November/December 2015 | V2 N5

PERFORMANCE TECHNICIAN

AIR/FUEL MIXTURE
ART OR SCIENCE?

PISTON RINGS, III

CAMSHAFTS, I

Vehicle Power & Performance Knowledge for Professionals

RAE
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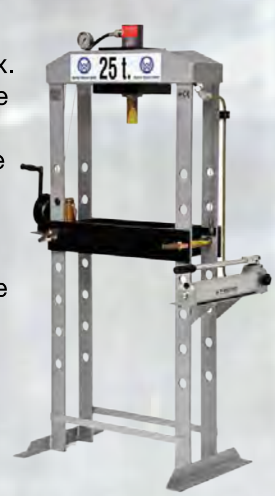

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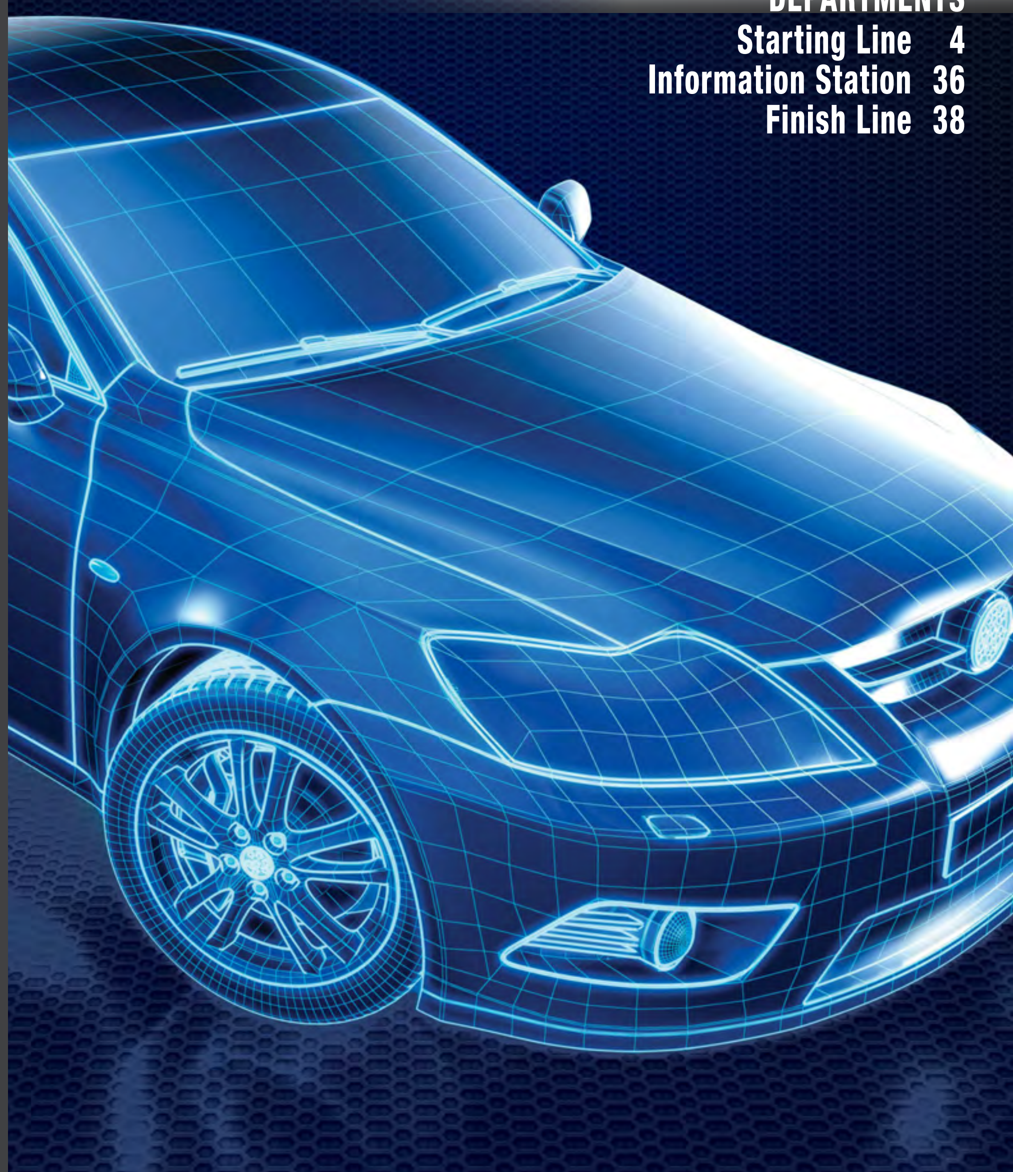
FEATURES

DEPARTMENTS



STARTING LINE

-Bob Freudenberger

MUD

As the editor of *Performance Technician*, I probably shouldn't say this, but I'm pretty tired of most forms of racing. Sure, I'd still like to do some drag racing if I ever had the time, but you couldn't pay me enough to sit through a NASCAR event (I had a big disillusionment about that organization years ago, which I'll write about some time), or pretty much any other motor competition, for that matter.

Don't get me wrong. I love the technology involved and the skill it takes to build high-performance cars and engines, but I've mostly worn out my excitment and enthusiasm for formal racing. Too much stress and seriousness, too much money, too little fun. I'd much rather spend my time building an engine than sitting passively watching other people drive.

So, it was refreshing and envigorating to experience something completely different (as Monty Python would say): a north Florida mud bog at "Hog Waller" outside of Palatka. While not the most incredible example of this type of racing, which honor I believe is reserved for the mud pits in Georgia, it was, well, a hoot.

You might be tired of my mentioning my grandsons, ages two and three, but my wife and I took them along since they love anything that looks like a truck. Little did we know how spattered with mud they'd be, but no harm done.

We positioned ourselves at a 90-degree turn, and we were well above the action in the pit, perfectly safe. Long about the second or third run in the unlimited class (the prize was $10K, which is an amount not to be sneezed at) a ...vehicle (not a truck, but a tubular steel frame with actual farm tractor tires and what I can only describe as a drag motor — the kind of engine our exec tech editor, Greg McConiga, might build) got "on its lid" directly in front of us. Right place at the right time department: I got it all on video. One of the big Cat front-end loaders that was standing by got the unfortunate vehicle out of there in just a few minutes, so the action wasn't noticeably abated.

Over the course of that afternoon, probably half-a-dozen competitors with their necessarily high centers-of-gravity went upside-down, but I don't think there were any injuries, even as far as a broken fingernail. Of course, they're not going

all that fast by racing standards, but helmets, five-point belts, and roll cages really did their job.

The mud flies, though. We got spattered when the vehicle just mentioned went over, and next to us was a family with two teenage kids who were thourougly "mudded." There are miles and miles of trails at the track where they'd run their four-wheelers before the formal racing began, and they'd availed themselves of them with vigor. Cute kids, and respectful.

Speaking of four-wheelers, the mile-high pickups with their seriously-modified V8s, open headers, and earth-mover tires were the rock stars, but the little conveyances propelled by relatively-quiet motorcycle engines were ubiquitous, swarming everywhere piloted by everybody from spry, outdoorsy great-grandmothers to mechanically-savvy children. It looked like a recipe for mass vehicular carnage to me, but I saw no incidents or even any awkward encounters. It was all so polite — "You go first" — with none of the "me, me, me, I'm important" kind of attitude I'd seen at racetracks. As I said, refreshing.

Without knowing that I was reporting for *Performance Technician*, the owner of a nationally-known monster truck swept up our little guys and planted them in the seats of the incredible machine, which moment will probably live in the boys' memories as a high point, figuratively and literally.

Some of our readers might be thinking that this kind of venue would be populated by backwoods yahoos who swill beer and pick drunken fights, but I'm here to tell you it was nothing of the kind. It was family-oriented, which I appreciate when I have the grandsons in tow, and entirely non-threatening all around. Laid back, as they say.

While there's no chance that I'll have the money, the room, or the time to build a monster truck myself, I am thinking of acquiring a 4WD four-wheeler that needs some work — after dealing with electronic engine management and high-tech engines stuffed into crowded chassis, how hard could those repairs be? — tearing around the trails just mentioned and fording the ponds and streams to bring back some of the fun I used to have racing dirt bikes in woods and sand pits.

One thing I can say for sure: It's going to take a generation or two before this kind of enjoyable activity goes electric. ■

LORD OF THE CIRCULAR CYLINDER SEALS
PISTON RINGS PART 3

-Greg McConiga

This final installment of our tech editor's ring trilogy gets deeply into the subtleties of preparation and installation. Talk about hands-on!

It may seem mundane, but preparation begins with a physical count. There's nothing worse than getting ready to prep eight rings and find you've only got seven — or, say, a side rail is missing. After thoroughly cleaning the pistons we verify the piston and ring combination fitment.

Ring sizes, widths, side clearance and back clearances are checked. Side clearance can be measured with a feeler gauge or with gauge pins. If you're mounting new rings on old pistons during an off-season freshening-up, make sure you monitor the ring groove wear. Grooves tend to open up nearest the bore wall over time, forming a "V" from root to mouth. Back clearance is checked by sticking the ring into the groove backward and rolling it around the circumference of the piston. Oil drain holes behind the oil control ring, oil feed holes into the pin area are checked, and the pistons are marked for skirt-to-bore measurement. Your pistons will come with a card that indicates where on the skirt to measure and it's important to follow that precisely since piston shapes are irregular due to cam and barrel variation.

BORE CLEANING

If I'm working with a fresh block and I've confirmed that all my bores are within a couple of tenths, I work out of one bore for fit checking. Block prep comes first after machining. I use Dawn dish detergent because it lifts grease and oil so well, and I use hot water and an oversized bore brush that I mount in a drill motor that I drive one direction and then the other, stroking it in and out of the bores for several minutes each. I also presoak a couple of low-lint paper shop towels (available through Cleveland Cotton Products) in WD-40 before starting so that I can wipe right through the water and protect the bore from rust. I don't know why, but a "green" bore will flash

If you are using an oil control ring support rail, it must be installed correctly. The dimple is there to keep the support rail from rotating and the convex side of the dimple faces down to catch the edges of the cutaway where the pin passes through.

rust in a heartbeat, so I don't even start blowing it dry, I just wipe through the water and apply the WD-40 to keep the rust from coming up. After block cleaning, I apply WD-40 or Marvel Mystery oil to the gallery brushes and run the galleries to make sure there's no place for rust to start, and I wipe the bores with MMO or WD-40 until they all wipe perfectly clean on a white, low-lint paper towel.

FITMENT

The first ring check I perform is the expander fit. On a racing application with a dry sump or vacuum pump using low or very low-tension oil control rings, I want the expander to lay in the bore with some space between its ends.

The side rails can all be checked at once by stacking them in one bore. Normally, you'll see oil side rail gaps at something between .015 and .030 in., and they will be consistent from batch to batch. I've almost never had to grind one. The top and second rings I purchase are always file-to-fit, and I generally run toward the tight side of the recommended gap range unless it's a nitrous application.

You must take a great deal of time and care when filing thin rings and rails. Move the ring on the table as close to the grinding wheel as possible, take very little material off at a time and support the ring if need be by using an old standard tension top ring as a support piece under the low-tension ring you're filing. Make sure to go slowly to control the heat generated by the grinding wheel — you do not want to change ring hardness. Don't force the ring into the wheel too quickly because you can bend a thin ring if you get in a hurry. Just figure that you're going to be grinding rings for at least half a day and maybe even a full day, depending on the application and how thin the rings are.

After you file each ring, lightly deburr the sharp corners using a fine diamond file. Do not create a "funnel" at the ring ends, either one that faces in toward the piston or out toward the bore wall. Deburring uses a light touch and you're only just lightly cleaning the ring ends. They should be smooth and square to each other and when test fit in the bore the ring should be light tight all around the circumference.

DEBURR AND POLISH

When installed on the piston, the rings should freely slip around the groove without sticking. If the rings are not coated or Diamond finished on the sides, I'll lightly wet sand them with a ring holding fixture on a granite block or piece of plate glass with 2000 grit just to make them slick and smooth on the sides, followed by a good cleaning and a light oiling with WD-40 until installation. Take your time if you're installing gapless rings as the side rails vary in axial width from as little as .010 in. depending on the ring set, and they can easily be overheated or bent during grinding. Record your end gaps, side clearances, back clearances and piston groove dimensions as well. You'll need that to modify your next build — possibly reducing end gaps for example — or to monitor parts wear from season to season so you can anticipate when you need to order replacement pistons.

PUT 'EM ON

Once the rings are all file-fit, deburred, cleaned, and oiled, it's time to start prepping the pistons for installation. I start by using a short-bristled paint brush to paint a medium coating of Total Seal's AL-8 assembly lube into the grooves before I begin mounting my finished rings, and I treat the block with Total Seal's Quik-Seat dry cylinder wall lubricant.

Racing rings, unlike some street sets, do not have a couple of chunks of brightly colored plastic blocking the expander ends to keep you from overlapping them. I guess they're assuming we're smart enough to figure out how to avoid that. You'll find that a fair number of racing pistons with reduced compression height (the distance from the piston pin centerline to the head of the piston) will have so little space between the piston head and pin that the oil control ring groove runs through the pin bore. There are a couple of ways this has been handled; in the past, they used an "L"-shaped button stuck in against the pin to form the missing part of the oil control ring groove, but nowadays we just use a steel oil support rail.

The rail has a dimple that faces down and is positioned in the gap left by the pin boring operation and the oil control ring rests on the support rail. The rail is pretty stiff, so get a good hold on it during installation to avoid scratching the side of the piston up as you put it on. When installing the oil control expander I position the ends opposite the gap formed by the support rail, put my thumb over the ends to prevent overlap, then wind the side rails to space the three gaps 120 degrees apart.

If you are someone who likes to check the oil control tension by using a fish scale to drag-test it through the bore, here's the correct procedure: Install the piston upside down in a dry bore with just the oil ring installed and pull the piston through the bore with the bore parallel to the floor and record the pounds of pull needed to sustain motion once motion begins, NOT the breakaway pounds reading. I don't generally check my rings like this. I just record turning torque with all eight pistons installed for each of my builds.

The second ring goes on next, usually a Napier, and if it's .043 in. or less I can usually just install it by hand, spreading it with my thumbs. Use a ring expander if you lack the hand strength to do that. The top ring follows and I orient the top and bottom gaps 180 degrees apart if I'm running conventional rings. If you're using a gapless ring, the thin rail always goes down so the main ring can protect it.

Normally, rings are marked with a dot or pip or the word "top" on the ring, but in those rare cases where there are no marks just remember that the inside chamfer of the top ring faces up and the inside chamfer of the second ring faces down 99.99 percent of the time, and the top ring will be the one with a chrome face or moly filling around the outer circumference. Your best option is to lay the rings out on the packaging they came in so you don't mix them up.

