arbon, whose name derives from the Latin *carbo*, meaning coal, is the fourth most abundant chemical element in the universe by mass after hydrogen, helium and oxygen. It was well known to ancient Egyptians and Sumerians, and doubtless to their predecessors and contemporaries as well.

Our modern recognition of carbon as an element dates to the work of Antoine Lavoisier in 1789. Because carbon freely forms long chains of stable carbon-to-carbon bonds and combines readily with hydrogen, there are more compounds containing carbon than all those containing any other elements combined, except for hydrogen. And, indeed, carbon chains accompanied by hydrogen are the basis of every organic compound, including, of course, gasoline, petroleum, propane, ethanol, etc. In fact, all life on earth is carbon-based.

In our work we deal with a broad array of hydrocarbons, ranging from fuels to plastics, from belts and hoses to oils and greases. My focus here will be on hydrocarbon fuels, particularly gasoline and various "gasohols" (mixtures of gasoline and alcohols, whether ethanol, methanol or isopropanol), and diesel fuels. We'll be looking at a variety of carbon compounds arising from processes within the modern engine—some intentionally produced and others not.

The familiar combustion chemistry of gasoline goes something like this: gasoline + oxygen + (compression + heat) = water + carbon dioxide + more heat. However, in the real world such ideal combustion simply doesn't occur with total regularity, so we're left with various byproducts of incomplete combustion, most famously carbon monoxide (CO) and unburned hydrocarbons (HC). To add an additional layer of complication, modern fuel blends contain a wide variety of additives designed to work as detergents, stabilizers, antiknock compounds and the like. So-called oxygenated fuels mix in one or more alcohols or similar oxygen-containing organic compounds with the base fuel stock. Finish 🕏 off the cast of characters with unwanted contaminants such as sulfur or even water, and you've got a potentially nasty brew in the tank.

By SAM BELL

Gasoline direct injection allows smaller displacement engines to develop more power, along with improved fuel economy. But your shop may have to deal with some of the unintended side effects of this technology.



Changes in combustion chamber temperatures and pressures must also be factored in: Too high a temperature and you start producing oxides of nitrogen  $(NO_X)$ ; too low and you can flood the engine with unburned fuel (HC). Suffice it to say that once the combustion event has taken place, a broad array of carbon-based compounds is produced (see "What's Cooking?" on page 41).

While most of this material will exit the vehicle as exhaust waste gases, some blowby will find its way through the piston ring end gaps and into the crankcase. Once these blowby gases are drawn out of the crankcase, they're then reintroduced into the intake where they mix with the incoming air prior to passing through the intake valves and into the combustion chamber. Similarly, a small volume of exhaust gases may also be reintroduced into the intake via the exhaust gas recirculation (EGR) system in cars so equipped, or via valve overlap and partial sequestration within the dynamic operating parameters of a variable valve timing system.

Historically, raw fuel from carburetion or, later, centralized (throttle body) fuel injection would mix with these blowby or EGR gases and dissolve most deposits the gases might have left to mark their passage. I can remember the figurative siren's call of opening up the throttle on a seemingly deserted stretch of highway to "blow the carbon out." I can also remember the real siren's wail shortly after I flashed by the radar car at 120+ mph one night. Let's just say the judge was nonplussed by my explanation at the time.

When intake valve deposits became a significant driveability problem in the mid-1980s, gasolines were reformulated to incorporate more robust detergent packages. The advent of port injection reduced the solvent effect in the throttle body area and the upper reaches of the intake plenum, but at least still largely reduced or prevented the accumulation of carbon deposits on the intake valves and passages. (Prior to this era, there was generally little or no need for throttle body cleaning.)

Recently, however, the increasingly widespread adoption of gasoline direct injection (GDI) technologies (see the

# **GDI: GASOLINE DEPOSITS INSIDE?**

sidebar on page 42) has led to a resurgence of carbon deposits within the entire intake manifold and, quite critically, within the cylinder head's intake ports and on the intake valves themselves. Whether it's called GDI, FSI, DFI, SIDI, Skyactiv or EcoBoost, it's direct injection.

