TSB: MO-2005-09-30

Technical Service Bulletin

Date: 10/03/2005

Product Description: All AMSOIL Synthetic Motor Oils

Subject: Using AMSOIL motor oils in Chrysler engines experiencing spark knock

OBJECTIVE:

To inform Chrysler vehicle owners about Chrysler Technical Service Bulletin TSB 09-05-00 (1). The Chrysler Bulletin describes the replacement of the engine intake manifold plenum pan gasket. If the plenum gasket leaks, it may disrupt the performance and service life of the motor oil.

ISSUES:

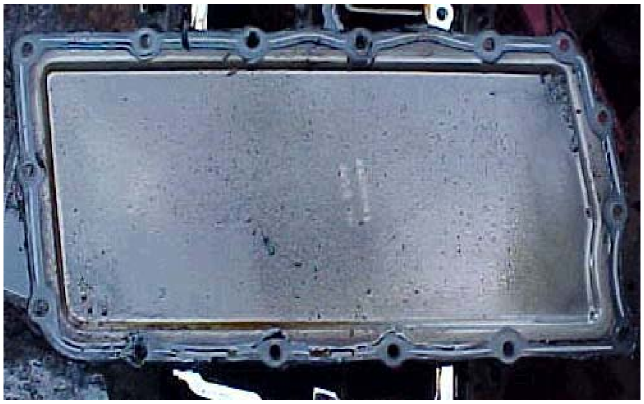
Chrysler has indicated in this technical bulletin that certain 3.9 L, 5.2 L, and 5.9 L gasoline engines could develop intake manifold plenum pan gasket leaks. These models are:

Years	Models
1994-1999	AB, Ram Van
1994-1999	AN Dakota
1994-1999	BR/BE, Ram Truck
1998-1999	DN, Durango
1994-1998	ZJ, Grand Cherokee
1996-1998	ZG, Grand Cherokee

The Chrysler TSB 09-05-00 noted two symptoms of a plenum gasket oil leak: (1) engine spark knock during acceleration (2) increased oil consumption. This oil leak is internal and is not visible from the outside of the engine. Figure 1 is taken from a 1999, 5.2L, V8, Dodge Ram Van, which illustrates a severe case of plenum gasket leak; note the deposits around the gasket. Figure 2 is taken from a 1998, 5.2 L, V8, Dodge Dakota, which illustrates a mild case of plenum gasket leak; note the oil film on the pan.

Figure 1. severe case of leaking plenum gasket

Figure 2. mild case of leaking plenum gasket



TECHNICAL DISCUSSION:

The Chrysler bulletin indicates that when the plenum gasket leaks, engine combustion blow-by gases, oil vapor and air from the crankcase filter/ breather may be drawn past the leaking gasket and into the intake manifold. This may cause engine spark knock during acceleration.

Professor M. David Checkel of University of Alberta, Edmonton, Canada has written a paper, “Damage Associated with Uncontrolled Knock in Spark Ignition Engines” (2). This paper identifies the causes of engine spark knock and its effect on engine operation, parts and motor oils. Beyond the undesirable pinning noise of the engine, the major effects are:

- Increased cylinder pressure and temperature.
  Overhead parts such as pistons, head gaskets or exhaust valves can fail due to high temperature and excessive thermal expansion.
  Effects on motor oil: The higher the engine temperature, the faster the engine oil is oxidized. As oil oxidized, viscosity increases.

- Increased NO_x formation and blow-by gases.
  Engines produce considerably more NO_x during knocking combustion than normal combustion.
  Effect on motor oil: NO_x reacts with fuel and oil condensed on combustion chamber surfaces to form hard deposits as shown in Figure 3. The photo is taken from a 1999, 5.2 L, V8, Dodge Durango. When NO_x in the blow-by reach the crankcase, it will acidify the oil and react with fuel compounds absorbed in the oil. These reactions produce surface deposits and solids known as sludge.

Another effect identified in the Chrysler Technical Bulletin is oil consumption. A leak from the plenum pan gasket would result in excessive air and oil vapor being drawn into the engine intake system. In the long term, continued combustion of oil vapor from the crankcase may lead to excessive combustion chamber deposit buildup. This buildup of excessive deposits may lead to piston ring gap plugging, sticking rings and excessive blow-by, exaggerating the NO_x exposure of the engine oil. Combustion chamber deposits will further promote engine knock through reduced combustion chamber volume and the formation of “hot spots”.