PUT 'EM IN

Installation into the bores is accomplished with rod guides and a size-specific tapered bore ring compressor. I like the ones from ARP or Total Seal best as they seem to have the most gradual taper and installation goes more smoothly with them than with some of the others I've tried. If you're using a gapless ring, you only need to make sure that the rail is "clicked" into the "L" ring groove, then center the ring as you insert it into the compressor. Before installing, I paint the skirts with AL-8 assembly lube, install the lubricated upper half of the rod bearing, press the piston home, install the bottom bearing half and rod cap, and roll the engine over to prepare to fill the next bore.

TEARDOWN INSPECTION

Teardown is just as important as assembly because as you relax rod bolts you can check stretch and you can look at the oiled parts, bearings, head gaskets, springs, valve adjustments, and rings to see how everything did that season. Look, if you've got a lot of blowby — if you're pushing oil out of the oil tank or the breathers — that's a pretty good sign that your rings aren't getting the job done. Oil consumption and pistons that show a clean edge all around the circumference where the oil wash has cleaned up the piston head are tell-tale signs of a potential ring or bore problem.

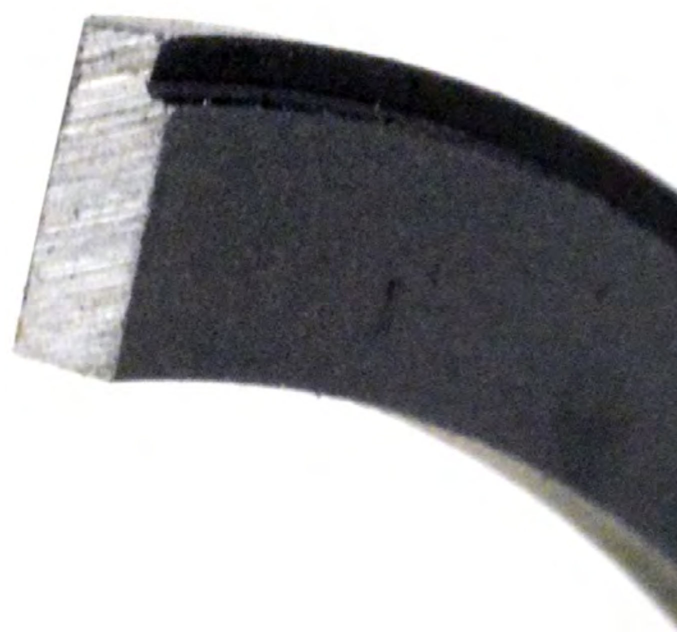
You should also look at each piston between the top and second ring. If there's no combustion color between the rings, guess what? Your compression ring is doing the job. While we call the second ring a compression ring, it's really just there for oil control. The oil ring handles the gross oil control, the second ring takes care of fine oil control, and the top ring contains combustion pressure. If you're relying on the second ring for combustion control, you're in trouble. Make sure you check the ring ends for signs of butting and adjust your end gaps accordingly. If butting was a problem and it was too severe, you'd already have had the engine apart to fix it, but if you see it just shining the ends you might want to add a couple of thousandths to the gap.

Part of racing usually includes producing more power or building an engine with better reliability. Ring seating and sealing is an important part of the formula. Extracting more power during the expansion or power stroke, and increasing the efficiency of the intake and exhaust strokes can both affect the efficiency and tune of the engine. Attention to detail during ring preparation makes all of that possible. ■

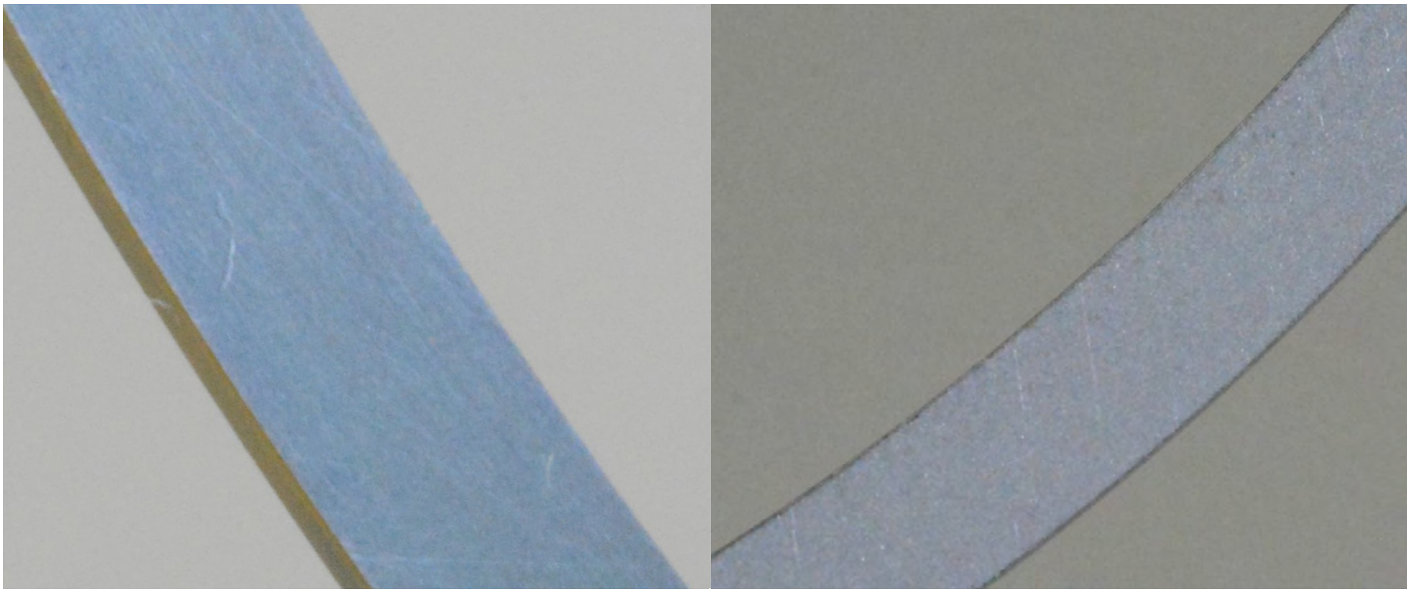
I'd like to thank Keith Jones of Total Seal Piston Rings for spending quite a bit of his time walking me through some of the newer technology and correcting a few of my bad habits. His contribution cannot be overstated.

These pistons came out of engines during an end-of-season teardown. You can see the minimum contact grooves, also sometimes called anti-detonation grooves because in theory they shield the top ring from the destructive forces of the supersonic shock wave generated by detonation by disrupting wave propagation. You can also see the groove in the land between the top and second ring that's called an accumulator groove. It's supposed to provide a little extra volume for the gases that get past the compression ring to vent into so the pressure doesn't equalize across the ring and cause flutter — looks like it wasn't needed. What you really are looking at is a top ring that worked really well because there is nearly no color present below the top compression ring. There is a lot of chatter about pressure or vacuum present around the rings and about how rings flutter or unseat during operation. While this might be the case in some applications, it's clearly not the case here. If this ring unseated, it would have left the piston marked with carbon below the top ring.

Pictured is the AL-8 assembly lube used in the ring grooves to prevent microwelding, and on the skirt, and the Quik Seat product for the bore.

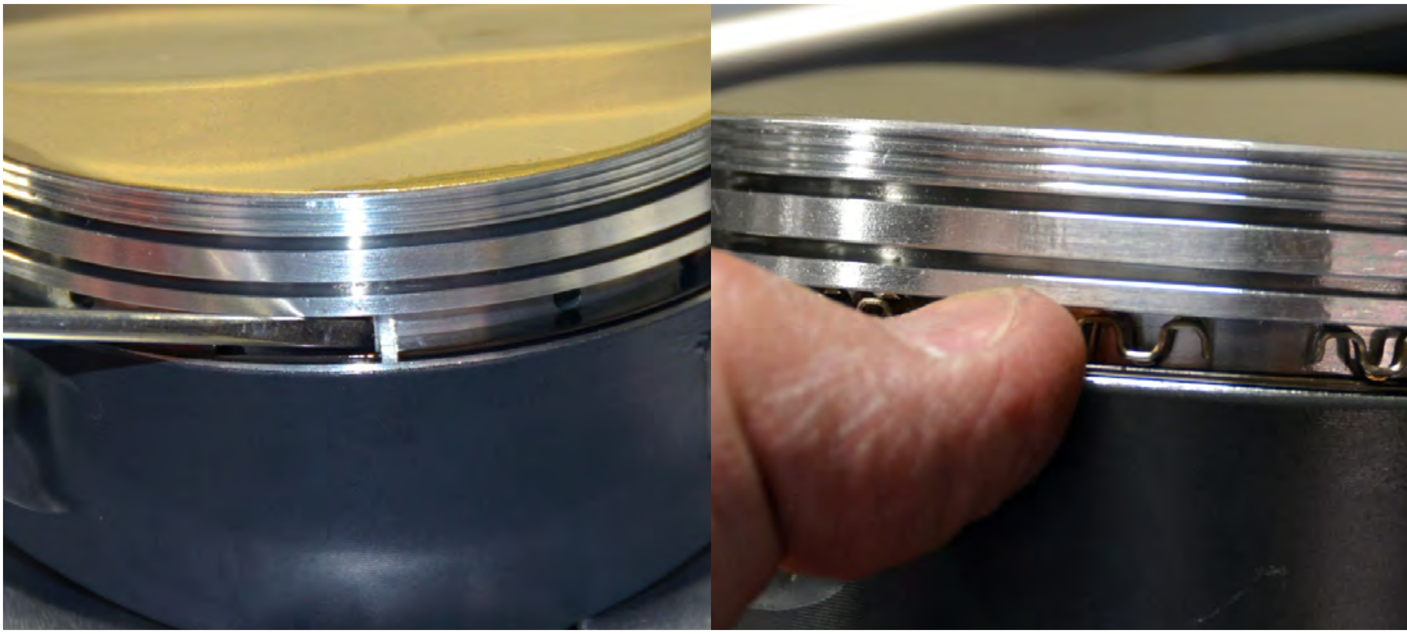


The freshly-filed end of this ring is dressed and ready for cleanup. The Napier profile is clearly visible. The hooked end of the Napier engages the cylinder wall and is used for oil control. While it might be called a second compression ring, that's a misnomer — it's really there for fine oil control.



You can clearly see the differences between Total Seal's Diamond finished ring and the C33 steel top ring. The Diamond finished ring is very highly polished and the C33 still displays a bit of roughness and some tooling marks. The friction-reducing face coating is seen as a thin gold-colored layer on the ring face. If you're running anything other than these highly-polished rings, a little wet sanding work with 2000 grit and a piece of place glass will dramatically improve how the ring feels in the groove. You won't have to touch a Diamond finished ring — you paid them to do the hard work.

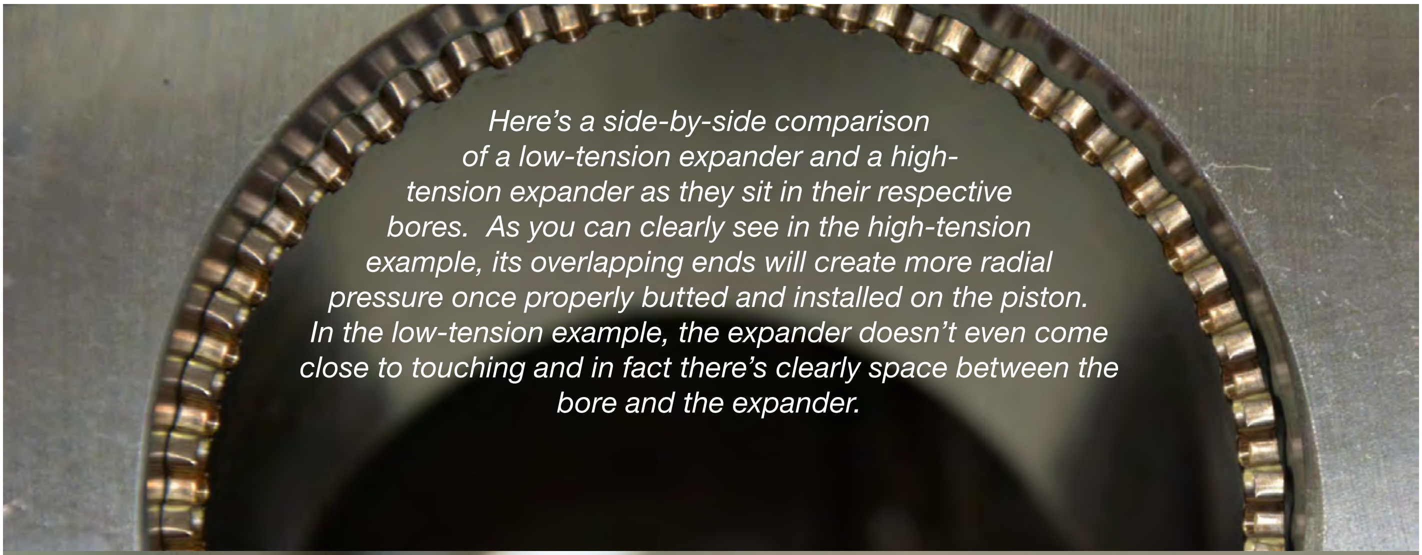
Here's a .9 mm Napier second ring. It measures .0352 in. and appears considerable smaller and more delicate that the previously-shown .043 in. Napier. Grinding smaller rings is a challenge. You have to minimize the amount of the ring overhanging the table on the ring grinder and in some cases you might use a piece of an old .043 in or 1/16th ring as a support to keep the end of the ring from dancing against the grinding wheel or getting caught and bent down over the edge of the table.



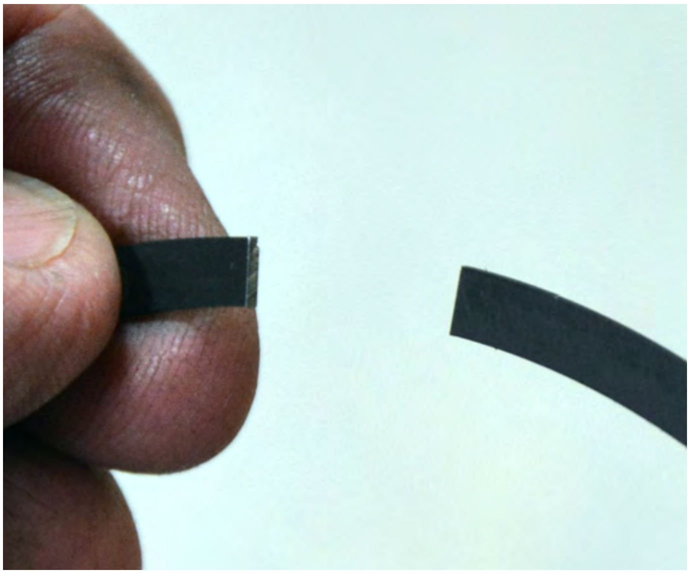
Once installed, the support rail gap will end up over one of the skirt faces. Install the expander opening on the other skirt 180 degrees from the support rail gap.

