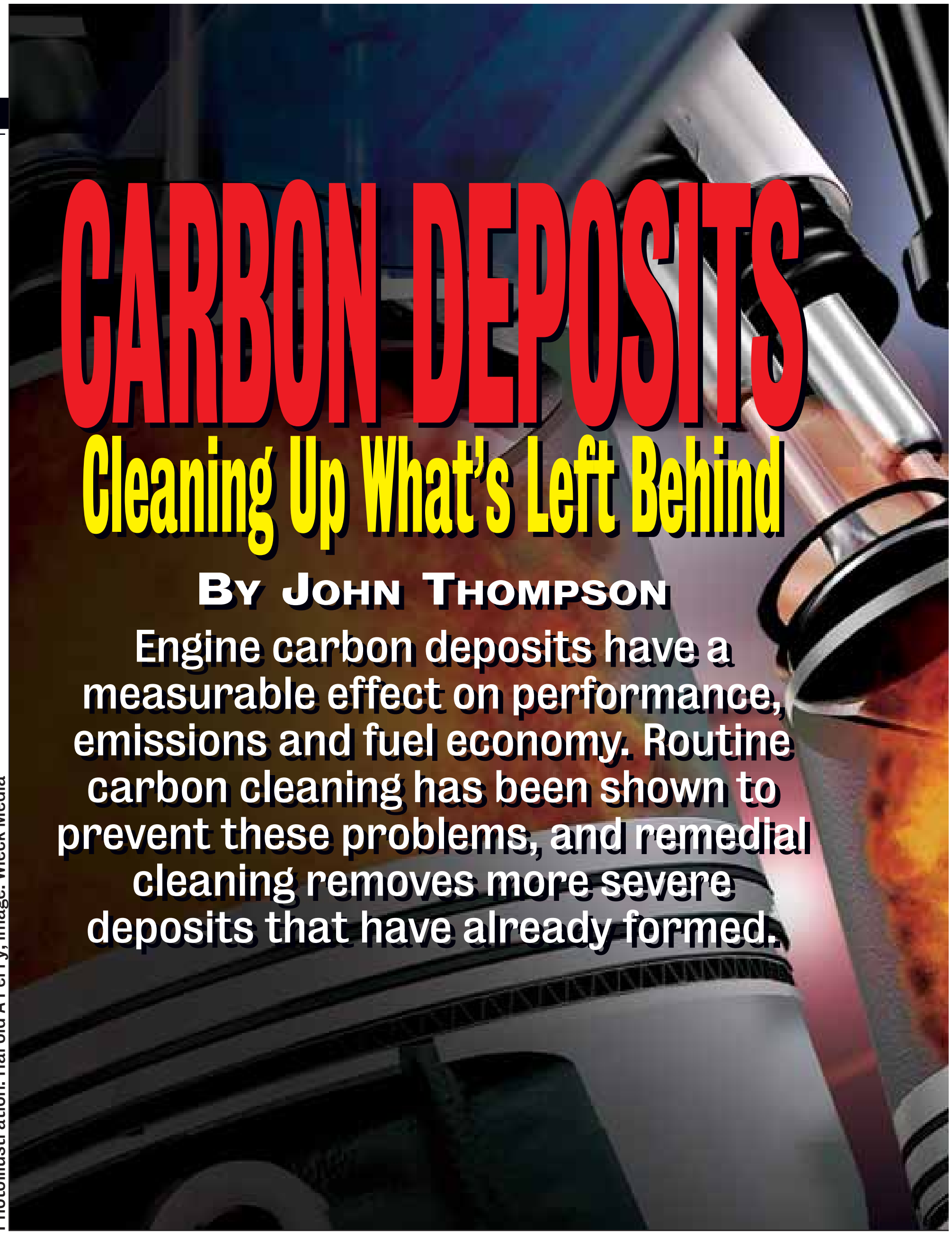
CARBON DEPOSITS

Cleaning Up What's Left Behind

BY JOHN THOMPSON

Engine carbon deposits have a measurable effect on performance, emissions and fuel economy. Routine carbon cleaning has been shown to prevent these problems, and remedial cleaning removes more severe deposits that have already formed.



