Basics Series: Detonation

by Greg McConiga

"I am created Shiva, the Destroyer; death, the shatterer of worlds."

-From the Bhagavad Gita

If you race or hang around with racers long enough, you will eventually find yourself surveying the remains of tens of thousands of dollars in parts -- the shattered corpse of a once loud, once proud, and once powerful engine, killed by the racer's mortal enemy: detonation.

Detonation is a complicated problem. There are thousands of complex interactions that lead up to the end result, which is the total and catastrophic destruction of all things aluminum, steel, titanium, and cast iron. Some say you can live with small amounts of detonation, but I suggest total avoidance because it doesn't take much to go from "what you can live with" to "the parts you drive over."

The results of detonation-induced failure will be subtle, like EF-5 tornado or train wreck subtle. Parts will be pounded, turned inside out, caved in, burned and broken in ways that will leave you shaking your head and wondering how you didn't see THAT coming, and further wondering how to approach failure analysis. With so much widespread damage, it's hard to know what the beginning of the process was and what the end was because you often have so much scrap metal in front of you that finding a beginning or end seems impossible.

I'll go out on a limb here and say that detonation probably accounts for nearly 100% of racing engine failures. It's impossible to put an exact number on it, but I'd bet that most of what we attribute to reciprocating parts failures start out as detonation failures, particularly if we're investing in high-quality parts

If you see this much aluminum stuck on the exhaust valve guide boss, you are in trouble. The shower of molten aluminum sticks to everything on its way out the pipe.

selected for the application and we don't over-rev the engine to the point where the valves undergo "assisted closure" on the piston head until the locks uncouple from the retainer (we do have to catch the valves with the pistons a little bit sometimes! Just a little bit...)

What is detonation, exactly?

Besides bad? In a few words, it is an uncontrolled combustion process that occurs when some part of the air/fuel mixture is compelled to burn at supersonic rates (nominally1,126 feet per second at sea level, but the speed of sound increases with temperature, density, and pressure, like the conditions inside a combustion chamber).

Where normal chamber burn times take something around one to four thousandths of a second and propagate at roughly 80-90 feet per second in a racing engine, detonation progresses at something over 1,126 feet per second and completes in microseconds; it's literally an explosion. Detonation is initiated and spread by shock compression and it can occur any time after the ignition system strikes the spark that begins normal combustion. It's characterized by sharp pressure spikes that violently batter anything in the combustion chamber or on the reciprocating assembly. The violence of detonation increases as engine output per cubic inch rises and in extreme cases it can destroy an engine so quickly that by the time you've become aware of it, it's often too late. On racing engines with open or only slightly muffled exhausts you don't hear detonation so much as feel it as a shudder and/or power loss. If you're running nitrous, you might hear something like a rapid, snapping machine gun sound – briefly, before white sparks blow out the exhaust and the backfiring begins. Detonation failures under boost or on laughing gas are malevolent and spectacular. If you like sparks and explosions, buy fireworks -- they're a lot cheaper, and you don't have to worry about killing anyone with flying engine parts.

Normal combustion flame fronts move between 20 and 90 feet per second under

If you think you may be entering into detonation, but you're not certain, pull the headers off the car and take a close look at the port under a bright light. You'll see little aluminum "diamonds" glistening back at you. If you see this your weekend is over and you've got some disassembly work to do.

most conditions for most gasoline-based fuels, and proceeds by thermal conductivity, where heat moves from a hotter reacting mass and conflagrates into a cooler unreacted mass, triggering the start of combustion. Because gasoline is "chemical soup" and a combustion chamber on a running engine is dynamic, the actual chemistry of combustion is impossibly complex. A very simplistic explanation is that components that make up the fuel are undergoing dissociation (separating at a molecular level into elements or compounds that can react with the oxygen), or association (recombining into new compounds), and absorbing heat (endothermic), or giving off heat (exothermic) before, during, and after the actual act of combustion (which is defined as combining oxygen with fuel -- the "burning" of the fuel) occurs in the chamber.

That's all combustion really is, oxidizing the fuel, the rapid combining of oxygen and fuel.

