

A Literature Review of Abnormal Ignition by Fuel and Lubricant Derivatives

Elana M. Chapman
General Motors - Global Powertrain Engineering

Vincent S. Costanzo
Aramco Services Company: Aramco Research Center

ABSTRACT

Abnormal ignition, especially preignition, in gasoline engines has been a phenomenon that has been reported for many decades, going back to at least the 1920s in the literature. In the last 10 years, another abnormal combustion issue that has been deemed as preignition has been observed and documented. It is not clear if these issues from the early years are related or similar in nature to the present ones. Was the issue solved and now back again? Did changes occur in engine designs that caused this abnormal combustion phenomena to reappear? This paper serves as a review of literature from the 1920s through the 2000s on instances of abnormal ignition by fuel and lubricant derivatives, and what has been observed and learned. The different terms used to describe these phenomena are defined and clarified. Trends observed with the mechanisms and causes are discussed. Similarities between historical and more modern observations are highlighted, and areas of possible future work are suggested. Quick resolution of the current fuel/lubricant derivative ignition issue is required to minimize risk of engine hardware damage and enable utilization of advanced technologies to significantly improve vehicle fuel economy.

Keywords: abnormal ignition, preignition, postignition, surface ignition, wild ping, rumble, stochastic preignition, fuel/lubricant derivative ignition, end-gas autoignition, knock

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INTRODUCTION AND MOTIVATION

According to one of the early fathers of the automotive industry, Charles Kettering, "The automotive industry was considered a mechanical one until fuel difficulties caused a realization that the internal-combustion engine is only a piece of apparatus for the effective utilization of chemistry" [1]. Back then, knock and pre-ignition in the engine were considered a problem and their cause was debated. They visualized preignition as "red-hot particles of carbon in there setting the mixture afire" [1]. And, there were suggestions that a fuel additive will assist in controlling the combustion process with some simple experiments that showed that it could be controlled [1].

There have been many changes in the automotive industry since the 1920s in the areas of internal combustion engine technologies, fuel specifications, and engine oil specifications [2]. As for engine technology, the drivers of the technology have been to reduce vehicle emissions and improve engine specific power and vehicle fuel economy. Those changes in vehicle emissions and fuel economy over the years have required all three areas to make changes and improvements so that the engine technology could succeed [2]. Some of the significant changes include: improvements in engine oil technology for wear reduction and fuel economy improvement,

removal of lead (Pb) from the fuel to allow for the use of catalytic converter systems on vehicles, and improvements in the air and fuel handling on engines.

One significant issue that was discovered in the early 1920s was abnormal combustion in the engine. There were many papers from 1920s through the 1940s discussing the issues of preignition from various locations: a spark plug preignition due to material breakdown [3], a high-pitched knock observed in spark-ignition engines resulting from premature ignition by an overheated surface in the combustion chamber [4], and as a result of the conditions in the engine itself that generated the preignition tendency [5]. A report in 1941 by NACA (National Advisory Committee for Aeronautics) demonstrated the preignition characteristics and performance of fuels under engine conditions [6]. The issue has been around for some time, both in the aircraft industry and in automotive industry, for spark ignition engines [7] [8]. In the 1950s at the General Motors Research Laboratory, Withrow and Bowditch outlined the issue through photographs of the autoignition occurring as a result of combustion chamber deposits [8]. Their paper provides references of the issue back to 1943 as field complaints attributed to autoignition and wild pings.

From the time these abnormal ignition events were observed in the 1920s, and then studied in detail in the 1950s and 1960s with solutions proposed, these issues appeared to largely be absent in the 1970s. The authors believe that this may be in part due to changes in fuels and lubricants to address these issues, as well as changes to fuels and engines that were made to address emissions regulations in the 1970s. Foremost, the removal of lead from fuel and a resulting decrease in fuel anti-knock resistance led to a corresponding need to lower engine compression ratios, which may have resulted in avoiding regimes of in-cylinder conditions that were prone to these abnormal ignition events. It is worth noting that at this same time many fuel additives that were known to suppress abnormal ignition events were removed from fuel in order to allow aftertreatment systems to function correctly, yet these abnormal ignition events no longer seemed problematic. In more recent years (2000s to present), potentially similar observations of abnormal ignition have been observed. The authors believe that this may be due to advances in engine design and development, and changes in commonly used engine hardware technology (e.g. turbochargers and boosting) resulting in higher in-cylinder pressures and temperatures, which potentially leads to a progression into similar regimes of behavior of abnormal ignition problems which were observed in the past. Even if modern problems are not identical to those observed in the early to mid-20th century, there is the potential to apply knowledge and insight gained from study of those problems to the study of modern problems.

A review of the literature was completed to determine if researchers' conclusions from past observations aligned with current abnormal ignition issues observed in modern engines. The focus of this literature review will thus be to:

1. Clarify the descriptions and provide definitions of abnormal ignition observations, particularly focusing on those that were due to derivatives of the fuel and/or lubricant
2. Review the issues observed in the 20th century, and how they were addressed and mitigated through changes in engine hardware, fuel and lubricant
3. Briefly highlight the issues currently described in the literature since 2000 and proposed changes to mitigate the issue
4. Compare and contrast the observed behaviors of abnormal ignition caused by fuel and/or lubricant in the 20th century to those in the 21st century
5. Propose further study to determine if past solutions could apply to the current issue

DEFINITIONS AND BACKGROUND

In 1954, the Coordinating Research Council (CRC) proposed standardized terms to refer to abnormal combustion phenomena observed in spark-ignition, propagating flame engines - see [9] or [10] for these definitions. While the authors of this article acknowledge those definitions, in our view more carefully worded terms and definitions (which are in the spirit of the original CRC terminology) are required. This will be evident in the subsequent definitions below. Thus, for the sake of clarity, the following definitions are used in this article:

Normal ignition is the ignition of the fuel-air-residual gas mixture by engine hardware at the desired time in the engine cycle. It results in a propagating flame. Typically, the source of this ignition is a spark discharge.

Abnormal ignition is the ignition of the fuel-air-residual gas mixture (that results in a propagating flame) by any means other than the normal ignition mechanism. The terms preignition and postignition can be used to indicate when in the engine cycle the abnormal ignition occurs, as described below.

Preignition is the abnormal ignition of fuel-air-residual gas mixture prior to the normal ignition. It results in a propagating flame, prior to the flame that would have arisen from the normal ignition mechanism.

Similarly, the term **postignition** refers to abnormal ignition of the fuel-air-residual gas mixture after the normal ignition (but that still resulting in a propagating flame). In general, preignition is more problematic than postignition as it can lead to higher than normal in-cylinder pressures and temperatures, which can then lead to end-gas autoignition and further to problematic engine noise or other damaging phenomena as described below.

It should be emphasized that the terms preignition and postignition refer to when the ignition (that is, the initiation of a propagating flame) occurs, and do not refer to the subsequent overall rate of combustion or combustion phasing. (For example, in Figure 2, in the case of rumble there is earlier than normal combustion phasing due to many postignitions.)

