Causes of Detonation

Detonation is influenced by chamber design (shape, size, geometry, plug location), compression ratio, engine timing, mixture temperature, cylinder pressure and fuel octane rating. Too much spark advance ignites the burn too soon so that it increases the pressure too greatly and the end gas spontaneously combusts. Backing off the spark timing will stop the detonation. The octane rating of the fuel is really nothing magic. Octane is the ability to resist detonation. It is determined empirically in a special running test engine where you run the fuel, determine the compression ratio that it detonates at and compare that to a standard fuel, That's the octane rating of the fuel. A fuel can have a variety of additives or have higher octane quality. For instance, alcohol as fuel has a much better octane rating just because it cools the mixture significantly due to the extra amount of liquid being used. If the fuel you got was of a lower octane rating than that demanded by the engine's compression ratio and spark advance detonation could result and cause the types of failures previously discussed.

Production engines are optimized for the type or grade of fuel that the marketplace desires or offers. Engine designers use the term called MBT (Minimum spark for Best Torque) for efficiency and maximum power; it is desirable to operate at MBT at all times. For example, let's pick a specific engine operating point, 4000 RPM, WOT, 98 kPa MAP. At that operating point with the engine on the dynamometer and using non-knocking fuel, we adjust the spark advance. There is going to be a point where the power is the greatest. Less spark than that, the power falls off, more spark advance than that, you don't get any additional power.

Now our engine was initially designed for premium fuel and was calibrated for 20 degrees of spark advance. Suppose we put regular fuel in the engine and it spark knocks at 20 degrees? We back off the timing down to 10 degrees to get the detonation to stop. It doesn't detonate any more, but with 10 degrees of spark retard, the engine is not optimized anymore. The engine now suffers about a 5-6 percent loss in torque output. That's an unacceptable situation. To optimize for regular fuel engine designers will lower the compression ratio to allow an increase in the spark advance to MBT.

The result, typically, is only a 1-2 percent torque loss by lowering the compression. This is a better trade-off. Engine test data determines how much compression an engine can have and run at the optimum spark advance.

For emphasis, the design compression ratio is adjusted to maximize efficiency/power on the available fuel. Many times in the aftermarket the opposite occurs. A compression ratio is "picked" and the end user tries to find good enough fuel and/or retards the spark to live with the situation...or suffers engine damage due to detonation.

Another thing you can do is increase the burn rate of the combustion chamber. That is why with modem engines you hear about fast burn chambers or quick burn chambers. The goal is the faster you can make the chamber burn, the more tolerant to detonation it is. It is a very simple phenomenon, the faster it burns, the quicker the burn is completed, the less time the end gas has to detonate. If it can't sit there and soak up heat and have the pressure act upon it, it can't detonate.

If, however, you have a chamber design that burns very slowly, like a mid-60s engine, you need to advance the spark and fire at 38 degrees BTDC. Because the optimum 14 degrees after top dead center (LPP) hasn't changed the chamber has far more opportunity to detonate as it is being acted upon by heat and pressure. If we have a fast burn chamber, with 15 degrees of spark advance, we've reduced our window for detonation to occur considerably. It's a mechanical phenomenon. That's one of the goals of having a fast burn chamber because it is resistant to detonation.

There are other advantages too, because the faster the chamber burns, the less spark advance you need. The less time pistons have to act against the pressure build up, the air pump becomes more efficient. Pumping losses are minimized. In other words, as the piston moves towards top dead center compression of the fuel/air mixture increases. If you light the fire at 38 degrees before top dead center, the piston acts against that pressure for 38 degrees. If you light the spark 20 degrees before top dead center, it's only acting against it for 20. The engine becomes more mechanically efficient.

There are a lot of reasons forfast burn chambers but one nice thing about them is that they become more resistant to detonation. A real world example is the Northstar engine from 1999 to 2000. The 1999 engine was a 10.3:1 compression ratio. It was a premium fuel engine. For the 2000 model year, we revised the combustion chamber, achieved faster bum. We designed it to operate on regular fuel and we only had to lower the compression ratio .3 to only 10:1 to make it work. Normally, on a given engine (if you didn't change the combustion chamber design) to go from premium to regular fuel, it will typically drop one point in compression ratio: With our example, you would expect a Northstar engine at 10.3:1 compression ratio, dropped down to 9.3:1 in order to work on regular. Because of the faster burn chamber, we only had to drop to 10:1. The 10:1 compression ratio still has very high compression with attendant high mechanical efficiency and yet we can operate it at optimum spark advance on regular fuel. That is one example of spark advance in terms of technology. A lot of that was achieved through computational fluid dynamics analysis of the combustion chamber to improve the swirl and tumble and the mixture motion in the chamber to enhance the burn rate.

Chamber Design

One of the characteristic chambers that people are familiar with is the Chrysler Hemi. The engine had a chamber that was like a half of a baseball. Hemispherical in nature and in nomenclature, too. The two valves were on either side of the chamber with the spark plug at the very top. The charge burned downward across the chamber. That approach worked fairly well in passenger car engines but racing versions of the Hemi had problems. Because the chamber was so big and the bores were so large, the chamber volume also was large; it was difficult to get the compression ratio high. Racers put a dome on the piston to increase the compression ratio. If you were to take that solution to the extreme and had a 13:1 or 14:1 compression ratio in the engine pistons had a very tall dome. The piston dome almost mimicked the shape of the head's combustion chamber with the piston at top dead center. One could call the remaining volume "the skin of the orange." When ignited the charge burned very slowly, like the ripples in a pond,, covering the distance to the block cylinder wall. Thus, those engines, as a result of the chamber design, required a tremendous amount of spark advance, about 40-45 degrees. With that much spark advance detonation was a serious possibility if not fed high octane fuel. Hemis tended to be very sensitive to tuning. As often happened, one would keep advancing the spark, get more power and all of a sudden the engine would detonate, Because they were high output engines, turning at high RPM, things would happen suddenly.

