 percent of a gasoline contributes 65 percent of the deposits found in the combustion chamber.

Shore and Ockert (28) suggest that polynuclear aromatics (PNA) in the fuel are the precursors of combustion chamber deposits, Thus, it has been shown that:

- There is a linear relationship between ORI of a fuel and 2-methyl naphthalene and PNA.
- Pure isooctane does not contribute significantly to ORI. Adding an alkyl benzene to isooctane does not affect ORI, but adding naphthalenes to isooctane results in significant increase in both deposits and ORI.

On the basis of this and other work, it is suggested that the order of increasing effect on ORI is:

saturates and alkylbenzenes<naphthalenes<poly-alkylated naphthalenes<higher fused PNA

It should be emphasized that many of the high-boiling aromatics cited as responsible for CCD actually have boiling points above the final boiling point of gasoline. Also, other aromatics such as ethyl benzene have not been reported to be a major concern for CCD. Finally, as fuel specifications are changing to meet new regulations such as California Phase 2 or federal RFG, it is expected that the fuel contribution to CCD will be reduced and attention will be focused on the additive contribution.

E. *CCD Formation and Additive Type, Formulation, Composition , and Treat Rate:*

Lewis et al., (29) shows the effects of additive type on both CCD and ORI. These data show an advantage for a polyether amine additive (PEA) over a polybutene amine additive formulation [referred to in many recent articles as polyolefin amines (POA)]. This comparison shows that PEA at 200-400 ppm treat produced CCD similar in weight to base fuel, while a detergent containing 250 parts per million by weight (ppm) of a POA plus a mineral oil carrier produced significantly more deposits (Figure 7). From the same study, measured ORI values are plotted for several different types of polybutene additives all at 200 ppm and indicate that all gave similar increases in ORI relative to the base gasoline (Figure 8).

Cheng (6) showed the effect of mineral oil viscosity on CCD by spiking various mineral oils into Indolene at a non-commercial treat rate of 2500 ppm. In this study, the higher the molecular weight of the oil, the greater the CCD. The same study showed that one synthetic carrier oil formed less deposits than mineral oils.

Nippon Oil (7) showed when comparing 400 ppm of PEA to 1400 ppm of a POA, the deposit weights were higher for the POA at the higher treat rate. The study showed that regardless of which detergent was used, the deposits were chemically similar and both were higher in weight than fuel with no additive. The study also showed that both POA and PEA were included in CCD along with engine oil, but PEA decomposes more easily than POA.

Swaynos and More (8) showed a similar comparison in that different detergents (PEA or POA) could produce the same levels of CCD in IVD type engine tests. The POA packages which performed best contained synthetic carrier fluids.

Kellerman (30) also showed that there was a chemical similarity of deposits when using different amine-based dispersants. This study showed that the nitrogen functionality was similar between these dispersants and that the intact nitrogen heads were not found. It also showed that there is little evidence of intact polymer backbones. This would indicate that the detergents themselves (POA and PEA) may not be responsible for CCD. Finally, it has been shown that ORI and CCD can be reduced below base fuel levels when a high dosage of PEA additive is used (52).

F. *Surface Materials and Coolant Temperature and Their Effects on CCD:*

With increasing concerns regarding our environment and demand for better fuel economy, modification or reduction of engine deposits is highly desirable (1). It was found that three items including fuel composition (aromatics level), coolant temperature, and certain surface materials had a significant influence on CCD. These effects were much larger than compression ratio, intake temperature, or equivalence ratio for influencing CCD. As an example, at eight hours of operation, it was found that cast iron or stainless steel coupons had over 1000 micrograms of deposit, while ceramic coupons had only 200 micrograms (Figure 9). Finally, it was found that changing coolant temperature from a typical value of 95°C to 40°C increased the deposit level from about 800 to 1000 micrograms. The following suggests that control of CCD might be accomplished by changing materials of construction and/or coolant temperature.

G. *Model for CCD Formation:*

This section contains several proposed mechanisms for CCD deposit formation that are hypotheses (some supported by data), but nevertheless they have not yet been universally accepted. After reading the preceding sections one might imagine that fuel not fully vaporized (caused by high boiling compounds, poor atomization, driving cycle, etc.) collects in cool surfaces where it can remain liquid. The liquid then undergoes with time a chemical transformation to the deposit. More sophisticated models of deposit formation follow.

Kittleson (31) shows that a similarity could exist between CCD in gasoline engines and diesel soot emissions. He relates this similarity to a thermophoresis driving force as hypothesis. In a diesel engine, less volatile fuel is atomized by passing it through a fuel injector at an extremely high pressure drop. This fluid motion charges the fuel which leads to agglomeration of liquid droplets. Next, the diesel engine operates at a much higher compression ratio and higher in-cylinder temperatures; the result is that there are large particles and a huge thermal gradient between the bulk gas and the wall. The thermal gradient directs the droplets to the wall. It is possible that a thermophoresis could also exist in a gasoline engine. Instead of agglomerating charged particles, one might consider high-boiling-point liquid droplets which have not been completely atomized.

Lepperhoff (9) proposed another mechanism which described how deposits may be formed. This paper clearly shows that deposit mass per unit area is increased as the coolant temperature is lowered. The mechanisms for the deposit build-up and growth are as follows. The low temperature walls cause the condensation of gaseous compounds. After a time, sticking and incorporation of particles occurs by transport phenomena. Later as the deposit grows, adsorption of gaseous compounds can occur due to the high soot portion of the deposit. Finally, reaction of the "mixture" and time compress the deposit into its final state.

In the mechanism of deposit formation, gaseous components and liquid droplets will condense and adsorb to the wall surface due to low wall-surface temperature. The particles move to the wall by thermophoresis and are deposited by sticking, incorporation, and impaction. Thermophoresis (9) means a difference in the energy level of the gas molecule at two sides of the particle. On the high- temperature side, there is a greater tendency for molecules to collide than on the low-temperature side. The sticking is caused by adhesive force between the wall and the particles. Incorporation is the attachment of the particles in liquid to the surface layer.

Edwards et al., state (24) that CCD may be like coal and show the chemical similarity. The main difference between coal and CCD is the higher concentration of carboxylic/carbonyl and phenolic groupings found in the CCD. This is due to the oxidative chemistry taking place during the combustion process. The average building block of these deposits appears to be 2-4 ring PNA originating in the fuel. The mechanism of formation appears to be a polymerization of these heavy PNA via condensation of coordinated oxidation products and via radical initiated addition/substitution reactions. Strong correlations between fuel aromatics content and CCD structure are observed: highly aromatic fuels yield highly condensed CCD while lower aromatic fuels generate "fluffier" (less condensed) CCD.

Another hypothesis (9) is that the process of deposit formation is divided into the induction phase and the deposit growth phase. No particle can adhere to (or on) a dry, non-sticky wall. To build up deposits, a contact medium between the wall surface and particle is necessary. These contact mediums are high-boiling components, mostly hydrocarbons. During the induction phase, the deposit formation starts with the condensation of high-boiling hydrocarbons at the wall. In this very thin sticky layer, particles are caught similar to flypaper effect. The deposits grow continuously by additional sticking and incorporation of particles to the layer. With growing deposit thickness, the insulation effect takes place. This leads to an increase in the surface temperature, and low bonding forces restrict the deposition of more particles. Gaseous components diffuse through the porous layer and are adsorbed or condensed in layers of lower temperature. This results in an increase in the layer density. Once deposits are attached to the wall, other chemical reactions can take place (pyrolysis, dehydration, polymerization, etc).

Daly (32) proposes a mechanism for deposit formation showing thermophoresis where partially burned hydrocarbons from the flame front moved to cooler surfaces of the combustion chamber (cylinder head and piston top). The molecules are partially oxidized or changed by a thermochemical reaction and, because of their high boiling point, condense on the cool surface. As heat is transferred, the condensed liquid film evaporates slightly leaving a more viscous thin film. The viscous thin film likely forms two zones. One film immediately facing the new oncoming gases is liquid and porous; the second film is more dense and even solid. The ratio of zone 1 to zone 2 is highly influenced by the composition of fuel, oil, and additive. The two film theory, it should be pointed out, is not shared universally . Others have analyzed the deposits and found them to be homogenous.

III. OCTANE REQUIREMENT INCREASE (ORI)

A. *Knock and Octane Number*

The engine phenomenon "knock" includes the propagation of strong pressure waves across the combustion chamber caused by autoignition or spontaneous combustion of heated and compressed mixture of fuel and air in the end gas. The autoignition of the end gas occurs when the energy released by the chemical reactions is greater than the total heat transfer to the surroundings. As a result, the temperature of the end gas increases, thereby accelerating the rate of reactions involved (33).

The autoignition reactions, leading to the formation of free radicals, consist of a large number of simultaneous, interdependent reactions called chain reactions (34,35). The ease with which autoignition occurs depends upon the structure of the hydrocarbon fuel. For example, n-heptane is prone to autoignition while 2,2,4-trimethylpentane (isooctane) does not readily autoignite.

To determine the octane quality of fuels, a standard engine and standard test procedures are used. The engine used to determine the octane quality is a Cooperative Fuels Research (CFR) single-cylinder engine operated under the ASTM D 2699 and D 2700 test methods. The octane quality of a fuel is determined by comparing its knocking tendency with that of the primary reference fuels. These are binary mixtures of n-heptane and isooctane which have assigned octane numbers of 0 and 100, respectively (36).

Although autoignition induced knock in an engine depends primarily on the antiknock quality of the fuel, engine design and operating parameters also play a very important role by influencing end gas temperature, pressure, and the time that the end gas is subject to elevated pressure and temperature (33).

B. *Combustion Chamber Deposits and ORI*

Carbonaceous deposits formed in the combustion chamber are the major cause of ORI. It has been shown that over time/mileage the octane appetite of a clean engine will increase to some stabilized octane requirement due primarily to the accumulation of combustion chamber deposits (40,41,42,43). This increase in octane requirement relative to the new engine/vehicle initial octane requirement (determined by its design and manufacture) defines ORI. While a strong correlation between CCD weights and ORI has been documented (37,38), other data do not support such a correlation (55). Additionally, deposit location in the combustion chamber also plays a role in determining ORI (20,39).

1. Causes and Mechanisms of ORI

Dumont (44) postulated three mechanisms by which combustion chamber deposits contribute to ORI in spark ignition engines: volume effect, catalysis effect, and thermal insulation effect. The volume effect is based on the assumption that combustion chamber deposits reduce clearance volume and significantly increase compression ratio. The effect of combustion chamber deposits on compression ratio accounts for only 10 percent of the total ORI in unleaded fuel (20) and up to 40 percent of the total ORI in leaded fuel (43,44). The catalysis effect of combustion chamber deposits in promoting engine knock is not significant as was demonstrated by Dumont's dust injection experiments in which various dust particles introduced into the intake air mixture of deposit-free single-cylinder engine suppressed rather than promoted autoignition.

The thermal insulating effect of combustion chamber deposits has been reported to be the dominant factor contributing to ORI (20,43,45,46). Surface temperatures of combustion chamber deposits increase significantly with deposit thickness. As a result, bulk gas temperatures and, therefore, octane requirement are increased by the following two mechanisms:

(a) Additional heating (or thermal regeneration) of the incoming air caused by the elevated surface temperature of the deposits.
(b) Reduced heat transfer from the working fluid while being compressed by the upward motion of the piston and the advancing flame front, resulting in higher end gas temperatures.