For all uncoated or Diamond finished top and second rings, I normally spend a little time wet sanding with 2000 paper, a glass or granite plate, and a ring fixture. This is just a few quick strokes to knock down any burrs around the gap and to smooth up the ring faces just a bit. It makes quite a difference in how the ring feels in the groove as you rotate it.

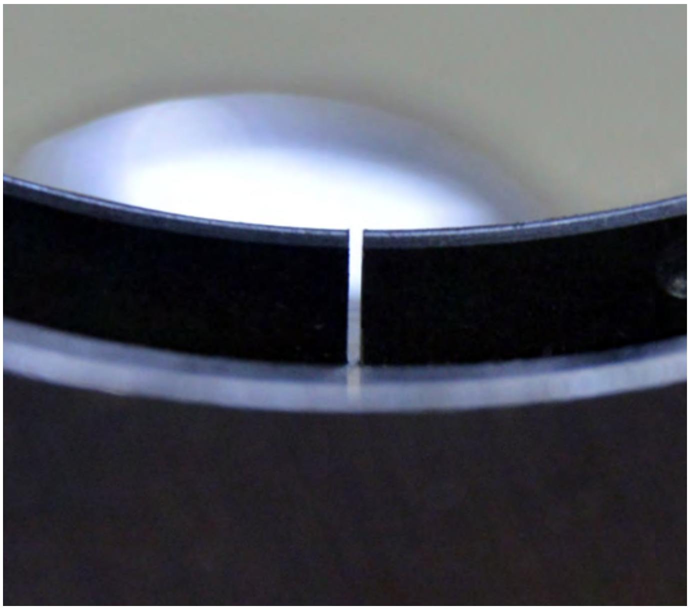
The best and easiest way to check the oil control ring end gaps is to stack them all up with the gaps aligned, and measure them all together. Side rail gaps are normally about .015 to .030 in. They are remarkably consistent from batch to batch, so getting a good reading on them by doing this is pretty easy. Trying to do them one a time is like threading a noodle through a needle — they just twist and flop around all over the place.



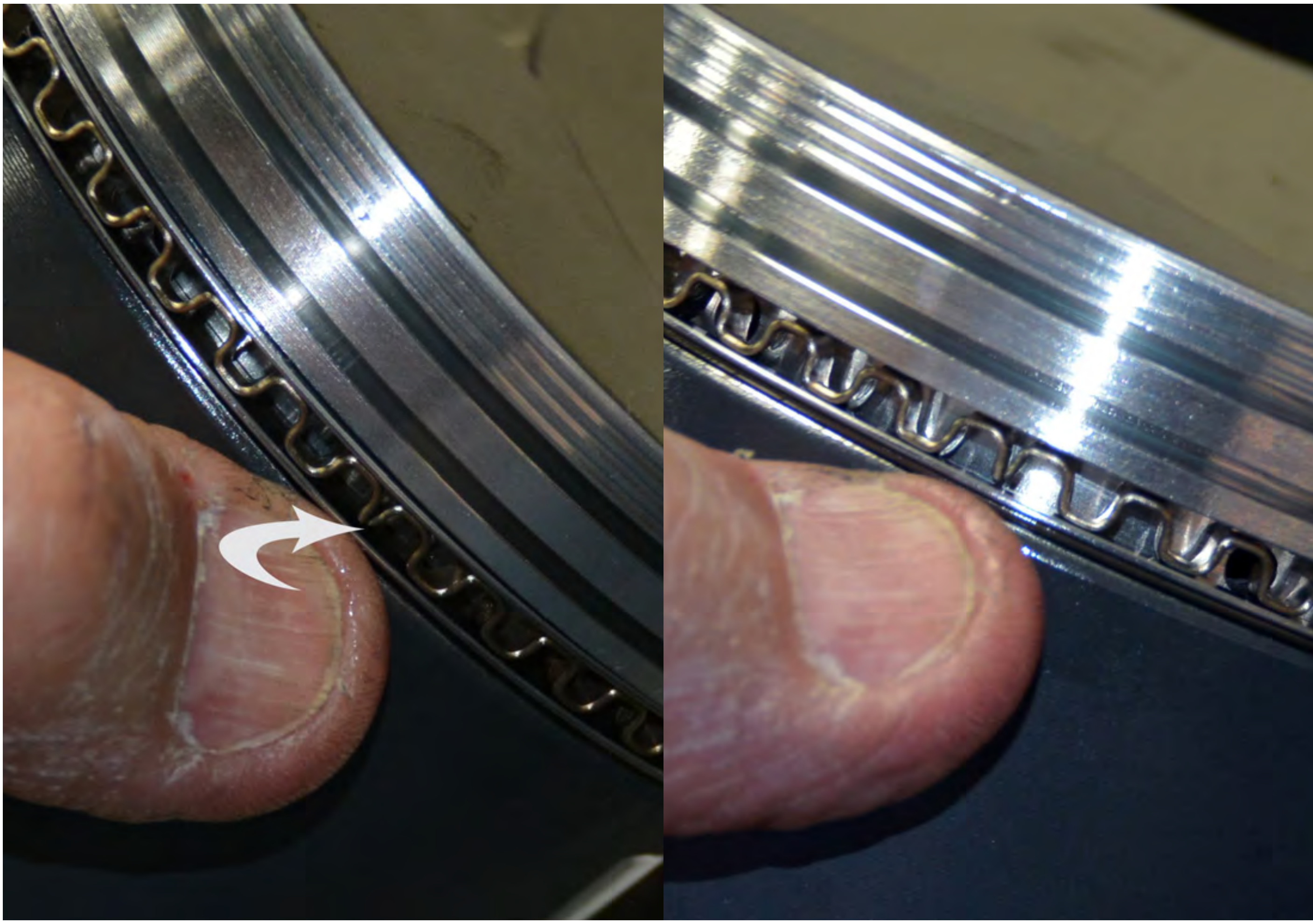
Here's a side-by-side comparison of a low-tension expander and a high-tension expander as they sit in their respective bores. As you can clearly see in the high-tension example, its overlapping ends will create more radial pressure once properly butted and installed on the piston. In the low-tension example, the expander doesn't even come close to touching and in fact there's clearly space between the bore and the expander.



Once the end gap is ground and checked, use a fine diamond file to carefully deburr the freshly-ground end. You only want to remove the burrs and sharp edges. You do not want to change the profile of the end of the ring, or put the ends of the rings out of parallel.



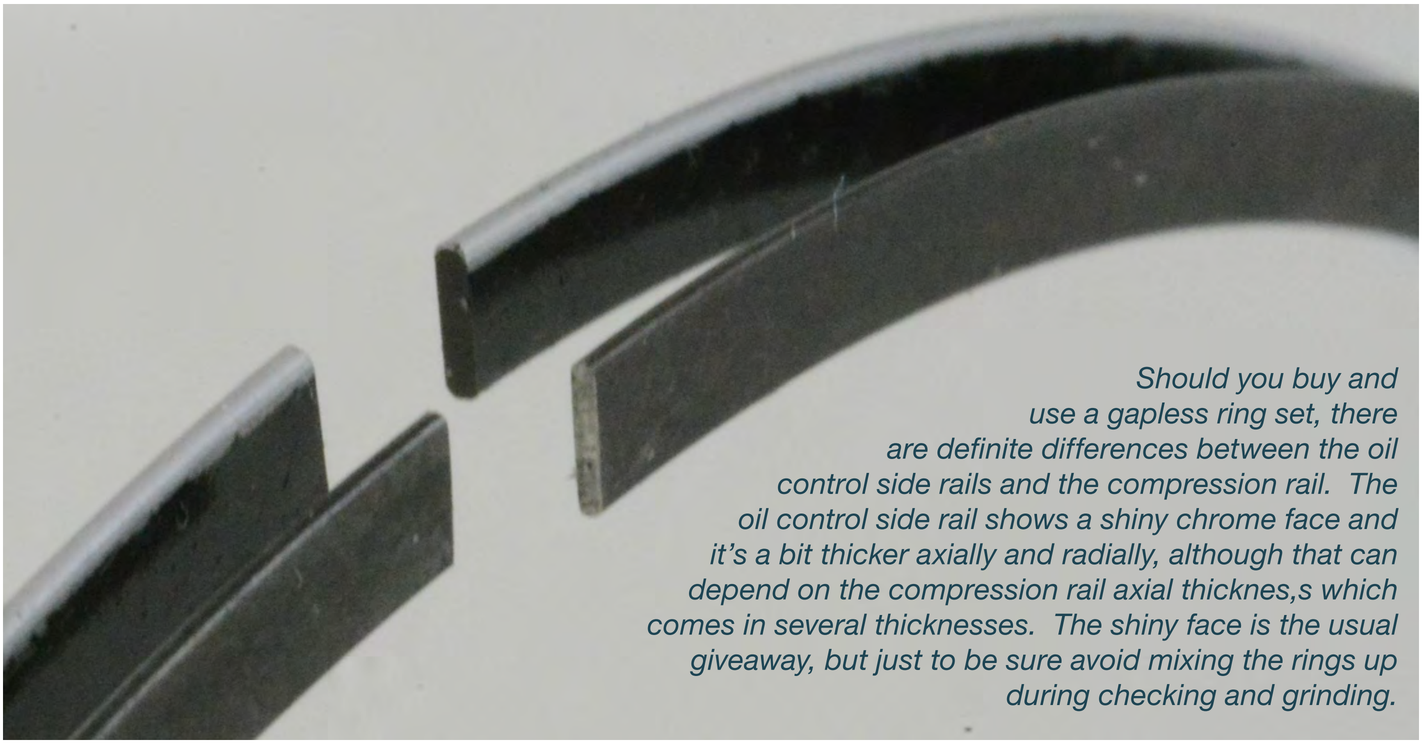
The ends of the piston ring must be parallel and the ring must be light-tight in the bore around the entire circumference. After grinding, just lightly deburr the ring ends to remove any sharp edges left from the grinding process.



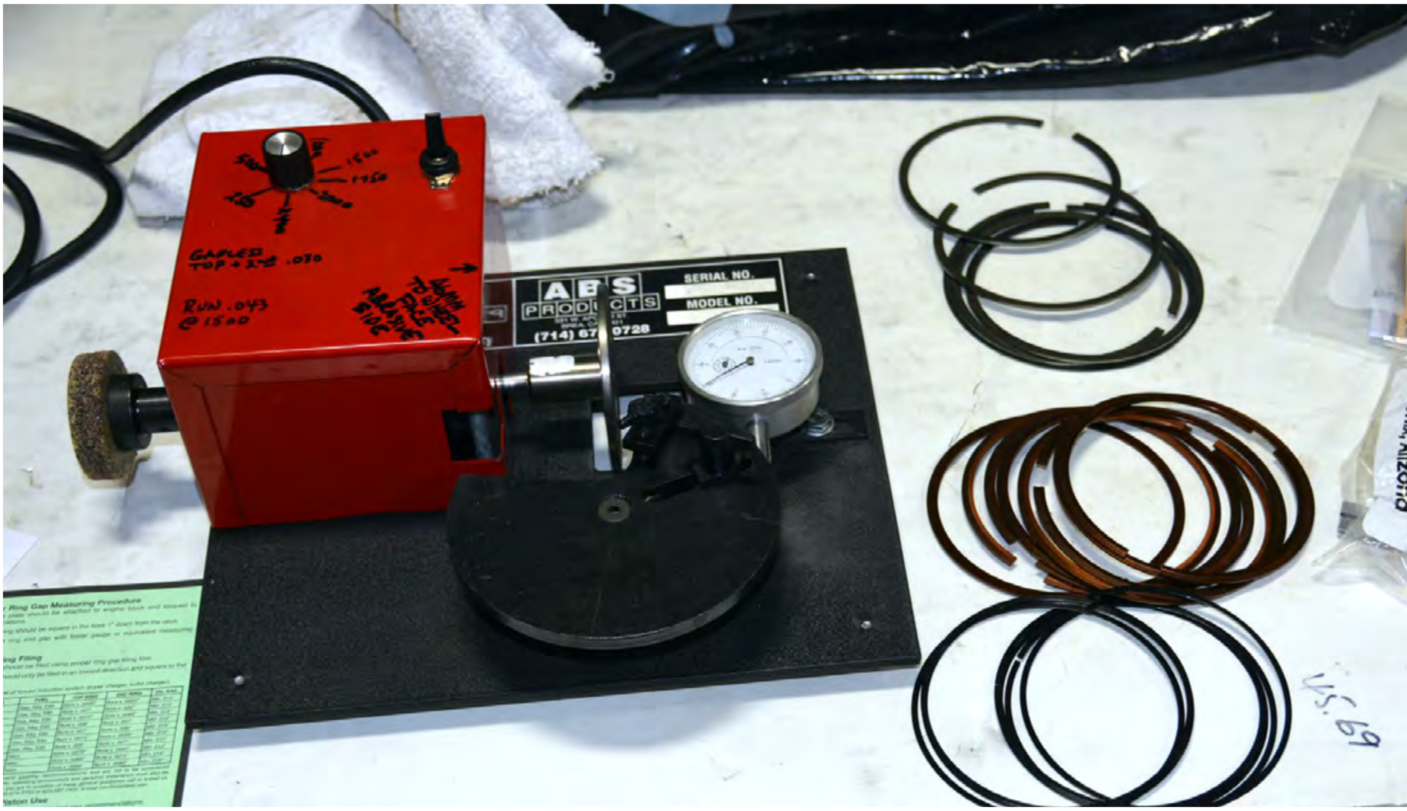
Always, always, always confirm that the expander ends are butted against each other after the side rails are installed. You'd think lapping the ends would be next to impossible to do, but never underestimate folks. You'd be surprised at what determination can get you...

The oil control ring expander is what sets ring tension. The side rails are just along for the ride. The corrugated segments collapse slightly as the ring is pushed into the bore and the total radial tension is set by how much or how little overlap the expander had in the bore prior to installation.