End-gas autoignition is the spontaneous ignition of fuel-air-residual gas mixture ahead of a propagating flame. It can result in rapid release of chemical energy causing local high-pressure waves to propagate in the combustion chamber. When extreme, these high-pressure waves can cause engine damage.

Even when engine damage does not occur, these high-pressure waves can result in objectionable noise. There are various terms, such as knock, rumble, thud, thumping, and wild ping that are used to refer to the noises associated with the vibration of the engine structure as a result of end-gas autoignition. The most common term used today to refer to these sounds is "knock".

As evident in Figure 1, it is critical to distinguish between abnormal ignition, end-gas autoignition, and knock. In particular, note that abnormal ignition does not necessarily result in end-gas autoignition, and furthermore that end-gas autoignition does not necessarily result in engine noise phenomena. As a general rule, though, the earlier that abnormal ignition occurs in the engine cycle the higher the likelihood (and severity) of end-gas autoignition occurring, and thus the higher the likelihood and severity of engine noise phenomena occurring as well. It is also worth emphasizing as well that not all end-gas autoignition is caused by abnormal ignition: end-gas autoignition can be induced by sufficiently advanced "normal" combustion phasing for a particular operating condition and fuel.

As described above, the occurrence of abnormal ignition is itself problematic as it can lead to other problematic and potentially damaging engine phenomena such as severe engine knock. The source of preignition (or postignition) can either be (1) some permanent combustion chamber component such as a hot spark plug electrode or a hot exhaust valve, or (2) some object derived from the fuel and/or lubricant that is present in the combustion chamber (historically this object has been thought to always be a combustion chamber deposit).

In 1954, the Coordinating Research Council (CRC) defined “surface ignition” as “the initiation of a flame front by any hot surface other than the spark discharge prior to the arrival of the normal flame front. The flame front or fronts so established propagate at normal velocities” [9]. The term “surface ignition” is *not* preferred here because it (1) is too general, and (2) can be misleading if the ignition source is, for example, a deposit particle moving through the gas space or was a liquid derived from the fuel and/or lubricant. Some authors have also used the term “deposit-induced surface ignition”, but again this term is not preferred as it often presumes the precise cause of the ignition is known.

To avoid ambiguity, and be more clear about the source of the abnormal ignition, in this paper the following terms are used to refer to the types of preignition or postignition as classified by their source:

Hot component ignition is the abnormal ignition of the fuel-air-residual gas mixture (resulting in a propagating flame) by a permanent combustion chamber object such as a hot spark plug electrode or a hot exhaust valve. These components are noncombustible, but potentially catalytic.

Fuel/lubricant derivative ignition is the abnormal ignition of the fuel-air-residual gas mixture (resulting in a propagating flame) by an object derived from the fuel and/or lubricant, such as a stationary or moving combustion chamber deposit. Fuel/lubricant derivatives are in general combustible, and furthermore may contain catalytic materials. Combustion of the fuel/lubricant derivative is one possible mechanism that induces the abnormal ignition of the fuel-air-residual gas mixture; the fuel/lubricant derivative not combusting but reaching a sufficient temperature to ignite the fuel-air-residual gas mixture is another possible mechanism.

As stated above, as defined here the terms hot component ignition and fuel/lubricant derivative ignition refer to the source of the abnormal ignition (in other words, where the flame corresponding to the abnormal ignition originated from). In particular, note that these terms do *not* attempt to refer to the mechanism that led up to or induced the abnormal ignition, and instead only refer to the observation of what induced the abnormal ignition. For example, if excessive accumulation of combustion chamber deposits on the piston increased the effective compression ratio which resulted in overheating of the spark plug electrode, and the spark plug electrode then became the source of abnormal ignition, one would say this was an occurrence of hot component ignition because the spark plug electrode initiated the abnormal ignition.

It is worth noting that abnormal ignition by one source can induce abnormal ignition by another source in subsequent cycles. For example, a preignition caused by a fuel/lubricant derivative can result in increased heat transfer to a component in the combustion chamber (such as the spark plug) and result in hot component preignition in the subsequent cycles.

As before, the terms preignition and postignition can be used to describe when either hot component ignition or fuel/lubricant derivative ignition occurred. For example, the abnormal ignition of the fuel-air-residual gas mixture due to a hot deposit particle that occurred prior to the normal spark discharge would be an example of fuel/lubricant derivative preignition.

The issue of hot component ignition is primarily one of appropriate engine component design, whereas the issue of fuel/lubricant derivative ignition is primarily one of appropriate fuel and lubricant selection, design, and matching to the engine. Fuel/lubricant derivative ignition can be especially problematic as it can be difficult to control in an engine and moreover challenging to study in a controlled way. The focus of this review paper is a historical examination of various fuel/lubricant derivative ignition phenomena, and in particular the factors affecting them and the hypothesized mechanisms by which they were thought to occur.

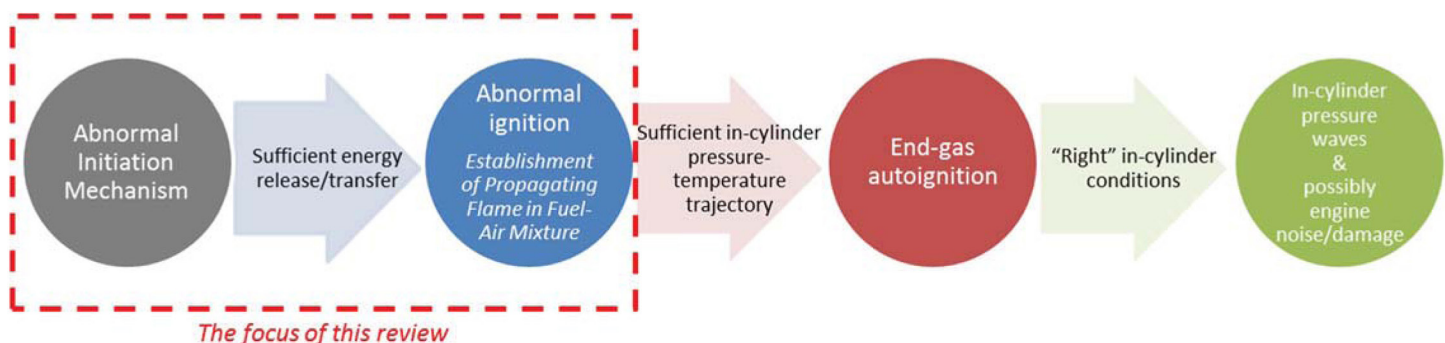


Figure 1. Steps by which abnormal ignition can lead to engine noise and damage, and the portion of the process that this review paper focuses on.

HISTORICAL OBSERVATIONS OF ABNORMAL FUEL/LUBRICANT DERIVATIVE IGNITION

The primary terms used to refer to fuel/lubricant derivative ignition phenomena that were observed in the mid-20th century were “rumble” and “wild ping”. The respective terms refer to the characteristic sounds these distinct phenomena produced.