If you're a nitrous oxide user you already use dissociation to your advantage because N2O undergoes exothermic dissociation at about 560 degrees, heating the combustion chamber and producing nitrogen which slows or buffers the combustion process and oxygen which combines with the extra fuel you add to increase power. These dissociation/association reactions are separate from the actual act of combustion (combining with oxygen to form new compounds) and explain, in part, why temperatures in the cylinder don't reach theoretical maximums. Combustion temperatures are moderated by heat absorbing chemical changes that gases undergo pre-, during and post-combustion, and since temperature IS pressure in a closed system pressure is like-

All of the damage was confined to the second bay. Number four rod failed because the crank shook so hard that it destroyed number three main bearing, which then shared its death debris through the oiling hole in the crank with number four rod bearing. The rod bearing seized, the rod work-hardened as it was bent to and fro, and finally broke just above the rod bearing bore.

wise moderated. This is a good thing because common engine building materials would not survive if combustion temperatures and pressures did, in fact, reach theoretical maximums.

To look at just one small example out of dozens, we all know that one byproduct of gasoline combustion is water because we see the vapor (steam) in the exhaust and we see the rust in our engines if we don't pickle them after each weekend on the track. For every gallon of gasoline consumed, about a gallon and a quarter of water is produced, and as one pound of water is converted to steam it absorbs about 970 BTU of heat -- heat that is no longer available to produce power.

There are dozens of engineering books out there that will give you the complete thermal picture, but be advised they make thick reading unless you're far more current on your calculus and chemistry than I am.

Other ways to break your parts

Subsonic shock waves are a normal part of the combustion process. Spontaneous detonation can occur as the shock waves that form ahead of a normally turbulent flame front exceed supersonic speed and initiate detonation in the remaining air fuel mixture. Combustion chamber shape, obstacles like a large compression dome or sharp edges, can reflect or redirect pressure waves and cause them to combine or become additive pushing the speed of the shock wave past supersonic.

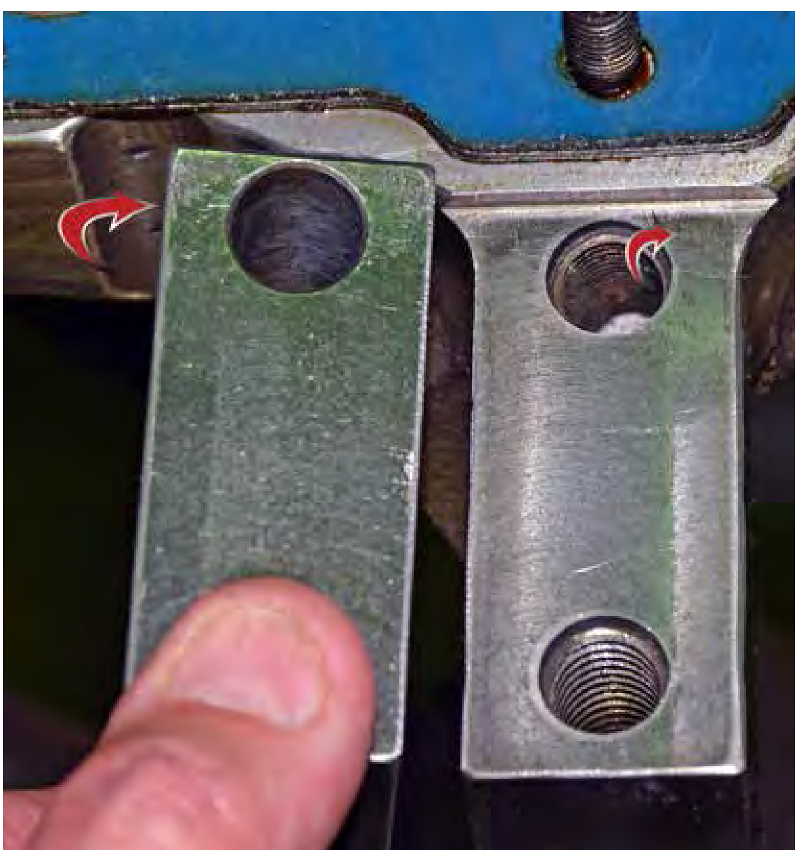
Think about sound -- it travels in "shock waves" -- and think about the effect you've heard when you've listened to a surround-

It's plain to see what has happened in this picture. You can see the bluish-white discoloration that is the result of detonation. The point of origin seems to be consistently around the transition from the exhaust valve pocket to the intake valve pocket and you can see the coarse appearance of the piston top where aluminum was eroded away by detonation. Number three melted and torched through when the protective boundary layer was compromised.

sound system. Properly designed, the sound seems to be everywhere, uniform and equal. That's reflection and redirection at work. Think about times when you've noticed how music seems louder or quieter due to local conditions like the location of walls, alcoves, carpets, hard surfaces, barriers, or even atmospheric conditions.