Field technicians report that both the Lexus IS 250 and VWs FSI offerings are beset by a veritable plague of clogged intakes. Later Lexus models solved the deposit problem with a dual injector approach. This system couples the primary direct injector used during stratified charge operation with an auxiliary port injector which operates under homogenous charge conditions specifically known to help scrub away intake deposits. While this strategy certainly increases upfront manufacturing and production costs, it may prove effective in the long term, especially when balanced against lost customers alienated by disassembly and cleaning costs that can easily range as high as \$1200 a pop.

Meanwhile, the diesel world has seen similar problems arise in the wake of the adoption of EGR and throttle plates. There are well-documented cases of diesel intake airflow restrictions of 80% or more.

### Symptoms & Diagnostics

What clues should lead you to check for carbon buildup? You may encounter one or more misfire codes (P030x), especially on cold start-up and driveaway, often accompanied by a P0316 code or a proprietary P13xy code, indicating a misfire within the first 1000 revolutions after start-up. While it's possible that you might encounter a rich condition code such as P0172 or P0175, or the more generalized fuel trim malfunction code P0170, often there may be no DTC to tip you off.

The most common driveability symptoms resulting from carbon buildup in the intake are a lack of power (especially at higher engine speeds), a failed  $NO_x$  emissions test and/or excessive ping on acceleration. Cold-start difficulties, including cold rough running or cold stalling, may also occur, and are especially common in Valvetronicequipped BMWs. Datastream may show unusually large negative fuel trim corrections, especially at higher engine speeds or on hard acceleration. Abnormally low mass airflow (MAF) readings during wide-open throttle (WOT) acceleration or Calculated Load values substantially below 100% under the same conditions may be other tip-offs.

On turbocharged applications where WOT-calculated load values often exceed 100%, look for lower-than-normal figures. (As usual, have an assistant drive or, better yet, use your scan tool's movie, graphing or recording mode, then review the results once you're safely parked.) Unfortunately, neither these symptoms nor the occurrence of any of the DTCs mentioned are exclusive to carbon buildup, so you'll have to find ways to rule out other causes, which is to use your borescope (possibly with a securely attached mirror) through a spark plug hole. Carefully rotate the engine by hand until the intake valves for your cylinder are fully open. If your scope shows you a rounded mass above the valve's head, you've found the carbon you were looking for.

Speaking of scopes, can you identify carbon buildup by looking at a vacuum waveform? The answer is a conditional maybe, at best. If the buildup is relatively uniform, it will affect the waveforms of each cylinder approximately equally, so you'd need a very good library of known-good waveforms from known-clean engines. Even then, the buildup would have to be pretty significant before it would rise to detectable levels at low to moderate en-



Photographs of black carbon hiding down black holes are notorious for not showing much of anything except blackness. What you *can* see in this photo is a small amount of carbon buildup on the head of the valve. Next step is to get that stuff out of there.

might include worn intake lobes, a contaminated MAF sensor, excessive fuel pressure, leaking injectors, etc.

On some applications, a quality flexible borescope, the thinner the better, may allow you to see the intake ports and valve heads well enough to pin down the diagnosis. A small-diameter scope can sometimes fit through a major vacuum port, such as that for a brake booster, purge or PCV hose, to allow you to maneuver it out of the plenum and downstream to one of the intake ports. Often, however, this approach will not be practical. A good alternative

gine speeds. If you had a known-good waveform in your library from somewhere above 4500 rpm, you *might* be able to pick up a good clue from the vacuum waveform.

What about compression testing? For cranking compression pressures to be affected, you'd need an almost completely obstructed intake. Even at idle, only the very worst obstructions would restrict the incoming air sufficiently to be measurable. As is the case with vacuum waveforms, only under the very high airflow rates of near red-line operation will lesser deposits be detectable.