A recent study (45) suggested that the net heat transfer through the cylinder head and piston face decreased by approximately 15 percent over a 180-hour test. It was also reported that a rise of 7°K in unburned gas temperature at 10 crank angle degrees after top dead center causes a one Research octane number (RON) rise in engine octane requirement.

While the effect of combustion chamber deposits on ORI is well documented in the literature, the contribution of intake system deposits to ORI is not as well understood. Intake valve and port deposits are reported to influence ORI in some engines, but not in others (45,47,48,52). The extent by which intake system deposits contribute to ORI is highly engine dependent.(46,49). It has been postulated that intake system deposits affect inlet flow characteristics, which ultimately affect:

- the turbulent heat transfer at the wall
- the local mixture strength in the end gas by altering the mixing pattern of the residual gas and the fresh charge
- the combustion rate and cycle-to-cycle variation (40).

2. *Functional Effect of ORI*

Ever since the 1920s (55), octane requirement increase has been a direct constraint on engine performance. Insufficient octane quality of fuel can result in detonation and engine knock. Light knock is objectionable due to its nuisance noise, and it can be a major source of customer dissatisfaction. Severe knock, especially at high engine speed, can cause damage to engine components due to rapid local rate of pressure and temperature rise in the combustion chamber. Knock limits the power output and efficiency of an engine in its design stage. Without knock, an engine could be designed to have a higher compression ratio leading to higher efficiency and power output. In the operational stage, knock limits the maximum operating spark advance of an engine, thus limiting its maximum knocklimited power and thermal efficiency (49).

3. Fuel Composition and ORI

Previous research has shown that fuel composition and additives can affect octane requirement increase. Some aromatic hydrocarbons appear to affect CCD and the resulting ORI (25,28,50). Regression analysis has shown that ORI correlates well with heavy aromatics (C_{10} and higher) primarily found in Reformate and FCC blending streams (25,37). Fuel additives also play a role in determining the magnitude of the octane requirement increase. For example, POA-derived additive formulations have been shown to contribute to CCD and ORI, while PEA-derived fuel additives have an insignificant effect on CCD and ORI as compared to unadditized base gasoline. (39,51). Octane requirement equilibrium, a reversible dynamic process, also is affected by the choice of fuel additives. In a statistically designed 29-vehicle field test, a rapid and large reduction in ORI equilibrium occurred following the change from a POA-based formulation to a PEA-based formulation (39,51).

4. *Vehicle/Engine Design and ORI*

Vehicle/engine design has a major effect on ORI (20). In a 36-car ORI evaluation program, for a given fuel, ORI varied from 3 to 7 RON among various late model vehicles (39). With a single make, ORI can vary significantly (56). It has also been shown (51) that the response to additives varies significantly among engine types. ORI in some engines is relatively insensitive to additional CCD, while the ORI of other engines can be significantly affected. These phenomena are not well understood.

C. *ORI Determination*

There is no industry-approved procedure in the US to determine the ORI of an engine or vehicle, and consequently the contribution of fuel and fuel additives to ORI. In Europe, however, a CEC Working Group is developing an ORI procedure using the Renault F2N/F3N engine and a knock-limited spark advance (KLSA) technique. The ability of this procedure to accurately discriminate fuels/additives based on their contribution to ORI has not yet been proven with a field correlation.

In the US, the Coordinating Research Council (CRC) collects and distributes data on ORI submitted by member companies on a voluntary basis. The octane requirements are generally determined using the CRC E-15 procedure (53), but no formal procedure exists for vehicle preparation and operation. In these surveys, ORI has generally been on the decline over the last decade (4), as shown in Figure 1.

An ORI procedure based on the proposed CRC intake valve deposit test protocol with the 2.3-liter Ford engine is currently being used by some to evaluate fuels and additives. Based on data presented at the CRC CCD Workshop in Orlando in November 1993 (54), it may not discriminate fuel/additives adequately.

The determination of the ORI in a vehicle population is a very expensive and exacting task. Some engine designs are very sensitive to ORI, while others are relatively insensitive (51). It is, therefore, very critical to choose a diverse and representative mix of vehicles.

Octane requirement , and consequently ORI, are very dependent on the mechanical condition of an engine. It is, therefore, necessary to ensure that the vehicle is properly prepared prior to the start of any test program. This includes exacting preparation of both the intake and exhaust valves and seats and careful monitoring of engine oil control which is another important aspect of engine preparation.

Verification of the initial octane requirement prior to evaluation of a fuel/additive for ORI is the most critical aspect of any ORI test (39). The dependency of ORI on the initial octane requirement (4,55) makes this initial determination of the vehicle's octane requirement even more important. Variation in octane requirement within a given engine family needs to be identified during this period, so that all vehicles within a given make are similar. A ± 1.0 octane number difference in this initial octane requirement has been proposed.

One method to further validate the results from any ORI test includes a post-test evaluation of combustion continuing deposit accumulation until the engines reach deposit (or ORI) equilibrium. In general, higher initial rates of deposit accumulation associated with a given fuel/additive yield higher ORI when compared to heavier initial rates of deposit accumulation (51). For highest accuracy, octane requirement determinations using the CRC E-15 rating procedure should be made by the same trained rater over the entire test. Correction factors for barometric pressure, ambient temperature, and humidity must be assessed, if applicable. Once octane requirement equilibrium is achieved, an engineering best-fit octane requirement curve is derived from all the octane requirement determinations for a given engine/vehicle including chamber deposit mass and appearance, intake valve deposit mass and appearance, and cylinder leakdown and compression measurements.

To be able to draw meaningful conclusions from any ORI program, it is imperative that a statistical test design be employed (39). This requires the analyses of previous ORI programs, representing various models and multiple vehicles per model. This provides the investigator with an estimate for variability, which in turn determines the statistical power associated with given differences in ORI. During the deposit accumulation stage of any ORI test, a realistic driving cycle should be used with the goal between two fuels to be at a certain confidence level (minimally 90 percent). Figure 10 is an illustration of this type of information being used to design an ORI program.

D. Conclusions

Ever since the 1920s, it has been recognized that ORI is a constraint on engine performance. Light knock is not harmful mechanically, but it is easily perceptible and can be a major source of customer dissatisfaction. Heavy knock can cause engine damage, especially at high engine speed when it can be difficult to detect. If ORI could be reduced or eliminated, the automobile manufacturers could use higher compression ratios and more aggressive spark advance schedules with a resulting increase in fuel economy and performance.

The literature shows that combustion chamber deposits are the major contributor to ORI. The deposits act mainly as a thermal insulator and reservoir effectively raising the in-cylinder temperatures and increasing the tendency to knock. Important factors in the formation of CCD are vehicle design, operating conditions, fuel composition, and deposit control additive type and dosage. It is also shown that ORI is difficult to measure accurately since vehicle-to-vehicle response differs and since test variability is relatively high. Large-scale, expensive testing is required to determine real effects.

IV. FUEL ECONOMY

A. *Effects of Combustion Chamber Deposits on Fuel Economy - An Engine Designers View*

The ORI described in the previous section has a significant impact on the fuel economy of an engine. Since ORI is considered to be unavoidable, engine designers have to estimate the ORI and reduce the compression ratio accordingly to achieve a given octane requirement target. Should the estimation be too conservative (that is, the actual ORI is lower than expected), the engine would not fully utilize the potential fuel efficiency it could have achieved. On the other hand, should the estimation be too aggressive, the engine may have a spark knock problem. How much octane reserve a new engine shall have depends on the individual engine designer. The average ORI for modern engines is about 4 Research octane numbers (4,57); thus, it is reasonable to assume the average octane reserve is 4 to 5 octane numbers. Based on literature data, every octane number requirement is equivalent to 1 to 2.5 percent fuel economy depending on the engine and the compression ratio (58-65). Using the average value, 1.35 percent fuel economy per octane number requirement, the fuel economy that is not realized due to the octane reserve is approximately 6 percent.

Furthermore, there is a large variation in ORI from engine to engine and from cylinder to cylinder. The variation can be as large as 10 octane numbers (57). The octane reserve can only cover those engines with lower than average ORI. For those engines with higher than average ORI, the choice for those engines without knock sensors is either to use premium gasoline or to endure engine knock. Engines equipped with knock sensors fare slightly better, since knock is avoided due to retarded spark timing.

B. *Theory*

The basic mechanistic effect imposed by combustion chamber deposits on engine fuel economy is to primarily act as an insulator (40). Deposits formed on the metal surfaces inside the engine cylinder have a lower thermal conductivity than the actual metal, and thereby reduce the amount of heat that is transferred from the combustion gases to the engine coolant. With CCD present, therefore, the combustion process is allowed to progress at a higher thermodynamic efficiency, and consequently fuel economy is improved. It should be noted that in other sections of this report the influence of CCD on other performance parameters is discussed. Of particular note should be the discussion of deposit effects on ORI and the corresponding influence on fuel economy. Included in that section should also be items on the relative impact of volumetric efficiency and the possible changes which may occur with flame speed development.

C *Literature Abstracts*

Nakamura et al., (66) found in eleven different cars that as deposits grew and octane requirement increased, fuel economy measured in a "10 mode" cycle improved by up to 13 percent. The cars were running on unleaded gasoline on the road, and it was confirmed that most of this improvement was due to combustion chamber deposits by removing all CCD and remeasuring fuel consumption. They also showed (66) that in another car that ran on chassis dynamometer at a constant speed of 60 Kmph, fuel economy improved by about 9 percent in 10,000 Km, with most of this coming in the first 5,000 Km. In another experiment, Nakamura coated the cylinder head surface of a research engine with Teflon, and found that octane requirement increased and fuel economy improved depending upon the thickness of the coating. With a coating 0.08 mm thick, a fuel economy improvement of 15.4 percent was reported under fixed speed and load conditions.

Spink et al., (67) reported that three test fleets, each consisting of fifteen Japanese and European models of the late 1980s, and each fleet running on a different fuel + additive combination, had around 17 percent improvement in fuel economy over 10,000 miles as measured by on-the-road consumption data. Almost all of this improvement was found in the first 3,000 miles. In this case, part of the improvement can be attributed to the reduction in friction losses during "running-in." For the same fleets using the ECE test cycle, the fuel economy improvement data was found to be in the range of 2.4 percent to 4.5 percent. The initial measurement in this case, was at the end of 1,000 miles, and the final measurement after 10,000 miles. Fuel economy appears to change rapidly at the start of deposit build-up. If the "clean" engine measurement is not made in a truly clean engine, the first measurement and the apparent change brought about by deposits could be smaller.

Graiff (48) reported on measurements of fuel consumption at different speeds/road load conditions using two bench engines and a vehicle. By removing the combustion chamber deposits and repeating the experiments, an increase in fuel consumption of about 2 percent was found on average across all test conditions.

Woodyard (68) reported a similar level of 1.5 to 2 percent improvement in fuel economy for studies with two different bench engines. Here, a range of different additive and fuel combinations were tested for 100 hours prior to removal of CCD and measurement of fuel economy.

Yonekawa et al., (69) have assessed the changes caused by CCD on the energy balance in a single cylinder engine by analyzing the pressure curves and attributing the improvement in fuel economy at a fixed speed and load. Heywood (34) showed that the heat loss to the coolant constitutes a much larger fraction of the fuel heating value at low speeds and loads compared to full load. Hence, fuel economy benefits are less likely to be noticeable at high loads, but this aspect probably requires further study .