Pressure waves in the combustion chamber act the very same way and can be concentrated or focused into a point. An air/fuel mix under heat and pressure that is smacked with a supersonic pressure wave does what black powder does when you hit it with a hammer while it's burning: it explodes. Don't ask me how I know that and don't attempt this at home.

Crevice detonation occurs when small, non-homogenous pockets of fuel are "cooked off" ahead of the approaching flame front. You'll often see signs of it above the top piston ring on the outer edge of the piston. Usually the higher octane lighter ends burn first. You can actually see "fingers" of flame reaching out ahead of the flame front leaving heavier and typically lower octane components behind. Piston manufacturers sometimes machine reduced contact grooves or anti-detonation grooves in the top ring land that provide three main benefits: They lower friction by reducing total surface area in contact with the cylinder wall, they act to smear the fuel collected in the area above the top ring down the cylinder wall so it can be vaporized, stirred and exposed to the developing flame front in a mixed and combustible form, and they disrupt supersonic pressure waves that might detonate fuel accumulated on the top ring.



This is a Dart Big M block, and it's a pretty stout piece. It took so much abuse that the number three main cap is loose in the register. See that step at the top of the picture? Normally the cap is tightly captured between that and one like it on the other side of the engine. You normally have to tap the main caps into place during installation or pry them out on disassembly. Not this time. This time the cap fell out, and the arrows indicate fretting -- where the cap shook so hard that metal transferred from one surface to the other. I'm not kidding when I tell you this is a violent process!

Separate, but equally destructive

A second form of abnormal combustion is pre-ignition. What is pre-ignition and how does it lead to or cause detonation? Pre-ignition is a completely separate phenomenon from detonation. Pre-ignition is exactly what it sounds like -- it is the fuel in the cylinder lighting off ahead of the actual timed ignition event. A cylinder hot spot can be caused by carbon deposits, a thin piece of metal jutting out into the chamber from a head, head gasket, or piston, or any thin, sharp edge left in the combustion chamber that can become a "glow plug" initiating cylinder burn ahead of the ignition system. It acts just like over-advanced timing. There is a universal rule that applies to all reciprocating engines that states that peak cylinder pressure needs to occur at somewhere between 10 and 20 degrees after top dead center... most often around 14-15 degrees after. There are slight variations on this rule attributable to internal engine geometry (rod-to-stroke ratios and TDC to BDC dwell ratios), but they are so slight that only the guys looking for the last foot pound of torque spend the money and dyno time to find those tiny advantages. The point is that in nearly all applications engine timing is all about trying to put the peak cylinder pressure as close to 14-15 degrees ATDC as possible. You need the rod and crank to "knee over" so that the pressure is forcing the piston down, not only to ensure the most efficient capture of the energy of the expanding gases, but also to allow the descending piston to cause a rapid pressure decay in the cylinder, accompanied by rapidly falling temperatures (in a closed system, temperature and pressure rise and fall together). If it's your wish to avoid detonation, then pressure decay is your friend. If the timing is over-advanced, then peak pressure

This engine is chock full of classic detonation failures. The number three piston is smoked, the ring is trapped in the groove because the top of the piston is pounded down enough to capture it and the number four piston is missing its skirt because when the rod broke on four it swung through the piston knocking the whole base of the piston off, right down to the wrist pin bore. The pin was in the oil pan.

occurs before TDC, which bucks the piston as it attempts to rise and with that rising pressure comes increased temperatures, and that is what triggers the spontaneous combustion of end gases that we call detonation. It is possible to have pre-ignition without detonation in inefficient combustion chambers, so contrary to popular belief having pre-ignition doesn't automatically mean that detonation will follow. In most cases, yes, but not always.