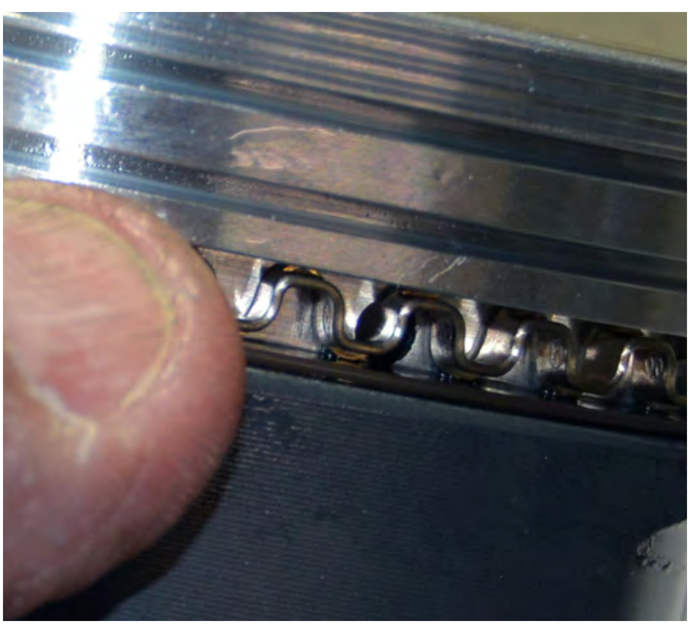
When you call to order rings and you ask for "standard-tension 2 mm oil control rings," understand that that means low tension. The axial width of the ring determines the tension, which is why as rings get thinner they get lower in tension. While an old 3/16th oil control ring might run 22-28 pounds, a 3 mm oil control ring might be down around 10-13 pounds and a 2 mm ring could be around 6-8 pounds. Therefore, asking for a standard-tension 2 mm oil control ring means that you're going to get a very low tension oil control ring BECAUSE it's only 2 mm thick. That's how it works.



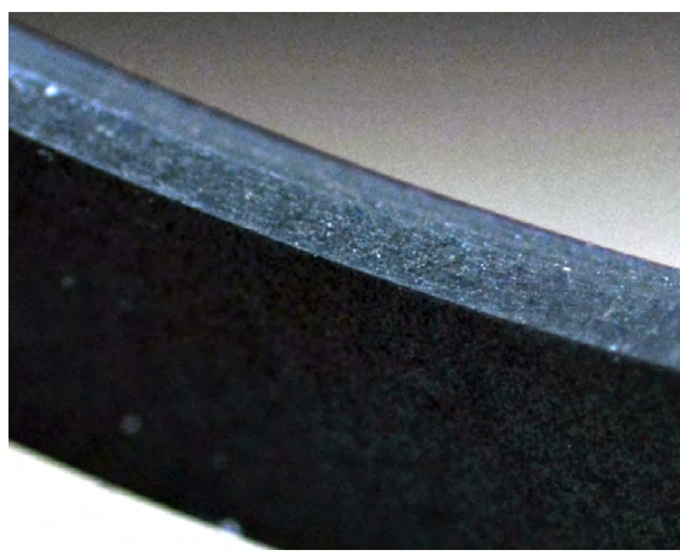
Should you buy and use a gapless ring set, there are definite differences between the oil control side rails and the compression rail. The oil control side rail shows a shiny chrome face and it's a bit thicker axially and radially, although that can depend on the compression rail axial thicknes,s which comes in several thicknesses. The shiny face is the usual giveaway, but just to be sure avoid mixing the rings up during checking and grinding.



It's not that you can't do a good job with a hand grinder, it just that it takes you all day to do it. This unit from ABS has a table that the ring is clamped to and a dial indicator to help you get the exact end gap you need. If you do use a hand ring grinder, don't make the common mistake of trying to grind both ring faces at the same time. One face at a time, please, take your time, and keep the ends square.



With the support rail in place, wind the expander onto the piston and butt the ends. Then, place your thumb over the butted ends to keep them from overlapping each other as you wind the lower oil control side rail ring in place. Once you get one side rail on, you won't have too much to worry about.



The inside diameter of a ring may or may not be chamfered. If it is, the chamfer of the top ring faces up in the groove and the chamfer of the second ring faces down in the groove unless marked otherwise. I've never seen a ring marked contrary to this rule, but that doesn't mean that it can't happen. Normally, rings will have a dot or the word "top" on the rail near the gap opening.

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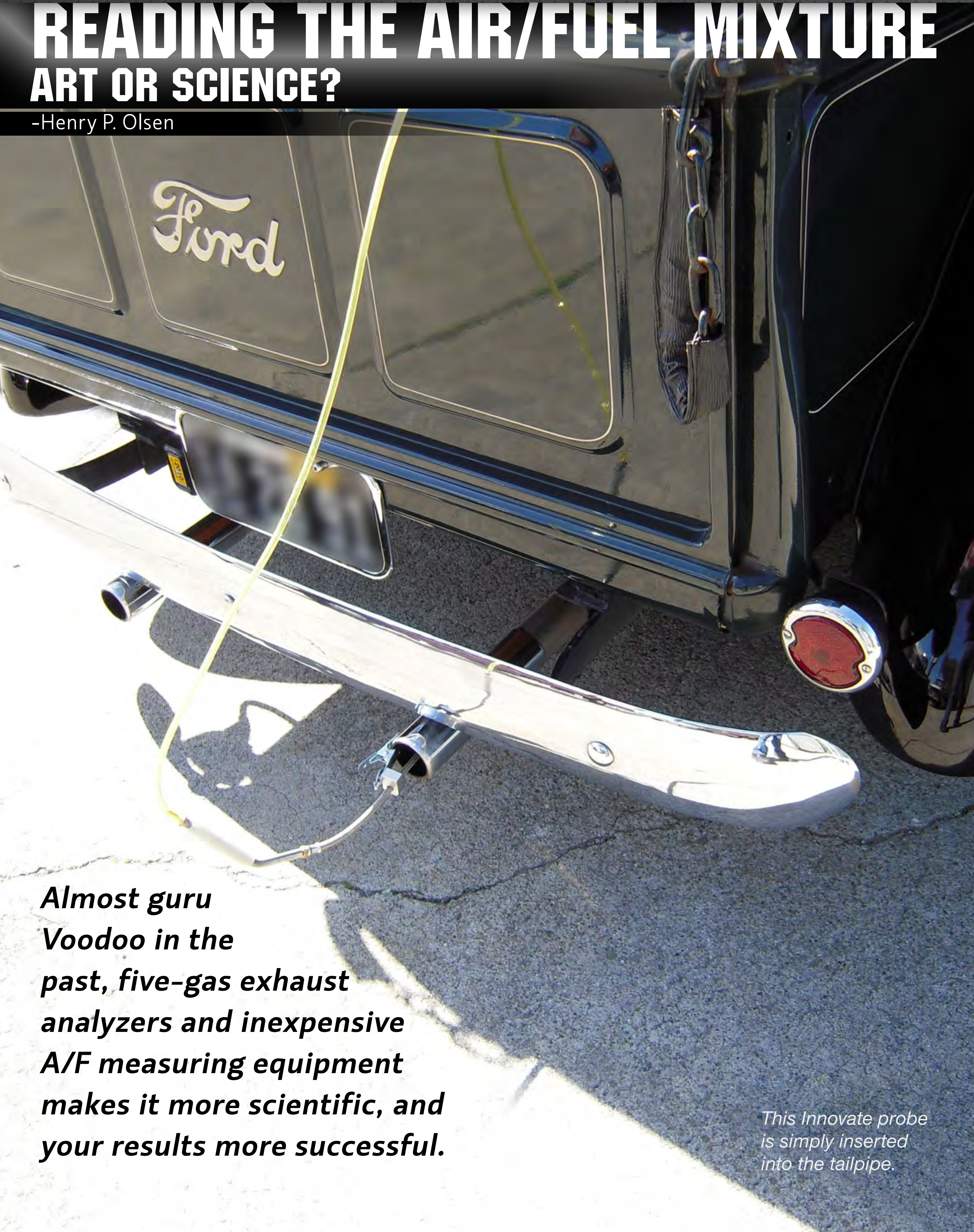
READING THE AIR/FUEL MIXTURE
ART OR SCIENCE?

-Henry P. Olsen



Almost guru Voodoo in the past, five-gas exhaust analyzers and inexpensive A/F measuring equipment makes it more scientific, and your results more successful.

This Innovate probe is simply inserted into the tailpipe.

The ability to determine, then tune the air/fuel mixture of either a carbureted or fuel injected engine has often been thought of as a black art that very few people could do properly. The advances in air/fuel mixture reading technology, however, have made it possible for almost anyone to observe the mixture at any engine operating condition. These readings will help you tune the engine for maximum power, maximum fuel efficiency, or the lowest possible exhaust emissions. The proper tuning of this critical ratio is one of the most important steps that should be performed on any engine, whether street or track. There is no magic setting that will work for every engine, and performance tuning is part art and part science.

To state what should be obvious, an engine that's tuned to provide each cylinder with the ideal air/fuel mixture along with the ideal ignition spark timing will more than likely perform better than a similar engine that has not been properly tuned.

DYNO OR REAL DEAL?

If you are installing a new or rebuilt engine in a vehicle, it is to be hoped that the engine builder can provide you with air/fuel mixture recommendations (and ignition spark advance curves) so that the engine can be tuned to perform properly from the beginning. If you do not have access to tuning guideline, you'll have to determine what air/fuel mixture setting and ignition spark timing the engine will perform best with by tuning the engine in the vehicle during real-world operating conditions. An engine or chassis dyno can also be used to tune an engine for maximum power, but it cannot duplicate those real-world conditions the engine will actually see (such as the G-forces the engine itself and the fuel system will experience during a race). Tuning the engine in the vehicle at the track during the real deal is not just recommended, it is critical if you expect to achieve the most power possible.

While tuning on a dyno is interesting and instructive, it can't duplicate real-world conditions.

If you are tuning on a dynamometer, be sure that you match the inlet air temperature and pressure to what will be experienced in competition or on the street or all your tuning work will be meaningless. You should also keep in mind that inlet air temperature is very important when tuning any engine, but it is even more critical on a computer-controlled fuel-injected engine because the PCM (Powertrain Control Module) uses the air temp sensor signal and intake pressure (vacuum) readings to calculate what ignition spark timing and fuel injector pulse command it should use.

READING PLUGS AND PIPES IS OLD HAT

Back in the days of leaded gasoline, a good tuner could get a good idea of what was happening in the cylinders by using an illuminated magnifying glass to look at the color of the insulator nose of the spark plugs just above where the insulator comes through the steel case. If the mixture is too lean, it will leave no color, while a rich mixture will cause the "fuel ring" to become more prominent. Over-rich mixtures will give the plug a sooty appearance.

Pulling the header off and looking at the color of the exhaust ports in the cylinder head and at the first six inches of the exhaust headers is also used as a way to determine what the air/fuel mixture is, but the header and spark plug color can only show what the air/fuel mixture was at the last load condition encountered before you did the check. In the days of leaded gasoline and point ignition, this method worked well, but today reformulated unleaded fuels and high-energy ignition systems have made this much more difficult because very little color is ever seen on the spark plug. On the other hand, looking at the insulator for signs of detonation, which is seen as specks of aluminum, can still be an effective way to determine if the ignition timing is too far advanced for the octane rating of the fuel being used.

Engine builders also use exhaust gas temperature sensors when they are tuning an engine on a dyno, but the temperature of the exhaust gas really only indicates the temperature of the combustion gases, not the true air/fuel ratio, or the amount of power the engine is producing. For example, if you do not have enough ignition spark advance you will see the exhaust gas temperature go up, but that increase may actually mean that less power is being produced — there is more unused energy in the exhaust gases, which then burns in the exhaust ports and header pipes. That energy should've been expended inside the cylinders.

TWO TOOLS

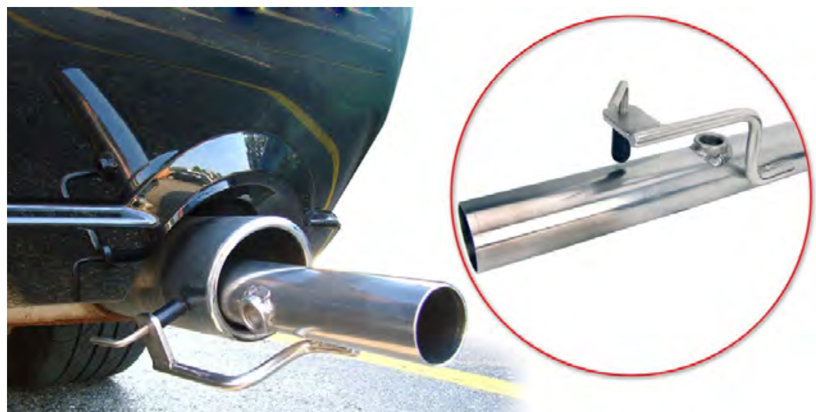
Today, most tuners are taking advantage of the advances in exhaust gas analyzing technology that read and record the air/fuel mixture at any rpm or operating condition at a very affordable price. The two most accurate tools used to read the holy ratio are a five-gas exhaust analyzer and a wide-band A/F (Air/Fuel) sensor-based digital air/fuel meter. Both have their strong points and weak points, but when you use your intelligence to interpret what both are telling you, you'll be well on your way to tuning success.

A modern infrared exhaust gas analyzer allows you to determine what the air/fuel mixture is by looking at five of the elements in the exhaust gas. The readings are very accurate and reliable, but the response time is in the 10 to 15 second range.

A wide-band A/F sensor-based digital air/fuel meter system has a response time of less than a second, but since it determines what the mixture is by looking at the oxygen/unburned combustibles in the engines exhaust it can give you false readings. These faulty readings are often the result of problems such as a misfire or an exhaust leak — the sensor reads the extra oxygen that's arriving at its business end even though it's really just outside air. Also, the sensor can be damaged if it is exposed to leaded gasoline, oil, or certain silicone sealants, plus its accuracy will degrade over time due to exposure to the byproducts of the combustion process.

SENSOR HISTORY AND TECHNOLOGY

A discussion of the science and evolution of "oxygen sensors" (an inaccurate term we're stuck with) is appropriate here. Believe it or not, it was in the 1960s when Robert Bosch GmbH of Germany started research into the idea of electronically monitoring an engine's air/fuel ratio continuously so that adjustments to the amount of gasoline delivered for combustion could be made dynamically. The "Nernst cell" principle was used to generate a voltage signal from the electrical potential between ambient air and the gases in the exhaust stream. Such a signal could be interpreted by electronic logic, which would then make decisions on how much fuel should be added to the intake air to



The FAST A/F ratio meter uses a test pipe with a bung for the sensor.

Mixture monitoring sensors have evolved from the one-wire thimble type through planar to the AFR sensors of today (courtesy Robert Bosch).

produce a near-ideal charge. In 1976, Swedish car makers Volvo and SAAB working with Bosch engineers introduced the Lambda Sond feedback system that put the principle into practice.

Although two-way (meaning hydrocarbons and carbon monoxide) oxidation-type catalytic converters were already in use to cut the release of those gases into the atmosphere, getting rid of oxides of nitrogen emissions required the adoption of the three-way "reduction" catalyst (reducing NOx to harmless nitrogen and oxygen), which in turn depends on near-perfect "Lambda" (in engineering language, the Greek letter that represents the ideal stoichiometric 14.7:1 air/fuel ratio by weight) to do its job.