Kalghatgi et al., (70) have measured a reduction in specific fuel consumption of about 7 percent as deposits build up in an engine test. By removing the deposits in stages, they established that almost all of this effect was attributable to cylinder head deposits, and that piston top deposits had little effect.

D. Conclusions

The fact that CCD reduce heat transfer from the combustion chamber to the coolant appears to be well accepted. This can raise efficiency resulting in improved fuel economy. Perhaps the best recent report of this effect was presented by Graham to the CRC CCD group in August 1994. A 25-car road test was conducted and at the end of 15,000 miles, fuel economy and emissions were measured. All engine deposits were removed and the fuel economy and emissions measurements were repeated. Over the whole fleet, there was a drop in fuel economy of 2.2 percent from the removal of deposits.

V. COMBUSTION CHAMBER DEPOSIT INTERFERENCE

Several OEMs in the United States and Japan have identified a new problem which has occurred with some vehicles in the field. This information first gained prominence at the CRC Workshop on Combustion Chamber Deposits in November 1993 (54). This phenomenon manifests itself as an audible metallic noise coming from the engine compartment during cold-engine start-up. It has been attributed to the piston contacting the cylinder head (71). Three factors have been identified as contributing to this phenomena:

- Reduction in the squish height
- Build-up of combustion chamber deposits
- Manufacturing tolerance variability of squish

As commonly stated, nominal squish height is the minimum distance from the squish area of a piston to the cylinder head (see Figure 11) in an assembled engine at room temperature under quasi-static conditions. In addition to the items mentioned above, however, the actual running clearances can vary significantly from the cold static values due to a variety of reasons including the following:

- Differential rates of thermal expansion
- Elasticity of components and bearing oil films under dynamic load
- Dynamics/geometry of the engine components

In an operating engine, therefore, the actual running clearances may be significantly smaller than the nominal values, and when squish areas are located perpendicular to the wrist pin axis, the effective squish height is further reduced due to the cocking of the piston during cold starts. In some cases, the clearance can reach zero, resulting in contact between the piston and the cylinder head causing a tapping noise similar to that of deflated hydraulic lifter. This noise has been referred to as Combustion Chamber Deposit Interference (CCDI) to differentiate it from "Engine Knock." This noise generally occurs only during cold start. When the engine warms up and piston-to-bore clearances increase, the noise goes away (71).

Several questions need to be answered at this point: Why squish has recently become important; what the function of a squish area is; why a small squish height is important. In order to answer these questions, some background information is appropriate. With the increased emphasis on vehicle emissions, the OEMs are attempting to reduce cycle-to-cycle variability and increase combustion efficiency within the engine. One approach to this is to increase in-cylinder turbulence. Turbulence is needed to enhance the burn rate in a combustion chamber for improved combustion characteristics, which lead to better fuel efficiency and lower exhaust emissions (73-77). In an engine, turbulence is usually generated with squish, swirl, and/or tumble (72) (see Figures 11,12,13). In the past, squish had been used mainly on diesel engines (78-80), while gasoline engine designers had focused on generating swirl to achieve the desired burning rate. Swirl (see Figure 12), however, requires sophisticated intake port configurations and is generally not efficient because the strong swirl motion is generated during the intake stroke and then dissipates during the compression stroke. The turbulence it generates is concentrated near the cylinder walls instead of in the spark plug gap area where it is needed for burn rate enhancement. Similarly, tumble (see Figure 13) requires special intake porting and piston dome configuration and is most effective up to the mid-range of the compression stroke. Both of these options have an associated loss in volumetric efficiency (80) and are limited by underhood clearances and the geometries of intake runners. Conversely, squish (see Figure 11) does not require special intake port configuration, and generates turbulence near top dead center on the compression stroke which is the most critical time that in-cylinder turbulence can enhance the burn rate.

Toyota has shown that one of the most effective ways to get fast burn is by air motion from squish. Matsumoto presented (76) performance results from a gasoline engine with four different combustion chamber configurations. One had squish and swirl induced by piston shape. Two had only squish, one with a bathtub combustion chamber, the other hemispherical. And finally, the fourth had no squish or swirl. The design without squish or swirl had the slowest burn rate, the highest octane number requirement, and the highest fuel consumption. The test data show that hemispherical "squish only" chamber had the fastest burn rate, the lowest ONR, and lowest fuel consumption. The chamber with both squish and swirl and the bathtub squish-only chamber gave intermediate performance. Heywood (72) showed the relationship between squish velocity and crank angle for various amounts of squish area and squish height. Figure 14 shows this relationship with squish height represented by c/L (clearance height divided by stroke) and squish area represented by Db/B (bowl diameter divided by bore diameter). To put this in perspective, if it is assumed a bore to stroke ratio of 1.0 and

3.0" bore, a c/L of 0.011 is equivalent to approximately a 1 mm squish height. The maximum squish velocity increased with decreases in squish height and increases in squish area. Gasoline engine designers now realize that squish is an effective method of turbulence generation from a cost and efficiency standpoint, and are incorporating squish area into more designs.

As emissions standards become more stringent and fuel efficiency requirements increase, one can expect that squish will be more widely used in engine designs of the future. In addition, due to federal and state regulations many fuel suppliers are adopting intake valve deposit (IVD) type deposit control additives in their gasoline packages. It is not surprising to see that some low squish height engines, operated under conditions that favor CCD formation, develop CCDI problems. Gasoline with high aromatics content and some intake valve deposit type additives have been shown to accelerate deposit formation rate (1,13,71) and may exacerbate the CCDI problem. With the current fuel and fuel additive technology, however, CCD do exist at some level and therefore a minimum squish height may need to be established and manufacturing variability reduced. If this were officially established, both the automotive industry and fuel industry would have a baseline for future evaluations.

IV. THE EFFECT OF CCD ON EMISSIONS

Probably the issue with the clearest mandate of the categories discussed in this work is the effect of CCD on exhaust emissions. Increased use of detergent additives brought on by government regulation (81) and market pressures to improve fuel performance will significantly reduce deposits on carburetors, port fuel injectors (PFID), and intake valves (IVD) as a source of engine-out emissions in the near future. This leaves CCD as perhaps the last area where fuel-related deposits may contribute to emissions. To compound this, the possibility has been raised that incremental increases in CCD caused by some PFID/IVD additives may increase emissions, thereby negating some or all of the beneficial effects of a cleaner induction system.

The CCD emissions issue is not as clearly defined as for PFID and IVD emissions. Unlike PFID and IVD, there is no existing technology to truly "clean" combustion chamber deposits below a base fuel level in finished gasoline, and all engine combustion will result in some level of deposit. Even specially-prepared, single-component additized fuels cannot eliminate CCD in modern fuel injected engines (1). For IVD and PFID, the obvious standard of comparison is to a clean valve or injector. For CCD, the level of deposit achieved during operation with unadditized base fuel is the proper basis for comparison. As described earlier, however, this number varies widely with the composition of the base fuel as well as the effects of engine design, manufacturing and wear tolerances, driving cycle, and engine oil. Also, due to the difficulties and variability in obtaining either emissions or CCD data for comparison, most experimental data to date are based on undifferentiated levels of CCD compared to a mechanically-cleaned engine.

In order to address the real world effects of CCD on emissions, an understanding of the functional, or incremental, nature of these effects is required. The following sections discuss the theoretical and experimental evidence available.

A. *Theoretical Effects of CCD on Emissions*

1. *Hydrocarbon and CO Emissions*

Hydrocarbon emissions may be primarily categorized as a near-surface phenomenon. Six major sources of unburned hydrocarbon emissions have been identified in homogeneous charge spark-ignited engines (33,82,83,84), almost any of which could potentially be affected by CCD, in some cases both positively and negatively. These are:

- Unburned fuel-air mixtures trapped in the piston top land and ring crevices.
- Adsorption/desorption of fuel by engine oil films and/or deposits in the combustion chamber.
- Quenching of the propagating flame at cold wall surfaces in the combustion chamber.
- Gas phase quenching when the engine is operating under extreme conditions of stoichiometry and spark timing.
- The effects of liquid fuel in the combustion chamber.
- Exhaust valve leakage.

Crevices have been identified as perhaps the most significant contributor to hydrocarbon emissions in the combustion chamber (84,85,86). The piston-top-to-land clearance has been identified as the most important crevice relating to unburned hydrocarbon gas (84), and critical piston-top-land-to-bore clearance at which HC concentration decreases sharply has been investigated (86). CCD may be envisioned to reduce crevice volume between mechanical part surfaces by filling in gaps between piston rings, valve seats, and gasket surfaces. CCD may also increase crevice volume in the sense of porosity within the deposit and by the continuous process of CCD growth and flaking.

The dynamic growth and flaking of the deposits themselves were the subject of speculation as a source of HC emissions (87). Carbonaceous polynuclear aromatics accumulated in the combustion chamber may result in increased HC emissions when rejected from the combustion chamber.

Retention of fuel gas and/or liquid deposited surfaces during compression is enhanced due to the porous nature of the deposit and potentially the chemically similar nature of the deposit. Fuel adsorbed by the deposit is released on the exhaust stroke when the pressure is comparatively low (88). It is possible that fuel retained by deposits may upset the stoichiometry of the remaining bulk mixture, inducing gas phase quenching.

Carbon monoxide emissions are effectively a function of stoichiometry (33). Rich mixtures favor the formation of carbon monoxide, while lean combustion produces very little. Crevice volume effect described above which increase carbon emissions are likely to produce carbon monoxide as well.

2. *NOx Emissions*

In contrast to the multiple surface-oriented mechanisms associated with hydrocarbon emissions, NOx formation is held to be largely a bulk gas phenomenon. Three different mechanisms identified as affecting NOx formation (33) can be envisioned as having a CCD component:

- Reduction of heat transfer due to deposit build up.
- Increased compression ratio due to volumetric effects.
- Altered flame front temperature due to changes in fuel-air mixture ratio.

Nitric oxide (NO), the most important NOx species generated in spark ignition engines, is formed primarily in the compressed, post-flame gases, particularly those burned just after spark discharge (89,90). The rate of formation of NO has been shown to exhibit a strong exponential dependence with temperature (33). A 50° K increase in temperature at 2000 has been estimated to increase NO produced by 44 percent (91). Because of the competing reactions involved, however, the range over which NO formation is truly exponential is rather narrow. Above or below a critical range, the function is much less dependent of temperature. Also, the time span over which NO forms is on the order of millisecond before the cooling as temperature drops low enough to "freeze" the NO concentration.

The primary mechanism by which CCD is envisioned to affect NOx formation is the same as for ORI, by thermal insulation. The conductivity of carbonaceous deposits may be a factor of 500 less than bare aluminum. Decreasing the heat transfer from the cylinder increases charge mixture temperatures, leading to higher post-combustion temperatures. It has been estimated that CCD effects increase in-cylinder burned gas temperatures by at least 50° K (91). The deposit volume also decreases the effective combustion chamber volume, thus increasing the temperature due to increased gas compression. This effect is of an order of magnitude less important than the insulating effect.

Another potential CCD effect on NOx emissions is through changes in in-cylinder stoichiometry caused by fuel adsorption by the deposit. The rate of NO formation peaks at the stoichiometric composition and decreases rapidly with leaner or richer mixtures (33). Depending on how closely the engine calibration is designed to operate compared to stoichiometric, CCD may increase or decrease NO formation by this mechanism.