What contributes to detonation?

Flame front speed and an engine's tendency to detonate are affected by:

- Chamber design (which includes the walls, floor and ceiling of the chamber). Everything should be as smooth as possible. Flat, shallow, and blended chambers are more efficient and they move the rate of burn toward the upper end of the normal scale. If the end gases are exposed to heat and pressure for a shorter period of time they are less likely to detonate. The "walls" and "pockets" of old tub chambers create reaction surfaces that can cause pressure waves to focus or reflect, inadvertently concentrating them into a supersonic pressure wave.
- Quench area is the total area in the chamber where the distance between the flat parts of the cylinder head and the flat parts of the piston top are very close, typically .030 to .050 in. This is a design element that you build into your engine. Quench increases turbulence and shoves mixture around the edge of the bore into the center of the chamber in closer proximity to the plug, reducing flame front travel distance. It also helps with mixing, and a thoroughly stirred mixture is a happy mixture. "Quench" also refers to the

Right: This is the load side (lower bearing) of number three main. This is one unhappy "H" series Clevite racing bearing. It's beaten, blackened, burnt, and abused. The center bearing on the crankshaft often takes the most abuse as the crank "rings" and bounces in the bore during severe detonation. It makes sense when you think about it -- maximum flex or deflection occurs in the middle of any span.

cooling effect that relatively cooler engine parts have on a hot flame front, often extinguishing it altogether.

- Fuel types and distillation rates are important, as is uniformity of the racing fuel you use. Uncle Bob's Racin' Gas won't have the same quality or repeatability of something like VP. It needs to be the same octane and it needs to evaporate at the same rate from batch to batch. Fuel consistency is key to tuning.

- Air-fuel homogenization is affected by a number of other characteristics in this list, but the goal is to keep light ends, heavy ends, high-octane and low-octane components thoroughly mixed so the mixture reacts predictably. Highly homogenous mixtures act like higher octane fuels than what their test octane numbers indicate.
- Uniformity of cylinder fill, which is dependent on uniform intake and exhaust design, affects fill consistency from hole to hole. You're only as good as your worst hole because you end up tuning to it.
- The quality of the igniting spark and the size of the flame kernel formed. The larger the flame kernel the faster the flame front forms, stabilizes, and moves through the unreacted mass. Included in this is spark plug gap and total ignition energy delivered to the cylinder.
- Ignition timing and advance curve. The timing curve should result in peak pres-

I snapped this one on my iPhone after locating all the pieces in the pan. The rod bolts did not fail, as you can see. One is still in place holding onto what little bit of the rod is left and the other is in one piece holding onto what's left of the dowel insert and threads of the other side. The rod has that classic banana curve that tells you that it was seized on the crankpin and then bent left, right, left as the crank rotated until it finally snapped. It's blackened from the heat it generated as it work hardened during the bending process and from the heat from the failing rod bearing. You've got to give ARP its due – the company builds one hell of a tough rod bolt!

sure at 14-15 degrees ATDC to take advantage of internal engine geometry and the pressure decay caused by the piston receding. Over-advanced timing will lead to detonation, overheating, engine damage, and power loss; retarded timing will lead to power loss and potentially increased water jacket and exhaust temperatures.

- Turbulence in the chamber. Turbulence is our friend because it takes the entire surface of the flame front and wrinkles it like a wadded-up piece of paper, increasing surface area and exposing more unreacted air and fuel to the flame front. It is helpful to remember that the flame front is three-dimensional, so combustion occurs 360 degrees around the flame kernel. Turbulence also helps keep the mixture more uniform. Because gasoline is chemical soup, it must be kept stirred to prevent high and low octane components from separating or stratifying. There is research that suggests that the effective octane increases with violent and thorough mixing.

Noticed the heat-blackened back of number three main bearing lower insert. This bearing did not spin. As you can see, it measures 1.0260 across the center of the bearing . . .

