CATERPILLAR®

Gas Engines Application and Installation Guide

G3600-G3300

- Detonation and Preignition

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G3600-G3300 Detonation and Preignition

General Description

Detonation (often referred to as knock) and surface ignition (preignition) are the most destructive forms of abnormal combustion. These are sometimes misunderstood in gas engine discussions. This section will give the definitions and explanations for knock and preignition.

The next two paragraphs paraphrase Massachusetts Institute of Technology (MIT) Mechanical Engineering Professor John Heywood, a noted author on the subject of Internal Combustion Engines. (see reference 1).

Knock (detonation) is the name given to the sound that results from the autoignition of air and fuel ahead of an advancing flame front. As the flame propagates across the combustion chamber, the unburned air-fuel mixture ahead of the flame, called the end gas, is compressed which increases its pressure, temperature and density. Some of the end gas air-fuel mixture may undergo chemical reactions prior to normal combustion. The products of these reactions may then autoignite spontaneously. When this happens, the end gas burns very rapidly, releasing its energy at a rate 5 to 25 times the rate of normal combustion. This causes high frequency pressure oscillations in the cylinder that produce the sharp metallic noise called knock. It also causes higher heat transfer rates into the combustion chamber components causing high component temperatures which, in turn, can advance the autoignition event even further until critical components (pistons, valves, plugs) can fail.

The other abnormal combustion phenomenon is surface ignition. Surface ignition is ignition of the air-fuel mixture by overheated valves or spark plugs, by glowing combustion chamber; deposits or any other hot spot in the engine combustion chamber. In general, it is ignition from any source other than normal spark ignition. When surface ignition occurs prior to the normal spark, the event is called preignition. This is the most severe and evident (loud knock) form of abnormal combustion.

Preignition is more critical the earlier the ignition starts prior to the spark. The preignition causes pressure and temperature to rise abnormally near the end of compression. This can lead to very high cylinder pressure and further knocking of the end gas. This kind of preignition is usually started by glowing combustion chamber deposits and cannot be controlled by spark timing. This is because the spark ignited flame front is not the cause of the knock.

Timing is an effective deterrent to the normal knock event. By retarding timing, the end gas temperature, pressure and density are lowered which will deter knock. This is the basis for the detonation sensitive timing systems developed by Caterpillar. These DST systems (Caterpillar Timing Control and Electronic Ignition System) retard timing to correct knock. If the knock persists, such as in the case of preignition, the engine will be shutdown to protect the engine from potential damage. This damage will most often result in a piston seizure if left uncorrected.

There are many other variables of engine operation that can contribute to knock or preignition, in addition to the timing. Anything that leads to higher temperature, pressure or density in the combustion chamber will increase the tendency for knock occurrence. Some of these variables are listed below with a quick explanation of why each of them may lead to detonation or preignition in natural gas burning engines.

Causes Of Detonation

Fuels

Fuel With Higher Lower Heating Value (LHV)

After an engine is set up on site, it often experiences changes in lower heating value. If the change is in the direction of higher LHV, the engine will naturally get richer if there is not an automatic air fuel ratio control device in place to counter the change. The mixer is essentially a volume flow device and if the energy content of the fuel is increasing within the same volume, the actual air fuel ratio in the engine will become richer as the fuel increases in lower heating value.

Richer air fuel ratios on lean burn engines allow the engine to run closer to the point of detonation. On lean burn engines, richer air fuel ratios reduce the amount of air in the cylinder. With less free air to absorb heat, the combustion temperatures increase making detonation more likely. In extreme cases, the fuel can change considerably in short periods of time. This is typical of gas processing plants where the gas engine usually sees a processed furl with a lower heating value in the 900-1000 btu/ft^3 range. If the processing plant has a problem resulting in the plant not functioning, the gas engine will often see the unprocessed gas from the gas field. This fuel may have lower heating values as high as 1200-1400 btu/ft^3. This can happen well within 10 seconds.

An air fuel ratio control can manage this kind of change while avoiding detonation. Without automatic air fuel ratio control, the engine will knock severely until the timing retard(from DST or EIS) cools the engine sufficiently or the engine shuts down. In another extreme case, there are some landfills that produce fuel high in Methane and low in CO_2, (these usually exist in a 55% CH_4, 45% CO_2, combination). This can happen on landfills without flares when the engine is not operating. There are small amounts of this "rich" landfill gas (as much as 70% CH_4, has been measured, in one case) that get into the engine causing detonation and guttered valves at very low loads. Operators must have a good knowledge of their fuel chemistry and fuel chemistry changes to properly apply natural gas engines.