B. *CCD/Emissions Data*

To this point, literature data in modern engines (91-95) consistently agree only to the extent that trends indicate CCD contributes to exhaust NOx emissions relative to a clean engine. Reports of changes in HC emissions with CCD are inconsistent, and while CO is expected to follow HC effects, very little has been reported. As with ORI, the results vary greatly with vehicle to vehicle and model effects.

The effects of CCD on NOx emissions were little studied until recently, though historic data did show a link (96,97). Average deposit effects in the above studies ranged from zero-25 percent change in NOx emissions compared to a clean engine. Results in mixed fleet auto (92), matched pairs of test cars (93,94), and test stand engines (91,93,95) all showed an increase in NOx emission in deposited engines compared to a clean engine. The variability of the effect by engine model is seen in Houser (93), in which the change in NOx emissions with CCD varied from 0 to 20 percent for three different engine types on test stands and 10 to 60 percent for three different engine types in the matched vehicle pairs. Bitting et al., (94), reported NOx reductions averaging 20 percent for a mechanically cleaned engine. The result was shown to be statistically significant at the 95 percent confidence limit.

While HC emissions have been tied to CCD historically (40,96,98,99,100,101), these studies focused primarily on leaded fuels in carbureted engines. Intake valve deposits were also often not controlled or kept independent of CCD. More recent studies in modern engines with unleaded fuels produced less consistent results. Fleet test data presented by Wagner (92) and engine test cell data by Bower et al., (95) showed no trend in HC emissions with increasing CCD. A four model paired-car test by Bitting et al., (94), on the other hand, indicated HC emissions increased about 17 percent in deposited engines, though the results were noted as being not statistically significant at a 90 percent confidence level. Likewise, CO emissions showed no significant relation to CCD in Wagner's (92) fleet data, but showed a statistically significant 30 percent reduction when CCD were removed in the work by Bitting et al., (94).

It appears that modern engine designs coupled with advanced emissions control devices have significantly reduced the effects of CCD on hydrocarbon emissions. For example, fluctuations in stoichiometry caused by CCD may be within the normal variation and frequency controlled by oxygen-sensored engines, thus leading to a reduced effect of tailpipe emissions. The efficiency of modern combustion chamber designs may in some ways be enhanced by deposits while compensating for the deleterious effects. Deposits which effectively reduce the gap in the end-gas region of low squish height engines, for example, may increase the turbulence-generating effect of the design and act to increase the efficiency of the burn.

It should be noted that in several studies in which PFID/IVD detergents were employed and the engine emissions performance was compared to operation on base fuel, the overall emissions effect of using the detergent was positive (52,103).

C. *Incremental Effects of CCD on Emissions*

The central question to any deposit control strategy remains, "What is the benefit to be gained from a reduction in deposit level?" With respect to IVD and emissions, data exist for which analysis of the deposit-emissions functionality can be made and quantified with level of statistical significance. For instance, a description of the functionality of the IVD emissions relations was derived from data by Houser (103) and by an API industry panel. In this analysis, second order effects were found to be statistically significant. It was postulated that a cleanliness threshold level exists beyond which no emissions benefit could be identified. While the study was performed on a single model, the fleet was large enough to obtain a statistically significant answer in a typical, modern engine.

Unfortunately, to date no published information exists nor conclusions can be drawn relative to an incremental CCD-emissions relation.

While the data review above links CCD to NOx and, to a lesser extent, HC emissions in deposited engines compared with clean engines, there is no consistent trend, much less statistically significant set of data, available over a range of CCD levels. Fleet data presented by Wagner (92) and test stand by Houser (93) showed essentially no response by emissions across a range of deposit levels, indicating NOx emissions are relatively insensitive to CCD beyond the initial effect. If generally true, this may be explained by the relatively small difference in insulating value of a thin layer deposit compared to a thicker one, either of which would have a substantially lower heat transfer coefficient than bare metal. On the other hand, Houser (93) also presented data which indicated increasing NO emissions with incremental

CCD in three-matched pair vehicles. Studzinski et al., (91), also trended increasing NOx with increasing CCD, though a significant shift in the baseline makes interpretation of the data difficult.

D. *Conclusions*

A strong link exists between NOx exhaust emissions and CCD in comparison between clean and deposited engines. Though data in modern engines are less consistent, a historical link also exists between CCD and HC emissions and, to a much lesser degree of certainty, CO emissions.

No definitive data exist to describe a functionality, or incremental effect, of CCD with any of the above emissions.

From a mechanical design standpoint; it has also been shown that HC emissions can be reduced by reducing flame-quenching by reducing crevice volumes. CO emissions can be affected by fuel-air ratio control, and NOx emissions can be reduced by controlling peak combustion temperatures.

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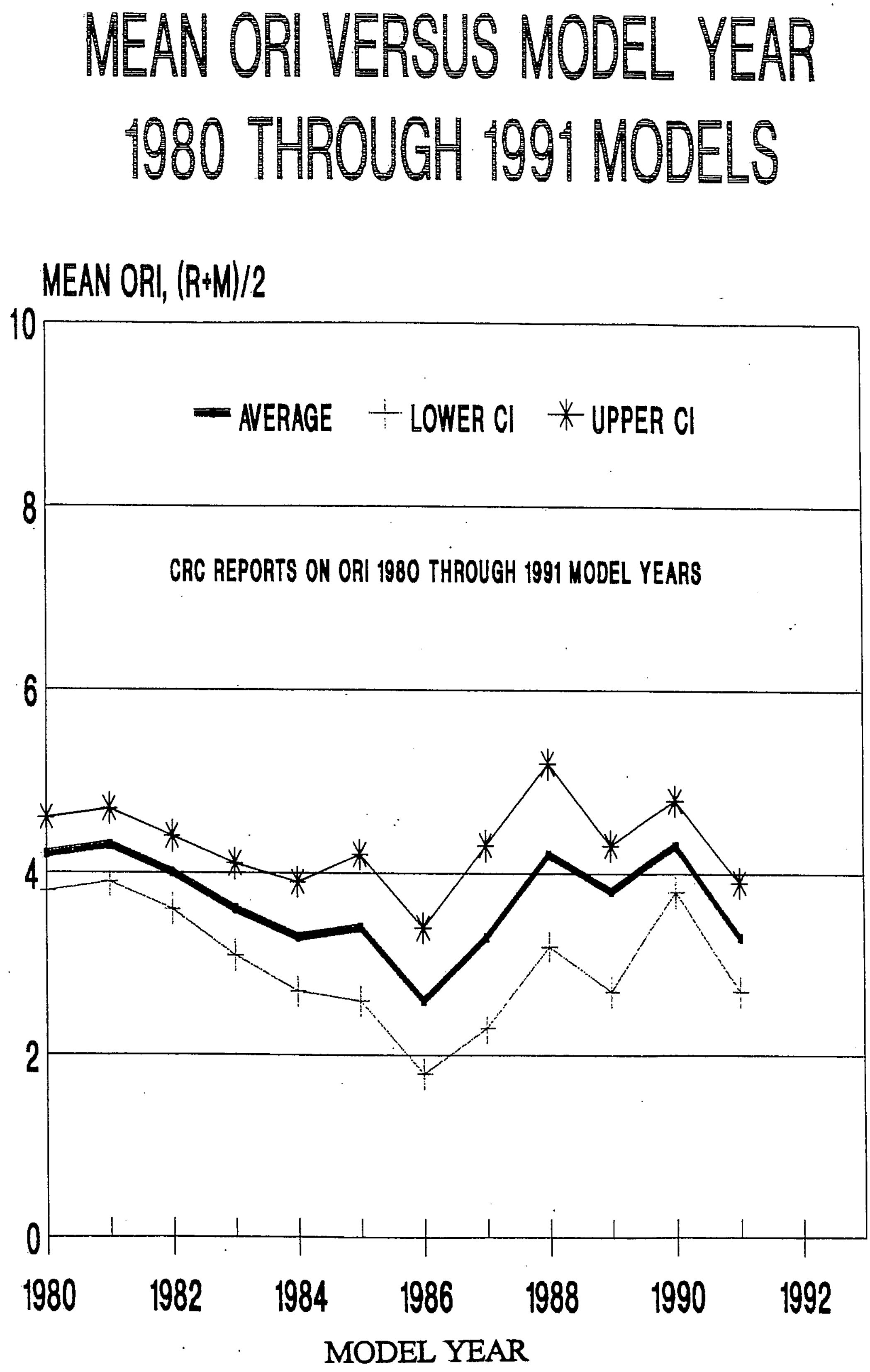
ATTACHMENT 1

CRC COMBUSTION CHAMBER DEPOSIT COMMITTEE SUB PANEL ON LITERATURE SEARCH

Don Swaynos	Exxon Chemical (Leader)
Dave Arters	Amoco Oil
Majid Ahmadi	Oronite Technology
Bill Bitting	Texaco Oil
Steve Cheng	General Motors
Peter Fuentes-Afflick	Oronite
Joe Graham	Shell Oil