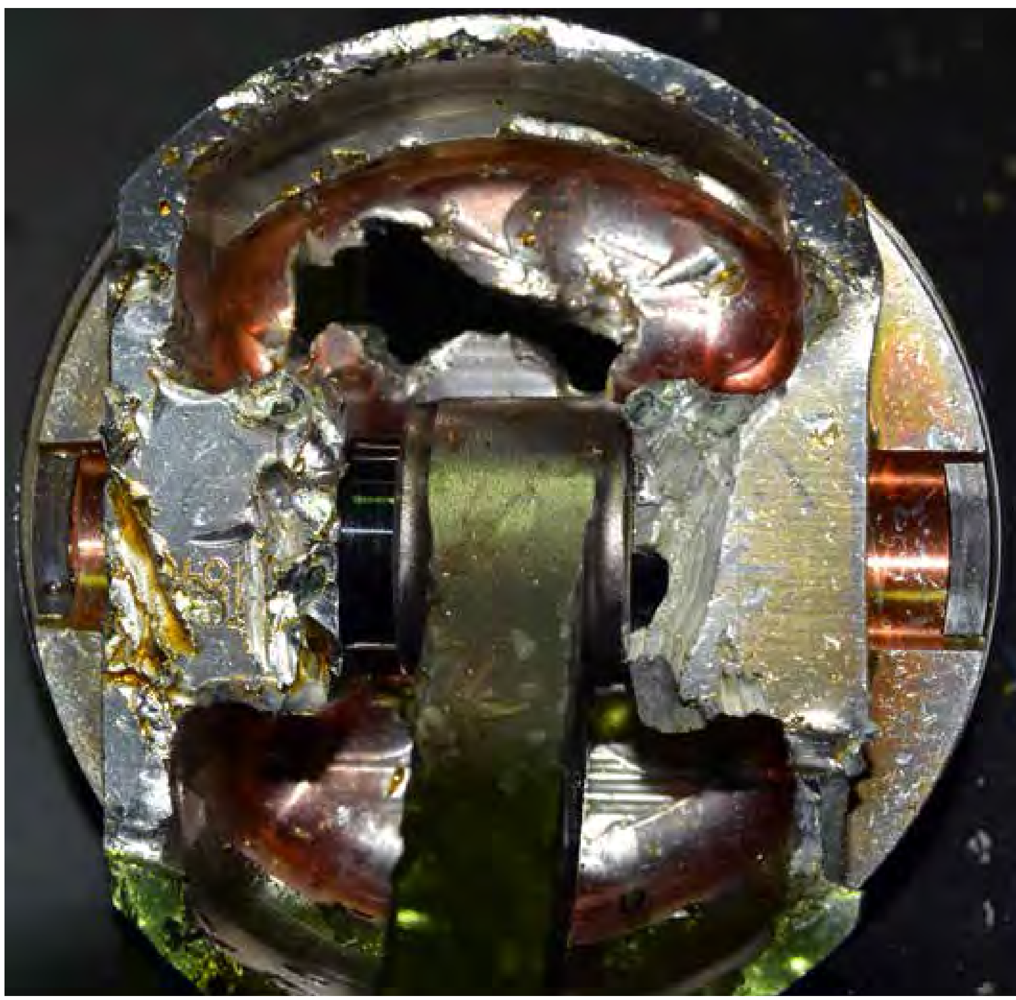
. . . while on the end of the bearing where no load occurred it measures 1.0025 of an inch. The bearing has been pounded out 23 and a half thousandths by the crankshaft as it transmitted the force of detonation into the crank.

- Engine speeds. As engine rpm increases, timing advance requirements go down because the high velocity of the mass of incoming air and fuel creates additional turbulence as it slams into the limited confines of the cylinder, and as we now know turbulence increases the rate of combustion.
- Mixture ratios. If you have to err, err slightly rich. The increased evaporative cooling will help control cylinder temperatures and a rich mixture is less prone to detonation. Lean mixtures burn slower because it takes more time for the flame to "jump" from molecule to molecule if the distance between them is greater. The result is longer burn times that expose the end gases to temperature and pressure for longer periods. Cylinder walls, heads, and valves (notably the exhaust valve) are also exposed to higher temperatures longer, leading to chamber temperature increases that precede pre-ignition, which can then lead to detonation.
- Spark plug location. The more central the location in the chamber, the less distance the flame front must cover to consume the contents of the cylinder. Again, faster burn means less time that the unreacted components are exposed to temperature and pressure.
- Compression ratios. Static and dynamic compression ratios have to be reasonable for the application. Allow for boost and intake valve timing when calculating dynamic compression and effective compression ratios.