Figure 3. crown and ring grooves with heavy deposits

Figure 4. deposits on Piston

As a result, engine oil begins to degrade rapidly following the development of spark knock. Less engine oil in the sump, due to oil consumption, promotes less cooling capacity and acid neutralization capabilities which further degrades the engine oil.

TSB: MO-2005-09-30

Technical Service Bulletin

Date: 10/03/2005

Product Description: All AMSOIL Synthetic Motor Oils

Subject: Using AMSOIL motor oils in Chrysler engines experiencing spark knock

RECOMMENDATION:

Before purchasing vehicles listed in TSB 09-05-00, owners should:

1. Check and review the maintenance record to ensure proper vehicle maintenance has been performed.
2. Have vehicle inspected and run performance diagnosis to ensure the vehicle is in proper running condition.

AMSOIL recommends current vehicle owners following Chrysler's recommended diagnosis and repair guidelines per TSB 09-05-00, keep detail vehicle maintenance records, have the vehicle inspected and run engine diagnosis checks .

If spark knock or high oil consumption is noticed, a more complete inspection for sludge and deposits should be performed.

After repairing the leaking plenum pan gasket, Chrysler recommends using Mopar Combustion Chamber Conditioner (part # 04318001) to remove carbon deposits in the combustion chamber. AMSOIL engine Flush is also recommended to remove any deposits from the engine crankcase after the repair.

REFERENCES:

1. **Chrysler TSB 09-05-00, *"Spark Knock and Oil Consumption Due to Intake Manifold Pan Gasket Oil Leak"*, February 25, 2000**

   http://dodgeram.info/tsb/2000/09-05-00.htm

   http://www.alldata.com/products/diy/index2.html

2. **Checkel, M. David, *"Damage Associated with Uncontrolled Knock in Spark Ignition Engines"*, Department of Mechanical Engineering, University of Alberta, Edmonton, Canada, February 2002**

Submitted By: DW/DY **Approved By: Alan Amatuzio** **Approval Date: 12/27/2005**

Distribution: __Internal _X_All

Damage Associated with Uncontrolled Knock in Spark Ignition Engines

monograph by Dr. M. David Checkel, P.Eng.
Professor, Dept of Mechanical Engineering
University of Alberta, Edmonton, Canada T6G 2G8
dave.checkel@ualberta.ca

February 2002

Abstract

This paper first describes the causes and effects of knock in spark ignition engines. It then discusses the mechanisms by which knock damages engines, including both immediate thermal damage of severe knock and eventual lubrication-related problems of moderate knock. It is written to give the casual reader an understanding of an area where a great deal of research has been reported in the technical literature.

Knock results if combustion chamber end gases auto-ignite before they can be consumed by normal flame propagation. This auto-ignition is associated mostly with high gas temperatures and the factors leading to increased end gas temperature are briefly discussed. Knock intensity can vary depending on how much end gas auto-ignites. The classic signal of knock is a rattling, pinging noise in the engine. However, this noise may not be detectable by the driver, particularly for moderate knock occurring when vehicle noise is high. Beyond the undesirable noise, knock has several other effects including increased cylinder pressure and temperature, increased NOx (oxides of nitrogen) formation, increased cylinder leakage (blowby) and increased cylinder heat losses. For continuing, severe knock, the primary damage mechanism is thermal. Overheated parts such as pistons, head gaskets or exhaust valves can fail due to high-temperature softening or due to interference caused by excessive thermal expansion.

With lower knock intensity, engines may have sufficient cooling capacity to control component temperatures and avoid direct thermal damage. However, in this situation, the engine is subject to increased thermal stress and increased chemical stress due to sharply increased NOx production. The increased combustion chamber leakage associated with knock delivers high-NOx blowby gases into the crankcase and valve cover areas. The NOx acidifies the oil and, aided by the high oil temperatures associated with knock, reacts with fuel components from the blowby to create solid compounds. These compounds form solid surface deposits and oil-borne sludge, both of which interfere with the lubrication system's capabilities. Hence, engines subject to consistent knocking operation face increased lubrication-related problems which may shorten the engine life.