Figure 1


MEAN ORI VERSUS MODEL YEAR
1980 THROUGH 1991 MODELS

INTAKE

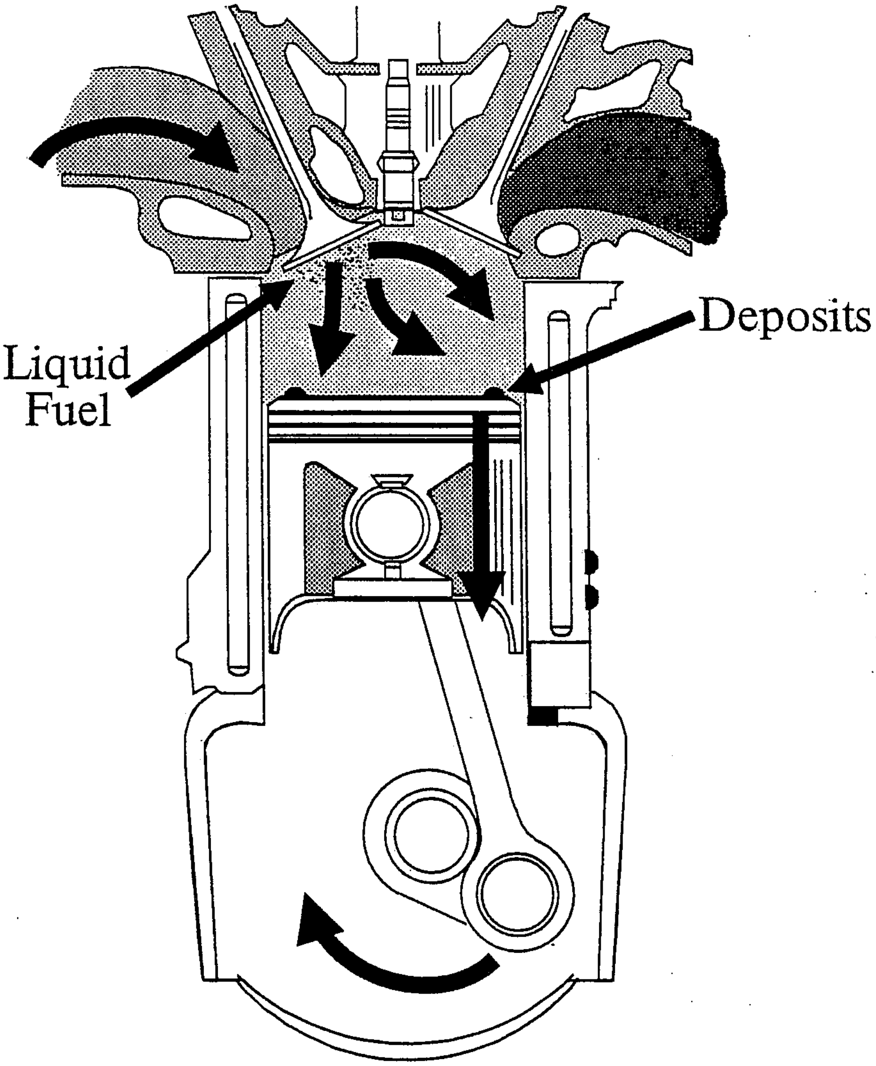


Figure 2

COMPRESSION

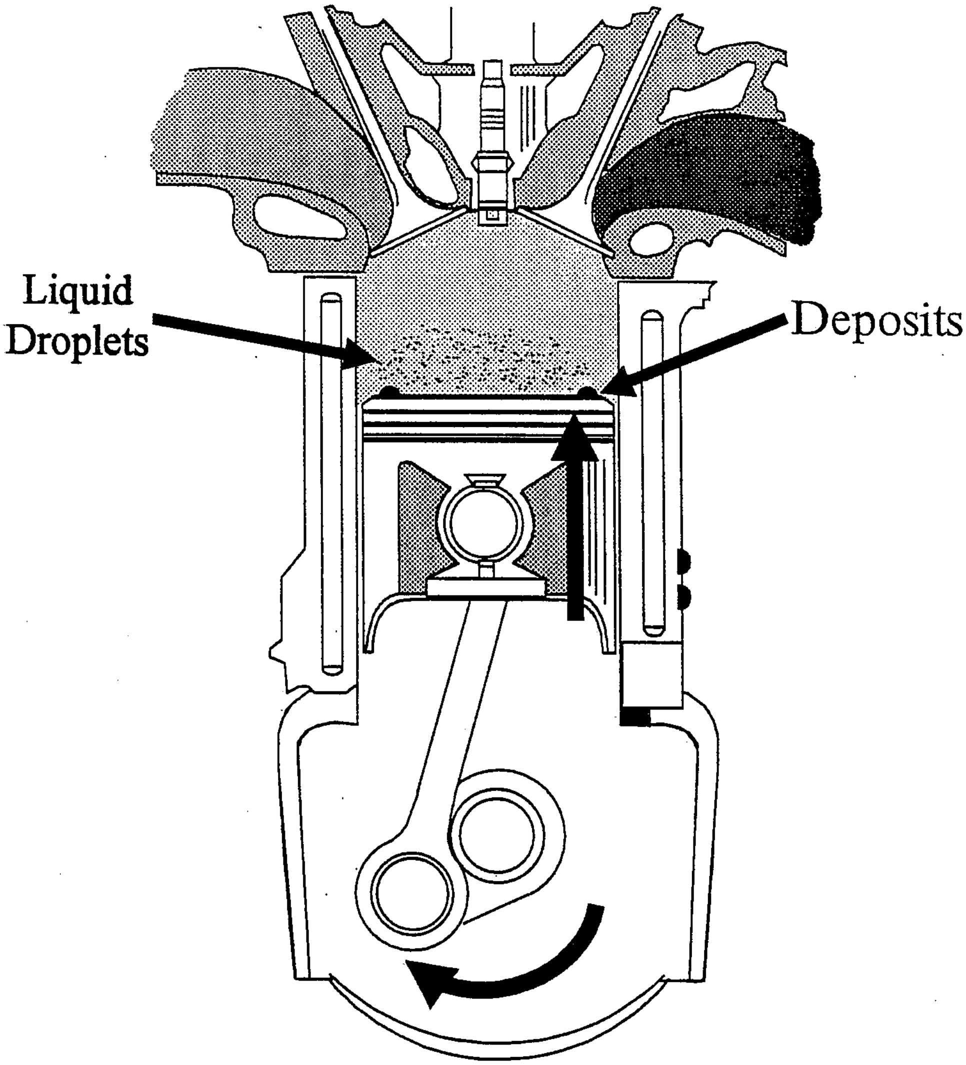


Figure 3

POWER

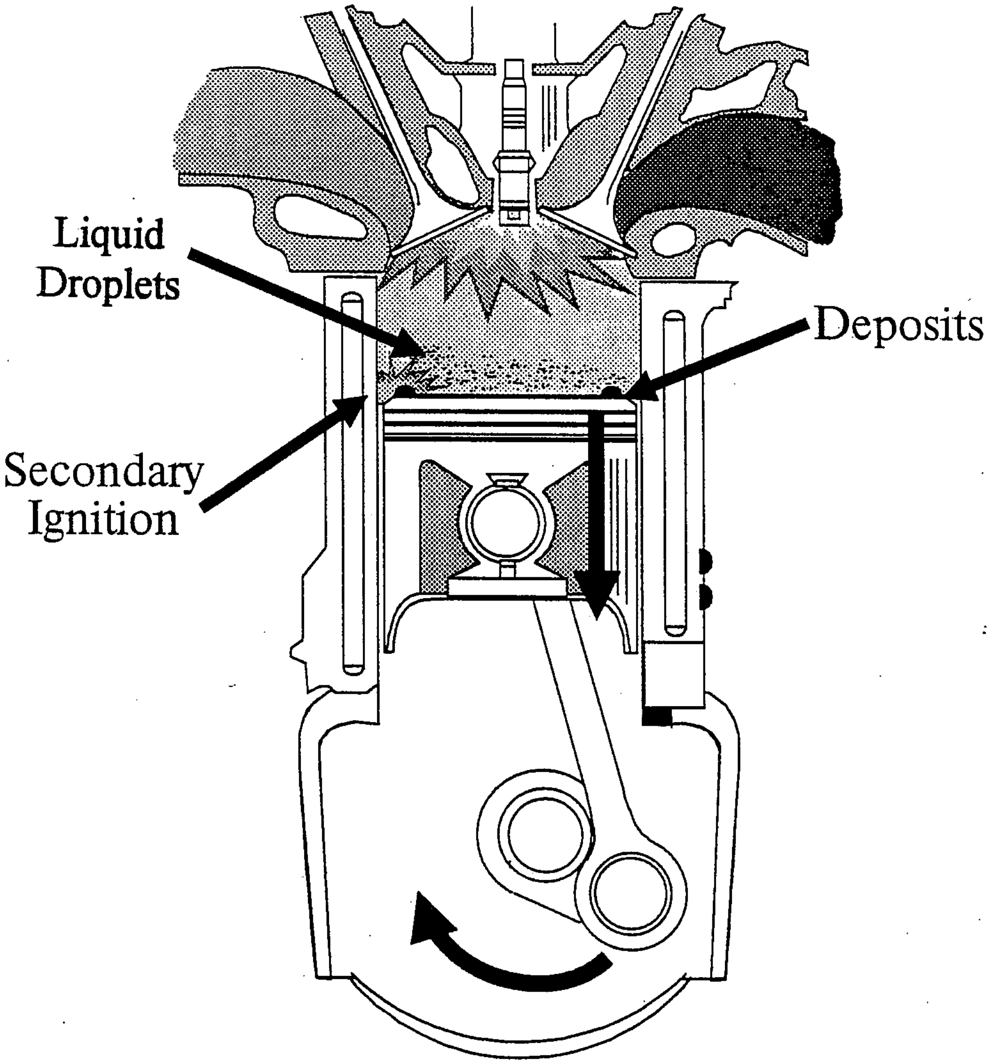


Figure 4

Secondary ignition can occur anywhere within the combustion chamber.