Rumble was a low-pitched noise in the roughly 800 to 1400 Hz range [10]. This noise was ultimately found to be associated with bending vibration of the crankshaft due to abnormally high rates of pressure rise near top center [11]. These high pressure rise rates were attributed to “too rapid burning of the fuel-air mixture”, associated with a repetitive pattern of single or multiple abnormal ignitions occurring immediately before or after the normal spark discharge [11].

Figure 2 below shows a typical pressure trace for rumble as compared to normal combustion and a “knocking” cycle. Note the rapid pressure rise and high peak pressure, but lack of pressure oscillations. Figure 3 shows the propagation of multiple flames during rumble. The normal spark discharge occurs 16 degrees before top center at the location marked “16B”. In particular, note that in this case all of the abnormal ignitions occurred after the normal spark discharge, and would result in a pressure trace similar to that of Figure 2.

These abnormal ignitions were found to be caused by “flaked” deposit layers on the combustion chamber surfaces [11]. It was hypothesized that these deposits which were partially adhered to the

surface, but also partially flaked away from it, could get hot enough themselves to begin to burn [12] since they had less contact with the “cold” combustion chamber surfaces. In contrast, those deposits that were well-adhered to the wall generally would be at a relatively low temperature and unable to combust [13] [14].

Rumble was generally observed in engines that had extended operation at light duty schedules, and would occur primarily at higher engine loads and at higher engine speeds [15]. Presumably, the extended operation at lighter loads produced deposits that were more prone to cause abnormal ignition, and the high load/speed conditions resulted in the deposits getting hot enough to cause an abnormal ignition.

It was recognized by early investigators that rumble was a distinctly different phenomenon than engine knock. Multiple investigators utilized a reference fuel system that consisted of blending leaded isooctane with leaded benzene [10]. Isooctane was very resistant to rumble; benzene was very prone to rumble. Thus, mixtures of these two fuels provided a fuel of very high antiknock quality but varying fuel/lubricant derivative ignition resistance. This system is analogous to the system used for rating octane number of fuels. It is referred to as the LIB system, and the number refers to the percent of isooctane in the blend [10]: the higher the LIB number, the more resistant to these abnormal ignition phenomena the fuel was. The leaded isooctane-benzene blend that would not exhibit rumble for a given engine was said to be that engine's “rumble requirement” LIB number.

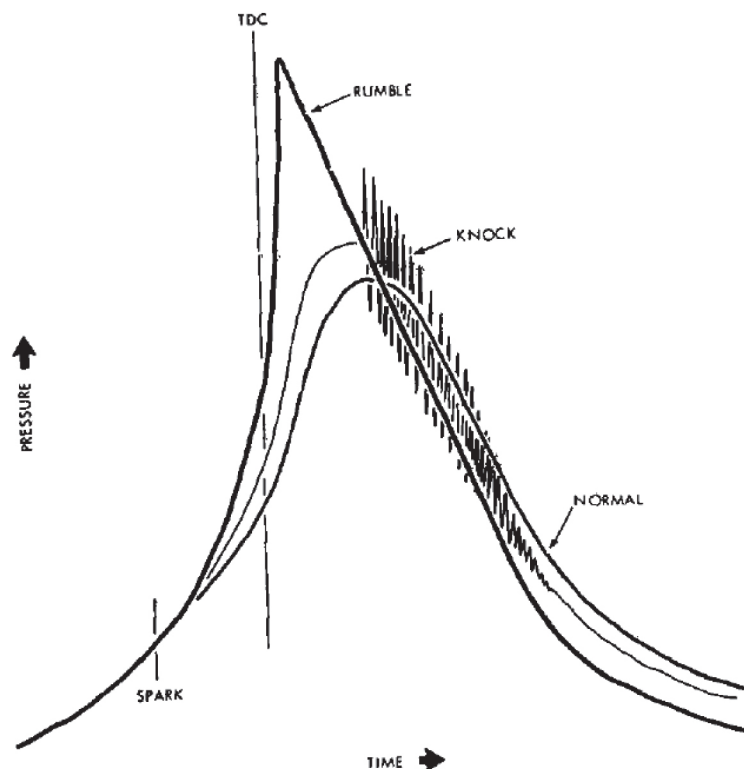
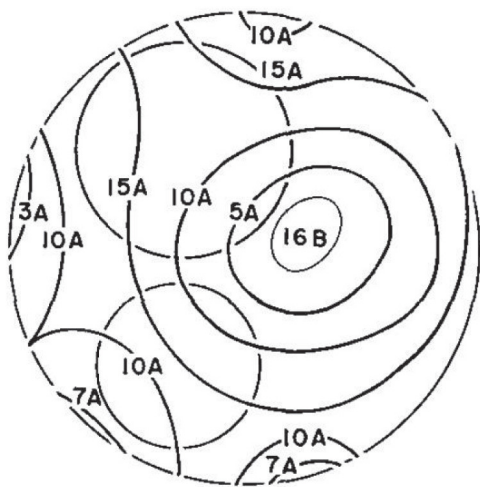


Figure 2. Pressure-time diagrams for normal combustion, a “knocking” cycle, and a cycle during rumble [10]. Copyright © SAE International. Reprinted with permission from paper 650391.

Wild ping was characterized by “sharp intermittent noises of short duration” [11] and by “one or more erratic sharp cracks” [9]. This noise was thought to be the result of loose, flaked deposit particles causing significantly advanced preignition (which ultimately resulted in knock) [11]. The short-lived nature of wild ping was explained by the fact that these particles would quickly either be burned up or expelled from the combustion chamber [11].

In some visualization experiments, Withrow and Bowditch [8] reported visually observing glowing deposits flaking from the combustion chamber surfaces and a “sharp knock” that they thought was similar to wild ping. To produce this, they operated the engine for an extended period of time at idle and a coolant temperature of approximately 49°C. Upon allowing the coolant to reach approximately 90°C, under idle conditions “nothing unusual was observed except for a dull red glow at the edges of the flakes” of the deposits [8]. However, “as soon as the throttle was opened the space in the combustion chamber was filled with glowing particles which reminded one of fireworks” [8] and the engine continued to fire without the normal ignition. From this, one conclusion is that wild ping was generally observed during engine accelerations. It is worth further noting that some experimental examinations of wild ping would specifically operate the engine through a level-road full-throttle acceleration to determine if wild ping occurred, and if so when it occurred [16].

One important characteristic of wild ping is its seemingly erratic occurrence. In what appears to be primarily observations of wild ping, Hirschler and coworkers [17] observed that, if examined over a sufficiently long time period, the occurrence of these abnormal ignition events occurred at a regular frequency. This can be seen in the data of Figure 4 below: when observed over short time periods, the occurrence of deposit-induced ignition appears highly erratic. However, when the cumulative count was examined over a much longer time period the behavior was very consistent.



NUMBERS DENOTE CRANK ANGLE

Figure 3. Flame propagation during rumble. The off-center circles without labels are the intake and exhaust valves; the contour lines with labels indicate the time of flame arrival at each location on the head. Note the presence of multiple ignition sites [11]. Copyright © SAE International. Reprinted with permission from paper 610401.