Outline

1. Introduction
2. What Knock Is and How it Occurs
3. The Damage Mechanisms for Severe Knock
4. NOx Formation in Engines
5. Effect of Knock and NOx on Lubricating Oil
6. A Specific Example
7. Summary

1. Introduction

Knock has been associated with spark ignition engines since Nicklaus Otto and Eugen Langen got the first engine with a serious compression ratio running in 1876. Whether it is called "knock", "spark knock", "combustion knock", "detonation" or "ping"[1], the phenomenon hits every spark ignition engine as you try to optimize engine efficiency and power output. Basically, the factors that improve efficiency and power, (like high compression ratio and full throttle operation), also bring on the characteristic rattling noise associated with knock. Engine developers soon found that once that noise appears the engine begins to overheat, the efficiency drops off and eventually various forms of engine damage appear. The phenomena of knock have been a subject of much research over the past century and are now quite well understood. Knock can be controlled by a combination of fuel octane quality, engine design features and careful adjustment of engine operation. However, avoiding knock still limits engine efficiency so engine designs necessarily continue to flirt with the border of knocking operation.

This paper describes the fundamental causes of knock and the immediate engine damage that can result from severe knock. It also describes the relationship between longer periods of mildly knocking operation and the lubricating problems which appear.

2. What Knock Is and How it Occurs

Normal Combustion Spark ignition engines burn a premixed air/fuel charge which is close to the chemically correct or *stoichiometric* mixture. This air/fuel mixture starts at roughly ambient temperature and pressure but is compressed by the piston to a much higher pressure and temperature. Shortly before the piston reaches top-dead-center (TDC), an ignition spark is fired. In normal combustion, a flame front grows from the spark and propagates rapidly across the combustion chamber, progressively burning all of the air/fuel mixture before the piston has moved a significant distance from TDC. It is important to realize that the compressed air/fuel mixture is very hot when the piston has compressed it fully and that the remaining unburnt mixture gets even hotter as it is further compressed by the rising combustion pressure. In fact, this mixture is well above the auto-ignition temperature (AIT) at which it would spontaneously ignite if it was given enough time. However, with the high temperature and turbulent mixing in the combustion chamber, the flame front normally burns fast enough to consume the entire mixture before any of it has time to auto-ignite. In addition, while the flame front burns across the chamber very rapidly, it is still slow compared with the speed of sound, so the pressure rises equally fast at all points across the cylinder.

Knocking Combustion Knock in spark ignition engines occurs when the "end gas", (the unburnt air/fuel mixture ahead of the flame front), auto-ignites before it can be consumed by the

---

[1] Obert, Edward F., "*Internal Combustion Engines and Air Pollution*", 3rd Ed, Intext, 1973, p108-109 provides a definition of several terms associated with knock and abnormal ignition.

flame front propagating across the cylinder. Auto-ignition is triggered by high temperature but it does not happen instantaneously. Auto-ignition occurs after a series of pre-flame reactions that break down the fuel and the rate of these reactions increases exponentially with increasing temperature. As auto-ignition starts to occur at one point in the end gas, the exothermic reactions raise the pressure and temperature of the end gas around them, so it is normal for virtually all of the unburnt air/fuel mixture to auto-ignite at one instant. This abrupt reaction happens faster than the speed of sound, raising the end gas pressure to a level much higher than the rest of the cylinder. To equalize the pressure difference across the cylinder, a strong pressure wave travels from the end gas region across the cylinder into the previously burnt gas. The pressure wave reflects off combustion chamber walls and sets up a resonance pattern in the chamber with a characteristic frequency determined by the chamber dimensions and the speed of sound in the burnt gases. For typical combustion chamber dimensions, the resonant frequency is approximately 5 to 10 kHz. Some of this sound energy is transmitted via engine parts to the air, resulting in the brief bursts of high frequency noise that we associate with knock.[2]

3. What Causes Knock?

High End Gas Temperatures Lead to Autoignition and Knock Knock was a mysterious process in the early days of engines but this was largely cleared up by the pioneering high-speed photography of Withrow and Rassweiler[3]. Now, after more than a century of knock research, it is clear that end gas autoignition leads to knock and that the end gas will autoignite if:

a) it has a sufficiently long time to autoignite before being consumed,
b) it is sufficiently reactive, and
c) it is sufficiently hot.