EXHAUST

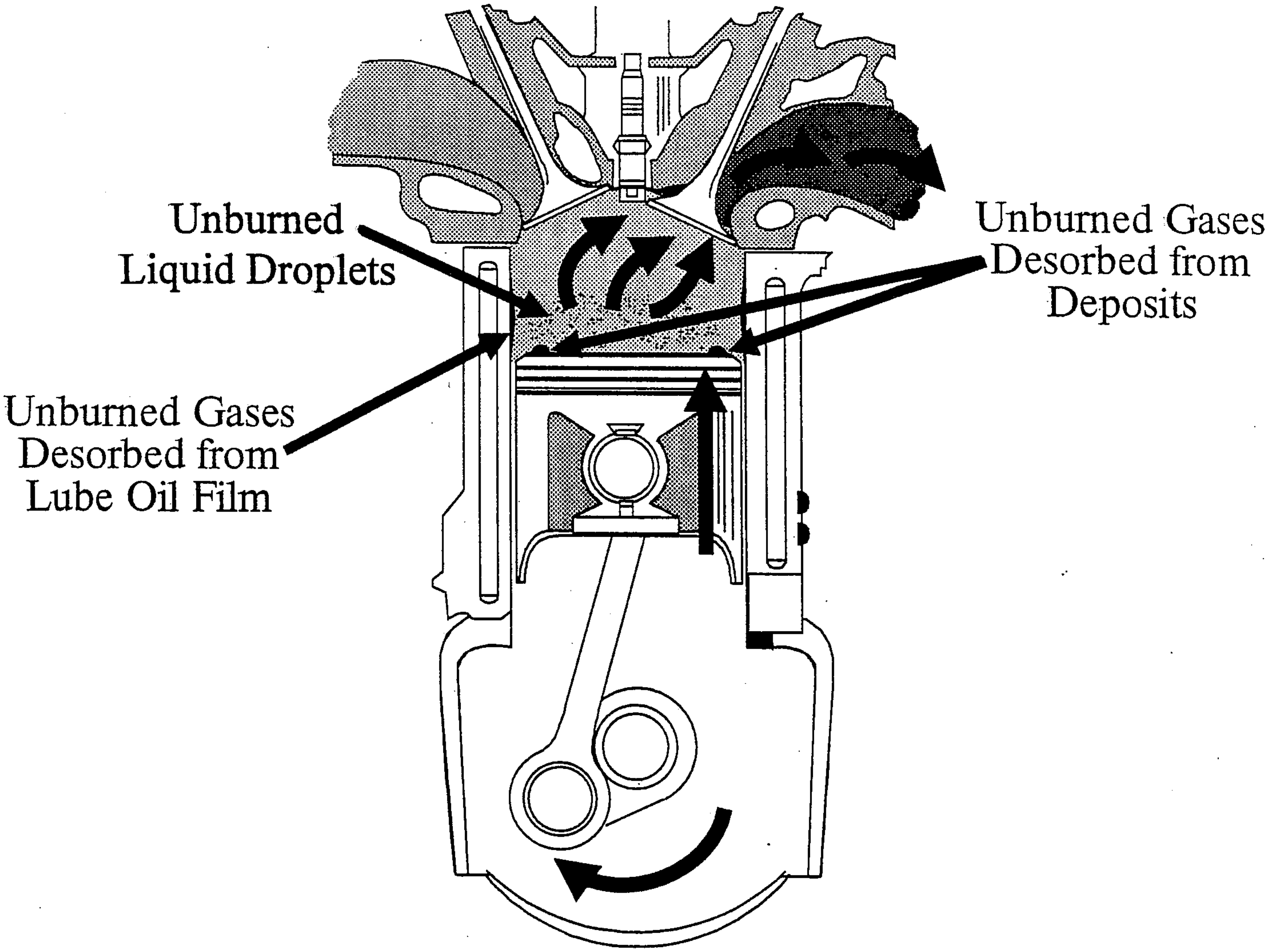


Figure 5

Figure 6

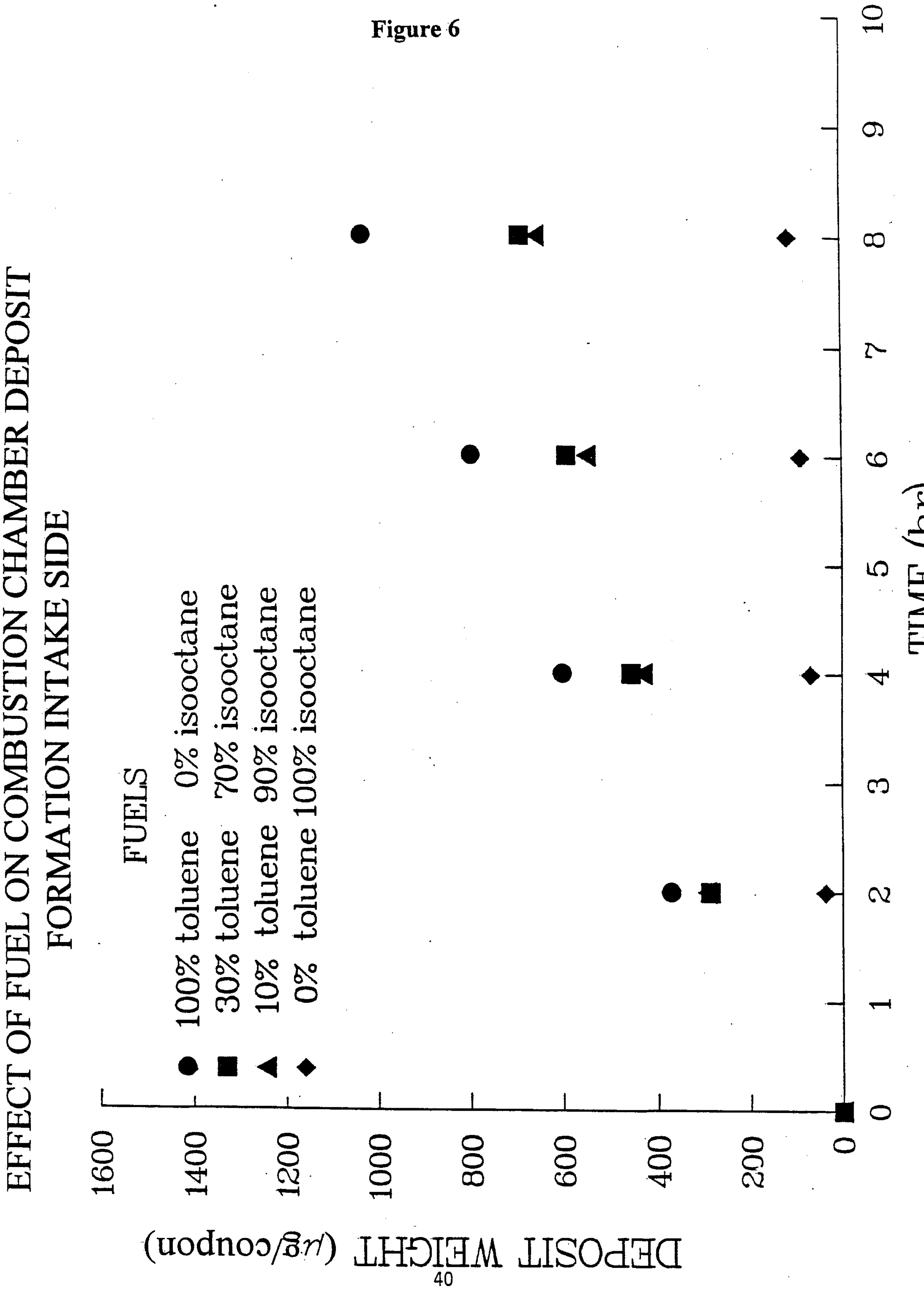

EFFECT OF FUEL ON COMBUSTION CHAMBER DEPOSIT FORMATION INTAKE SIDE
FUELS
● 100% toluene 0% isooctane
■ 30% toluene 70% isooctane
▲ 10% toluene 90% isooctane
◆ 0% toluene 100% isooctane
DEPOSIT WEIGHT (µg/coupon)
0
200
400
600
800
1000
1200
1400
1600
TIME (hr)
0
1
2
3
4
5
6
7
8
9
10