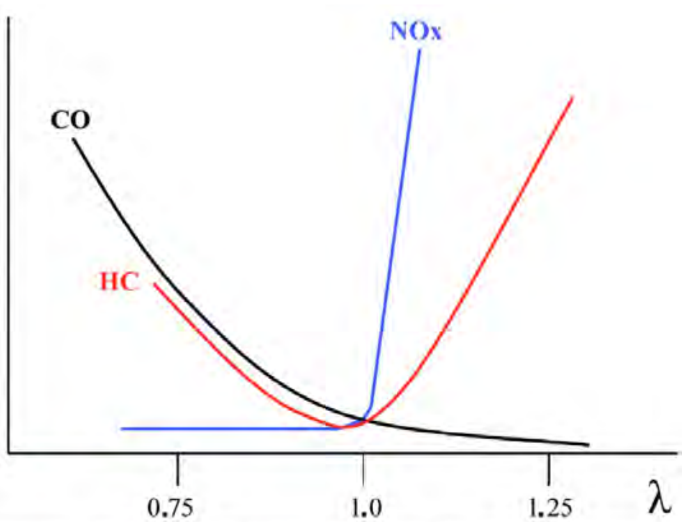
The original oxygen sensor comprised a steel housing with a hex and threads, a louvered shield over the tip, and a hollow cone-shaped "thimble" made of zirconium dioxide (ZrO2), which is coated inside and out with a thin layer of micro-porous platinum. The outer layer is exposed to the exhaust stream, while the inner layer is vented to the atmosphere and attached to a single wire that runs to the engine management computer.

This is essentially a galvanic cell — the zirconium dioxide acts as the electrolyte, and the platinum layers serve as electrodes. Once the ZrO2 reaches about 600 deg. F. it becomes electrically conductive and attracts negatively-charged ions of oxygen. These ions collect on the inner and outer platinum surfaces. Naturally, there is more oxygen in plain air than in exhaust, so the inner electrode will always collect more ions than the outer electrode, and this causes an electrical potential — electrons will flow.

When the engine is running lean, more oxygen will be present in the exhaust stream than when it is rich. That means there will be more ions on the outer electrode, a smaller electrical potential, and less voltage. Just remember "L=L" for Lean=Low.

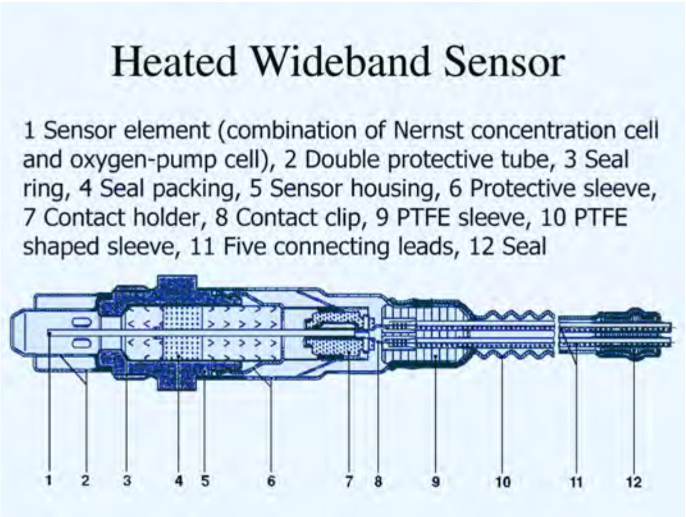
The voltage produced is small, never exceeding 1.3V (or, 1,300mV) or so, with a typical operating range being between 100 and 900mV. This is sufficient for the computer to read, however. If it receives a sensor signal of less than about 450mV, it recognizes a lean condition, and if it gets more than that amount of voltage, it sees rich running. Either way, it instantly corrects by adjusting the injection pulse width (the length of time the injectors are energized per combustion cycle in milleseconds).

The next step in the development of Lambda probes was the addition of an electrical heating element in the early 1980s. As already mentioned, the sensor has to reach 600 deg. F. before it can generate a signal, and this heat source causes it to get to that temperature faster than it would from exposure to exhaust alone. It also prevents it from cooling off during idle, which can throw the system into open-loop.



The air/fuel ratio effect on harmful emissions

This is how exhaust gas emissions rise and fall in relation to the Lambda value. Generally, emissions increase whenever the mixture is not stoichiometric, which air/fuel ratio is represented by the number "1."



If you have not yet encountered the wide-band oxygen sensor, it is time to get familiar with it. This is what it looks like inside. Note that the pumping cell allows it to produce a signal directly proportional to the air/fuel ratio, as opposed to the high and low switching of traditional oxygen sensors.

The "planar" sensor, which appeared in the mid-1990s, was another big improvement. Instead of a heavy thimble, planar sensors have a flat ZrO2 element (less than 2mm thick) projecting into the exhaust stream. The electrodes, conductive ceramic layer, and heater are laminated into a unified strip that is smaller, lighter, and more resistant to contamination than the thimble design. The integrated heater element also requires less electrical power.

Another advantage is that planar sensors send signals five to seven times per second for much more precision in fuel management. To put this into historical perspective, the O2 sensors used on cars with feedback carburetors sent roughly one signal per second, and those used with throttle body injection provided only two to three signals per second.

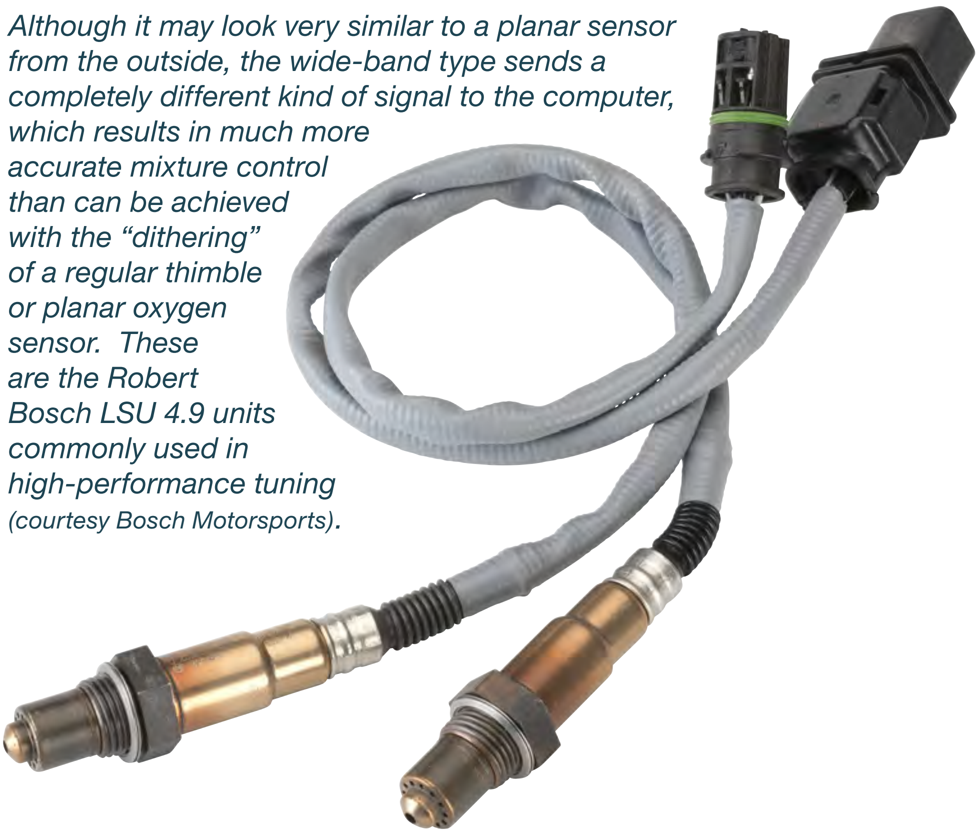
But planars aren't where we are today. While they're faster and better than thimble-type sensors, they still operate in basically the same manner. At stoichiometric, when the air/fuel ratio is perfectly balanced, conventional sensors have an output voltage of about 0.45V (450mV). When the fuel mixture goes even a little rich, the sensor's voltage output does not just increase slightly. It shoots up to its maximum output of about 0.9V. When the mixture is lean, sensor output quickly drops to 0.1V. Every time the oxygen sensor's output jumps back and forth, the computer responds by decreasing or increasing the amount of fuel delivered to the combustion chamber. The rapid flip-flopping achieves something approaching an average stoichiometric condition. But averages are not good enough for optimal fuel efficiency and the latest emission control standards. More precise control over the air/fuel ratio is needed.

Everything changed when the wide-band sensor (also known as a wide-range, air/fuel, AFR, or lean sensor) appeared in the late-1990s, which has made lean-burn engines with stunningly efficient characteristics possible. It doesn't simply send a lean/rich toggle. Instead, it tells the computer how lean or rich the mixture is by providing useable linear output over a wide range of a/f ratios.

It adds an electrochemical "pumping cell" to the planar sensor's layered ceramic strip. This pumps a sample of the oxygen in the exhaust into a "diffusion" gap within the sensor. The sensor is designed so that a certain amount of current is needed to maintain a balanced oxygen level in the diffusion gap. This current is directly proportional to the oxygen level in the exhaust, and amounts to an analog input to the computer. This is superior in speed and accuracy to simply switching rich to lean at the 450mV threshold.

From left to right, these FAST meters measure ethanol/methanol, diesel, and gasoline air/fuel ratios.

Although it may look very similar to a planar sensor from the outside, the wide-band type sends a completely different kind of signal to the computer, which results in much more accurate mixture control than can be achieved with the "dithering" of a regular thimble or planar oxygen sensor. These are the Robert Bosch LSU 4.9 units commonly used in high-performance tuning (courtesy Bosch Motorsports).



An injector flow bench is the gold standard of finding out how much fuel is actually being delivered to each cylinder.

A wideband AFR sensor provides precise readings for air-fuel ratios from very rich (Lambda 0.7, or an air/fuel ratio of about 11:1) to pure air, no fuel. The sensor receives a reference voltage from the computer and generates a signal that corresponds to the fuel mixture. It operates at a temperature about twice that of older O2 sensor designs, and it reaches this within 20 seconds after a cold start. Response time to changes in air/fuel ratios is less than 100 milliseconds, much faster than that of any previous sensor, which provides optimal mixture management. It also makes it ideal for tuning purposes.

Even AFR sensors can be fooled if there is an air leak between the exhaust manifold and head, or by a misfire that pumps an unburned air/fuel charge into the exhaust. These situations cause a false signal that makes the ECM mistakenly adjust the mixture.

IN PRACTICE

Most of the digital air/fuel meters base their readings on the Lambda scale; it is then converted to air/fuel mixture based on the fuel being burned. A Lambda value of 1.0 (stoichiometric) is the chemically perfect ratio of air-to-fuel for a complete burn. For pure gasoline, that is 14.7 lbs. of air for 1 lb. of fuel, but the stoichiometric mixture is different for every fuel. Some may need 14.7 lbs. of air for a complete burn of a pound of fuel, while others may need six lbs. of air . Many tuners believe that it is better to read air-to-fuel ratios in Lambda since it will be accurate with any fuel, but you should use the readings you are most comfortable with.

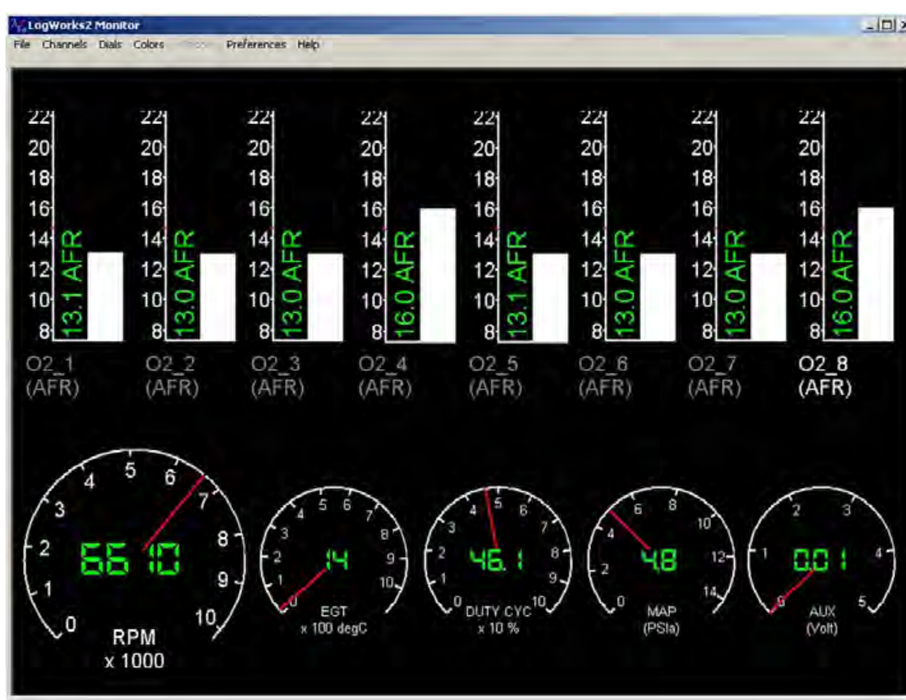
There are several different brands of wide-band A/F sensor-based mixture meters on the market, such as unit sold by FAST (Fuel Air Spark Technology). Many of these systems have data recording capabilities so you can record and play back the A/F ratio readings, plus things such as throttle position, engine rpm, air temperature, engine vacuum, and so on. If you are doing advanced tuning of the air/fuel mixture for each cylinder, Bosch Motorsports offers a Lambdatronic LT4 controller. This provides controlled pumping current to supply up to four sensors. The Lambda value, the sensor temperature, and diagnostics are available via the CAN (Controller Area Network), or an analog signal. Many of the top NASCAR teams use the Bosch LSU 4.9, mounting it in the collector of the headers. For fuel distribution tests, they use one Bosch LSU 4.2 sensor in the header tube of each cylinder because it is more durable than the LSU 4.9.

It is common for the air/fuel mixture to vary from cylinder to cylinder in production engines. This can be caused by the design of the intake manifold, the normal variance of fuel flow from the fuel injectors (if used), or the G-forces the engine will experience during real-world operating conditions. Advanced tuning using one AFS for each cylinder can allow a tuner to read the air/fuel mixture of each cylinder. One of the pioneers in tuning carburetor-equipped race engines is Keith Wilson of Wilson Manifolds, who uses the readings he gets from one sensor in each header tube. Keith is then able to modify the intake manifolds of NASCAR and NHRA Pro Stock engines to ensure that each cylinder of the engine has the ideal air/fuel mixture during the high G-force conditions they experience during a race. A fuel injector flow bench, such as the ASNU unit we use, can allow you to perform flow tests on the injectors themselves to find out if fuel delivery is uniform for all, which is a great tuning tool. For those of you who want to do some further reading on how much the air/fuel mixture can vary from cylinder to cylinder, the Society of Automotive Engineers has a paper 1999-01-1170 titled "The Determination of Air/Fuel Ratio Differences Between Cylinders in a Production Engine Using Exhaust Gas Oxygen Sensors."