The first two factors are generally controlled by engine design. For a given engine, the combustion chamber design and spark timing set the combustion period. Likewise, the fuel grade and mixture strength set the mixture reactivity. A successful engine design uses an adequate fuel grade and a combination of spark timing and mixture strength that will prevent knock at the end gas temperatures set by normal intake air temperature and compression ratio. Thus, engine design tries to control the first two factors to avoid auto-ignition. The third factor, end gas temperature, is strongly affected by both engine design features and engine operating conditions. Also, since higher temperature makes mixtures more reactive and makes them react more rapidly, factors which affect end gas

---

[2] You can demonstrate how our hearing converts a short burst of high frequency tone to a "tick", by using a computer speaker to produce a 5 to 10 kHz tone for progressively shorter periods. If the sound lasts longer than 20 ms it is easy to hear the high frequency tone. Sounds shorter than 10 ms sound like a "tick". A PC compatible program called KNOCKSIM.EXE can be downloaded from web page http://www.mece.ualberta.ca/courses/mec541/index.htm to assist in this demonstration.

[3] Withrow, Lloyd and Rassweiler, G.M., "*Slow Motion Shows Knocking and Non-Knocking Explosions*", SAE Transactions, Vol 39, p 297, 1936

temperature are more critical than those that affect combustion time and fuel reactivity.

Operating Parameters Affect End Gas Temperature and Mixture Reactivity End gas temperature is affected mostly by the engine compression ratio, the spark timing and the mixture temperature / pressure before compression. Secondary effects include mixture strength and various factors that affect mixture heat transfer such as engine component temperatures and combustion chamber deposits. Again, the compression ratio and spark timing are part of the engine design so they should be set at values which avoid knock. (However, manufacturing tolerances, wear and deposits can alter these critical parameters away from their design values resulting in knock during operation.) Temperature of the air/fuel mixture before compression is a critical factor. Increasing the intake temperature increases the end gas temperature by a multiple of the intake temperature increase. Thus hot operating conditions lead to knock. Higher intake system pressure also raises end gas temperature since the higher density end gas cools less due to proportioinately lower heat transfer. Changes in mixture strength are also important. Slightly rich fuel/air mixtures are the most reactive. However, compressing slightly lean mixtures produces higher end gas temperatures because of differing specific heat ratio[4] and reduced evaporative cooling. As a result, rich mixtures (with excess fuel) are commonly used to prevent knock. Exhaust gas recirculation (EGR) makes the mixture less reactive but raises the initial temperature. While adding EGR generally reduces knocking tendency, it can also lead to knock in some circumstances, particularly when the EGR is poorly distributed in a multi-cylinder engine so that some cylinders receive more heat but not sufficient EGR to prevent knock.

Combustion chamber deposits can strongly affect knocking tendency of spark ignition engines[5]. The combustion chamber design generally places the end gas in a "squish zone" such that a thin layer of end gas is close to the cylinder head and piston, allowing it to lose heat rapidly. (Likewise, aluminum pistons and cylinder heads are commonly used in higher performance engines because, due to its higher heat transfer coefficient than cast iron or steel, the aluminum presents a cooler surface to the end gas.) The deposits work to promote knock in three ways. First, the volume of the deposit reduces clearance volume and increases compression ratio, resulting in sharply higher end gas temperature. Second, the deposits interfere with heat transfer from the end gas region to the cylinder head and piston, again increasing the end gas temperature. Changes in end gas heat transfer can also have a strong effect on whether knock occurs. In addition, as the surface of the combustion chamber deposits gets hot during combustion and exhaust strokes, it feeds heat back to the fresh mixture during intake and compression. Ultimately, this can lead to pre-ignition at deposit "hot

---

[4] The specific heat ratio is $k = Cp/Cv$. For a gas being compressed through volumetric compression ratio, $r = V_1 / V_2$, and starting at initial temperature, T_1, the final temperature, T_2, is given by: $T_2 = T_1 \text{ x } r^{(k-1)}$. For example, for a combined compression ratio (mechanical plus combustion) of $r = 30$, and initial temperature of $T_1 = 70°C = 343$ K, the end gas temperature will reach 1128 K = 855°C for $k = 1.35$ and only 952 K = 679°C for $k = 1.30$.

[5] Obert, Edward F., "*Internal Combustion Engines and Air Pollution*", 3rd Ed, Intext, 1973, p314-318

spots" which strongly increases knock tendency by effectively advancing the ignition timing[6].

3. The Damage Mechanism for Severe Knock

The commonly used ideal cycle for a spark ignition engine includes instantaneous combustion at TDC so knocking combustion, which instantaneously finishes the combustion near TDC, would appear to be ideal[7]. However, knock also leads to higher heat losses from the combustion chamber. This happens for three reasons:

1. the combustion products are at a higher pressure and temperature immediately after knock occurs than would be the case if combustion occurred progressively so that some expansion before combustion finished,
2. the pressure waves force hot gas against the piston and head, effectively scrubbing away the thermal boundary layer that insulates the hot combustion products from chamber surfaces, and
3. because knocking combustion finishes closer to TDC, there is more time for heat loss before the expansion stroke cools off the mixture. (Normally, optimum spark timing results in peak cylinder pressure close to 15° after TDC at which time the rate of piston travel has become significant.)