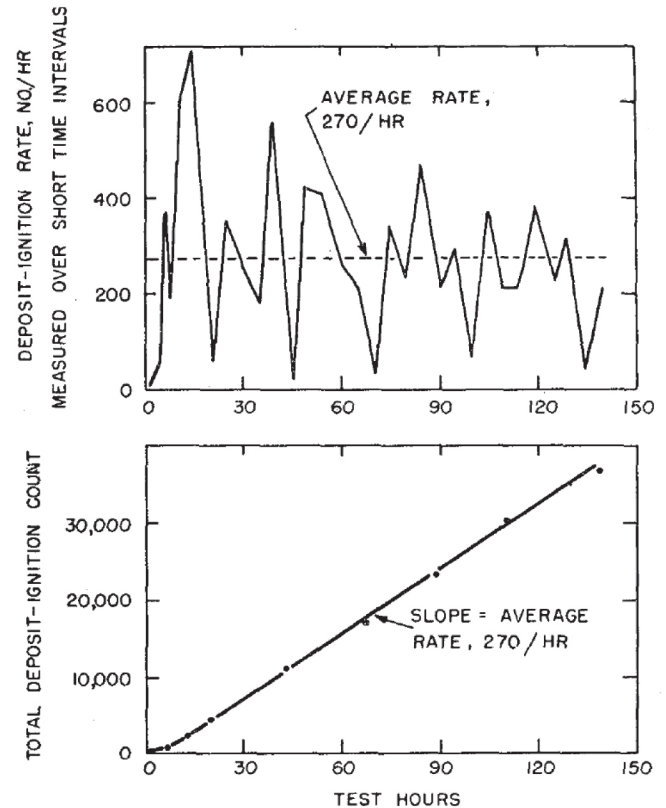


Figure 4. An observation of abnormal fuel/lubricant derivative ignition over “short” time intervals (above) and cumulatively (below) [17]. Copyright © SAE International. Reprinted with permission from paper 540220.

In so much as the deposits in the combustion chamber affect abnormal ignition, previous experimenters concluded that a knocking cycle can break deposits free from the combustion chamber surfaces, resulting in advanced ignition in the next several cycles [10], consistent with some of the observations with wild ping. Furthermore, heavy knock has been observed to clean the combustion chamber surfaces of deposits, resulting in reduced fuel/lubricant derivative ignition for a period of time afterward. [10]. Note that this observation appears consistent with the observations in Figure 4 above.

It is worth noting that, as evident from the above, the overwhelming consensus in the technical community previously was that the source of these abnormal ignition events caused by fuel/lubricant derivatives was combustion chamber deposits. The authors of this review could not locate any mention of abnormal ignition by a fuel/lubricant derivative that was hypothesized to have occurred by a means other than a combustion chamber deposit.

One interesting observation was made in a study by Tomsic [18] in which abnormal ignition was observed after a short period of operation (< 2 hours) of a “clean” engine with a leaded fuel. In fact, it was observed by Tomsic that abnormal ignition tendency was highest early in a deposit accumulation test [18] and that after 2 hours of operation the combustion chamber consisted only of “speckled” granular deposits. It was hypothesized by B.M. Sturgis [11] that this was due to very small particles of deposit being in the gas space. Note, however, that subsequently it will be shown in this paper that general the smaller the deposit particles are, the less likely they are to

cause abnormal ignition. Thus, it is possible that the observation of Tomsic was caused by a means other than a deposit particle. This is the only reference to abnormal ignition by a fuel/lubricant derivative in a “clean” engine that the authors of this review could locate.

HISTORICAL EFFECTS AND HYPOTHESIZED EXPLANATIONS

The following sections detail the various aspects observed in the literature since the 1920s. Again, the issues seemed to arise due to changes in compression ratio of engines, or researchers trying to develop boosted engines through supercharging. The authors have broken down the impacts into specific contributing factors that have been identified, which include effects from base fuel, fuel additives, base oil, oil additives, and engine hardware and operating conditions. The authors will also cover the hypothesized mechanisms that produce the effects of abnormal ignition from fuel/lubricant derivative, and discuss the deposit composition and mechanisms with detailed explanations.

To assist the reader, the following outline of this paper section is offered as a reference:

1. Effects of Fuel
 - a. Base Fuel Effects
 - b. Fuel Additive Effects
2. Effects of Oil
 - a. Base Oil Effects
 - b. Oil Additive Effects
3. Effects of Engine Hardware and Operating Conditions
4. Effects of Deposit Properties

Effects of Fuel - Base Fuel Effects

Since the early 1940s, it was believed that the fuel itself had some impact on the preignition performance of an engine, as noted by various NACA reports released in that time frame [19] [20]. The issue of preignition was occurring in aircraft engines so there was great concern in determining the cause and applying the right solution. Hundere and Bert concluded that the fuel affected the preignition performance of an engine in two ways: 1) “the temperature required for surface ignition and the combustion-chamber-surface temperature vary with the fuel used”, and 2) “some fuel components induce preignition through the formation of combustion-chamber deposits that are capable of supporting surface ignition” [7]. Hence, as Hundere and Bert outlined about the fuel tendency for preignition, the review of the literature will focus on the fuel aspects that form deposits and the tendency of the fuel to ignite easily.

Deposit Induced Preignition versus Hot Spot or Spark Plug testing of Fuels

Campbell, from General Motors, expressed the theory that the deposits in the cylinder causing the preignition effect were largely due to the lead from the fuel [21]. Later research concluded that the lead anti-knock additives were not the major problem and that the cause was the high melting point ash from oil additives which were

durable enough to result in run-away preignition from deposits [22] [23]. Around the same time period, while studying the mechanism of deposit formation in the combustion chamber and how this influences knock, Dumont performed fuel studies of leaded and unleaded fuels with high and low sulfur [13]. As shown in Figure 5, the lead (TEL in the figure which refers to Tetra Ethyl Lead) contribution from the fuel had a higher effect on the deposits than the sulfur. Although, the combination of the lead and the sulfur produced an increase in the deposits overall. It would seem from these results that lead does contribute to deposits in engines.

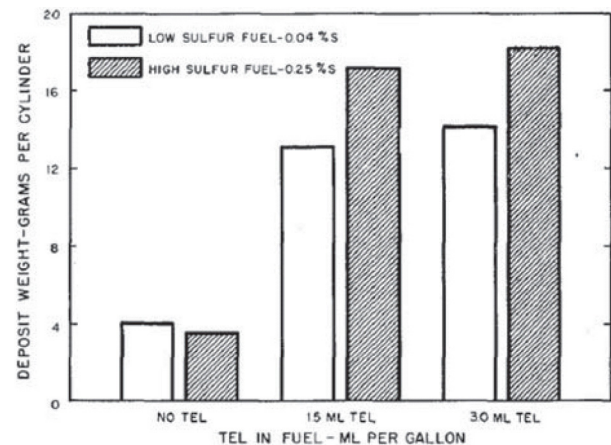


Figure 5. Effect of TEL and sulfur concentration on equilibrium combustion-chamber-deposit-formation after 12,000 miles of medium-duty road test operations [13]. Copyright © SAE International. Reprinted with permission from paper 510209.