# **GDI: GASOLINE DEPOSITS INSIDE?**

While some manufacturers have tried to pin the blame for carbon buildup on the use of low-quality fuels, field data shows that even the assiduous use of so-called top-tier fuels fails to prevent the problem completely. Not surprisingly, frequent short cold-weather trips do seem to exacerbate the issue. Overall, there does not yet appear to be a good preventive solution to what is essentially a design problem which, if nothing else, fails to account for current real-world North American fuel formulations.

We're not alone, either. Technicians in Australia and New Zealand also report similar problems. Part of the difficulty stems from slower-burning components of the fuel blend. Many of these "heavy-fraction" molecules sur-

ments for gasoline fuels will reduce this level to 10 ppm in all gasoline fuels by 2017. According to the EPA, the current emissions standards, when combined with the reduction of gasoline sulfur content from the current 30- ppm average down to a 10-ppm average, will result in "dramatic emissions reductions for NOx, VOC, direct PM2.5, carbon monoxide (CO) and air toxics. For example, in 2030, when Tier 3 vehicles will make up the majority of the fleet as well as vehicle miles traveled, NOx and VOC emissions from on-highway vehicles will be reduced by about 21%, and CO emissions will be reduced by about 24%."

European gasoline regulations already limit sulfur to 10 ppm, perhaps accounting, at least in part, for the fact



Considering the amount of work that was required to reveal it during a decarbonizing service, one would hope that the oil separator for this PCV system will never be as accessible again. It would be a disservice to the customer to pass up the opportunity to clean and reseal it.

vive the combustion process and exit, only to find their way back into the intake tract whose relatively cooler surfaces prove ideal to condense them out of gaseous form. Log on to *http://www .toptiergas.com/retailers.html* for a current list of approved fuels and more technical information under the "deposit control" tab.

A couple of requirements for these top-tier fuels are of some particular concern. One specifies an ethanol content of 8% to 10%, while another specifies a *minimum* sulfur content of 24mg/kg, or 24 parts per million (ppm). Newly adopted EPA requirethat versions of the same problematic engines do not appear to suffer as much from carbon buildup under European driving conditions. New fuel formulations are constantly being developed and tested, so there is some hope for the future.

In the meantime, BG Products and Wynn's, among others, offer chemicals and equipment designed to remove baked-on intake deposits. The procedure should be performed only outdoors or after connecting the vehicle to a very good exhaust extraction system to avoid filling your shop with toxic fumes. (Of course, this precaution should be taken for any procedure that requires running a vehicle indoors for an appreciable length of time.)

The BG approach starts with adding a can of one of their gasoline enhancers to the tank before warming the engine to normal operating temperature. You then install a fogging device by the throttle body and set a throttle prop to hold at about 1200 rpm. The fogger is connected to a pressurized dispenser filled with one of the company's proprietary chemical blends formulated to dissolve baked-on carbon deposits from the valves and passageways. The fog process continues for about 15 minutes and should be followed by an equal time of running without the fogging to clear out any residual chemicals.

Wynn's Direct Injection Power 3 (DIP3) claims to be even easier to use: Remove the air cleaner, hold the throttle of the previously warmed engine at about 2000 rpm and spray in about 200mL of the fluid in short bursts, being careful not to stall the engine or exceed 3000 rpm. Let everything stabilize for a minute or more, then reinstall the air filter.

As usual, I'd recommend following up either of these services with an oil and filter change, since some of that nasty soup will undoubtedly find its way into the sump. Don't forget to include this cost in your estimate, as most GDI engines require carefully formulated synthetic (read: "expensive") oils in an attempt to minimize wear on the highpressure injection pump plunger and the camshaft lobes driving it (see "Taking the Plunge" on page 43).

In general, "soft" carbon deposits are more readily dissolved than "hard" ones. If you were able to see the deposits before starting your work, you may learn to tell them apart and predict the likelihood of success in fogging them off. Sometimes a second round of treatment may be required, so be sure to verify the effectiveness of your work prior to performing that oil change.