The extra heat loss results in lower cylinder pressures during the expansion stroke, thus hurting engine power and efficiency. For example, Obert[8] shows that, at the onset of light knock in a particular engine, head and cylinder heat transfer increased by about 15% while power decreased by about 12%.

With greater knock severity, the extra heat transfer can also lead to overheating engine parts and thus serious engine damage. For example, Stone[9] shows that average heat flux to the piston can increase by more than 50% with moderate knock. Typical examples of knock-related engine damage include melted spark plug tips, broken exhaust valves, melted piston crowns, holes in pistons, broken piston rings and complete engine seizure. While early efforts to understand knock blamed some of the damage directly on the cylinder pressure spikes, it is now clear that simple heat transfer is responsible. For example, piston rings break after expanding to the point where they seize in the cylinder liner or after contacting bits of melted piston material adhering to the cylinder liner.

The severity of knock ranges widely depending on how much end gas participates in the auto-

---

[6] Taylor, Charles F., *The Internal Combustion Engine in Theory and Practice, Vol 2*, MIT Press, Revised Ed, 1985, p84

[7] Keating, Eugene L., "*Applied Combustion*", Marcel Dekker, 1993, p368-372

[8] Obert, Edward F., "*Internal Combustion Engines and Air Pollution*", 3rd Ed, Intext, 1973, p467

[9] Stone, Richard, "*Introduction to Internal Combustion Engines*", 3rd Ed, SAE Intl, 1999, Fig 12.4, p475

ignition and how frequently knock occurs in each cylinder. Heywood[10] points out that trace knock and knock during acceleration rarely lead to direct engine damage. The extra heat transfer during trace knock is probably within the cooling capacity of the engine while knock during acceleration doesn't last long enough to damage parts by overheating. Such damage tends to occur when knock is severe and continuous at high engine load. In this case, the continuing knock leads to hot components. The hot components lead to pre-ignition of the charge before the spark occurs. This is the same as an advance in ignition timing so it worsens the knock, leading to a run-away condition and rapid engine damage.[11]

In contrast to the situation of run-away knock, it is possible for an engine with light knock levels to run more or less continuously without direct component damage, provided that the balance between engine cooling and knock-increased heat transfer is adequate to limit component heating. Particularly in situations where the vehicle cab is well insulated or the knock occurs at higher speeds where engine noise is high, light to moderate knock may not even be detectable. However, even in the absence of direct engine damage by component overheating, knock can affect engine life through increasing the thermal and chemical stress on the engine lubrication system.

4. NOx Formation in Engines

In recent decades, some of the most intensive automotive R&D efforts have been to reduce or eliminate the undesirable byproducts of combustion. One of the most-studied classes of pollutant byproducts is labeled "oxides of nitrogen" or NOx. This term covers several forms of nitrogen / oxygen compounds including nitric oxide, (NO), nitrogen dioxide, (NO_2) and nitrous oxide, (N_2O). NOx is undesirable as both an air pollutant coming from the exhaust and as a contaminant within the engine. As an air pollutant, NOx is directly toxic to humans, animals and plants and it is a highly reactive compound in the atmosphere where it contributes directly to formation of further smog compounds. Even inside the engine, the reactivity of NOx leads to problems with deposit and sludge formation so it is important to understand the relationship between knock and NOx.

---

[10] Heywood, John B., "*Internal Combustion Engine Fundamentals*", McGraw Hill, 1988, p456

[11] Heywood, John B., "*Internal Combustion Engine Fundamentals*", McGraw Hill, 1988, fig 11-9, p456, "The engine can be damaged by knock in different ways: piston ring sticking; breakage of the piston rings and lands; failure of the cylinder head gasket; cylinder head erosion; piston crown and top land erosion; piston melting and holing."