Photoillustration: Harold A Perry; image: Wieck Media

Many technicians and managers are well aware that severe combustion chamber carbon buildup can create significant driveability issues with today's engines. It's all too rare, however, for them to focus on the fact that carbon buildup and slowly deteriorating injector performance is a gradual process that not only affects engine performance but fuel economy as well. Combining the reality of today's high fuel cost with the fuel injector cleaning and decarbonization services your shop offers creates a genuine opportunity for preventive maintenance business. Despite the opportunity, the vast majority of these potential PM sales remain untapped.

The ever-increasing price of fuel in recent years has created a very emotional hot button. Increasing your share of profitable PM sales while saving your customers real dollars every time they pull up to a gas pump is truly a win-win proposition for all. Promoting carbon and injection cleaning services to the top of your PM sales focus will make real bottom line sense to both shop and customer.

Optimum cylinder combustion depends on the correct air/fuel ratio for engine operating conditions. With a stoichiometric 14.7 parts air to 1 part fuel, the fuel is the most variable and critical factor of the ratio. Fuel is supplied to the cylinders by the injectors. Each cylinder's individual injector is not only required to deliver a specific and precise amount of fuel, but the fuel must also be in a well-atomized form. To maintain optimum combustion efficiency, the injectors must be operating very close to OE design specifications, and hard or active carbon deposits within the combustion chamber must be at a minimal level.

Fuel injectors are designed to operate through several billion cycles during their useful life. Even if a customer drives only 12,000 miles per year, each injector on the engine will need to pulse approximately 18 million times. That's a fantastic amount of use for any mechanical device. Despite this incredible load, most injector designs rarely fail due to mechanical or electrical faults. The most common problem relating to injectors is restriction. Even slight restrictions will skew both the injector's atomization quality and the fuel volume it's able to deliver at a given engine load and rpm.

Given time, contaminants in fuel tanks, fuel lines or the fuel rail—or even in the fuel itself—will always restrict injector flow; that's a fact. Foreign particles such as rust will also accumulate within the injector filter or fuel filters to effectively reduce fuel flow. Extremely small rust particles may even pass through the tiny injector filter itself, causing altered spray patterns as well as reduced injector volume; they may even prevent the injector pintles from seating properly (see photo 1 on page 50).

Whether a pintle is sticking on or off its seat, overfueling of cylinders will always occur. If an injector's pintle is off its seat, not only will the corresponding cylinder be flooded with fuel, but also the PCM (via O_2 sensor feedback) will reduce fueling to other cylinders, causing a lack of performance (and a reduction in fuel economy), and creating the potential for engine, piston or ring damage. On the other hand, if a stuck pintle never opens, that cylinder will receive no fuel at all and the PCM will try to correct a lean bank issue by overfueling the rest of the cylinders on that O_2 sensor bank. These scenarios are common on vehicles whose fuel systems have not been regularly maintained. Injectors need to be very clean for optimum system performance and fuel economy.

Although a PCM (in closed loop) can alter injector flow by reducing injector pulse width, it cannot control a single

posits are a very poor heat conductor, the fuel vaporization process eventually will become less and less effective and, as a consequence, will reduce individual cylinder combustion efficiency, waste fuel, decrease performance and create undesirable emissions.

So exactly how and why does carbon residue accumulate? The singular reason is that there's always some degree of combustion inefficiency in the chamber to begin with. But the wasted energy from incomplete combustion that results in carbon accumulation in the first place (photo 2) can also accelerate and compound the waste of fuel energy.

Hexane is the primary chemical compound found in gasoline. Hard carbon deposits that accumulate in a gasoline engine are always an indicator of wasted energy from incomplete conversion of a specific type of hydrocarbon (hexane) to carbon dioxide. Like any other chemical, hexane can be separated into other substances only by a chemical reaction. In the case of an internal combustion engine, that reaction is known as *combustion*. When the hydrocarbons (HCs) contained in gasoline burn, the chemical reaction involves molecular oxygen. Theoretically, this type of combustion should have only two byproducts left over—carbon dioxide (CO_2) and water (H_2O). Of course, in the real world of a gasoline engine's four-stroke process, the reaction that takes place will never be total and complete.

During the combustion process, heat transforms unconsumed vaporized HCs into a solid or hard substance known as an *activated carbon*. Activated carbon will accumulate on hot components within the combustion chamber with an exceptionally grainy composition containing many small cracks and edges exposed at its surface, making it extremely porous and a natural absorbent of additional raw or unreacted hydrocarbons.