Fuel With Lower Methane Number

A lower Methane Number usually accompanies a change to higher LHV. When the Methane Number is lowered, the fuel is more likely to detonate. This changes the operating point at which detonation occurs, placing it closer to the running conditions of the engine. Lower Methane Number fuels burn faster. The faster burning creates higher temperatures and pressures in the cylinder, making detonation more likely to occur. The Caterpillar Fuel Usage Guides should be used to determine the correct engine timing to offset the effect of the faster burning lower Methane Number fuels.

Liquid Hydrocarbon Fuel

Liquids can show up in natural gas streams when pressure and temperature conditions are correct for a phase change from a gas to a liquid. This usually occurs at pressure drops in the gas piping due to tight turns or bends in the piping or when the gas sees a dramatic temperature change. The phase change is more likely to occur in hydrocarbons with increasing number of carbon atoms. The following table shows the boiling point (liquid to gaseous phase change) of the typical hydrocarbons that occur in natural gasses at 14.7 psia (1 bar) absolute pressure. These temperatures are not absolute indicators of liquid dropout since vapor pressure equilibrium will always allow some vapor (of these hydrocarbons) to remain in the gas. Table 1 also indicates the autoignition temperature of these fuels. Lower autoignition temperatures are more likely to detonate or preignite in the combustion chamber.

Gas	Formula	Boiling Point (F°)	Autoignition Temperature (F°)
Methane	CH_4	-258.7	1,220
Ethane	C_2H_6	-127.5	968
Propane	C_3H_8	-43.7	914
Butane	C_4H_{10}	31.1	600 (est)
Pentane	C_5H_{12}	96.9	500 (est)
Hexane	C_6H_{14}	155.7	478
Heptane	C_7H_{16}	209.2	433
Octane	C_8H_{18}	258.2	428

Table 1.

From Table 1, it can be seen that Pentane, Hexane, Heptane and Octane would prefer to be a liquid rather than a gas at room temperature and pressure. They can exist as gasses in very small quantities, however, they can pose problems when present in larger percentages. In cases where there is a known or suspected hydrocarbon dropout in the fuel system, a fuel heater can be used. Table 1 also shows why the heavier hydrocarbons create such a high tendency to detonate when they are present in natural gas fuels. Compared to Methane, some of the higher carbon value hydrocarbons are extremely easy to autoignite.

Oil From Auxiliary Equipment

There have been a number of documented situations where oil from auxiliary equipment has caused detonation in natural gas engines. In the Caterpillar Technical Center, small amounts of synthetic instrument oil from a leaking gas meter has caused detonation in a G3516 engine. The amount of oil was very small, but found its way to one of the end cylinders of the G3516 which immediately detonated. The autoignition temperatures of typical machine oils are in the 600-800°F range.

Similar occurrences have been seen from gas compressors that leak lubricating oil. Oil rings or intermediate rings installed upside down can allow enough engine oil into the combustion chamber to cause detonation. In a related but peculiar situation, a G3516 engine was getting slugs of benzene from a landfill fuel which caused the engine to detonate even during low idle. Care must be taken to avoid sources of oil or other highly volatile organic substances from entering the gas stream. Typical autoignition temperatures of selective oils are shown in Table 2 for comparison to Methane at 1220°F.

Oil Type	Autoignition Temperature (°F)
Cylinder Oil	825
Machine Oil	710
Kerosene	670
Heating Oil	580

Table 2.

Combustion Chamber Surface Temperature

High Jacket Water Temperature

High jacket water temperature due to poor cooling system design, performance or maintenance will lead to higher component temperatures in the combustion chamber. In turn, this heat is transferred to the cooler incoming intake mixture during the intake stroke and early compression stroke. The higher in-cylinder mixture temperatures are more likely to detonate.

High Oil Temperature

High oil temperature will increase the piston temperature due to less effective cooling of the piston with the hotter oil.

Plugged/Misdirected Oil Jets

A plugged or misdirected oil jet will decrease the effectiveness of the primary method of piston cooling. This is particularly true for gallery cooled pistons where the room for error in oil jet direction and delivery rate is reduced since the oil gallery is such an essential part of the cooling mechanism of that type of piston.