A 1945 NACA report on the preignition limited performance of fuels explained experiments and results from an R-1820-GC cylinder using an AC-87 spark plug as the preignition hot spot [20]. The fuels tested covered a wide range of hydrocarbon content. The data are provided in Figure 6 below and show that the differences in preignition-limited IMEPs are small compared to detonation-limited performance that would be obtained for the fuels under the same operating conditions (noted by author but no additional data given [7]). It should be noted, based on data from another NACA report by Spencer shown in Table 1 [19], that even though isooctane and benzene have the same surface ignition temperature, the fuels have different preignition limited IMEPs, with benzene being lower than isooctane. This is explained by the fact that the benzene gives a higher hot spot temperature than isooctane. Benzene combustion temperature is quoted to be about 240 °F higher than isooctane, and the radiant energy effects are considered to be greater due to the greater percentage of carbon. Since diisobutylene increases the combustion-chamber surface temperature by only a small amount, it was concluded that its low preignition-limited performance must be due to its low surface ignition temperature [20].

The increase in preignition limited IMEP shown in Figure 6 for the addition of lead is the result of the increased surface ignition temperature. This data shows that lead acts as an anti-preignition compound in the flammable mixture and/or that the lead deposits on the hot spot have the catalytic effect to destroy the surface ignition reaction [7]. The effect of lead acting as anti-preignition compound in the fuel-air mixture has been demonstrated with tests conducted in

the laboratory. The tests showed that the pre-ignition limited IMEP of a spark plug increased rapidly with time when the plug was new or completely free of leaded deposits. The same effect was not obtained when an unleaded fuel was used in the testing [7]. It should be noted that the lead can prevent preignition only when the surface ignition is caused by a metallic hot spot. Lead is a preignition agent when considering surface ignition from combustion chamber deposits [7].

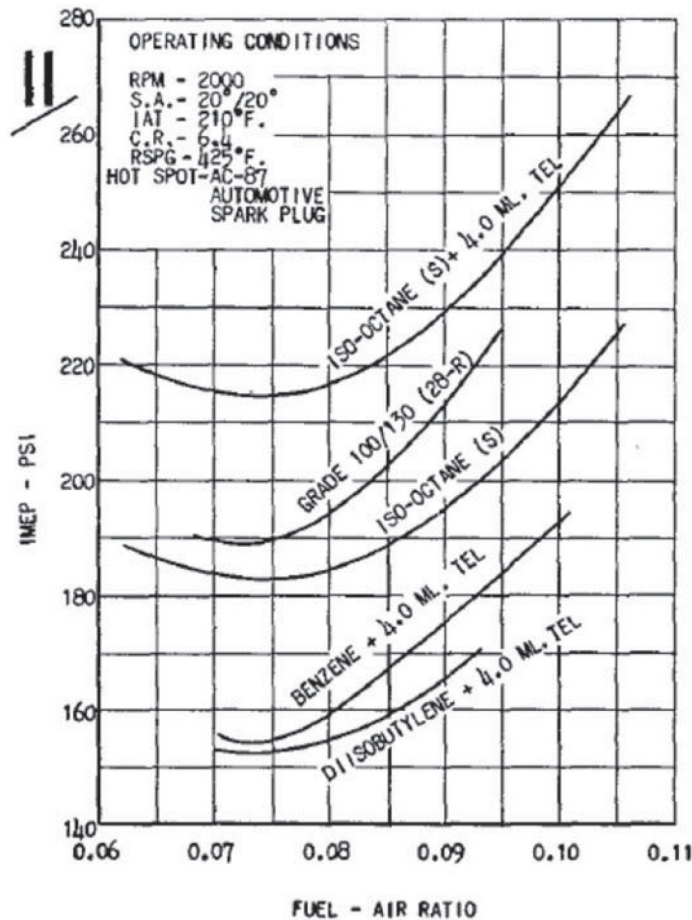


Figure 6. Preignition-limited performance of several fuels in an R-1820-GC cylinder using hot spark plug [20].

Additional experiments were run in a similar manner with similar fuels as Figure 6 above, however by using a finned hot spot rather than a hot spark plug. The results of the experiment reduced the differences between the benzene and diisobutylene [20].

Preignition with benzene had been reported to be more unstable than other fuels [6]. This was explained by the benzene having a lower slope in the hot spot temperature curve required for preignition versus ignition advance (ignition occurring earlier in the combustion cycle). For benzene, the temperature increase required to give advanced ignition is less than that for other fuels, relative to isooctane for the set of studies presented in this literature review. Because of other conflicting data in the literature, Hundere and Bert suggested that preignition characteristics of fuels should be studied concerning the preignition temperature and the ignition advance [7].

In 1952, Withrow and Bowditch discussed the issue of autoignition caused by combustion chamber deposits. They briefly mention the practice of car owners purchasing a tank of Ethyl gasoline at times to burn the carbon deposits out of the engine. Their data indicates that the gasoline was leaving lead salts, in addition to carbon as part of the total deposit, in the combustion chamber, and this special fuel was purging the carbon deposit from the engine under certain conditions. Because these observations have been made from the operation of fuels with and without lead, they suggest that the lead as well as other salts and metals that enter the engine from the air or from the oil are capable of reducing the ignition temperature of carbon and producing these events [8]. These substances are capable of lowering the ignition temperature of carbon, and accelerating the chemical reactions between the carbon deposits and oxygen from the air [8].

A review of the research into abnormal combustion phenomena was presented at the 5th World Petroleum Congress in 1959 [24]. Much of the work from this review article covers the period between the early 1940s up through 1958. Work by Sturgis noted the relative preignition resistance of single component hydrocarbons in automotive engines, as shown in Figure 7. Toluene and xylene were found to be more resistant to ignition by a hot spark plug than isooctane. Benzene, ethyl benzene, and cumene were considerably poorer or less resistant to preignition. Diisobutylene was more resistant to preignition than benzene, cumene and ethyl benzene at high engine speeds, but worse at lower engine speeds and ignited more easily. Generally, there was less tendency for surface ignition at low engine speeds because of the lower spark plug temperatures. Sturgis and his coworkers pointed out that preflame reactions exert an important effect on fuel ignition and help to explain the trends shown. TEL was found to improve the fuel ignition resistance, especially with fuels that undergo the pre-flame reactions, and conversely having little impact on fuels that do not go through preflame reactions [24].

From this same review article, a table was composed showing the data from a number of reviewers on the susceptibility of the fuel to ignition by glowing particles, shown in Table 2 [24]. This is an important factor in determining if deposit-induced abnormal ignition will occur. Some of the fuels show a different response than those of hot spot ignition, which indicates that the resistance of different hydrocarbons varies with the ignition source.