Obviously, PCM cold enrichment strategy is required even in the case of a brand-new engine because sufficient vaporization of atomized fuel on the backs of cold inlet valves is impossible to achieve. But the inevitability of carbon buildup accumulating on the valves will eventually result in cold (and sometimes even warm) engine performance issues such as stumble, sag, stalling, etc. Injec-

faulty individual injector. Just one inefficient injector will affect the overall performance and fuel efficiency of an engine. Aside from issues relating to fuel quality, the environmental heat injectors are subject to will invariably cause internal as well as injector tip clogging. Every day, unburned fuel additives adhere to injector pintles and orifices and will eventually alter injector flow volume and fuel spray patterns. After an engine is stopped, the injector tips become a heat sink and will bake residual fuel and/or fuel additives onto the nozzle tips. Eventually, this will cause such symptoms as lack of engine performance, leaking injectors and damage to other components such as O_2 sensors and catalytic converters when multiple cylinders are overfueled to compensate for one or more underfueled cylinders as the PCM attempts to maintain stoichiometry. But way before these issues become severe, a significant reduction in your customer's fuel economy will occur.

Part of the fuel injector's job is to atomize fuel by physically turning the liquid fuel supplied to the fuel rail into very tiny droplets. But in order for the fuel to be fully combusted and release as close to 100% of its energy as possible, it must be vaporized by the back of a hot intake valve. Only after vaporization can the fuel effectively mix with oxygen to form an efficient combustible mix. Even in a brand-new engine, total vaporization of fuel will never take place. Over time, the problem of inefficient atomization from restricted injectors will build carbon deposits on the valves. Because carbon de-

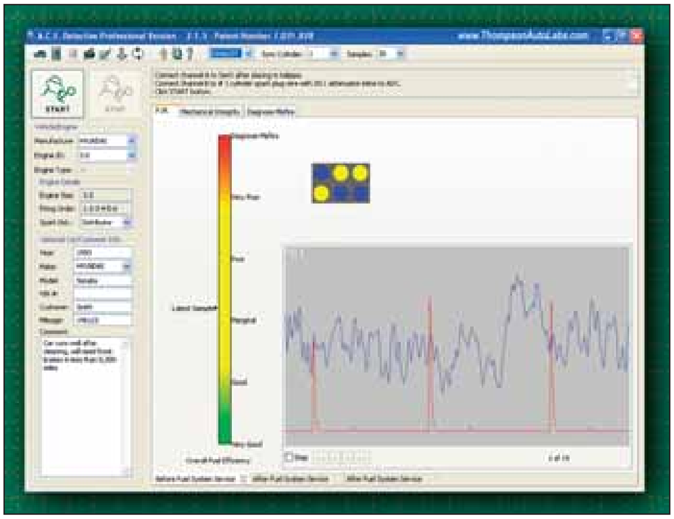


Fig. 1

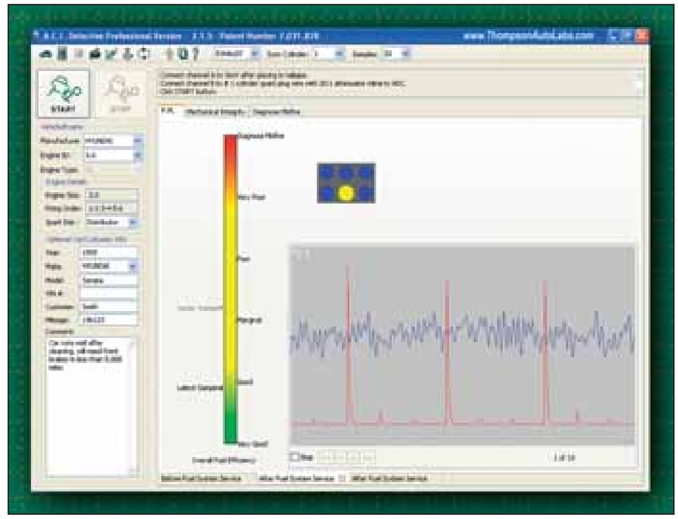


Fig. 2

Screen captures: John Thompson

tors spray their fuel volume very close to the beginning of an intake stroke; it's only later in the stroke that the inlet valve actually opens in order to draw air and fuel into the cylinder. Small portions of the atomized hydrocarbons sprayed by injectors onto the backs of the closed inlet valves will invariably be absorbed and transformed by heat into additional activated carbon residue.