Low Jacket Water or Oil Flow Rate

Low jacket water pump or oil pump flow can also affect the combustion chamber temperatures. If the lower jacket water flow levels result in reduced heat transfer in the oil cooler, behind the cylinder liner or in the cylinder head, combustion chamber surface temperatures will increase. The same is true for the effect that low oil pump flow has on piston temperatures.

Intake Mixture Temperature

High Aftercooler Water/Air Temperature

When the aftercooler water temperature (or air temperature in the case of air to air aftercoolers) increases, the aftercooler combustion air outlet temperature will increase. The higher intake manifold temperature that results will make the engine more prone to detonation since the compression and combustion processes have to start with a higher initial temperature. This will always lead to higher temperatures in the end gas making detonation more likely.

There have been cases where Propylene Glycol was used as a coolant medium in systems designed for Ethylene Glycol or Water/Ethylene Glycol mixtures. The heat transfer characteristics of the Propylene Glycol did not match the system design resulting in high intake manifold temperatures and high levels of detonation.

High Intake Manifold Temperature

This event is usually byproduct of poor aftercooler performance similar to the events previously described with High Aftercooler Water/Air Temperature. It can also be the result of high ambient temperatures or altitudes if the aftercooler system was undersized for these conditions. Fouling of the aftercooler core or aftercooler water heat exchanger will also decrease the effectiveness of the aftercooler core which will increase the intake manifold temperature. The intake manifold temperature can also increase unexpectedly if the intake plenum comes into contact with the engine block. This is more likely to occur when the engine is operating with a high jacket water temperature. The heat transfer from the hotter-than-designed intake plenum surface to the intake mixture will increase the intake mixture charge temperature.

High Exhaust Manifold Pressure

The higher the exhaust manifold pressure, the more hot residual exhaust gas will be left in the cylinder after the exhaust process. The more gas left in the cylinder, the hotter the combustion chamber walls and the intake charge will become, as it enters the cylinder and mixes with the hot residual exhaust gas.

The conditions that can increase exhaust manifold pressure include high exhaust stack back pressure and high exhaust manifold temperature. The wrong turbocharger can also influence the exhaust manifold pressure. Larger turbine housing clearances lower exhaust manifold pressure which helps reduce the tendency to detonate. However, smaller turbine housings, because of their reduced clearances, increase the exhaust manifold pressure. Smaller turbine housings restrict the exhaust flow requiring higher exhaust manifold pressure to move the exhaust gas through the turbocharger.

Valve Timing

The wrong camshaft will have incorrect valve timing which can lead to detonation. The intake closing event is often used on Cat natural gas engines to lower the effective compression ratio.

The "early inlet camshaft" is used on stoichiometric engines to lower the cylinder temperatures by effectively closing the intake valve prior to bottom dead center of the piston travel. After the intake valve closes, the cylinder mixture continues to expand which lowers the mixture temperature in the combustion chamber. At bottom dead center of the piston, the compression stroke begins with a lower mixture temperature than the aftercooler can provide on its own. The lower temperatures carry through the entire compression and combustion process resulting in a lower tendency to detonate. However, if a standard camshaft designed for naturally aspirated and lean burn engines is mistakenly used in place of an early inlet closing camshaft on a stoichiometric engine, the engine will react by getting into severe detonation at the stoichiometric engine power and timing settings.

Air Fuel Ratio

Engine Set Too Rich

Detonation margin on a lean burn engine is defined as the margin from the operating point (% Oxygen needed for low NO_x) to the air fuel ratio (% Oxygen) where detonation occurs while the engine is kept at constant load and timing. The point of detonation is relatively fixed and lean burn engines need to be set lean enough to have a comfortable margin from the detonation point.

Setting a lean burn engine too rich can result in a small detonation margin, thus causing the engine to always run in retarded timing to avoid detonation, shut down or in the extreme case, engine damage. Care must be taken to keep the engine operation as lean as required to produce the required emissions. If emissions are not an issue on site, the engine must still be kept leaner than the highest permissible NO_x level to maintain proper detonation margin.

The typical measure of air fuel ratio in the field is exhaust Oxygen. If an Oxygen meter is not available or there is a question about the reading from an Oxygen meter, the inlet manifold pressure is an excellent indicator of proper engine setting provided the load is known. On gen set engines, there is usually a power measurement available. Use the inlet manifold pressure provided by TMI data or on the spec sheet that accompanies the rating to check the correctness of the engine setting for a given power level.