IN TANDEM

In my mind, the best results are provided by using both the exhaust gas analyzer and the wide-band air/fuel meter methods in tandem. In the final analysis, the more sophisticated the instrumentation gets, the more careful you have to be with the data you get. Gas analyzers are really good, as are digital air/fuel meters, but care must be taken to make sure you are really seeing what you think you are seeing! There are countless examples of someone tuning the A/F mixture with a digital meter where the reading indicated that the mixture was extremely lean when it was actually not lean at all — the false lean reading was being caused by engine misfire. If you were to use a five-gas exhaust gas analyzer in such a case, you would be able to see the misfire problem. Once the ignition or engine mechanical issues are corrected, both the digital air/fuel meter and the exhaust gas analyzer will show you the same correct air/fuel mixture readings.

The readings from an infrared exhaust gas analyzer will allow a tuner to observe the air/fuel



Here are the A/F ratio readings of all eight separate cylinders at 6,600 rpm. Note that #4 and #8 are leaner than the others.

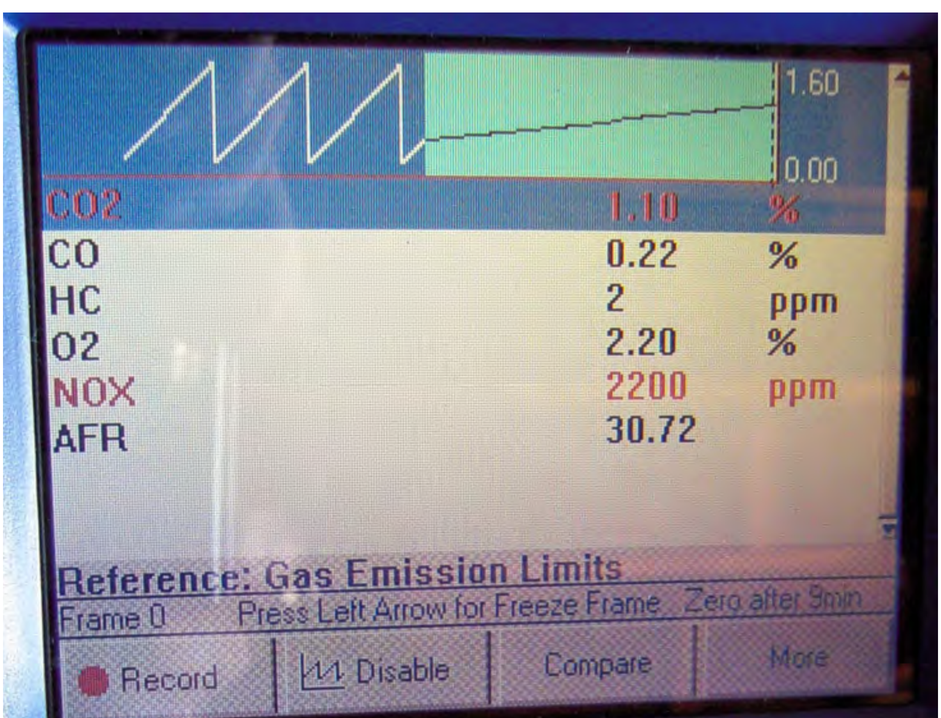
mixture, engine misfire rate, engine combustion efficiency, and excessive combustion chamber heat (typically from detonation). These readings can help an experienced tuner figure out what air/fuel mixture is needed and if the spark timing is too advanced.

- A five-gas exhaust analyzer reads:
- CO (Carbon Monoxide), an indication of the air/fuel ratio (CO is partially burned fuel).
- HC (Hydrocarbons), which represents the amount of unburned fuel in the exhaust (suggesting misfire).
- CO2 (Carbon Dioxide), the product of complete combustion — the best A/F mixture gives you the highest CO2 reading. The ideal ignition timing advance will also create the highest CO2 reading.
- O2 (Oxygen) — high O2 indicates a lean mixture, an exhaust leak, or perhaps that the engine has a "hot" cam. Note: if O2 content is above 2 to 3 percent, air dilution of the exhaust gases being measured is indicated and the accuracy of the all of the gas readings may be way off.
- NOx (Oxides of Nitrogen), the gas that's created by excessive combustion chamber heat. This reading can be used as an indicator of detonation caused by excessive spark advance, or perhaps the octane rating of the fuel is too low for the needs of the engine.

A lean fuel mixture (too little fuel for the amount of air in the cylinder) can cause an engine to have a surge or miss at idle and part throttle, stumble on acceleration, overheating, lack of power, or it can lead to serious internal engine damage. A rich fuel mixture (too much fuel for the amount of air in the cylinder) can cause an engine to "load up" at idle, foul the spark plugs, and also lack power or run sluggishly. The other negative effects of an overly rich mix are poor fuel economy, and the possibility of washing the oil off the rings and cylinder walls, which can cause serious damage to the bores, pistons, and rings.

A good starting point for the air/fuel mixture for most engines running on pure gasoline is 12.8-13.2:1, depending on combustion chamber design and how well atomized the fuel is. With that established, you can perform timed acceleration runs or top speed runs using trial-and-error jetting/programming changes to obtain the best results. The resulting air/fuel mixture reading can then be compared to the A/F ratio readings at various operating conditions.

When you operate an engine with an air/fuel mixture that is too lean, it will also not produce as much power as it should, plus it will tend to run hotter. As you lean out the mixture from the maximum power ratio, fuel economy will improve, but this will also make the driver open the throttle more to maintain the same vehicle speed. The ratio that results in maximum fuel economy can range from 14.2:1 to 15.5:1 on pure gasoline, or maybe slightly leaner depending on combustion chamber design and how well mixed and atomized the fuel is with the air. The challenge is finding a balance between the A/F ratio that will produce the maximum power, and what would provide the best possible fuel economy. When an engine has the correct air/fuel mixture for every operating condition, it will make all the power that was built into it, run cooler, and give the best mpg possible. ■

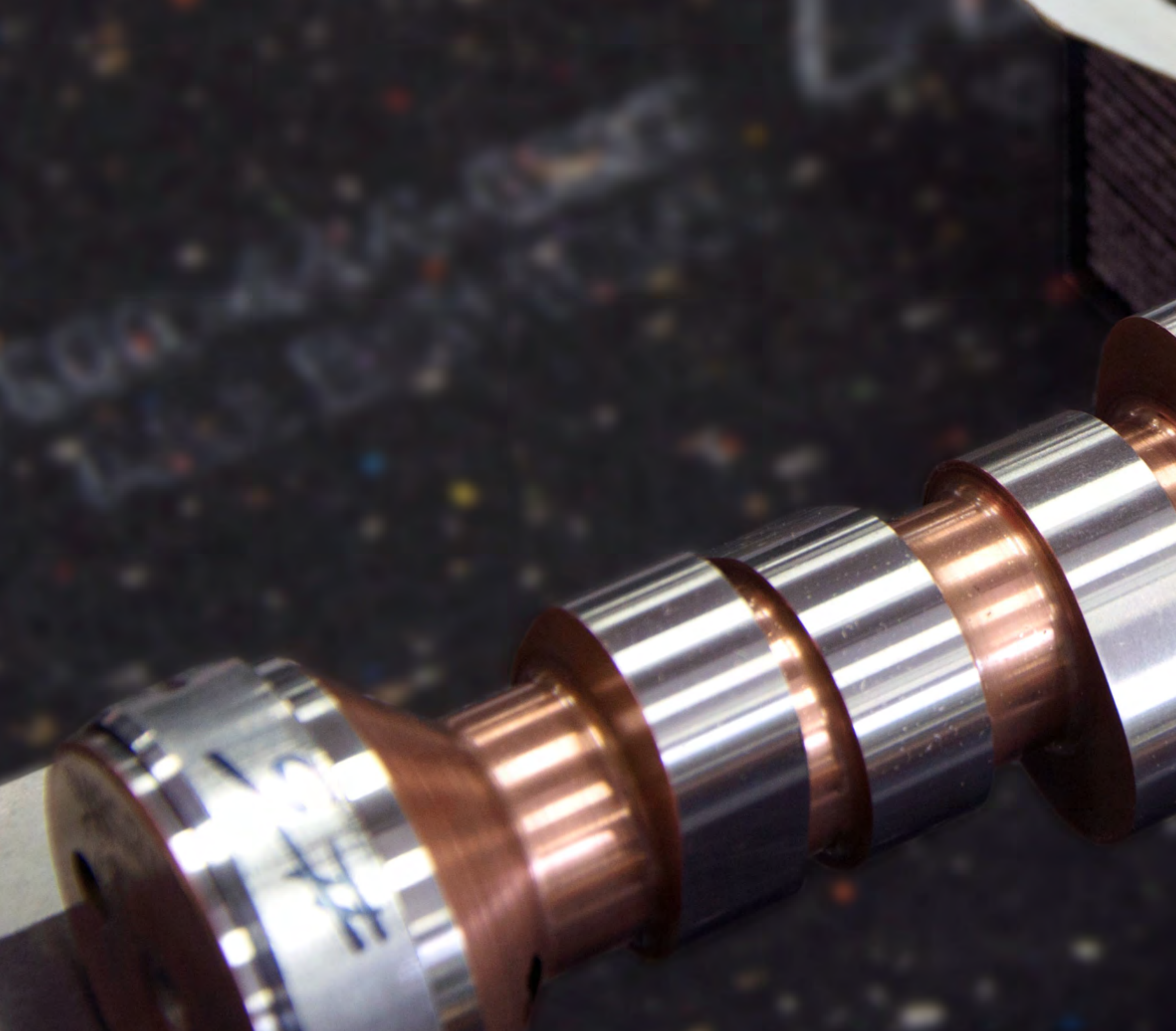


Reading the five important exhaust gases on an OTC Genisys EVO.

CAMSHAFT BASICS, PART 1
THE HEART OF THE ENGINE

-Greg McConiga

There's a whole lot more to the science of camshafts than you probably ever imagined. This series will help you make the right choice.



There is a lot more Big Science ground onto this simple device than first meets the eye. A cam is about timing the event, maximizing the flow at a specific point, controlling the valve, and keeping the lifter, pushrod, rocker, spring, and valve stable throughout the operational range of the engine. And, of course, it's all a compromise among the goals of economy, power, torque, and drivability.

While we in this industry think of cams as something unique to the automotive engine, they are, in fact, common to all manner of contraptions in the world of manufacturing and machine control. There are disc cams, rotary cams, wedge cams, roller gear cams, inverse cams (where the cam is stationary and the follower moves, not inverse lobed cams, more on that later), cylindrical cams, and translating cams to name just a few found in industry. For our purposes, we will from this point on only refer to the camshafts we all know and love, but it's important to remember that ours isn't the only industry where cams are found.

TRAPPING AIR

In the most common forms of the automotive racing engine, we attempt to consistently and uniformly trap the most mass of air and fuel above the piston, light it off, convert as much of the chemical energy into heat energy (released during combustion), then into the mechanical energy that drives the car forward. The crankshaft converts the reciprocating linear motion of the piston and the swinging connecting rod to rotary motion for delivery to the transmission and differential, while the camshaft (cam shaft, as two words, means a shaft with a cam or cams on it) converts the rotary motion of the shaft to a linear motion via the lifters or followers, or some combination thereof. The goal is to precisely and accurately translate the cam lobe designer's lift, duration, and event timing into accurate valve motion via the lifter, pushrod, and rocker system on an overhead valve engine, or directly into valve motion on an overhead cam engine on direct acting systems, or through a follower and lifter on indirect acting systems.

If we are high-performance overhead-valve engine builders, and if the cam grinder has done his development work correctly, from that point on our job as a builder is to make the lift and duration designed into the cam actually appear at the valve retainer — by using the lifters, pushrods, rocker arms, valve springs, and valves that most closely meet the required stiffness to match the profile and intensity of the lift and duration ground onto the cam lobes. You must confirm that as much

Taken from the crankcase, in this photo you can see how on this head the intake valve is significantly larger than the exhaust, and how the plug has been relocated to a more central location in the bore. The chamber form is very shallow, the valves are tipped away from the bore walls to help unshroud them and there is a lot of quench area showing. With tight 65 cc chambers, this head uses a piston with a dome on it of only about 1 cc to achieve a static compression ratio of 16.8:1. Central plug location means that the flame front progresses across the chamber more uniformly, the shallow chamber means that the surface area-to-volume ratio is good, and the extended quench zones help induce turbulence to speed combustion and keep the mixture stirred. This is a very efficient chamber, typically using only 28-30 degrees of spark lead at 8,000 rpm on a 4.625 in. diameter bore.

of your calculated lift and timing appears at the valve as is practical. Always confirm your cam at the retainer, with the engine as-built to race.

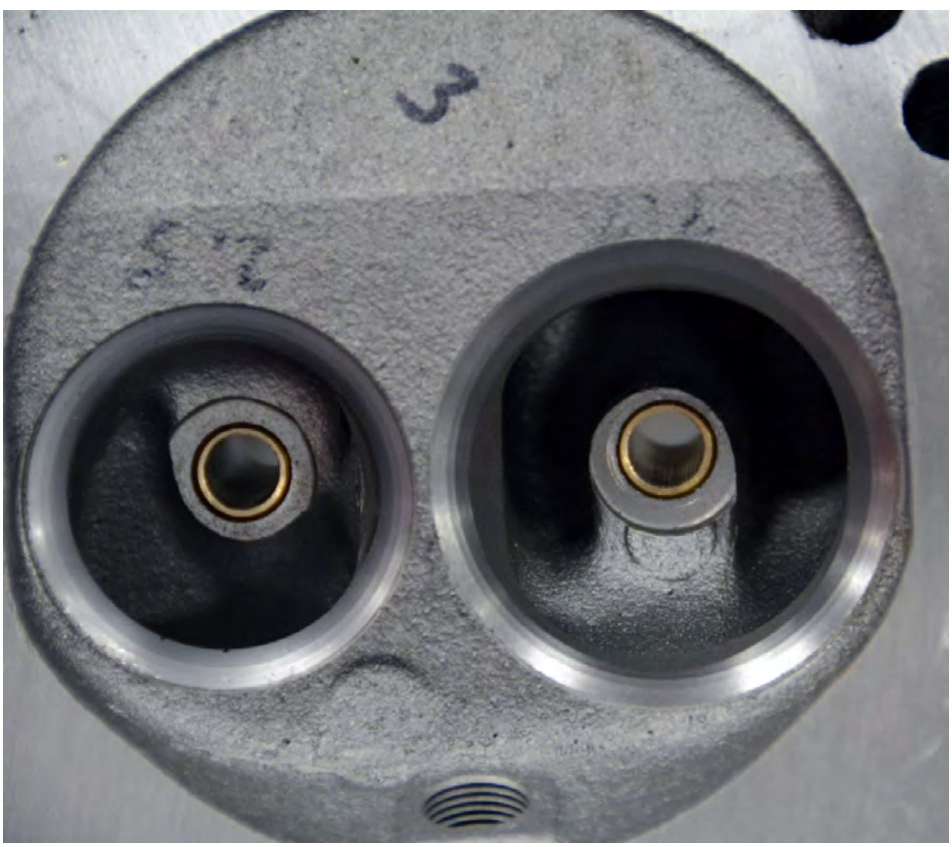
PULMINARY PARTS

If cams are the heart, then the cylinder heads are the lungs, and between these two is where all power is made or lost; these two parts, or more correctly systems, account for nearly all power production. While the biggest contributors to power, they are a little like a surgeon: They can't operate effectively without a strong supporting cast. Valve train stiffness and design aside, bores must be round, rings must seal, piston rockover must be minimized, internal clearances properly set, internal oil control and windage managed, and internal friction lowered as much as practical to avoid using up the power produced in an effort to roll over all the internal engine parts at the expense of rolling the tire.