If the deposits were heavy enough to cause DTCs to set or a noticeable performance problem, simple chemical methods alone are unlikely to be fully effective. And there are some potential pitfalls for the unwary as well.

## WHAT'S COOKING?

The products of complete combustion are water and carbon dioxide, but there are plenty of byproducts resulting from imperfect combustion. These fall into three broad categories—incomplete combustion, combustion byproducts and postcombustion oxidants.

Incomplete combustion includes unburned hydrocarbons and partially burned hydrocarbons such as aldehydes, ketones, carboxylic acids and carbon monoxide. Also in this category are thermal crack products and derivatives such as acetylene, ethylene and hydrogen, pure carbon soot and polycyclic hydrocarbons. (Polycyclic aromatic hydrocarbons, or PAHs, include several highly toxic compounds and have been identified as likely to cause cancers and lower IQs, and adversely affect development.)

**Combustion byproducts** include the nitrous oxides from atmospheric nitrogen, and sulfurous oxides from sulfur impurities in the fuels. (In addition to being among the most dangerous eye-irritants known, both nitrous oxide and sulfurous oxide compounds are also implicated in acid rain. Sulfurous oxides in sufficient concentration can also degrade the performance of oxygen and air/fuel sensors, and degrade catalytic converter performance.)

**Postcombustion oxidants** include important smog-forming compounds such as ozone, organic peroxides (powerful bleaching agents often also used in explosives) and "tear-gas" peroxyacetyl-nitrates, all formed when exhaust gases are exposed to sunlight.

All in all, the ingredients of this stew are an unsavory bunch. The vast majority of exhaust gases make it out the tailpipe; their effect on the rest of the planet is a discussion best left for another time. Unfortunately, though, a small percentage of these compounds makes its way into the intake manifold whether directly via an EGR system, or incidentally via the PCV system or via turbulence during periods of valve overlap. The relatively cooler surfaces of the intake tract readily condense these gases, allowing them to build up and do their mischief.

### Side Effects May Include . . .

One of the bigger worries about decarbonizing services is that a large chunk of carbon may break free. In the worst case, it may block a valve open, possibly allowing a catastrophic piston-to-valve collision. Or a piece may pass into the combustion chamber and even ignite. In rare cases, this may cause a backfire in the intake side or may merely interfere with correct ignition timing within the combustion chamber. Alternatively, such a dislodged chunk may stick to one of the combustion chamber surfaces, raising the effective compression ratio and possibly causing ping and excessive NO<sub>x</sub> production, or it may pass through into the exhaust stream.

Ford has recently expressed concern about thermal (overheat) damage to the turbochargers of some of its EcoBoost engines after decarbonization services. Ford's official position is that no such services are currently approved for its EcoBoost products. For vehicles still covered by the factory new-car warranty, there's an exchange cylinder head program in effect. For out-of-warranty service, Ford at one time recommended walnut shell blasting, although their current preference appears to be head replacement. There are also scattered reports of catalytic converter damage. whether blockage or partial meltdown, imputed to such events. Misfires have been reported as well.

As always, it's best to let your customer know about these potential issues *before* they arise. As a practical matter, this means informing him, as part of your initial explanation, of the proposed service. Use care and follow the manufacturer's directions scrupulously. Above all, don't blip the throttle until the service has been completed, as sudden changes in airflow are more likely to dislodge such chunks of carbon.

I have never been a fan of fear-based selling, yet it's obvious that selling this as a preventive maintenance service becomes much easier when you mention the potential negative consequences that might occur should your customer wait too long. Recommendations for service frequency vary greatly from model to model, and even from year to year in some cases. For the worst-af-

# STOP PREMATURE BRAKE PAD REPLACEMENT



SAFE & SOUND

Instead of glues that fail under high temperatures and extreme pressures, NRS hooks create a mechanical bond between the backing plate and the friction that will not fail throughout the life of the brake pad. We are so sure of NRS we offer a \$250 guarantee against delamination on any brake pad using it. Stop wasting time and money, on your next brake job use NRS equipped pads.