Air and/or Gas Temperature Variation at the Mixer

Air and fuel is mixed in a predominately volumetric fashion on most gas engines. The engine is initially set up for the given site conditions on a given day. Along with the set up parameters, the engine was set up at a given fuel and air density present at the mixer. If the densities change to the mixer, i.e. if the air temperature or fuel temperature change relative to one another, the air fuel ratio will change.

Typically on high pressure carbureted natural gas engines with the mixer placed after the aftercooler, the air temperature will be very consistent because of the aftercooler. The fuel temperature may change seasonally or with the day to day temperature swing depending where the piping is routed. As the fuel gets cooler, it will be more dense (more energy per volume) and will mix in relatively richer proportions than the original set up. This results in a lower air fuel ratio and an engine setting closer to detonation.

This also occurs on air to air aftercooled engines which have poor control of the cooled inlet air temperature to the engine. The air to air aftercooler, if not well controlled, will provide air to the engine that tracks the ambient temperature. If this happens, the air density will be constantly changing resulting in changes in the engine air fuel ratio. The fuel mixture will richen up when the air is warmed and becomes less dense.

Yet another example occurs on low pressure carbureted engines. Here, the fuel is typically less likely to change temperature relative to the air entering the mixer prior to the turbocharger. The air can vary with the ambient temperature while the fuel pipe may be buried in the ground until just prior to entering the engine area. The fuel may be very consistent in temperature. The air, however, will vary with the ambient temperature causing wide swings in air fuel ratio if left unchecked. Usually the low pressure carburation situation is the worse of the two mentioned above.

To combat the changing differential in air and fuel temperature, it is recommended that an air to gas heat exchanger be used to control the temperature differential between air and gas. Once controlled, the temperature swings will not cause air fuel ratio changes and, ultimately, a loss of detonation margin. Here is an example of how quickly the air fuel ratio changes because of temperature fluctuations. It only takes a 15°F change in air to fuel temperature differential at the mixer to increase the NO_x emissions from 2 grams/bhp-hr to 6 grams/bhp-hr. Detonation margin will be reduced by 2 degrees timing per 0.4% Oxygen due to the air fuel ratio change described above.

Ignition Timing

Advanced Spark Timing

Any advance to the spark timing will cause the mixture to begin burning sooner in the cylinder. The sooner the combustion begins in the chamber, the higher the cylinder temperature and pressure will be. Of course, the high temperatures will be more likely to light off the end gas and cause detonation.

On engines with electronic ignition systems, there is the risk that the engine can be put into magneto calibration mode while the engine is running. This can result in severe detonation since the timing can instantly advance by as much as 10-14 degrees. If an engine is close to detonation and this happens, the resulting detonation can be violent.

On a less detrimental plateau, timing can be misadjusted leading to reduced detonation margin. Follow the Fuel Usage Guides provided in the Engine Performance Books to determine the proper ignition timing for the site conditions.

Electronic Noise

On engines with electronic ignition systems, there is a risk that unwanted electrical noise can get to the control and change the timing of the engine. Engines must be properly grounded to keep extraneous electrical signals from "resetting" the electronic timing control.

The spark plugs must be well maintained to avoid resistor breakdown within the plug. The resistor is the plugs protection device to keep electrical noise during the spark from affecting other electrical equipment on or near the engine. The electrical noise from the plug can be intense enough to reset the timing signal from the Altronic Interface Boxes or early versions of the EIS control modules.

General

High Load

Higher engine loads require more fuel. The increased energy released in the combustion chamber at higher loads will add more heat into the end gas making the engine more prone to detonation. It is always good application practice to employ a derating strategy if the engine is going to see variable jacket water, oil or intake manifold (or aftercooler water supply) temperatures. A reduction in load will help offset the lost detonation margin that occurs when these temperatures increase.

Low Engine Speed

Lower engine speed allows the end gas more time to absorb heat from the slower combustion events. Thus most engines are more prone to detonation at lower speeds than higher speeds. To combat this, the Caterpillar Electronic Ignition Systems have timing maps that will retard the timing as the engine speed is lowered.

Slow Combustion Speed

As in the case of lower engine speeds, slow combustion rates can also increase the tendency of the end gas to absorb more heat and become more likely to detonate. Combustion system designs with higher turbulence in the cylinder have been developed by Caterpillar to take advantage of this fact. The higher turbulence creates faster combustion. This lowers the chances of the end gas to autoignite because there is less time for the heat transfer to take place.