Figure 7

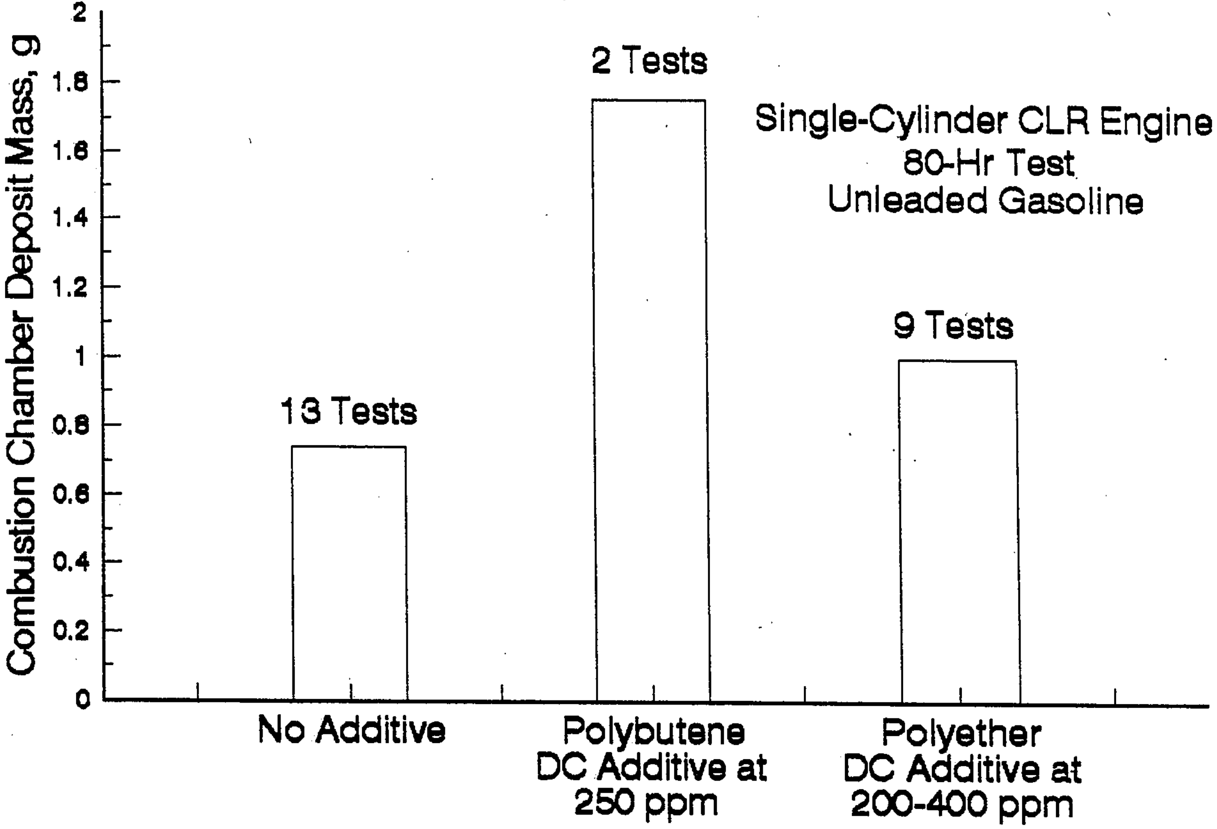


Figure 8

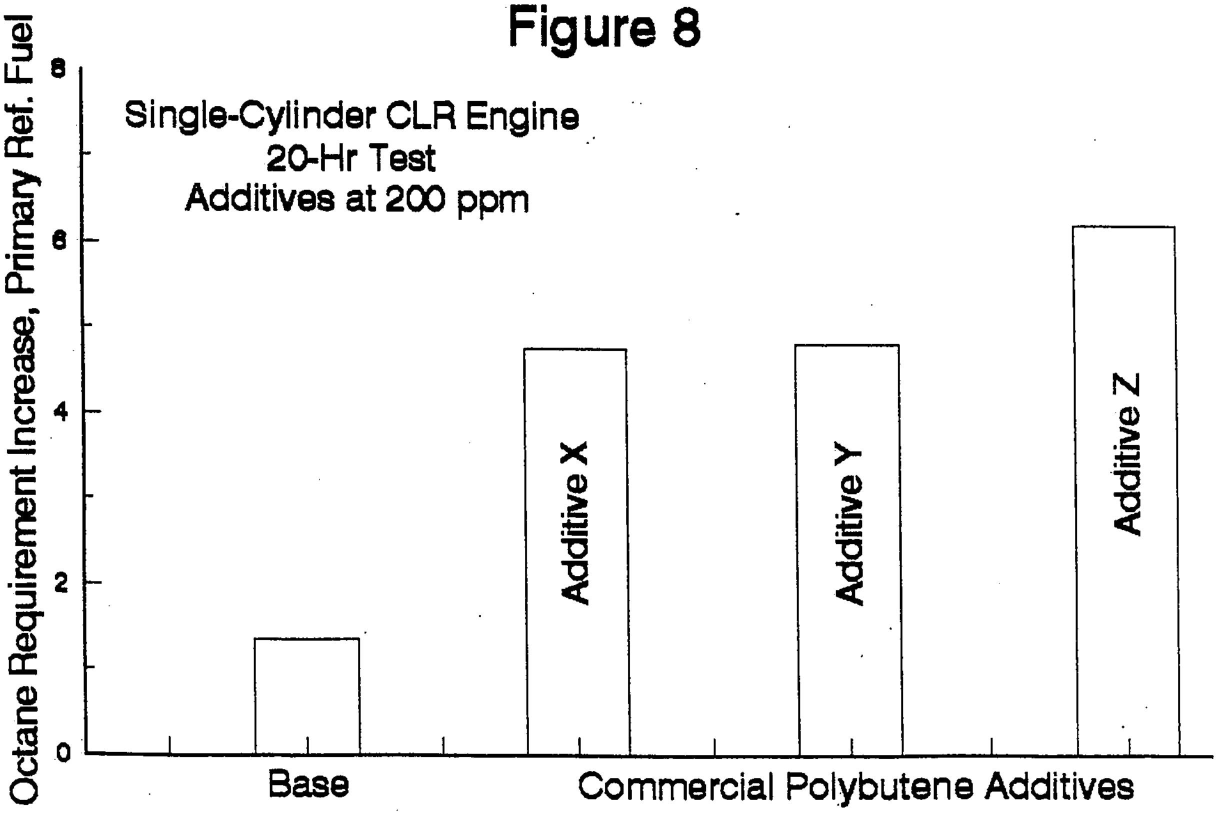


Figure 9

EFFECT OF COUPON MATERIAL ON COMBUSTION CHAMBER DEPOSIT FORMATION INTAKE SIDE

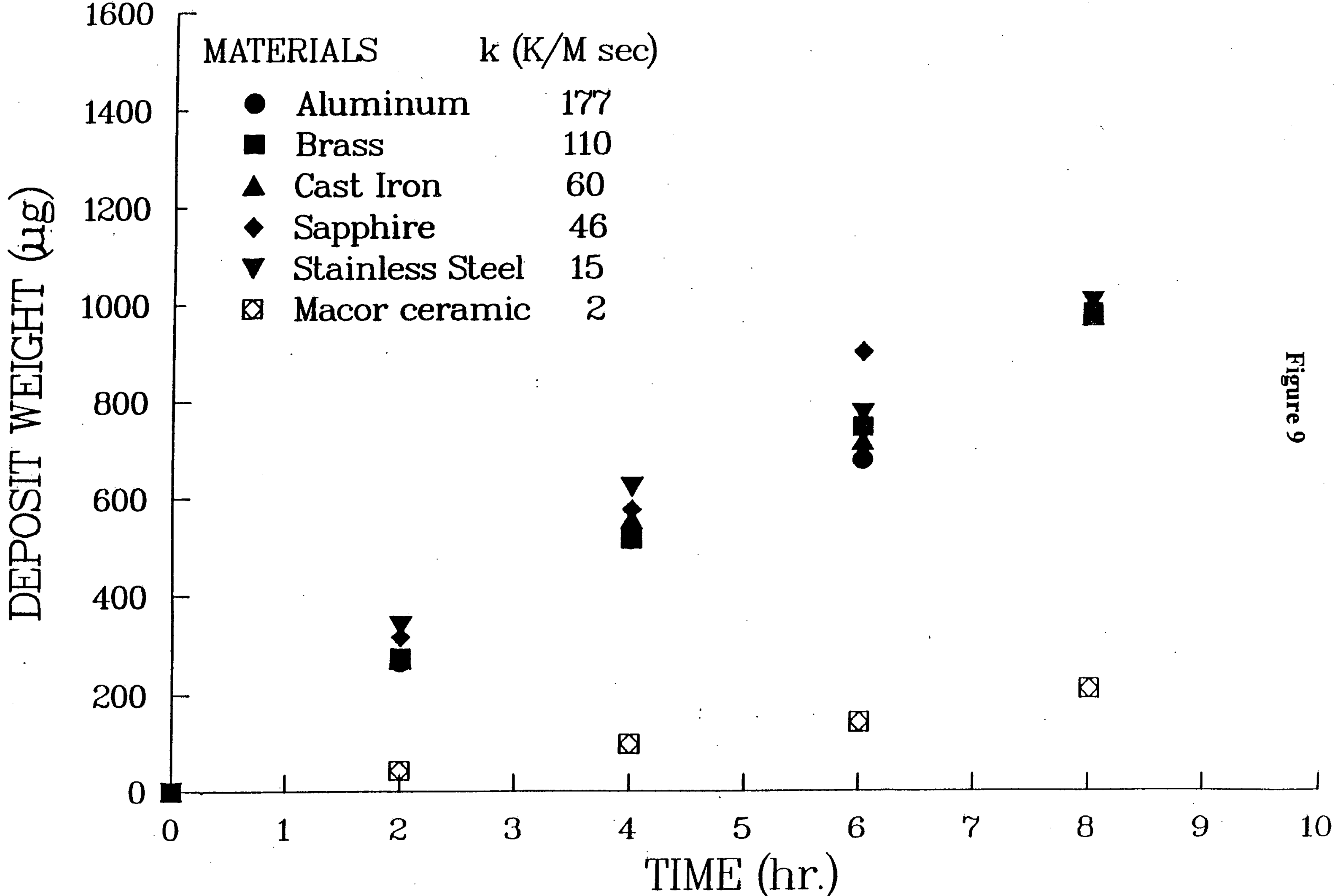


Figure 10

Statistical Design

36-CAR ORI
Evaluation in a
Reformulated
Gasoline

- Previous Programs Analyzed
  - 4 ORI Fleets
  - 80 Vehicles
  - 16 Models

- Estimated Statistical Power Based on