DELICATE CHOICES

There are two ways to buy cams, out of the catalog and with technical assistance. For street or moderate performance applications, buying from the catalog is probably the way most builders choose to go. Doing your own research, you might land on two or three likely candidates and then call in for help in narrowing it down to your final selection, and this is where you might become a bit frustrated. If you call in to three companies and ask for a recommendation after doing your research, you'll likely end up with three entirely different profiles. This isn't a conspiracy — selections are made in part by what you explain you are looking for in terms of results and in part by whatever "tribal knowledge" your tech consultants have about your application. They may know several customers with similar combinations and they might have recommended one cam over another several times and gotten feedback on how well it worked for those customers, or they may be using a broad recommendation worksheet that the company developed in house.

This is where our conversation gets a little dangerous. We can talk about "general rules" and "general applications," but we do this at the expense of specific knowledge about how a specific cam will work in a specific engine. I'm not nearly expert enough to tell you what to do or not do when it comes to cam selection, but I can help you with some general rules and engineering principles that apply to cam buying and installation. That said, as a practical matter, if you are building serious racing engines you will need to consult with your cam grinder to get the best recommendation for your engine and application for every engine you build. The calculations and physics involved in cam development are well beyond the ability of someone lacking extensive engineering training or years of experience, so



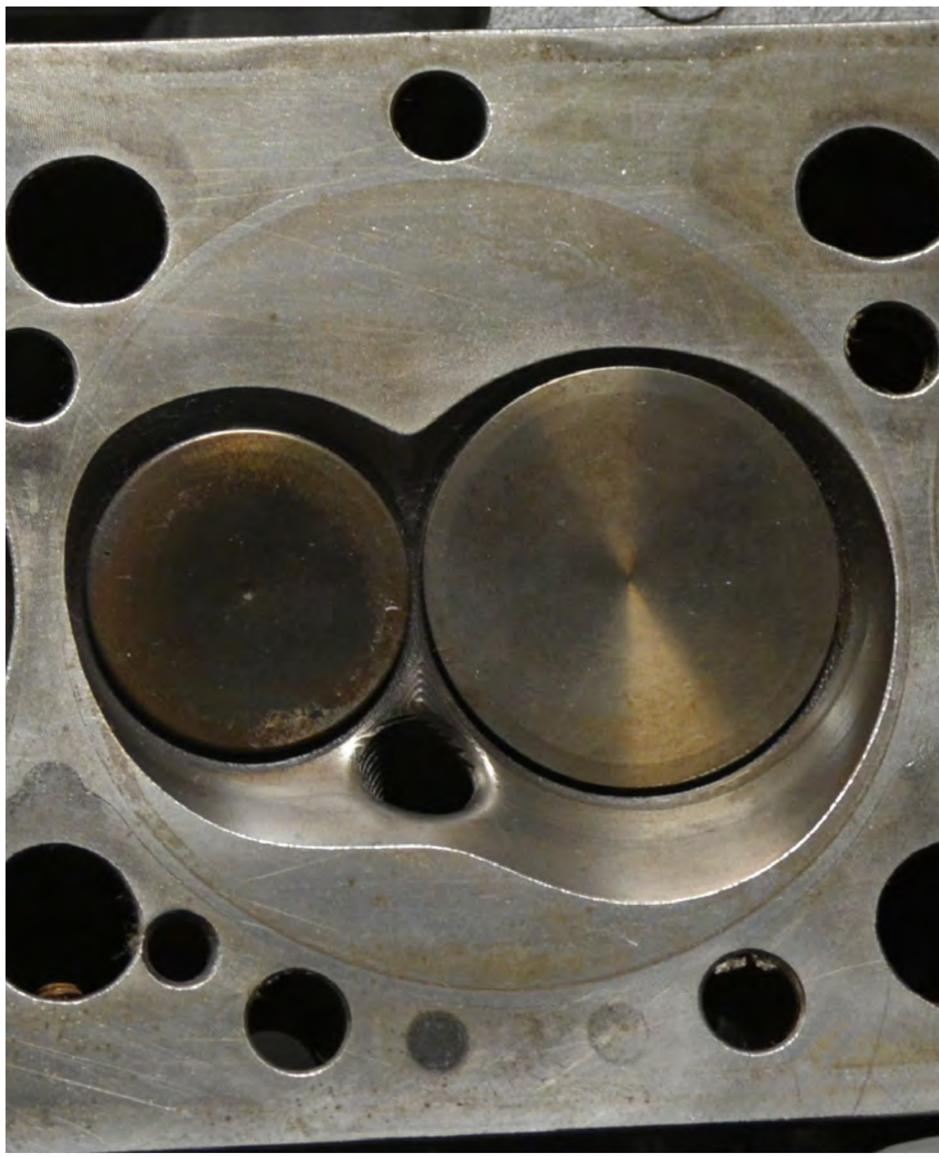
This is an early, pre-emissions-control street cylinder head. It's a much larger and much less efficient chamber with notably small valves, too much surface area, and a spark plug location that will make it hard to lead the spark enough to get good power production and stay away from detonation. This chamber is very inefficient and would require roughly 50-55 degrees of lead at 8,000 rpm. Not that it could ever spin that fast with those valves — or without driving over the rods and crankshaft!

you absolutely must have the help of those who have both the theoretical chops and the real world practical experience of back-to-back dyno testing to help you maximize your power output. Some companies have online forms to fill out and others use a pdf file that you can download and fill out, but in any case you'll have to have quite a bit of data to get the best recommendation for your application.

SAY WHAT?

They'll ask things like type of cam (flat, hydraulic, solid, roller — or mushroom lifter if you're really old-school), then attempt to quantify the desired level of performance you're looking for (mid-, top-, low-rpm power and torque requirements) and the application (for a circle track car, they'll need the class you're in and length of the typical track you race on), and for all other applications the desired output level for street-only use, if it's a dual purpose street/strip, and, if it's drag race-only, the class (if you're class racing). Or, you might be involved in off-road, marine performance, or truck or tractor pulling. You'll need to know the cylinder head type, manufacturer, modifications, and flow numbers at lifts from closed to 1.00 in. at 28 in. Hg; the engine block type, bore and stroke, rocker ratio, carburetor flow rate, rod length, piston type, make and modifications, static compression ratio, intake manifold type, valve sizes, lifter bore, and porting characteristics, plus vehicle weight, axle ratio, transmission type, operating rpm range from low to high, converter stall speed if you're running an automatic transmission, and tire size and diameter. They'll need to know about turbocharging, supercharging, or nitrous use if any of those apply to your application.

There may be other questions as well, so you'll need to be able to intelligently discuss your combination if you hope to get the best camshaft for your specific use, but all engine design, including the cam selection process, starts with the head and the combustion chamber design, including the ceiling (head and valves) and the floor (piston.) For an all-out racing effort, the cam grinder will need to know how much room he has to work in and how efficient the combustion chamber is for your build.



Once again, you can see that the chamber is tight and the plug location optimized on this cast iron small block Chevy cylinder head. While the chamber walls have been pulled back to relieve shrouding, the bore is still close since the valves are in line and some shrouding will occur. For this head, I'd expect that it will require about 32-33 degrees of lead at 8,000 rpm.

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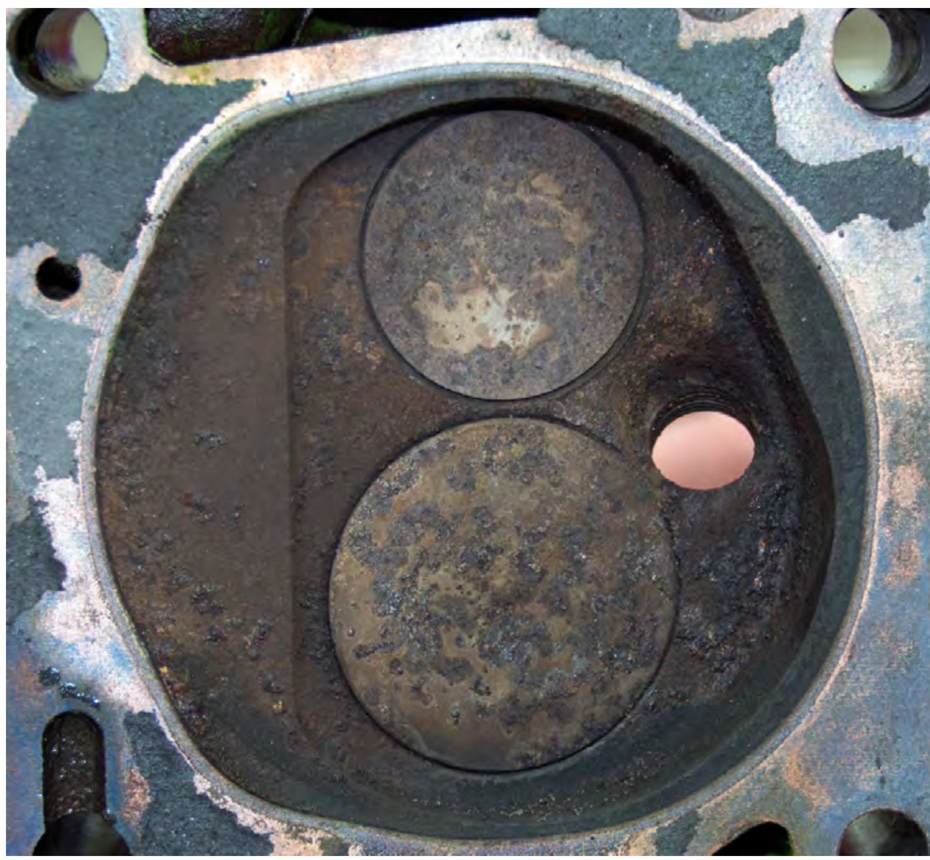
DYNAMIC COLLISION PATHS

Large chambers with big piston domes require a different cam than a shallow, heart-shaped, low-angle combustion chamber because the valves will be attempting to occupy nearly the same real estate as the piston, at least briefly, as the piston transitions over TDC during overlap, with piston-to-valve clearance at the minimum somewhere between 15 degrees BTDC and TDC for the exhaust valve and TDC to 15 degrees ATDC for the intake valve. It helps to think of it as an internal race, piston versus valve. The exhaust valve is "on the spring," racing the rising piston as the exhaust goes closed while the intake valve is "on the cam" chasing the falling piston as the valve comes open — and remember, increasing rocker ratios increases the rate of lift! The exhaust valve movement is less predictable because it's controlled by the vagaries of a spring, while the intake is totally controlled by a solid system from cam lobe to valve head, and that explains why minimum exhaust valve-to-piston clearance is typically twice what's allowed for intake valve-to-piston clearance over TDC. Adding to the mix, small, shallow, efficient chambers run a completely different rate of combustion with far less ignition lead, which also affects optimum cam design. So, if you get asked questions that might not seems pertinent to cam selection, don't fret — your technical guy is doing his job.

The fact that we will most likely use the advanced services of the cam grinder doesn't mean that you shouldn't have a bit of practical knowledge about how the camshaft actually does its job. The practicing racer knows to take advantage of all the resources out there, but knowing how duration, lift, and overlap affect the six engine cycles is handy when you're thinking about and designing your engine.

HEADS FIRST AND HEAVY AIR

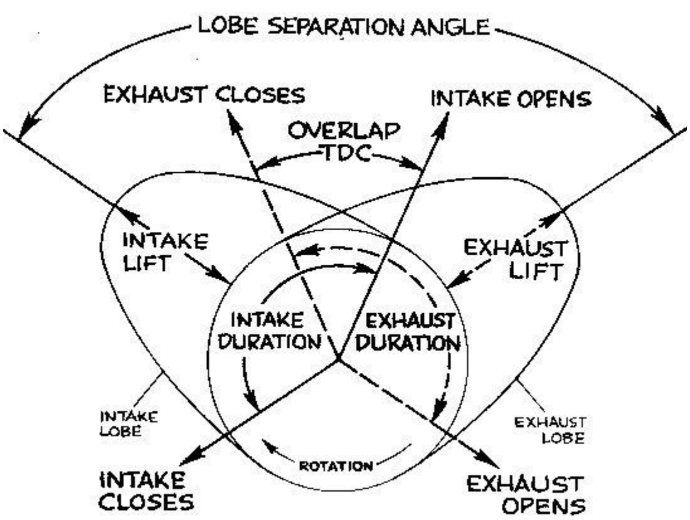
Your design all starts with the combustion chamber. The entire engine is built around first-things-first, and the cylinder head and chamber design and efficiency is the first consideration — the foundation — because everything else is designed around it. Since good cylinder heads are expensive and very good heads are very expensive, it is important to know how to choose your heads. A general rule of thumb suggests that you can support roughly two to two and a half times the intake air CFM in horsepower — an intake that flows 500 CFM can make about 1,000-1,250 horsepower — so if you know your car's weight and the required performance level needed to run your class, you know how good a cylinder head you have to buy.



Here's a vintage street engine head with a closed-chamber wedge combustion chamber. It's a bit of a compromise, but still not too badly done for the era (1969). The plug is more offset to the side than I'd like, but there is some quench area and the chamber is fairly small. The biggest problem we face with this style of head is the shrouding. The chamber walls are vertical and they restrict air flow for almost a quarter of the valve diameter. Getting this chamber to flow will take a cam with more lift than the open chamber wedge shown before — and it'll take about 36-40 degrees of spark lead at 8,000 rpm (assuming this engine could live at that speed, which it couldn't!)