Heavily carboned valves become a very effective fuel sponge, absorbing greater and greater quantities of raw hydrocarbons before they open. This effectively causes a lean air/fuel charge to be drawn into the chamber, resulting in a less efficient combustion stroke with additional unconsumed HCs available to be transformed into activated carbon deposits. Over time, increasingly leaner-than-desired air/fuel mixtures will be created through absorption of raw HCs to preexisting activated carbon during each successive intake stroke cycle. Carbon residue expands more and more, growing like a fungus and all the while wasting energy and creating the potential for other issues such as preignition or poor valve sealing or sticking.

While it's normal to expect that some degree of unconsumed hydrocarbons (and resulting hard carbons) will remain from even the most efficient results of an inherently imperfect combustion process, you should also take the time to look at and point out to your customers what is not "normal." The tailpipe can be a barometer of how much carbon "waste" (and buildup) has been occurring inside the combustion chamber. Obviously, a black and sooty tailpipe indicates greater combustion inefficiency (and fuel waste).

Carbon buildup in the combustion chamber will also affect heat transfer. You might already be aware that an additional heat buildup of just 30° to 40°F from excessive combustion chamber carbon deposits can cause preignition, resulting in a reduction in fuel economy, and that PCM-adjusted timing retard from an active knock sensor signal will cause even greater loss of engine efficiency. But did you know that excessive hard carbon deposits also effectively reduce an engine's volumetric efficiency? During the combustion and exhaust strokes, the cylinder head and piston rings that contact the cylinder walls absorb some portion of the heat of cylinder combustion; however, the piston crown acts as the primary heat sink.

Depending on the heat transfer characteristics of a particular engine, the amount of heat initially absorbed (and temporarily stored) by the piston during the combustion and exhaust portions of the engine strokes can be significant. A portion of this stored heat is inevitably transferred to the air/fuel charge during the intake and compression strokes. Heat transferred to the induction charge should be enough only to improve evaporation of the fuel to avoid condensation on the bore walls. Heavily carboned piston and combustion chamber surfaces that inordinately raise the temperature of the incoming intake mixture into the combustion chamber result in air/fuel

Makers of Carbon-Cleaning Equipment

3M Automotive Aftermarket Div.
http://solutions.3m.com/wps/portal/3M/en_US/3MAutomotive/Aftermarket/?WT.mc_id=www.3M.com/automotive

A & E Hand Tools
www.aeincorporated.com/ae_tools.php

ASNU
www.asnu.com

BG Products, Inc.
www.bgprod.com

BWD Automotive
www.bwdbrand.com

Carbon Zapp, Inc.
www.carbon-zapp.com

CARQUEST Corp.
www.carquest.com

Clore Automotive
www.cloreautomotive.com

Engine Clean Solutions, Inc.
www.engineclean.com

Injectoclean
www.injectoclean.com

Mac Tools
www.mactools.com

Matco Tools
www.matcotools.com

MotorVac Technologies, Inc.
www.motorvac.com

NAPA Echlin
www.napaechlin.com/web_app/cleenPlan/cleen3.aspx

RTI Technologies
www.rtitech.com

Snap-on Tools Co.
www.snapon.com

SPX/OTC
www.otctools.com

Terraclean
www.terraclean.net

Wynn Oil Co.
www.wynnsusa.com

Photos courtesy David Strickland

mixtures that attain relatively higher temperatures at the end of the intake stroke than at its start, and this in turn can reduce volumetric efficiency.

So just like restricted injectors issues, carbon deposits are undesirable, but over time become unavoidable. These energy-absorbing deposits build up not only on components directly exposed to the combustion chamber—such as pistons, rings and valves—but also on injector tips, throttle bodies and EGR passages. Deposits create cold performance and fuel economy concerns long before they show up as a severe driveability issue.

There are other engine components vulnerable to hard carbon accumulation:

Rings. Many of today's engines use aluminum pistons. Since aluminum pistons experience higher thermal expansion characteristics than cylinder bore walls, they must be designed to have sufficient clearance at the most extreme temperature conditions. Naturally, the expansion rates between the pistons and cylinder bore walls will be most extreme under full-load engine conditions, so under part-load operating conditions, the aluminum piston-to-bore clearance must be greater than ideal. This in turn increases the space between pistons and bore wall, increasing the likelihood of carbon buildup in the ring area.

Injectors. Aside from the injector plugging issues from fuel contaminants mentioned earlier, carbon deposits (from heat soak) that build up on fuel injector tips will inevitably cause an uneven fuel pattern spray. As a conical spray pattern deteriorates to unevenly atomized type patterns, an increase in activated carbon buildup will also naturally occur.