In the mid- 1960s, Pless also performed a literature review of the surface ignition and rumble found in engines. He summarized again some of the literature previously presented, and highlighted a few new papers that had been presented in late 1950s and early 1960s. In his review, Pless makes an interesting distinction between the hot spot and deposit ignition having different responses to ignition resistance of the fuels [10]. He summarized those as shown in Table 3. The table shows the rankings from the various researchers with agreement of the rankings for the fuels for the two different techniques (ignition mechanisms) for abnormal ignition: - hot spot vs. aspirated deposit ignition. There was also agreement that the two techniques produced different results between the fuels that caused them to be ranked differently between the two techniques [10]. Pless also noted that the agreement existed despite the differences in operating conditions and testing techniques. This further shows that the abnormal ignition source is important.

Table 1. Hot Spot Temperature required for Surface Ignition [19]

Fuel	Engine	Rpm	F/A	Surface Ignition Temperature, F	Hot-Spot Material	Remarks	Footnote Reference
Isooctane (S)	NACA combined apparatus	500	0.06	1570	Nichrome wire	Minimum temperatures required to give ignition without spark ignition	8
Isooctane (S)		500	0.13	1540			8
Benzene		500	0.06	1570			8
Benzene		500	0.13	1540			8
Methanol		500	0.10	1340			8
Methanol		500	0.15	1340			8
Isooctane (S)	CFR	1000	0.06	1620	Glow plug, diesel type, and probably nichrome	Minimum temperature at which no backfiring obtained when ignition switch was cut	8
Isooctane (S)		1000	0.06	1620			8
Isooctane (S)		2000	0.06	1740			8
Isooctane (S)		2000	0.10	1740			8
Benzene		1000	0.06	1630			8
Benzene		1000	0.10	1670			8
Benzene		2000	0.06	1780			8
Benzene		2000	0.10	1740			8
Isopropyl alcohol		1000	0.10	1880			8
Isopropyl alcohol		2000	0.10	1740			8
69 octane (38% benzene)	Renault	1250	About 0.076	1690	Metal (probably high nickel and similar to nichrome)	Minimum temperature at which no backfiring obtained when ignition switch was cut	5
Isooctane (S)	CFR	1800	0.077	2110	Platinum and platinum plus 10% rhodium	Surface ignition at 35 deg BTC	6
Benzene		1800	0.083	2070		Spark advance 35 deg BTC	6
Methanol		1800	0.145	2240		Surface ignition at TDC	6
Isooctane (S)		1800	0.077	1880		Spark advance 35 deg BTC	6
Benzene		1800	0.083	1880		Spark advance 35 deg BTC	6
Methanol		1800	0.145				6

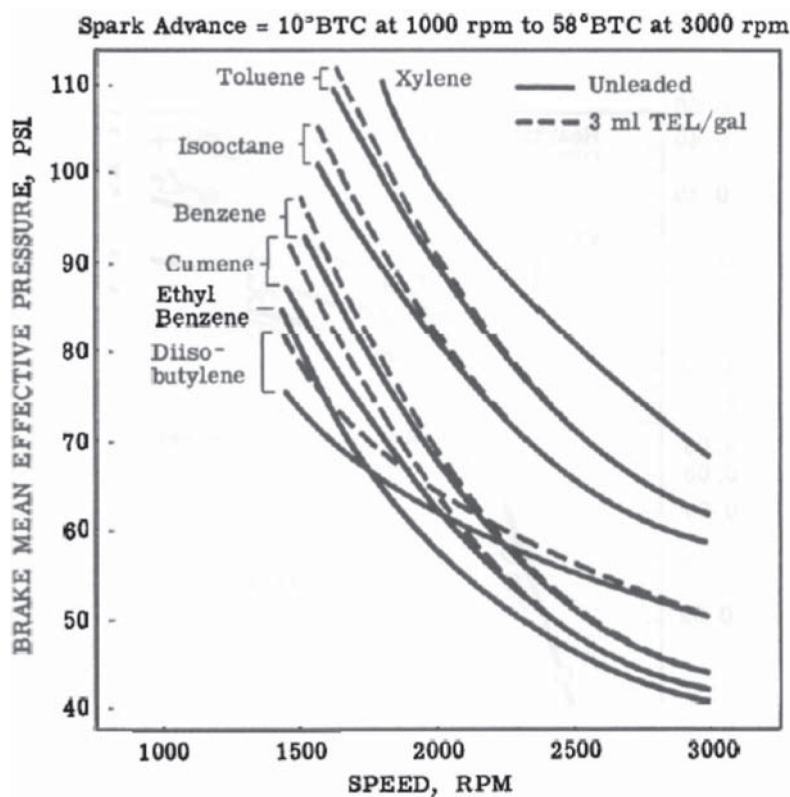


Figure 7. Relative Resistance of Various Fuel Hydrocarbons to Preignition from a Hot Spark Plug in a 10:1-CR Research Engine-160 °F Jacket Temperature, Stoichiometric A/F (Sturgis, et al.) [24]

Table 2. Relative Deposit Ignition Tendency of Various Fuels [24]

RELATIVE DEPOSIT IGNITION TENDENCY OF VARIOUS FUELS			
Abnormal Ignition Rate, % Relative to that with Isooctane ¹			
Fuel	Wild Ping Test Results by Mikita and Sturgis ²	Aspirated Particle Results by Sabina and Mikita ³	Aspirated Particle Results by Authors ⁴
Hydrocarbon			
Methylcyclohexane	94 (—)		
Isooctane	100 (75)	100	100 (90)
Cyclopentane	119 (—)		
Xylene	162 (131)	133	
Toluene	162 (156)	150	161 (—)
Cyclohexane	212 (119)		— (166)
Diisobutylene	225 (94)	161	155 (—)
Methylcyclopentane	325 (81)		
Benzene	450 (443)	300	263 (255)
Ethylbenzene	500 (418)		
Cumene	555 (394)	345	
Avg of Commercial Gasolines	(170)		(120)

¹Values shown in brackets are for 3 ml TEL/gal added to blend.

²Ratings made in CFR cylinder at 10° spark advance, 250°F IAT, 212°F jacket, 1800 rpm, 9:1-CR, 30 in. Hg MAP and 5% rich A/F.

³Rating made in COT engine at 5° spark advance, 300°F IAT, 212°F jacket, 2370 rpm, 6.8:1-CR, 40 in. Hg MAP and 12.5 A/F.

⁴Ratings made in CFR cylinder at 10° spark advance, 110°F IAT, 180°F jacket, 1200 rpm, 7:1-CR, 30 in. Hg MAP, 13.0 A/F.