We don't often think a lot about air, how heavy it is and how fast it must move in a typical two-inch by three-inch inlet conduit. Air is light by most definitions — it only weighs about .0807 pounds per cubic foot (at standard temperature and pressure — STP.) All good racers know that air isn't always at STP, which is why we often tune things a bit for colder, heavier air and hotter, lighter air, as well as compensating for altitude and humidity content when needed. What we need to use is the oxygen from the air, which is only about 21% of the total volume taken in by the engine.

To put things in perspective, think about your typical bedroom, 12 by 12 by eight feet. At 1,152 cubic feet, that's less air than is required by a 632 cubic-inch engine per minute at 8,000 rpm (632 times 8,000 divided by 3,456 is 1,462 cubic feet



This diagram shows you what to expect, more or less, with your camshaft. The lobe separation angle is the angle between the intake lobe center and the exhaust lobe center, and it's not as adjustable as you might think. You can roll the lobe centers around a few degrees to "tame" the cam down, but that's not your best overall solution. You start with lift, which is determined by the application and is based on a percentage of the intake valve size, followed by duration, which follows the lift number you're trying to achieve because lift and duration have a direct correlation related to how much velocity or acceleration the valve train can tolerate — there are hard limits on both. The intake lobe center is determined in part by the piston movement (reciprocating geometry comes into play), and overlap is the natural result of how much total intake and exhaust duration you end up with.

per minute at 100% volumetric efficiency), which means that engine would suck all the air out of your bedroom in less than 50 seconds! At .0807 pounds per cubic foot, 1,152 cubic feet of air amounts to almost 93 pounds, of which roughly 19.5 pounds is oxygen. Now go grab your barbells, carry them into your bedroom and put that together in your head! Hardly seems possible does it? What's really scary is when you think about a cube of air 100 feet on a side and realize that it weighs roughly 40 TONS! Why is understanding this and thinking about this important? Because moving air in and out of the engine is what makes power and the camshaft is the controlling entity when it comes to air movement. Air has mass and mass and velocity creates inertia. Inertia: A body at rest tends to remain at rest, and a body in motion tends to remain in motion. It's important to remember that.

MURKY MATH

Now let's think about the environment we are creating. At 1,000 rpm, an engine is rolling over at 360,000 degrees per minute, 6,000 degrees per second, and 6 degrees per 1/1,000 th of a second. At 8,000 rpm, we are rolling over at 48 degrees per millisecond, starting and stopping an inlet conduit of six to eight square inches on every other stroke creating a violent, pulsing, wet flow with both mass and velocity and, therefore, inertia. Part of that flow we need to somehow stuff into a cylinder, at the right time, over a piston moving at an average of over 100 feet per second (4.625 inches at a time!) and get that intake valve closed before the piston's upward velocity overcomes the inertial cylinder filling over BDC that the weight and speed of the aforementioned column of air and fuel generates before it leads to intake reversion. If it were easy, everyone would be doing it, right?

At the most fundamental level, our cam selection must balance intake closing with inertial filling, which increases volumetric efficiency (more air stuffed into the cylinder than what the cylinder physically measures) with reversion and backflow caused by piston rise; intake opening with exhaust backflow versus intake restriction (during overlap); exhaust valve opening with improved blowdown versus loss of power extraction caused by venting the cylinder earlier; and exhaust valve closing with exhaust side flow losses and backflow of exhaust into the intake side.

PULLED IN

The other consideration of intake open/exhaust closing over TDC overlap is that in a properly designed and tuned racing application, there should be a very high negative pressure present at the exhaust valve that is used to "jump start" intake flow into the cylinder for the next induction cycle. The negative pressure created by the overlap-driven induction cycle is often much higher than the negative pressure created by piston fall by a factor of three to six (15-25 inches of water for piston fall versus over 100 inches of water for the overlap induction).

Every choice you make in camshaft selection is, to some extent, a compromise. You can have drivability, but at the expense of power, torque at the expense of a smooth idle and fuel economy, high-speed operation at the expense of low-speed operation. What you intend to do with your little bundle of nuts and bolts moves power and torque up and down the scale and makes the engine more or less suited to either getting groceries, getting out of the turn or getting down the quarter mile.

In the next issue of *Performance Technician*, we'll continue with a few definitions and descriptions, and we'll begin to examine how event timing varies with engine speed and design. Stay "tuned." ■

IFT TO FLOW RATE

This is a spreadsheet that I made up of the flow rates (at 28 inches of water) for a set of cylinder heads I use. First of all, note that the intake-to-exhaust valve ratio is at 75.5%, which is considered "middle of the road." A Pro Stocker might have a ratio of as little as 65% to allow the engine to run the compression and rpm it needs to to be competitive.

High-compression naturally-aspirated engines are more efficient earlier in the expansion phase than low-compression engines and can use larger intakes and smaller exhaust valves than low-compression engines. If you look at cylinder pressure decay in a low-compression engine it, falls slowly — almost linearly at a 45 degree angle — and usable power can be extracted for more crankshaft degrees during the power stroke. With a high-compression engine, the cylinder decay curve looks like it's nearly a vertical drop as the piston falls from TDC. Because all the usable energy is extracted well before BDC on the power stroke, blowing the exhaust valve open early doesn't affect power production nearly as much as doing so would on a low-compression engine.

The bore size of an engine limits the combined sizes of the valves, but you can shift the ratio, using a larger intake, which only has about 20 inches of water pressure differential inducing flow around it, and a smaller exhaust valve, which when opened earlier might have 60-100 psi differential available to induce flow during the blowdown portion of exhaust. Using that excess pressure to dump exhaust gases would then reduce pumping loss and exhaust flow restriction during the piston-driven exhaust phase. It's important to remember the relationship of the pressure units we use in this conversation: 1 pound per square inch (psi) is equal to 2.04 inches of Mercury (in. Hg), which is equal to 27.68 inches of water (in. H2O). If you think of psi as a coarse measurement, inches of Mercury as a medium, and inches of water as a fine measurement, it'll help you keep things in perspective. You can measure closer with a ruler marked in 1/64ths than one marked in 1/8ths, right?

What is important to note is that at 70% of the chart — that is, .700 in. lift out of 1.00 in. total — the flow rates for both intake and exhaust are at roughly 90% of their total. And you'll also note that each .100 in. lift after this point produces correspondingly smaller gains. There's a point of no return on lifting the valve — you can do it, but the gains might not be worth the increased equipment failure rates associated with extreme lift. There is a reason to overlift the valve and it has to do with how much of the curtain area (the area of cylinder formed under the head of the valve between the seat and the valve) is open when the piston is traveling at maximum velocity on the intake stroke. ■

Valve opening, inches	Intake flow rates, CFM	Exhaust flow rates, CFM	Intake flow rates as a percent of total	Exhaust flow rates as a percent of total	Intake, percent of increase over last lift point	Exhaust, percent of increase over last lift point
0.20	158.8	133.9	28.85%	37.40%		
0.30	245.2	182.3	44.55%	50.92%	54.41%	36.15%
0.40	345.6	223.1	62.79%	62.32%	40.95%	22.38%
0.50	428.9	256.8	77.93%	71.73%	24.10%	15.11%
0.60	489.8	286.3	88.99%	79.97%	14.20%	11.49%
0.70	520.1	316.1	94.49%	88.30%	6.19%	10.41%
0.80	537.6	340.0	97.67%	94.97%	3.36%	7.56%
0.90	545.9	354.0	99.18%	98.88%	1.54%	4.12%
1.00	550.4	358.0	100.00%	100.00%	0.82%	1.13%

INFORMATION STATION

ACCESSORIES FOR 2016 TOYOTA TACOMA

A.R.E. Accessories is offering a full range of fiberglass truck caps, tonneau covers and commercial products for the new 2016 Toyota Tacoma pickup. The line is available for all cab and bed configurations. The products are painted to match the owner's truck using the exact OEM paint code and are backed by a limited lifetime warranty for the life of the original pickup truck it is installed on. Visit 4are.com or call 330-830-7800 for additional details.

C7 CORVETTE WIDE BODY STYLING & PERFORMANCE PACKAGE

Lingenfelter Performance Engineering now offers C7 Corvette owners a complete wide body styling and supercharger performance package that provides enhanced appearance and increases the LT1 engine's performance to 624 horsepower. Distinctive exterior restyling features include a carbon fiber extractor hood, splitter and rockers combined with a wide-body kit that flares the rear quarter panels two inches on each side to accommodate larger 20-inch Forgeline Wheels mounted on 335/25ZR20 Continental Extreme Contact EW tires. The performance enhancements ramp up the LT1 output to 624 horsepower with 600 lbs.-ft. of torque at 4,000 rpm. This power boost comes via a 6.2L Engine Package featuring an Edelbrock E-Force TVS2300 supercharger, Kooks headers and a CORSA Performance cat-back exhaust system. For more information, visitlingenfelter.com or call 260-724-2552.

CUSTOM-MADE MONOBLOCK WHEEL

Forgeline Motorsports now offer the AR1, a monoblock wheel design made to order and crafted to fit virtually any application, featuring an extremely angular split spoke pattern, extra-deep concave profile, and a radically angle-cut outer edge. It's currently available in 18, 19, 20, and 21-inch diameters with a range of widths and offsets, and depending on size, may be available in deep, medium, or shallow concave profiles. It is machined from a single forging of 6061-T6 aluminum, incorporates I-beam spoke technology to yield a wheel that is lightweight, stiff and has excellent fatigue strength. For more information, visit forgeline.com or call 800-886-0093.

CVT TRANSMISSION FLUID

CRP Automotive has introduced Pentosin CVT1 Multi-purpose Transmission Fluid, a fully synthetic, high performance fluid for continuously variable automatic gearboxes. It is completely miscible and compatible with other high-quality CVT fluids. The formula features additives that offer the highest levels in thermal and oxidative stability as well as high shear stability and excellent de-foaming properties. It offers high wear resistance and ideal friction performance for both CVT chains and CVT belts. For more information, visit: pentosin.net.

COMPACT LED LIGHT KIT

The KC Cyclone is a new multi-functional auxiliary LED lighting kit that is available in four different lenses: Clear, Diffused, Amber, and Red. It can be used as a dome light, or mounted in, on or under wheel wells, bumpers, engine bays and anywhere you can bolt a screw and a nut. The kit includes light, wiring harness, weatherproof switch and mounting hardware. For details, visit kchilites.com.

FRONT SWAY BAR FOR 1963-87 CHEVY C10

Hellwig Products offers a front sway bar for 2WD 1963-87 Chevy C10.

The bar removes the D-shaped polyurethane bushings on the factory control arms and adds an end link. The company says new design performs better, is easy to install and allows a few quick changes to switch between stock height and lowered vehicles. The sway bar is made from 1.25" solid, heat treated, chromoly steel and includes all the brackets necessary for installation. For more information, log onto hellwigproducts.com.

SWAP A GM LS-BASED ENGINE INTO AN A/G-BODY

Holley Performance Products and Hooker Headers have partnered together to offer versatile and complete swap kits for installing an LS engine into a 1978-1988 GM A/G-body. The parts include headers, exhaust manifolds, stainless steel exhaust systems, engine mounts, transmission mounts, adapter kits for specific transmissions, and complete plug & play EFI systems. You can check out the various parts by visiting holley.com. ■

Chevy Sway Bar

FINISH LINE

-Greg McConiga, Executive Technical Editor

WANDERING FULMINATIONS ON HIGH-PERFORMANCE

I'M NOT SURE HOW I GOT HERE... BUT WHAT I REMEMBER WAS FUN

So, racing season is behind us and the engines we normally service off-season are starting to roll in for pre-teardown analysis, teardown, evaluation and freshening. On one engine, we were nearly perfect. No leakage, good compression, bearings and rod bolts all perfect. Had a little problem with the intake gasket, which we've never had before so that will bear a little scrutiny, but otherwise it was as good as it can get with over 110 runs at more than a 1,000 horsepower.

Same builders, same parts list, same processes, and the other engine has a problem. Again, good on leakage, a little bit of the intake movement, rod bolts all on the money when loosened, but the bearings lost spread and the coating was pretty well gone on the rod bearings. It's a little bigger with maybe 200 more horsepower, but with fewer runs on it over the season. No sign of detonation, no over-rev, coatings scrubbed top and bottom, spread gone on the loaded and unloaded sides of the bearings on three cylinders in the two middle bays. How did that happen?? Of course, I've got a remediation plan, but how did I get here? After three or four years of routine engine upkeep, why am I now second-guessing myself about the process? Will I ever really know what I'm doing? Inquiring minds want to know…

Do you know the old saying? You can either have 40 years of experience, or one year of experience that you've repeated 40 times? The more time I spend doing this the more it seems that all I know can be condensed into some multiple of years and experience, like maybe two years repeated 20 times, or five years repeated eight times, or some variation thereof... and I'm not sure how I got here either! I understand that nothing is stagnant, particularly where ground transportation systems are concerned. Earlier this year, NHRA announced that it's implementing an rpm limit, scoop restrictions, and fuel injection systems in Pro Stock. I'm quite confident that the teams have been working and testing those systems quietly on the side for five years or more, but it will be interesting to see just how this all plays out with a bunch of clever racers and a software program to control it all. I'm reminded of something I once heard attributed to a local racing fuel injection legend: "If you ever see a fuel injection system that works as good as a carburetor, you know what they'll call it? A carburetor." Several recent tech articles I've read that swap base engines between carbs and fuel injection seem to come to the same conclusion. Without Pro Stock as a driving force, will we see high-end carb shops slowly fade into obscurity? I sure hope not.

There have been countless man hours invested in perfecting the 500 cubic inch, 11,000-12,000 rpm, carbureted Pro Stocker, and now we pitch those hours in the trash and start all over again. And how did we get here? Oh yeah, because we're all driving a bunch of identical-looking, jelly bean-shaped, personality-challenged, fuel-injected crap boxes. We're driving appliances. Sorry, but all new things aren't good and all old things aren't bad. I sure miss the hips and waists and Coke-bottle shapes of the late sixties. And I can't imagine a guy singing about his direct-injected, two-liter, sequentially-turbo'd half-a-car like he did about his 409 back in the day. You have to wonder — now that it's not super-secret, how much retired Pro Stock stuff will start finding a home in other classes?

I get it. Progress is good, unless you count the consumers killed at the intersection of Marketing and Commerce. And I understand that each generation has to ask the questions. What was I doing? Where was I going? How did I get here? What was I thinking? Technology drives the world today and for the most part it's positive. You have to wonder about the isolating effects it has when entire rooms full of people ignore each other and sit entranced by their cell phones and you have to wonder just how much of our disposable income we will spend for cell phones and cable, but just look at all the resources we have on tap! Now you can be so absorbed in the learning process that you might end up with 20 years of experience repeated twice!

I wonder where I was going with that... ■