As a result of attention to NOx as a pollutant, the formation processes and ultimate fate of NOx compounds are quite well understood and are discussed in many references. NO is formed when atmospheric oxygen and nitrogen combine during combustion at high temperature, following a chemical path called the Zeldovich thermal mechanism. According to the Zeldovich mechanism, both the amount of NO being produced and the rate at which it is produced increase exponentially with combustion temperature[12]. As a result, engines produce considerably more NOx during knocking combustion than normal combustion. For example, calculations using a STANJAN[13] combustion model show that the equilibrium NO concentration after combustion is about 4000 ppm (parts per million) for normal combustion with an end temperature of 2500 K, and more than doubles to about 10,000 ppm for knocking combustion with an end temperature of 2900 K. This is in accord with some of the results shown in the literature where significant increases in NOx emissions are produced by knocking combustion[14]. This increase in NOx emissions with light knock has also been used by engine researchers to detect trace knock operation in noisy engines[15].

Further calculations based on the Zeldovich mechanism show that both the ultimate amount and rate of NOx production are highest for a mixture just slightly lean of stoichiometric[16]. Such a mixture has high combustion temperatures, (as a result of being close to ideal), but also has some excess oxygen available for the reactions which lead to NOx formation. This is particularly important for engines which use a strategy of richening the mixture to avoid knock at high power. If the fuel system doesn't deliver sufficient fuel, the mixture may go lean, providing a condition where knock occurs <u>and</u> NOx production is at its highest.

As combustion ends, the burned gases in the combustion chamber are rapidly expanded

---

[12] eg. Borman, Gary L and Ragland, Kenneth W., "*Combustion Engineering*", WCB McGraw Hill, 1998, p110/118/252
or Heywood, John B., "*Internal Combustion Engine Fundamentals*", McGraw Hill, 1988, p572-577
or Stone, Richard, "*Introduction to Internal Combustion Engines*", 3rd Ed, SAE Intl, 1999, p102-105

[13] W.C. Reynolds, "*STANJAN Equilibrium Program*", Stanford University, 1987

[14] Ferguson, Colin R., "*Internal Combusiton Engines*", John Wiley & Sons, 1986, p397 Fig 9-20 shows the dramatic difference in NOx emission with spark advance, particularly for lean mixtures. (At 0.97 equiv ratio, you go from 2250 to 4250 ppm going from 20 to 40 deg spark advance.)

[15] Roberts, S.R., "*Non-Intrusive Knock Detection in a Turbo-Charged, Dual Fuel Engine*", MSc Thesis, Mechanical Engineering, U of Alberta, 1997

[16] eg Heywood, John B., "*Internal Combustion Engine Fundamentals*", McGraw Hill, 1988, fig 11-9, p582
or Pulkrabek, Willard W., "*Engineering Fundamentals of the Internal Combustion Engine*", Prentice Hall, 1997, Fig 9-3, p287

during the power stroke and exhaust blowdown. This rapid expansion cools the gases which would tend to reduce the NO concentration. However, the rate at which NO breaks down also slows with low temperature so the NO concentration tends to "freeze"[17]. When the combustion products are expelled from the combustion chamber they will eventually be mixed with oxygen, either as exhaust gases in the air or as blowby gases in the crankcase. In the presence of oxygen, the NO is eventually converted to NO_2, with the conversion process tending to produce ozone (O_3) at the same time. Like NO, NO_2 is also a strong oxidizer and is toxic to both animal and plant life. In the presence of water vapour or hydrocarbons, NO_2 undergoes further reactions, forming various acidic compounds including nitric acid. In the atmosphere, the resulting mix of gases is known as smog. Inside an engine, the reactivity of NO and NO_2 leads to problems in the lubricated spaces of the engine, (inside the crankcase and valve covers).

5. Effect of Knock and NOx on Lubricating Oil

Compared with normal atmospheric gases, NOx compounds are relatively unstable and tend to react easily. (For example, even almost-non-flammable gases like ammonia will explode when mixed with nitric oxide[18]). In the combustion chamber, NOx compounds react with high molecular weight fuel and oil compounds condensed on chamber surfaces to form hard, durable deposits. Additionally, when NOx compounds in the blowby gases reach the crankcase, they both acidify the oil and also react with heavy fuel compounds absorbed in the oil. These fuel compound reactions produce both surface deposits and oil-suspended solids known as sludge. Some of the problems of engines which consistently run at low knock levels are associated with the increased thermal stress on the engine, the increased NOx levels produced by knock, and the increased blowby associated with knocking operation. These factors combine to increase lubrication requirements while decreasing the capability of the lubrication system to meet those requirements.