Fuel Impact of Deposits in Engines

Through the 1950s and into the 1960s, researchers continued to study this phenomena that appeared to occur in cars with high compression ratio engines. From an initial study of deposit induced ignition, Hirschler, McCullough and Hall found that fuel volatility and oil volatility were important, and by lowering both, lower deposit ignition would occur [17]. These engines contained deposits from light duty operation but became an issue at high load accelerations [15]. In work performed by Felt, Warren and Hall, a vehicle road test evaluation was developed to evaluate the preignition and deposit forming tendency of the fuels. Three gasolines were blended to represent refinery streams that would be used to make a 100 RON fuel. The fuels had various Aromatic (18-48%) and Olefin (9-29%) compositions, with the same sulfur content and T90. Each fuel was run over a controlled test course to stabilize deposits (6000 miles) in the engine of nine vehicles with 10:1 compression ratio. To evaluate the preignition tendency of the fuels and their deposits, a high load acceleration was made on the deposit fuel each time the vehicle was tested on a chassis dynamometer. The response of the cars were slightly different with some being responsive and others showing no response. The preignition that was observed was not only affected by the deposits but also by the tendency of the fuel to be ignited by the hot deposit. It was shown that by increasing the aromatic content of the fuel this increased the preignition prone deposits in the car makes that were sensitive [15]. The data from these experiments in shown in Table 4 below demonstrating the impact of the fuel [15].

Table 3. Relative Surface Ignition Resistance of Pure Hydrocarbons [10]. Copyright © SAE International. Reprinted with permission from paper 650391.

Surface Ignition Resistance	Surface Ignition Resistance As Ranked by			
	Bowditch (2)	Sabina (10)	Sturgis (8)	Robison (3)
Hot Spot Ignition				
High	Toluene	Toluene	Toluene	Toluene
	Isooctane	Isooctane	Isooctane	Isooctane
	Diisobutylene	Benzene	DIB (high rpm)	Benzene
	Benzene	Diisobutylene	Benzene	Cyclohexane*
Low			DIB (low rpm)	Diisobutylene
Deposit Ignition - Aspirated Deposits				
High	Isooctane	Isooctane	Isooctane	Isooctane
	Diisobutylene	Toluene	Diisobutylene	Diisobutylene
	Cyclohexane*	Diisobutylene	Cyclohexane	Toluene
	Toluene	Benzene	Toluene	Cyclohexane*
Low	Benzene		Benzene	Benzene

*TEL added to prevent spark knock.

Table 4. Rumble Data with Three Test Fuels [15]. Copyright © SAE International. Reprinted with permission from paper 590018.

Fuel Composition	Fuel 1 23% Alkylate 68% Cat. Cracked 9% Polymer	Fuel 2 22% Alkylate 53% Cat. Cracked 25% Severe Reformate	Fuel 3 25% Straightrun 40% Cat. Cracked 35% Extracted Aromatics
Hydrocarbon Type			
Aromatics, %	18	30	48
Olefins, %	29	12	9
Inspection Data			
Gravity, deg API	61.9	58.8	52.1
ASTM 90% point, F	345	342	345
Rumble Data			
	Rumble, % of Observations		
3 Car Q	14	40	67
3 Car M	13	7	7
3 Car F	27	27	60
9-Car Average	18	25	45

In another vehicle study with engines of 11:1 compression ratio, the vehicle would only be driven for a few hundred miles before they were so preignition limited that the knock-rating test could not be performed. An investigation of the cause was made and found that the test fuel was an unusual batch of fuel with 19% of a solvent boiling from 300–410 °F in the mixture. Of that solvent, 70% (which became 13% of the blended fuel) consisted of bottoms from a catalytic reformer. It was determined that while the same fuel batch to batch had the same percent of aromatics, it was the increase in the aromatics in the last fraction of the fuel that caused the issue [15]. Data from this observation is shown in Table 5 below [15]. As is seen in the data from the fuel analysis, the Fuel A has a higher fraction above 338 °F [15]. Data from the rumble observations for the two blends is shown in Table 6 below and shows the impact of the rumble inducing deposits from both fuels [15]. In all cases tested, blend B showed less rumble, indicating the effect of higher boiling aromatics on the formation of rumble inducing deposits.

Table 5. Description of Two Fuel Blends of Fuel 2-E [15]. Copyright © SAE International. Reprinted with permission from paper 590018.

Composition, %	Blend A	Blend B
Isopentane + alkylate	39	39
Toluene	22	41
High-boiling aromatics	20	20
Commercial solvent ^a	19	0
Aromatics, %		
Whole fuel	48	48
Last fraction (338 F and up)	29	20
ASTM Distillation:		
90%, F	324	315
End point, F	395	375

^a Boiling 300–410 F; 70% catalytic reformer bottoms.

Table 6. Rumble Observations with Fuel 2-E, Blends A and B [15]. Copyright © SAE International. Reprinted with permission from paper 590018.

105 Octane Number Reference Fuel	Rumble, % of Observations ^a			
	1957 CRC Full-Boiling Reference Fuel		Primary Reference Fuel	
Fuel 2-E, Blend	A	B	A	B
Car F—11/1 Compression Ratio				
7% Grade	87	80	63	25
Chassis Dynamometer	100	80	83	b
Car Q—11/1 Compression Ratio				
7% Grade	75	40	17	b
Chassis Dynamometer	100	b	100	b

^a Medium intensity or greater.

^b Data not obtained.

An additional study was run by Felt, Warren and Hall with an 11.6:1 compression ratio engine. Two fuels were tested, one with 45% aromatics and the other with 0% aromatics and 99% saturates. The data and the results are shown in Table 7 below. The two fuels were used to develop and stabilize deposits in an engine prior to being evaluated with other fuels to determine their preignition tendency. The noise requirement for the 105 octane high aromatics fuels was not met due to the change in requirement from the deposits. With the high aromatic fuel, the preignition observations were at 90 and 100% of the time, where with the high saturates fuel, there were no observations [15].

Table 7. Knock and Rumble Requirements with Alkylate and Highly Aromatic Fuels [15]. Copyright © SAE International. Reprinted with permission from paper 590018.

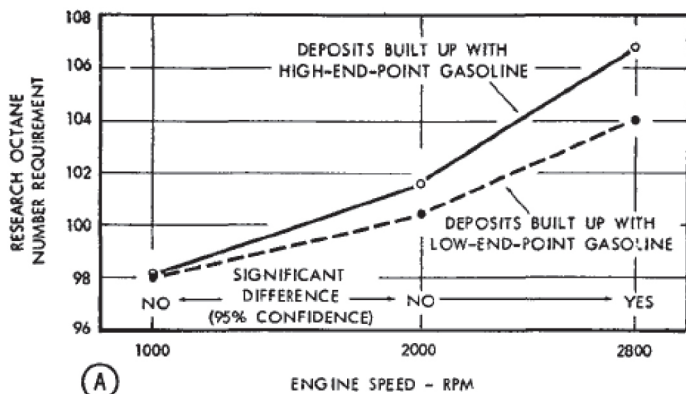
(Engine Q, 11.6/1 compression ratio; light-duty cycle, dynamometer tests; base fuels contained 3 ml tel)		
Fuel Composition	Alkylate 89% Full-Boiling Alkylate 9% Straightrun 2% n-Butane	Highly Aromatic 55% Extracted Reformate 33% Alkylate 5% Light Straightrun 7% n-Butane
Hydrocarbon Type		
Aromatics, %	0	45
Olefins, %	1	2
Saturates, %	99	53
ASTM Distillation, F		
10%	137	150
50%	213	255
90%	247	337
End point	419	418
Knock Requirements, Octane Number		
Primaries	99.9	Surface-Ignition and rumble limited on 105 octane number
1957 CRC reference fuels	100	
Rumble, % Observations		
105 octane number primary	0	89
105 octane number 1957 CRC	0	100
105 octane number test fuel	0	100

At about the same time as the work at Ethyl, work at General Motors Research was occurring. The issue of preignition was significant as it was limiting the potential efficiency of an engine. So that further gains in engine efficiency could be made with higher compression ratio engines, changes in gasoline composition were of great interest. Wiese was concerned with the influence of the fuel on the octane number requirement and the occurrence of preignition, specifically the trend towards higher aromatics in the gasoline during this time period. His specific focus was the impact of the volatility of the fuel at the tail end, aromatic content, and additives [25].