EGR. Since no engine is 100% combustion-efficient, some hard carbons will naturally exit through the exhaust system. Activated carbon "waste" will then be reintroduced through the EGR system and tend to accumulate and clog EGR passages. Engines suffering from excessive oil consumption issues can also add to the problem. Oil-based carbons can build up when piston rings become worn, enabling oil to leak past the rings from the crankcase. Oil can also be drawn directly into the combustion chamber from worn intake valves or guides. Oil-based carbon deposits will appear to have a gummy and tarlike consistency, as opposed to the drier activated carbon deposits from an inefficient or incomplete combustion process.

Spark Plugs. According to at least one spark plug manufacturer, carbon fouling accounts for around 90% of all spark plug troubles. NGK states that carbon deposits that build up on the firing end of the insulator nose of a spark plug will form a conductive path from the center electrode and down the insulator nose to where the insulator meets the metal shell for the electrical current to leak through. When voltage is applied, under certain conditions, the carbon path may sink enough current to prevent sufficient voltage to build up at the gap, and ignition misfire will occur.

Carbon deposits can also accumulate on the throttle body and intake manifold as well as in the catalytic converter and on oxygen sensors. Underlying component faults that cause cylinder combustion efficiency to be any less than what the engine was designed to deliver when new will accelerate the ticking of the carbon time bomb. For example, if the ignition system produces lower-than-normal spark kV in one or more cylinders, less HC will be combusted and increased deposits will accumulate. Too much fuel in the chamber (running rich), EGR system faults and dirty, dripping or clogged fuel injectors all will lead to combustion inefficiency and more wasted energy that will accumulate in the form of uncombusted and activated hard carbon deposits in the combustion chamber. That's why you should always recommend a good decarbonization procedure after performing an emissions-related repair that your customer has neglected for some time.

Photo courtesy BG Products

Photo courtesy Terraclean

From an emissions standpoint, the same environmental concerns that drove the development of unleaded fuels, higher energy ignition systems and electronic fuel injection also greatly reduced carbon deposits. Just three decades ago these deposits could accurately be described as massive. Further reduction in carbon deposits were realized later by the addition of various chemicals to create detergent fuels, which help keep excessive carbon deposits from adhering to hot metal surfaces like intake valves and fuel injectors. However, carbon waste deposits have reappeared with a vengeance in recent years. Since the EPA first established the minimum additive performance standards in 1995, most gasoline marketers have actually reduced the concentration level of detergent additives in their gasolines by up to 50%!

Fuel octane and the quality or type of fuel used in an engine can also be an area of concern. Driveability Index (DI) is a measure of gasoline's total volatility, or tendency to vaporize completely. A high DI number is less volatile than a low number. Premium grade gasoline is rated at a higher DI (less volatile) than regular or midgrade gasoline. Since fuels with a higher DI number or octane burn more slowly, higher compression ratio engines typically use higher octane fuels to avoid heat-induced preignition. Conversely, when using a high-octane (less volatile) fuel than an engine was designed for, fuel will burn too slowly, resulting in incomplete combustion, increased carbon deposits and driveability concerns such as increased cold start, warm-up sags, hesitations and stalling at moderate ambient temperatures.

Reading to this point should convince you that in order for an engine to achieve maximum fuel economy, each individual cylinder must be operating at maximum efficiency. In the case of a customer's apparently "good"-running engine, maximum fuel economy is dependent not upon the engine as a whole but on each individual cylinder operating with clean combustion chambers and injectors to achieve maximum individual levels of combustion efficiency.

Idle quality can be a very useful indicator as to individual cylinder efficiency of an engine with no apparent performance issues. Have you ever noticed how the idle quality of a quivering engine significantly improves after a good fuel and induction system service? Engines shake because the relative combustion inefficiencies between individual cylinders also create an imbalance in the power of their respective combustion strokes, and the degree of the imbalance directly relates to the intensity of the quiver. The subsequent exhaust strokes of inefficient individual cylinders will likewise produce asynchronous pressure pulses exiting through the tailpipe.