High Compression Ratio

The higher the compression ratio, the higher the temperatures and pressures of the end gas. Increased compression is used to improve engine efficiency; it is always accompanied by a loss of detonation margin (at similar engine conditions and timing). Timing must be retarded to compensate for a higher compression ratio. In addition, fuels used in a high compression ratio engine are usually limited to high Methane Number fuels.

Combustion Chamber Deposits

Combustion chamber deposits are usually a result of oil formulation or high oil consumption. Oils with high ash content (higher than 0.45%) can lead to deposits; this is often seen in landfill engines. However, there is generally not detonation associated with combustion chamber deposits in landfill engines because the fuel is very detonation resistant.

There have been other cases where combustion chamber deposits have caused preignition. Certain oils have caused deposits that over time will form a small irregular deposit that can get very hot and cause surface ignition (preignition). This results in random violent engine shutdowns. It usually takes about 1500-2500 hours for the deposits to build up to this level and then shutdowns can occur as often as 2 to 3 times per day. It is not fully known why some oils have a tendency to display deposit surface ignition and others do not. The safest way to avoid this situation is to use Cat Natural Gas Engine Oil.

This type of preignition is very difficult to diagnose because the cause of the event usually get burned away before it can be found. If an engine is experiencing random shutdowns that appear to be caused by a preignition event (more violent than detonation), investigate the oil being used. There have been cases where a change to another brand of oil ended the preignition, immediately. Although it is recommended that the pistons and cylinder head be cleaned if an engine has been experiencing deposit related preignition, there have been cases where changing oil brand or even using a lower viscosity oil have stopped the problem without the need to clean the combustion chamber.

Low Spark Plug Torque

If a spark plug is installed with low (inadequate) torque, the heat transfer from the electrodes will be impaired. If this condition is bad enough, the electrodes can become a source for surface ignition and preignition.

Prechamber Engines

All the previously mentioned occurrences will affect a prechamber engine with gas admission valves. In addition, there are a few other situations to look for.

Gas Admission Valve Misadjustment

If any of these are set to allow too much fuel into the main chamber, the engine will run too rich. This can cause main chamber detonation.

Prechamber Needle Valve Misadjustment

Allowing too much fuel into the prechamber can cause the prechamber mixture to burn too fast which will act like advanced timing. The main chamber will get too hot, too soon, possibly leading to end gas autoignition in a prechamber engine.

High Intake Manifold Temperature

One additional item to note, prechamber engines appear to be more sensitive to high intake manifold air temperature than other Caterpillar natural gas engines. Extra attention should be paid to the aftercooler system on prechamber engines to avoid high intake manifold air temperatures.

False Detonation

Misadjusted Valves

Valve train misadjustment can cause engine “noise” that may be detected by the Detonation Sensitive Timing system as detonation. Proper readjustment of the valve train will correct this situation.

Low Background Noise

From time to time, an engine will operate so quietly in terms of background noise (as detected by the engine's accelerometer) that normal valve train noise can be detected as a vibration event similar to detonation. This has been remapped in the EIS engines by forcing a maximum background noise level into the software. This is the new baseline that detonation events (higher vibration) are measured against.

Other Vibration

There have been cases where unbolted or loose joints in the engine exhaust system have vibrated enough that the Detonation Sensitive Timing system interpreted the event as detonation. The system retarded the engine timing. However, not being a true detonation event, it was not effective and the engine shutdown shortly afterward.

Check engine piping connections to avoid false detonation shutdowns. Camshaft pitting on a cam lobe near the detonation sensor can also be detected as false detonation. Anything loose mechanically can cause false detonation.

Another example of loose parts triggering detonation is a bolt left in a cooling system pipe. The bolt was continually bounced off the pipe by a pump impeller. Each time it hit the pipe the engine retarded timing because it "thought" a high level of detonation had just occurred .

Cold engines will occasionally exhibit false detonation at startup. This routinely goes away when the engine warms up.

Rating Guidelines For Detonation Margin

Detonation should be measured as consistent as possible. If there is not a DST or an EIS, the Service Mechanic will need to use the "trained ear" method. This is possible after some experience listening to engines detonate and learning the sound of the onset of light audible knock. It resembles the sound of walnuts or marbles being knocked together.