While number three main was being hammered into oblivion, the shrapnel from the main was being fed directly into number four rod bearing. This is officially called "not good" or "catastrophic failure."

This will give you some idea of how severe a beating this bearing got before it gave up. I can stick the tip of my pocket screwdriver into the space between the main cap and the bearing.

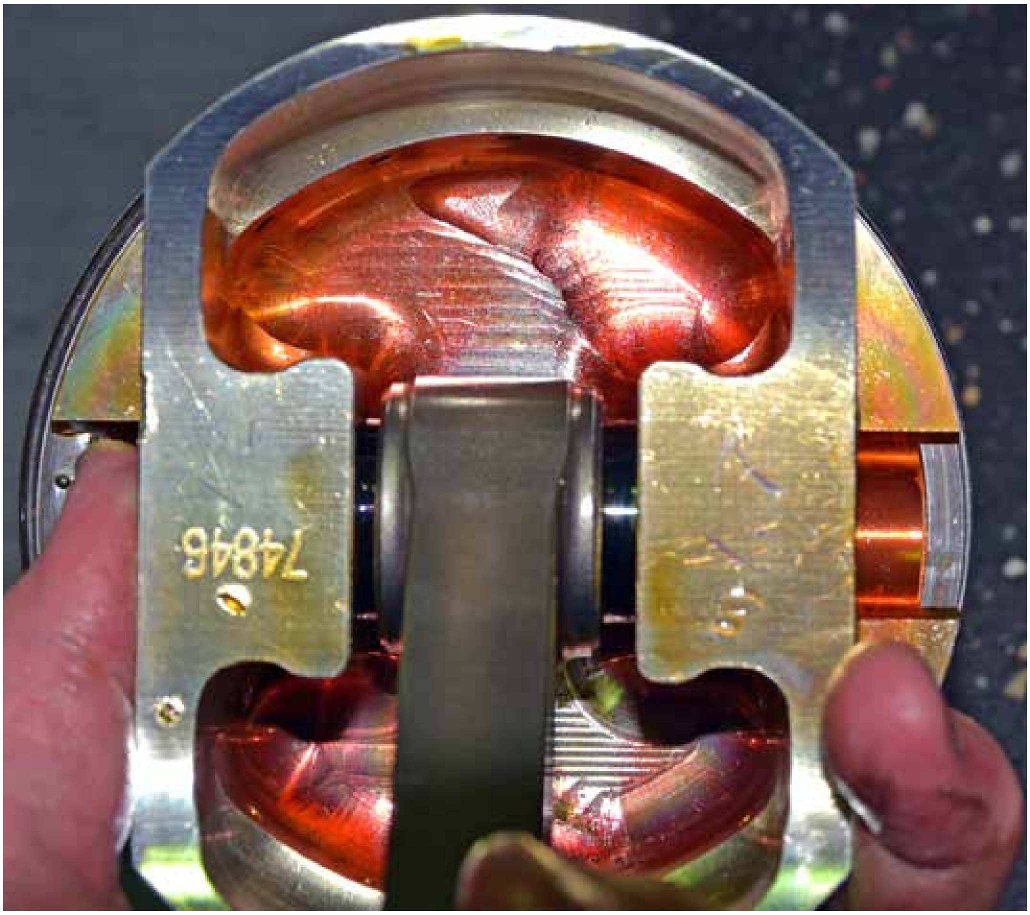
- Engine load. The higher the engine load the greater the tendency to detonation. If the application is high-load, then compression, timing and fuel selection become more critical.
- Engine operating temperatures and temperature gradients across the assembly. The cooling system has to be right-sized and inlet air must be kept as cool as possible. In some cases it's hard to right size the cooling system and stay inside chassis limitations. If that's the case, you need to account for it before your build starts. Hot is not good when it comes to detonation control. Detonation is particularly prone to initiating around the exhaust valve and valve pocket since that's the hottest spot in the combustion chamber, and engine cooling, timing, and fuel mixture control are very important in exhaust temperature control.