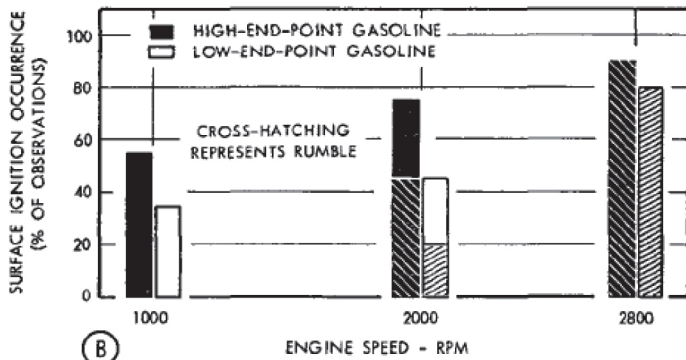
As for the tail end volatility of the fuel, Wiese showed that deposits build up from a high end point gasoline leads to higher deposits which increase the surface ignition occurrences. The data from the experiment is shown below in Figure 8 [25].

As for the aromatic content of the fuel, Wiese was trying to determine the impact of the fuel components on the deposit build up in the engine, and then the impact of the fuel with regard to surface ignition and rumble of the engine after those deposit forming fuels were used. There are some significant learnings from this paper, however only select figures below are shown from the data of those experiments. Two tests were performed with similar fuels, both low and high aromatics blends in vehicles. Test 1 was performed at constant steady state engine speeds while Test 2 was performed with vehicle

accelerations. In both tests, similar fuels were suggested to have been blended, although the low aromatic reference fuel in Test 2 had a higher final boiling point than Test 1 which could have some impact on the results. Both tests were run with similar test plan goals. In Test 1, differences in surface ignition and rumble were only higher with the high aromatic fuels for the highest engine speeds, as shown in Figure 9, 10, and 11 below. In Test 2, surface ignitions and rumble occur more often when deposits are accumulated with high aromatic fuels. The results were consistent for Test 2 as shown in Table 8, Table 9, and Table 10 below.



Average Octane Number Requirements With Deposits Built Up by the Use of High-End-Point Gasoline Compared to Those With Deposits Built Up With Low-End-Point Gasoline.



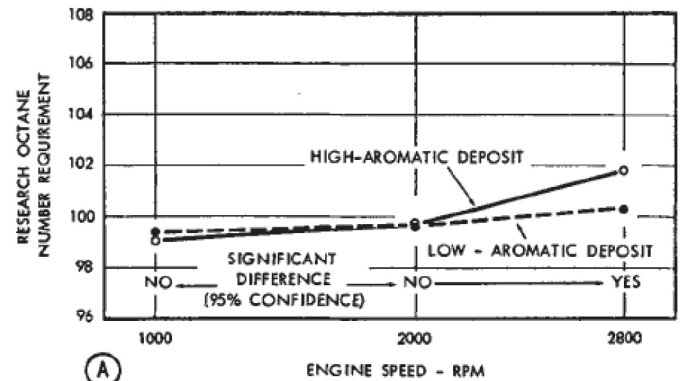
Surface Ignition Occurrence With Deposits Built Up by the Use of High-End-Point Gasoline Compared to That With Deposits Built Up With Low-End-Point Gasoline.

Figure 8. Tail-end volatility [25]. Copyright © SAE International. Reprinted with permission from paper 590023.

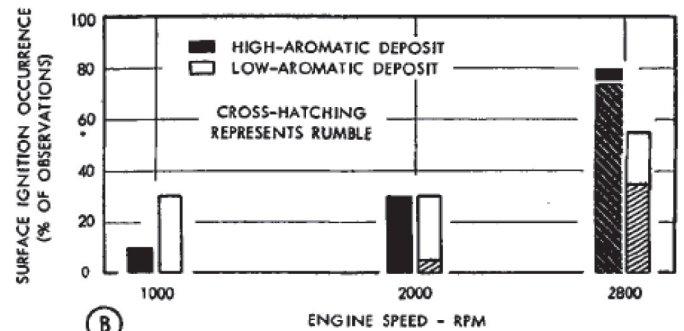
Reviewing both Tables 9 and 10 together, one can observe and conclude from this study that the composition of the deposit is more significant than the fuel the engine is run with respect to surface ignition and rumble. From the study, the difference in the best case versus worst case situation gave a 1.4 octane requirement improvement, and reduced the surface ignition and rumble by 25%.

In Wiese's explanation of this data, he concludes that the increase of the surface ignition is due to the use of high aromatic gasolines and the build of deposits in the engine. He also suggests that the major

share of the results is due to the octane depreciation of the aromatic fuel when used in an engine containing equilibrium suburban-duty deposits. He references research work that supports and contradicts his work. However, he suggests that his study showed surface ignition and rumble due to the combustion-chamber deposits which is the reason for the poorer performance (depreciation) of the aromatic gasoline, which is different than the other studies which had very few combustion-chamber deposits present.



Average Octane Number Requirements With Deposits Built Up by the Use of High-Aromatic Gasoline Compared to Those With Deposits Built Up With a Low-Aromatic Blend. (Commercial Reference Fuels)



Surface Ignition Occurrence With Deposits Built Up by the Use of High-Aromatic Gasoline Compared to that With Deposits Built Up With a Low-Aromatic Blend. (Commercial Reference Fuels)

Figure 9. Effect of deposits from aromatic gasoline A, commercial reference fuel [25]. Copyright © SAE International. Reprinted with permission from paper 590023.

Table 8. Effect of Aromatic Reference Fuels [25]. Copyright © SAE International. Reprinted with permission from paper 590023.

	Average Octane Requirement	Total Surface Ignition* and Rumble, %	Rumble, % ^a
Commercial Reference Fuels:			
High-Aromatic Deposit	99.3	65	25
Low-Aromatic Deposit	98.9	40	0
Difference	0.4	25	25
Significant Difference (95% confidence level)	no		
Aromatic Reference Fuels:			
High-Aromatic Deposit	100.3	65	35
Low-Aromatic Deposit	99.9	35	15
Difference	0.4	30	20
Significant Difference (95% confidence level)	no		

^a Per cent of total test observations during which surface ignition or rumble was objectionable.