Transport of NOx with Blowby Gases Pressurized cylinder gases leak past the piston rings and valve seals during the compression, combustion and power strokes, a process called "blowby". Normally, the majority of the blowby gases consist of unburnt fuel and air. This fuel/air mixture is pressed into the upper piston lands and inter-ring gaps during compression and forced past the rings during the peak pressure period of the power stroke. In a well-sealed engine, relatively less burnt gas than unburnt mixture makes it past the rings since the unburnt mixture was already ahead of it. However, during high power output and particularly during knock, the cylinder pressures at the start of the power stroke increase dramatically and the fraction of burnt gas in the blowby increases dramatically as well. Several factors combine to produce this shift. For example, the higher cylinder pressure leads to overall higher leakage and the end gases become burnt gas earlier due to knock than

---

[17] eg Borman, Gary L and Ragland, Kenneth W., "*Combustion Engineering*", WCB McGraw Hill, 1998, p252

[18] Checkel, M.D. et al, "*Flammability Limits and burning Velocity of Ammonia / Nitric Oxide Mixtures*", Jnl of Loss Prev. in the Process Industries, Vol 8, No 4, p215, 1995

they would for normal combustion. Also, knock leads to an earlier pressure peak and thus a longer duration at the highest pressure due to poor phasing between combustion and expansion.

Beyond the direct factors mentioned above, engines with poor cylinder sealing tend to leak considerably more burnt gases during the combustion and power stroke. For example, engines with worn or grooved pistons, cylinders and rings have a direct gas path into the crankcase and considerably higher blowby rates than normal. Likewise, engines with piston and ring groove deposits caused by excessive oil burning tend to have very poor combustion chamber sealing and also exhibit high blowby rates. Because the amount of unburnt gas in the piston land / ring gaps is more or less fixed, an increase in blowby rate considerably increases the burnt gas content of the blowby and thus considerably increases the NOx exposure of the lubrication system.

<u>Oil Degradation by NOx</u> The role of NOx in oil degradation has been well known for some time. Early engines which operated at high load and high oil temperature tended to develop durable deposits on surfaces in the lubricated areas. Under the same conditions, the oil tended to become thick and sludgy after relatively short operating periods. Controlling these problems has been a focus of research over a long period of time. Pioneering work on crankcase deposits by Bowhay et al[19] and engine sludge by Rogers et al[20] showed that fuel composition and engine operating variables were involved in both problems. More detailed studies on engine deposits narrowed the focus to olefinic fuel components and to NOx delivered from the combustion chamber via blowby[21],[22],[23]. Further work by Kreuz showed that the solid compounds associated with both crankcase varnish and oil-borne sludge were related, with both originating from the reaction of partially oxidized liquid fuel components and NOx leaked from the combustion chamber[24]. (It is important to realize that these problems are not the same as simple oil thickening due to high temperature degradation and

---

[19] Bowhay, E.J. and Koenig, E.F. "*Factors Affecting Low-Temperature Engine Deposits*", SAE Quarterly Trans. Vol 2, No 1, p132, 1948

[20] Rogers, D.T., Rice, W.W. and Jonach, F.L. "*Mechanism of Engine Sludge Formation and Additive Action*", SAE paper 560057, SAE Trans. Vol 64, p783, 1956

[21] Spindt, R.S., Wolfe, C.L. and Stevens, D.R., "*Nitrogen Oxides, Combustion and Engine Deposits*", SAE paper 560068

[22] Dimitroff, E and Quillian, R.D., "*Low Temperature Engine Sludge - What? - Where? - How?*", SAE paper 650255, 1965

[23] Geyer, J., "*The Mechanism of Deposit Formation and Control in Gasoline Engines*", Symp. on Deposit, Wear and Emission Control by Lubricant and Fuel Additives, American Chemical Society, Div. of Petroleum Chem., New York, 1969

[24] Kreuz, K.L., "*Gasoline Engine Chemistry as Applied to Lubricant Problems*", Lubrication, Vol 55, No 6, p53, 1969

polymerization of the oil itself [25].) The chemistry by which NOx and fuel hydrocarbons form acetone-soluble sludge and varnish compounds was further explained by Vineyard et al who were able to identify aliphatic nitrates and nitro-alkanes as the key precursors[26].

Rounding out this work on formation of solids due to contaminants in the oil, Spearot et al[27] traced the leakage of NOx from the combustion chamber and its evolution in the crankcase. They essentially confirmed that NO is the primary compound formed in the combustion chamber, showed that it turns to NO_2 in the crankcase, and showed that the crankcase NO_2 concentrations are raised sharply by slightly lean mixtures and by the same conditions that increase knock, specifically high load and slightly lean mixtures. High oil temperature is also a factor in accelerating the formation of solids from these oil contaminants. Hence, knocking operation, (which simultaneously increases NOx levels, increases blowby and increases oil temperature), provides a severe set of stressors for the lubrication system.