Hemi racing engines would typically knock the ring land off, get blow by, torch the piston and fall apart. No one then understood why. We now know that the Hemi design is at the worst end of the spectrum for a combustion chamber. A nice compact chamber is best; that's why the four valve pent roof style chambers are so popular. The flatter the chamber, the smaller the closed volume of the chamber, the less dome you need in the piston. We can get inherently high compression ratios with a flat top piston with a very nice bum pattern right in the combustion chamber, with very short distances, with very good mixture motion - a very efficient chamber.

Look at a Northstar or most of the 4 valve type engines - all with flat top pistons, very compact combustion chambers, very narrow valve angles and there is no need for a dome that impedes the burn to raise the compression ratio to 10:1.

Detonation Indicators

The best indication of detonation is the pinging sound that cars, particularly old models, make at low speeds and under load. It is very difficult to hear the sound in well insulated luxury interiors of today's cars. An unmuffled engine running straight pipes or a propeller turning can easily mask the characteristic ping. The point is that you honestly don't know that detonation is going on. In some cases, the engine may smoke but not as a rule. Broken piston ring lands are the most typical result of detonation but are usually not spotted. If the engine has detonated visual signs like broken spark plug porcelains or broken ground electrodes are dead giveaways and call for further examination or engine disassembly. It is also very difficult to sense detonation while an engine is running in an remote and insulated dyno test cell. One technique seems almost elementary but, believe it or not, it is employed in some of the highest priced dyno cells in the world. We refer to it as the "Tin Ear". You might think of it as a simple stethoscope applied to the engine block. We run a ordinary rubber hose from the dyno operator area next to the engine. To amplify the engine sounds we just stick the end of the hose through the bottom of a Styrofoam cup and listen in! It is common for ride test engineers to use this method on development cars particularly if there is a suspicion out on the road borderline detonation is occurring. Try it on your

engine; you will be amazed at how well you can hear the different engine noises.
The other technique is a little more subtle but usable if attention is paid to EGT (Exhaust Gas Temperature). Detonation will actually cause EGTs to drop. This behavior has fooled a lot of people because they will watch the EGT and think that it is in a low enough range to be safe, the only reason it is low is because the engine is detonating.
The only way you know what is actually happening is to be very familiar with your specific engine EGT readings as calibrations and probe locations vary. If, for example, you normally run 1500 degrees at a given MAP setting and you suddenly see 1125 after picking up a fresh load of fuel you should be alert to possible or incipient detonation. Any drop from normal EGT should be reason for concern. Using the "Tin Ear" during the early test stage and watching the EGT very carefully, other than just plain listening with your ear without any augmentation, is the only way to identify detonation. The good thing is, most engines will live with a fairly high level of detonation for some period of time. It is not an instantaneous type failure.

Pre-Ignition

The definition of pre-ignition is the ignition of the fuel/air charge prior to the spark plug firing. Pre-ignition caused by some other ignition source such as an overheated spark plug tip, carbon deposits in the combustion chamber and, rarely, a burned exhaust valve; all act as a glow plug to ignite the charge.
Keep in mind the following sequence when analyzing pre-ignition. The charge enters the combustion chamber as the piston reaches BDC for intake; the piston next reverses direction and starts to compress the charge. Since the spark voltage requirements to light the charge increase in proportion with the amount of charge compression; almost anything can ignite the proper fuel/air mixture at BDC!! BDC or before is the easiest time to light that mixture. It becomes progressively more difficult as the pressure starts to build.
A glowing spot somewhere in the chamber is the most likely point for pre-ignition to occur. It is very conceivable that if you have something glowing, like a spark plug tip or a carbon ember, it could ignite the charge while the piston is very early in the

compression stoke. The result is understandable; for the entire compression stroke, or a great portion of it, the engine is trying to compress a hot mass of expanded gas. That obviously puts tremendous load on the engine and adds tremendous heat into its parts. Substantial damage occurs very quickly. You can't hear it because there is no rapid pressure rise. This all occurs well before the spark plug fires.

Remember, the spark plug ignites the mixture and a sharp pressure spike occurs after that, when the detonation occurs. That's what you hear. With pre-ignition, the ignition of the charge happens far ahead of the spark plug firing, in my example, very, very far ahead of it when the compression stroke just starts. There is no very rapid pressure spike like with detonation. Instead, it is a tremendous amount of pressure which is present for a very long dwell time, i.e., the entire compression stroke. That's what puts such large loads on the parts. There is no sharp pressure spike to resonate the block and the head to cause any noise. So you never hear it, the engine just blows up! That's why pre-ignition is so insidious. It is hardly detectable before it occurs. When it occurs you only know about it after the fact. It causes a catastrophic failure very quickly because the heat and pressures are so intense.

An engine can live with detonation occurring for considerable periods of time, relatively speaking. There are no engines that will live for any period of time when pre-ignition occurs. When people see broken ring lands they mistakenly blame it on pre-ignition and overlook the hammering from detonation that caused the problem. A hole in the middle of the piston, particularly a melted hole in the middle of a piston, is due to the extreme heat and pressure of pre-ignition.