# **GDI: GASOLINE DEPOSITS INSIDE?**

fected models-those most prone to carbon accumulation-5000 miles may be a good interval, while for others every 15,000 to 30,000 miles will be often enough. Unfortunately, I don't yet know of any reliable source of information on this point, especially since driving style and conditions cause pronounced variability. Seasonal and regional variations in fuel formulations further complicate the question. Most Euro-brand techs seem to favor chemical cleaning annually or every 15,000 miles as a maintenance item. BG Products offers a limited warranty to owners who use their three-part induction service at least every 15,000 miles.

What should you do if you encounter a heavier carbon buildup? There are times when no amount of external chemistry will work to safely break up baked-on carbon deposits, although a second round of cleaning will turn out to do the trick often enough to make it worth a try. But for those times when even a follow-up chemical treatment proves ineffective, most manufacturers specify blasting the crud off with a walnut shell medium. Don't use any kind of abrasive media here! Rule 1: Read the directions first. Rule 2: Follow them, especially the parts about safety glasses, gloves and a face mask.

The most common procedures call for removing the intake manifold to expose the head's ports. Rotate the engine by hand in its normal direction of rotation so that the intake valves for one of the cylinders are completely closed. Mask the intake ports of the other cylinders. (Corrugated cardboard

## **GASOLINE DIRECT INJECTION (GDI)**

éon Levavasseur, a French engineer who also pioneered the first V8 engine layouts, invented the first viable gasoline direct injection system over 100 years ago. The earliest applications were all in aircraft engines.

Although several automotive manufacturers dabbled in the technology, it was not until 1955 that Mercedes-Benz, using a modified Bosch mechanical diesel pump, introduced the first "modern" car sporting direct injection—the gull-wing 300SL. The technology was simple enough: A low-pressure pump supplied fuel to a high-pressure injection pump. This chain-driven injection pump featured its own crankshaft. Like a miniature engine, the pump used its pistons to pressurize the individual fuel lines feeding each injector. Refinements including temperature and barometric pressure compensation were achieved via mechanical controls.

GDI works a lot like a diesel, where fuel is injected directly into the combustion chamber just after the end of the compression stroke. Pressures may exceed 200 bar, or about 3000 psi. Modern controls allow multiple injection and ignition events during a single power stroke.

You may well be asking yourself why GDI is suddenly such a big deal after 100 years. GDI offers several potential advantages of considerable interest to automakers striving to meet increasingly stringent fuel consumption and emissions regulations worldwide. These include:

•Decreased cold-start emissions, cut in some cases by 25% or more.

•Greater fuel economy. Unlike previous "lean-burn" or "stratified charge" systems that generally maxed out around 25:1, GDI offers real-world light-throttle cruise air/fuel ratios of 65:1, and, in some applications, even leaner mixtures during trailing-throttle deceleration.

Increased power and performance.

Decreased carbon footprint, especially for carbon dioxide.

Additionally, GDI allows higher compression ratios and pairs well with turbocharging, allowing an increased level of performance previously attainable only by higher displacement engines. The use of smaller displacement engines can greatly multiply fuel savings without sacrificing power. makes a good masking material; mark the bolt or stud holes, punch them with a Phillips screwdriver, fasten the cardboard in place using appropriate hardware and follow up with masking tape.) If you've removed anything else, such as a valve cover, mask those exposed innards as well. Load in a fresh batch of shells and fire away into the first set of intake ports.

You'll have to stop periodically to vacuum out the spent shells and dislodged carbon. Keep blasting until everything is scrupulously clean, including the far side of each intake valve. Clean out all debris, then mask off that set of ports and advance the engine until the next cylinder's intake valves close. Repeat until all the valves have been excavated. Large and small pieces of shells or carbon deposits are likely to be lurking throughout your work area. Time you spend cleaning them up now is time you won't have to spend correcting any damage they might cause later. Include this time in your estimate from the start. If any debris got onto a threaded stud or down a threaded hole, clean it out so it doesn't prevent you from hitting the correct torque specs on reassembly. In some instances it may be necessary to use a tap or die to clean the threads adequately.