Equivalent detonation levels are listed as follows:

DST/ElS - 6 bars (onset of retarded timing within DST or EIS)

Trained Ear - Light audible knock

Caterpillar has established Rating Guidelines for all engine ratings.

Detonation margins must be demonstrated on the various possible combinations of fuels. For example, if the engine is a low compression ratio version, the margin must be demonstrated on both pipeline and propane. On a high compression ratio version, the margins must be available on pipeline fuel and a simulated mid range methane number fuel as specified in the functional specification (An example of this is testing fuels with 65 or 70 Methane Number for the CHP market in Europe.) The simulation of a mid range Methane number fuel comes from blending propane and pipeline fuels, based on the prediction of Methane Number from the Caterpillar Methane Number program.

Stoichiometric Engines

Stoichiometric (Rich Burn) engines are setup to operate at the worst detonation point (between 0-2% exhaust oxygen). The detonation margin of 5 degrees timing has historically been used at Caterpillar for stoichiometric engines without electronic controls. The timing should be determined by the creation of a rating limit diagram. The rating limit diagram is created by following these steps:

1. Determine the exhaust oxygen where detonation is worst. Fixing air fuel ratio and increase load, with all other settings held constant, until detonation occurs. Three or four air fuel ratio settings will determine where the engine detonates at the lowest load. Subsequent detonation work should take place at this exhaust oxygen.

2. At the exhaust oxygen determined in Step 1, vary the timing and determine the load at detonation. Reset the engine to 0.5% exhaust Oxygen. This is where the exhaust temperatures are at their maximum. As the load is decreased, note the load at the point where the exhaust port temperature meets the rating guideline. Do this at constant intake manifold temperature, jacket water temperature and fuel Methane Number. The resulting diagram is shown in Figure 1.

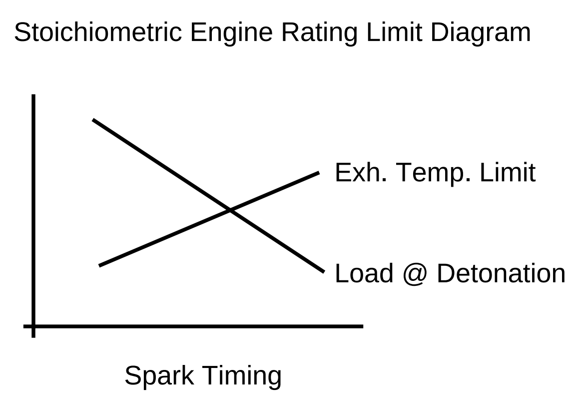

Figure 1.

3. The exhaust port temperature limit form the Rating Guidelines is compared to the

average exhaust port temperature from the engine.

4. The next step is to retard the timing 5 degrees from the load limit line, as shown by the dotted line in Figure 2.

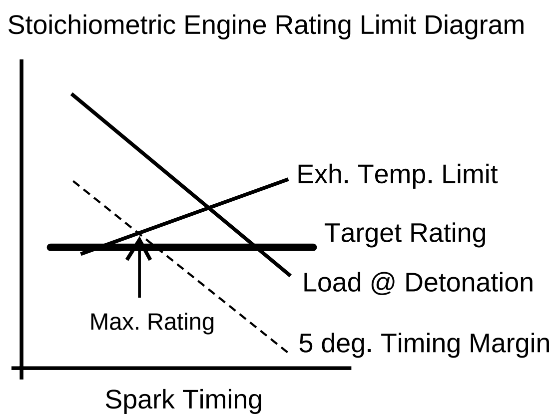

Figure 2.

At the intersection of the exhaust temperature and 5 degree retarded detonation line will be the maximum load (rating) for this engine. If the target rating is below this load, the most advance timing should be used to lower exhaust temperature, extend plug life and provide the best fuel consumption. The exhaust temperature and plug life are certainties, the fuel consumption can sometimes get worse if the combustion is too early (advanced) on low compression ratio turbocharged or naturally aspirated engines.

Generally, best fuel consumption should be used for these ratings. However, there may be other circumstances that call for retarded timing. One example would be an engine with oil life problems. Retarded timing lowers NO_x which reduces the oil nitration and the retarded timing cools the combustion temperatures which will lower the oxidation rate.