6. A Specific Example

A single example illustrating the problems of continuous light knock comes from the engine family which includes 1994-99 Chrysler V6's and V8's of 3.9L, 5.2L and 5.9L displacement. These engines had a tendency to develop on-going engine "ping", i.e. persistent but not catastrophic engine knock. A series of fixes were developed to treat the problem. However, the fixes were not always applied and were not always successful when applied. Since the knock was not generally catastrophic, it was treated as an irritant rather than a serious problem. Eventually, some of these engines have gone on to suffer lubrication-related failures that match those to be expected as a result of secondary knock-related damage.

These mid-1990's V type engines used regular grade 87 octane gasoline with approximately 9/1 compression ratio and a bore up to 102 mm. This combination would easily lead to engine knock at moderate to high throttle openings, particularly with a fairly aggressive spark advance curve, (which was needed to meet acceptable fuel economy targets). Knock was controlled by a combination of high EGR rate at moderate power levels and use of rich fuel/air mixture at high power levels. The engine control system did not include a knock sensor so there was no direct feedback to the engine controller in the event that knock occurred. Likewise, the engine fuel system

---

[25] Gallapoulos, N.E., "*Engine Oil Thickening in High-Speed Passenger Car Service*", SAE paper 700506, 1970

[26] Vineyard, B.D. and Coran A.Y., "*Gasoline Engine Deposits: I. Blowby Collection and the Identification of Deposit Precursors*", Symp. on Deposit, Wear and Emission Control by Lubricant and Fuel Additives, American Chemical Society, Div. of Petroleum Chem., New York, 1969

[27] Spearot, J.A. and Gallopoulos J.A, "*Concentrations of Nitrogen Oxides in Crankcase Gases*", SAE paper 760563, 1976

operated open-loop during all transient operations and when moderate to high power levels were demanded. (Closed loop fuel control was only used during idle and low-power cruise operation).

For fuel economy reasons, this system was designed to be close to knock and it did not have a feedback knock control system. Hence, fairly subtle shifts in a number of parameters could lead to knock and the engine controller would not change operation to counter those shifts. For example new engines would be susceptible to knock due to manufacturing variations which affected basic compression ratio, spark timing or EGR rate. With time, engines could begin to knock due to factors that increased compression ratio, decreased cooling or affected the fuel flow or EGR flow rates. These factors would include:

-combustion chamber deposit buildup, (higher compression ratio and hotter surfaces),
-EGR system fouling, (reduced EGR makes mixtures more reactive),
-fuel injector plugging, (reduced peak injector flow leans out the mixture when it ought to be rich for power and knock control),
-fuel pump wear, (reduced pressure at high flow rate leans out the supposedly rich mixture).

Any of these normal wear factors could make an engine drift into knocking operation at a point where it was not knocking when new.

Another specific problem that affected this class of engines in service was intake manifold leaks. A leak between the engine block and intake manifold would result in excessive air and oil mist being drawn into the engine intake system. In the short term, the extra air supply could lean out the mixture leading to knock in open-loop operation at moderate to high power, (where the engine controller assumed the mixture was rich enough to prevent knock). In the longer term, continued combustion of oil mist from the crankcase would lead to excessive combustion chamber deposit buildup. These deposits would raise the effective compression ratio, leading to further knock and would also insulate the head and piston, leading to hot spots and eventually pre-ignition. Buildup of excessive deposits from oil burning could also lead to ring gap plugging, sticking rings and excessive blowby, thus exaggerating the NOx exposure of the oil. Chrysler issued various Technical Service Bulletins aimed at solving this problem. (The original ones used a fairly crude test designed to detect excessive flow rates of crankcase gas and eventually this was replaced with a test designed to detect minor amounts of oil drawn into the intake manifold[28].)

Ultimately, solving the problem required both sealing any manifold leakage paths to stop the oil consumption and also removal of combustion chamber deposit buildup to stop the knock[28]. However, some of the vehicles which operated with persistent knock over a period of time also presented lubricant sludge and deposit problems typical of those to be expected with excessive blowby contamination building up and reacting in overheated lube oil.

---

[28] Dodge Ram TSB 09-05-00 for 94-99 V8 and V8 engines, 2000