It's a good idea to clean up the rest of the intake while it's off, and you may as well service the throttle body, too. Will you need new intake gaskets or O-rings? Probably so in most cases. Ask your favorite dealership parts contact for the skinny on what their techs do or do not actually replace on engines of similar mileage. When in doubt, replace.

Many vehicles will require reinitialization of the throttle after cleaning. Make sure you have the technical resources to perform this service, or arrange for a mobile service to provide them for you. Once again, make sure to include any additional costs in your initial estimate. If there's something else in the area that ought to be serviced soon and will become significantly more expensive to unearth again an oil separator, for instance—you may want to offer to package it in with the current job. Most customers will ap-

## TAKING THE PLUNGE

Most GDI systems in current production use a camshaft-driven high-pressure pump to feed their injectors (see accompanying photos). Both the lobes pushing on the pump plunger and the plunger itself experience significant forces. The sliding contact between the two pieces can result in very rapid wear.

Most manufacturers specify carefully engineered synthetic oils for this application. Not every synthetic meets



The bright wear on this trilobed cam attests to the considerable force it exerts on the GDI fuel system's high-pressure pump plunger.

the standards, so be sure you check before you pour in the lube. There have been numerous reports of premature failure of these components. In many cases, these may occur even during the new-car warranty period. Several OEMs have denied coverage when the customer cannot document the use of factory-approved oils. Current legislation in effect in almost every state requires you to specify both the brand and viscosity of oil on your customer invoices. If you haven't been doing so, this would be an excellent time to start. My advice? Use the factory-specified oil every time, and explain to your customers why you're doing so. Most will understand and appreciate your concern; after all, it's their investment you're protecting.

Be sure to use a suitable filter that will provide adequate protection over the life of the oil change. If you're using something other than the OE filter, choose a reputable brand and look for an assurance of longevity, such as "extended use" or "long-life." A statement such as "meets or exceeds manufacturer's specifications" is not



If you need to remove the pump housing, be sure to counterhold the hex on the outlet pipe (shown here pointing downward) as you remove the fitting leading to the rail. If the pipe loosens up from the housing, the assembly must be replaced.

necessarily enough. The specs in question may be limited to thread size and burst-strength alone, ignoring issues like microporosity and filtrate (dirt-holding) capacity.

And, of course, be sure to follow through on the customer education aspect by explaining both the procedure and the need for checking the oil level periodically. After all, there are some cars with a four-quart sump capacity for which oil consumption of a quart every thousand miles is "acceptable." If the drain interval is 10,000 miles, you could be looking for an additional six quarts between changes.

prove the additional preventive maintenance work if it's presented properly as an add-on option at the outset.

### Conclusion

While gasoline direct injection engines present numerous theoretical advantages, real-world automotive applications have been plagued by persistent and widespread carbon deposits on and within intake valves and ports. Current fuel formulations alone cannot effectively prevent all such problems. Incidences of premature pressure pump and camshaft failures are most commonly encountered where manufacturers' oil specifications have been ignored, although ultimate life expectancy for these components is often substantially shorter than that of other valvetrain parts even when the correct lubricants and drain intervals are used. Future advances in lubricants, engine design, combustion control and fuel formulations will determine GDI's ultimate fate.

Meanwhile, GDI-equipped vehicles present a new array of diagnostic challenges and service opportunities. As usual, those shops and technicians who take the time to study and understand this new technology's strengths and weaknesses and who invest in proper training, tooling and equipment will be well-positioned to assist their customers. Periodic chemical intake cleaning can be a valid and valuable preventive maintenance service for GDI engines, but it must be performed early enough to be effective and carefully enough to avoid damaging the engine and associated downstream components, including turbochargers and catalytic converters. Deeper cleaning via walnut shell blasting is appropriate for engines that fail to respond to chemical cleaning because of heavier deposits.

This article can be found online at *www.motormagazine.com*.