For most stoichiometric engines, the air fuel ratio varies as the fuel lower heating value changes. This occurs often in a gas compression application. When it occurs, the detonation margin can either increase or decrease. If the fuel is decreasing in Methane Number, the detonation margin will decrease due to the change in the fuel's tendency to detonate. However, some of the lost margin will be regained if the air fuel is moving richer relative to the worst air fuel ratio setting for detonation. If the engine is set properly (near the worst detonation air fuel ratio) and the Methane Number of the fuel increases and the lower heating value of the fuel decreases, the detonation margin will increase greatly because as the leaner air fuel ratio and increased detonation resistance of the higher Methane Number fuel.

The stoichiometric engine is set up to operate at the worst detonation point for the engine so that changes in operating conditions will help rather than make the detonation margin worse. The other major detonation variables that could make detonation worse include:

- Higher Load
- Lower Speed
- Higher Intake Manifold Temperature
- Higher Jacket Water Temperature

It has been the analysis of these variables that has led to the 5 degree detonation margin that is used on stoichiometric engines without DST at Caterpillar.

On naturally aspirated engines, the detonation testing is done with a high ambient temperature day in mind, Since there is no aftercooler on the engine, a 100°F intake temperature is likely to be a 105-110°F intake manifold temperature. This will cause more detonation to occur than the natural deration due to the high ambient. Naturally Aspirated engines should have detonation characterized with 110°F intake manifold temperature. The load carrying capability for Naturally Aspirated engines will be tested at the normal intake temperature and pressure conditions corresponding to ISO 3046/1 standards, but the timing of the engine should be related to the 110°F inlet manifold temperature detonation limit.

If detonation sensitive timing is used on a stoichiometric engine, the detonation margin can be reduced to 4 degree timing. This is being used on both G3400 and G3500 engines with EIS. The level of 4 degrees was established to avoid constant timing changes that can occur with DST if the detonation margin is too small. When the timing is changing often, the efficiency, NO_x, exhaust temperature and power carrying capability of the engine is constantly changing. This may lead to application or operational difficulties. Thus, a 4 degree margin is recommended with DST on stoichiometric engines.

Low Emission Engines

Low emission engines have no inherent advantage when the lower fuel heating value changes. In fact, when the fuel's Btu/cu ft increases (gets "hotter"), the lean burn engine wants to run richer due to the carburetor effect of metering the same volume of fuel. Detonation is more likely to occur at these richer air fuel ratios. Because of this combination, the detonation margin for a lean burn engine operating without controls of any kind needs to be very large from the target NO_x emission set point.

When detonation sensitive timing is used, the detonation margin can be lessened due to the increased level of control and protection on the engine. The DST compensates for detected detonation events by retarding the timing to "cool" off the cylinder through later, slower combustion. When the air fuel ratio gets richer on a lean burn engine the detonation margin drops quickly regardless of the fuel. When a stoichiometric engine gets richer, the detonation margin increases. Thus, the reason that DST is always a standard feature on low emission engines.

On low emission engines with Caterpillar air fuel ratio control, the detonation margin can be reduced even more and a higher rating (load) applied because air fuel ratios is well controlled. On low emission engines there must be sufficient timing margin so that the NO_x is not affected by continuously changing timing. This may be overcome in the future if the interaction of the air fuel ratio control and DST can be coordinated to keep the emissions and engine efficiency constant.

The G3600 engine uses an in-cylinder combustion sensor to control air fuel ratio. The control is always coupled with detonation sensitive timing to provide the maximum detonation protection.

Resultant Detonation Damage

The resultant component damage from detonation and preignition can vary. The first sign of detonation, beyond the knocking sound, is usually nibbling of the piston. This will occur at sharp edges in the combustion chamber (usually the piston bowl edge and crown edge) and near hotter components such as under the exhaust valves. As detonation continues, the piston can continue to get hotter and melt more and more of the piston. This usually leads to piston scuffing. Continued detonation may lead to a piston seizure. In extreme cases, a piston which seizes at high speed may pull apart. Violent preignition can lead to seizures in very short periods of time (as short as 10 seconds) and can also destroy components such as spark plugs and valves.

Detonation and preignition situations all have root causes that can and must be located and corrected to avoid the possible damage previously described. Detonation usually builds upon itself and makes the conditions for detonation during the next combustion cycle more likely to happen. (The piston gets hotter and hotter with detonation.) There are many possible causes for detonation and preignition, but proper engine application along with proper maintenance techniques for both the engine and associated systems should provide protection from detonation and preignition.

References

1. Heywood, John B., *Internal Combustion Engine Fundamentals,* New York, 1988.