  - 36 Vehicle Design
  - $\alpha = 0.1$

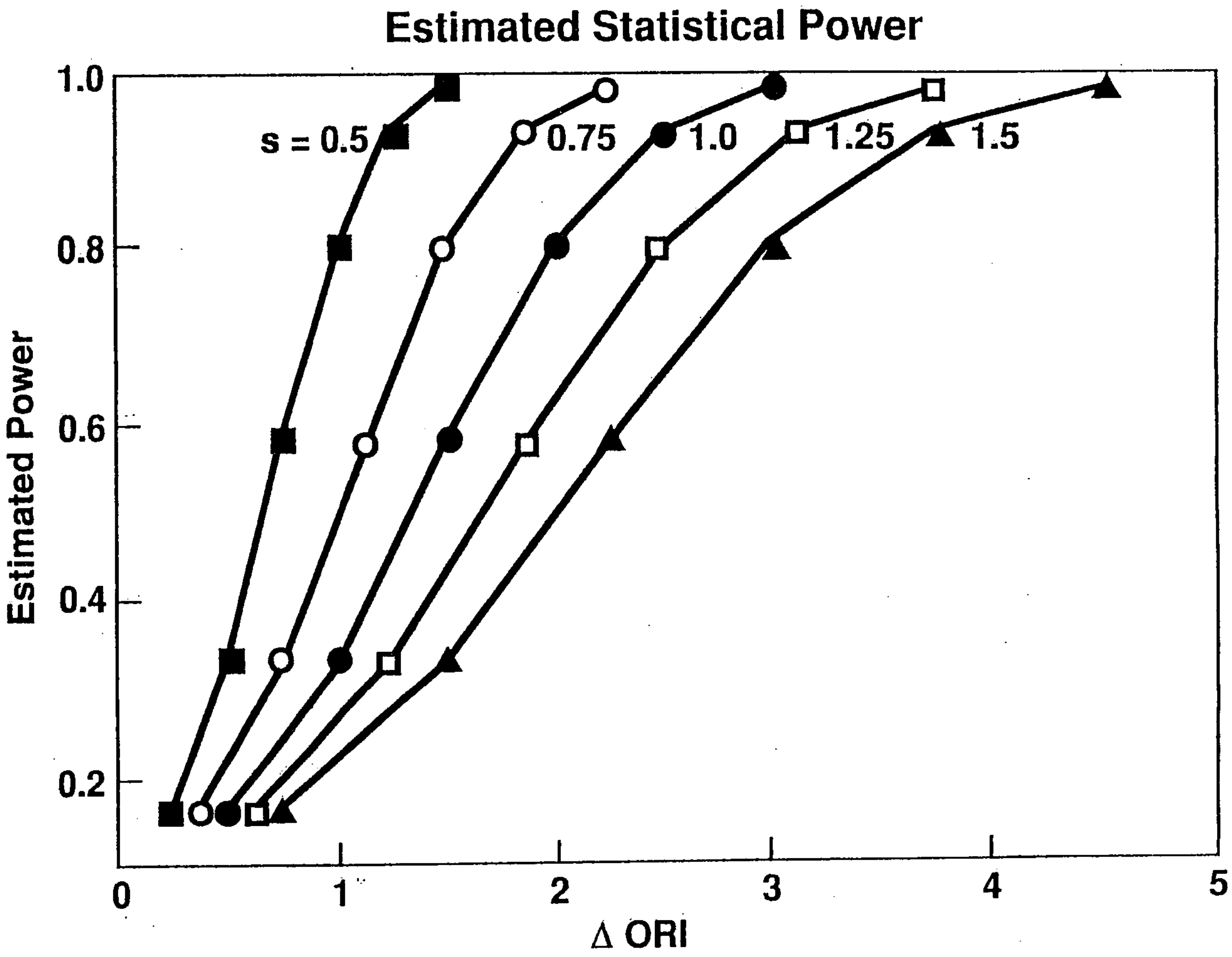


Figure 11

SQUISH

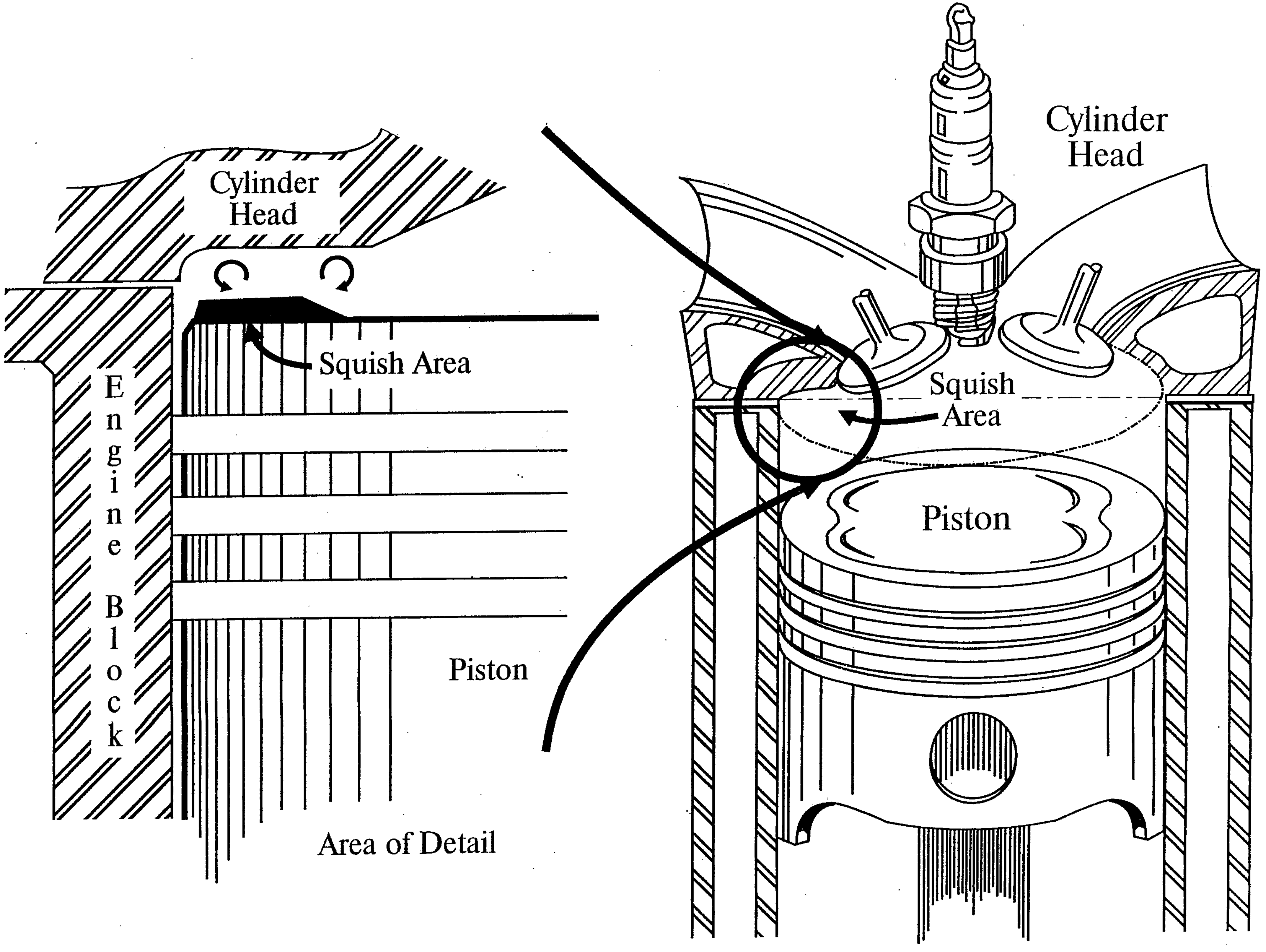


Figure 12

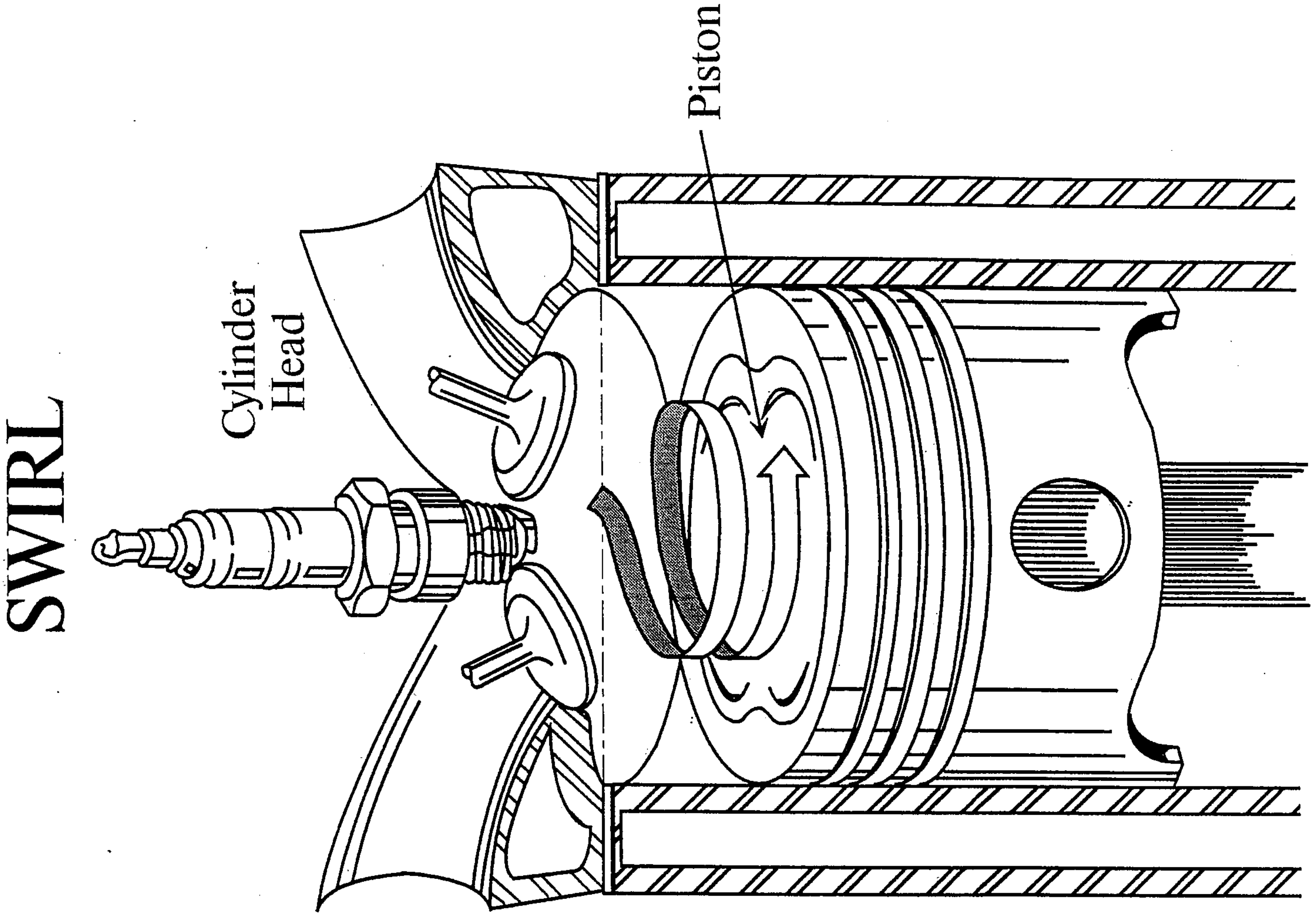


Figure 13

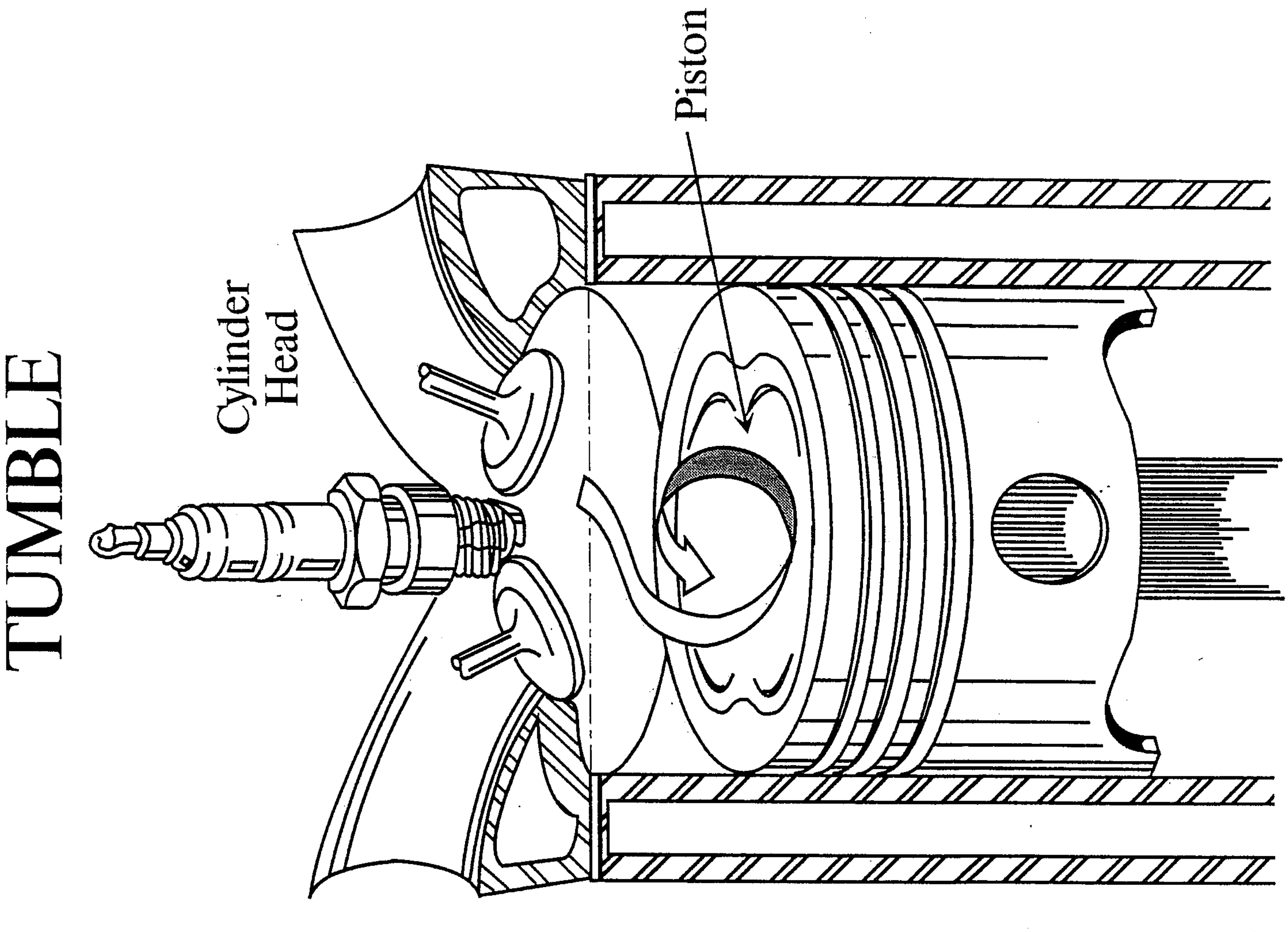
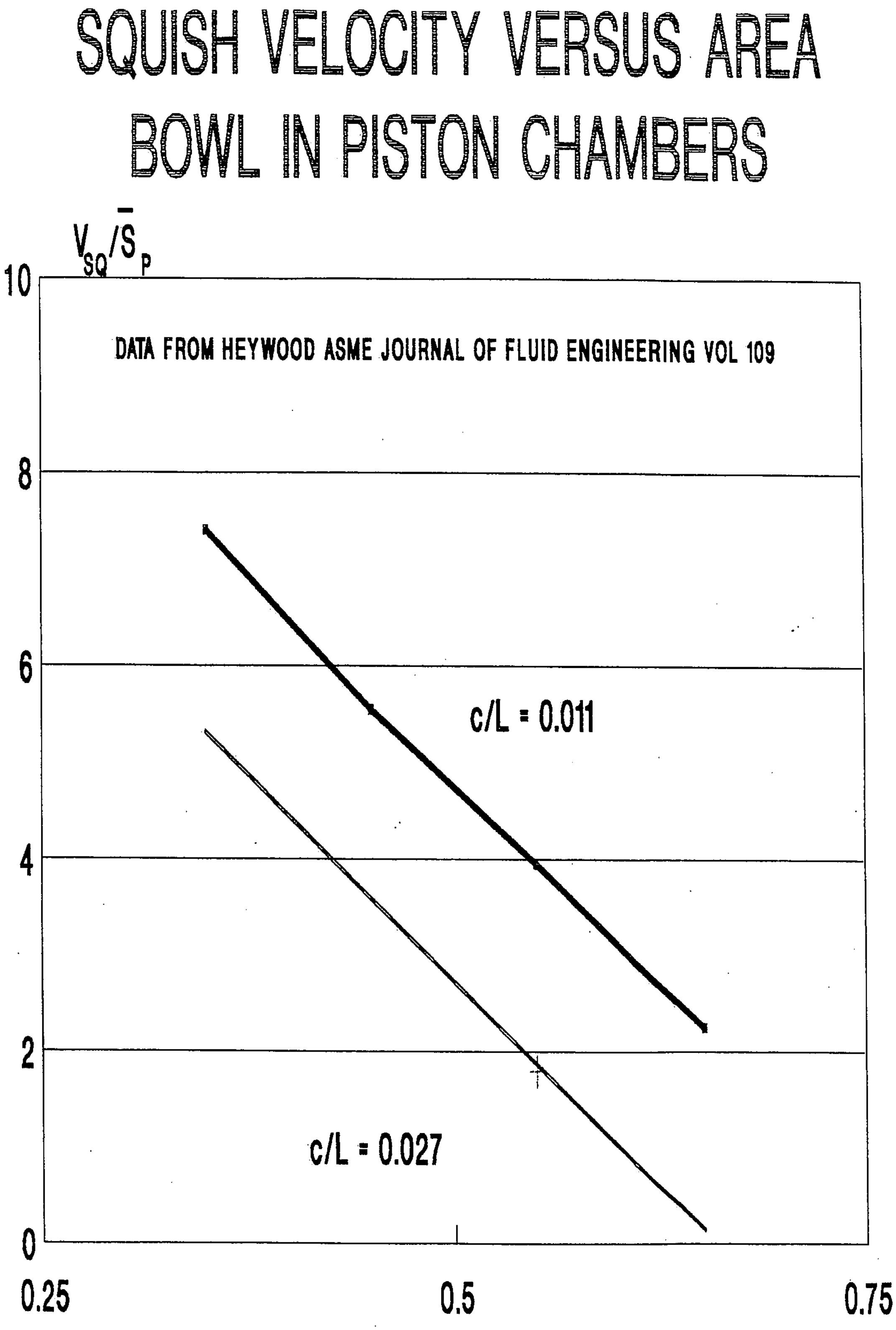


Figure 14



Where: c/L = Clearence Height/Stroke
D_B/B = Bowl Diameter/Bore Diameter
V_{SQ}/S_P = Squish Velocity