Poor old number three was just bobbing along happily until his neighbor gave up. Of course, he wasn't really contributing to the family anymore since he's got a gaping hole in his piston. Still, nothing like the remnants of an unattached connecting rod wheeling around your living room at 8,000 rpm to put the finishing touches on a pretty rough day. Notice the color of the bottom of the piston? That's an important clue to the point of origin for this five-alarm screw up -- I'm amazed that it wasn't worse. The cam was bent so badly we couldn't get it out of the block but the pan didn't get perforated. It looks like a madman went to work on the inside of it with a ball peen but it was still holding oil when it arrived.

Left: Here you can plainly see the sandblasted appearance of the piston top just to the left of the hole. It seems to defy reason that a boundary layer a few molecules thick can protect the piston, and certainly thermal inertia plays a part as well, but this picture tells the tale. Once the boundary layer is pushed aside by the shock waves, it's an 1,800 degree flame versus a material with a thousand degree melting point. No question about who won that round.

The clue to the source of all this trouble lies in the discoloration of all eight of the pistons. This was a heat-related problem originating with the cooling system or the tune up that was applied. The cooling system was improperly filled and bled, there was a fuel system supply problem (regulator, jetting, or fuel quality), or the base timing/programmed timing was way off the mark. We aren't certain because we didn't get to do the engine installation and start up on this one.



- Ambient air temperatures and humidity. High air temperatures and low humidity encourage detonation; low air temperatures and high humidity lessen the possibility.

What does it do to your engine?

The pictures accompanying this article tell it better than I can with words. It's more than just the hammering pressure spikes that physically break things. Once detonation sets up, the boundary layer (a thin layer of relative quiet cool gases just a few molecules thick that normally protects the head and piston) gets blown aside by the force of the coalescing shock waves preceding the supersonic flame front, and the aluminum parts, with a melting point of something near 1,000 deg. F. (depending on the alloy) are exposed to an 1,800 deg. F. flame front (typical for a high-output gasoline engine). The result of a material with a thousand degree melting point being exposed to 1800 degrees is pretty predictable -- it melts. Melted parts are often attributed to pre-ignition, but detonation causes them as well. Detonating engines tend to run hot in part because if the boundary layer is interrupted, heat transfer into the head and block increases. This explains why, once started, detonation continues and gets progressively worse as heat builds in the materials surrounding the chamber.

Detonation marks it territory in any number of ways. The shock and heat cause everything from a four-corner scuff on the piston to melted parts. Look for deformed or cracked valves, a sandblasted appearance on the piston top, broken rings and lands, stuck rings captured in the groove, melted piston tops or pistons that have been torched down the side, bearings that have lost spread or increased in width in the

I'm not certain why the camera shows the color shift that it does, but it's not as apparent in person as it is in this photo. In the photo, you can clearly see the detonation as it tracked across the piston surface. The piston top feels dry and coarse to the touch, and under magnification you can see how pocked and scarred the aluminum is.

center portion of the bearing, and failed head gaskets. If your car is equipped with exhaust gas temperature sensors, you can expect to see EGTs drop with detonation (which might be counterintuitive, but it's because the heat is being retained in the engine hard parts.)

Avoiding it

It starts with design. Today's cylinder heads incorporate low, flat combustion chambers with no "walls" for pressure waves to react off of. Heart shaped, very shallow combustion chambers allow for sufficient compression with flat top pistons, which in turn creates a large quench band in the chamber at TDC. All of this creates a very efficient, fast burn chamber that takes very little total ignition timing, which in turn limits the amount of time that the end gases are exposed to high temperatures and pressures.

Design also includes building your project with the right compression ratio. Builders sometimes go for more compression than needed and correct for it by richening mixtures or backing off ignition timing, but band-aiding a bad design may actually cost you more torque than simply lowering static compression during the design phase.

Cooling system design, cold air inlet systems, properly designed and jetted fuel delivery systems, the correct selection of your fuel and your tune up are all critical elements in avoiding detonation. Good technique in filling and bleeding your cooling system, indexing your plugs, setting plug gaps correctly, and building your engine with excellent oil control into the cylinders are equally important (the octane rating for engine oil is pretty low!) if you hope to avoid the destructive devil of detonation. ■