Perhaps you remember the age-old test of holding a rag in the exhaust stream at the tailpipe. If the rag was periodically sucked back toward the tailpipe, it was an indication that a cylinder was misfiring. Well, guess what? Any combustion inefficiency in a cylinder is a

Photo courtesy Carbon Zapp

"partial" misfire, and the same principle applies. Uneven exhaust pulses are driven by the unequal partial pressure of oxygen (PpO_2) contained in a less efficient cylinder's exhaust stroke. If all cylinders of an engine are combusting with the same relative efficiency, the PpO_2 of each individual cylinder's exhaust stroke will be identical. On the other hand, dissimilar pressure from combustion-inefficient cylinders will create repeating asynchronous pressure waves in the exhaust.

Exhaust stroke pressures will vary in direct relationship to the relative combustion efficiency of each cylinder and can now be measured in real time by software capable of analyzing individual cylinder exhaust strokes via signals from a pulse sensor inserted into the tailpipe. A screen shot of the ACE Detective-PM software shown in Fig. 1 on page 48 displays a sample of each cylinder's exhaust stroke pulses (blue) referenced between one cylinder's ignition event (red) on a V6 engine. The waveform shows an example of an engine with inefficient combustion (flagged in yellow by the software's cylinder and bar displays) in a number of cylinders. The disparity in exhaust stroke pressures between cylinders on an otherwise apparently good-running engine indicates that a fuel injection and decarbonization service may be needed on this vehicle. Fig. 2 shows a drastic improvement in the relative ex-

Photo courtesy Carbon Zapp

haust stroke pulses after such a service was performed.

So how will you service your customers' fuel injector and carbon issues? A variety of carbon-cleaning equipment is available, and a list of suppliers is provided on page 48. One of the simplest methods is a chemical additive that's introduced to the plenum and fuel rail through a delivery system suspended from the hood by a hook, such as BG Products' Inject-A-Flush (photo 3 on page 50). This type of equipment is pressurized by shop air to introduce strong chemical solvents to the fuel rail and induction systems in order to clean fuel injectors and help remove upper engine deposits.

A second option includes on-car cleaning machines that are connected to the vehicle's fuel system inlet and return lines with vehicle-specific adapters (photo 4 on page 52). This type of machine bypasses the fuel supply from the vehicle tank, replacing it with the fuel/solvent tank located inside the machine. A mixture of chemical cleaning solution and gasoline is supplied to the fuel rail to pass through the injectors and run the engine. Carbon and other contaminants in the injector nozzles, on the intake valves, in the combustion chamber, on the O_2 sensor and in the catalytic converter are removed and exit through the exhaust system.

Even this type of cleaning is typically only about 75% effective (or less) in cleaning fuel injectors. For this reason, both the first and second type of injector-cleaning equipment may be best suited for preventive maintenance types of services rather than for solving driveability issues arising from high-heat-soak engines or from injectors clogged by sediments such as rust or water contamination of ethanol blend fuels. Introducing solvents to an engine to chemically remove carbon does do a reasonably effective job in cleaning the tops of intake valves, but potentially plugged or disintegrating injector pintle baskets are not replaced and you have no way of knowing their condition. The high-heat-soak conditions typical in the drive cycles of today's traffic-challenged commuters harden deposits trapped in injector inlet screens, and the injectors themselves make a totally effective chemical cleaning impossible. Even though some contaminants may become soft enough for chemicals to dislodge, some or all of the injectors may not be cleaned. Leaking injectors, weak pintle springs and poor spray patterns, among other potential problems, may still exist.

The most thorough cleaning and evaluation of fuel injectors can be performed only by physically removing injectors from the engine, followed by cleaning without using caustic chemicals. Off-car cleaning equipment utilizes ultrasonic baths (photo 5 on page 52) that produce sound waves well above the range of human hearing (33 to 40kHz), achieving total injector restoration. This method immerses the injectors in a nonflammable ultrasonic cleaning agent (typically linear alcohol and sodium silicate) contained within a basin.

Contrary to what you might assume, the application of sound waves at extremely high intensity and high frequency does not directly "shake" the dirt and debris loose from the injectors. Ultrasonic frequencies cause air bubbles to form within the bath. The energy released from the collapse of millions of microscopic cavitations while the injectors are electronically pulsed is what actually cleans the dirt from the injectors. As the bubbles formed in the cavitating fluid collapse, they form tiny but powerful jet streams of pressure directed at both internal and external injector surfaces.

After cleaning, injectors can be fitted to the rail of a flow bench for testing. The initial test is electrical, to check each injector's resistance. Resistance readings are noted and each injector is compared to the others for differences between a matched set of injectors. To eliminate the possibility of electrical faults before the injectors are reinstalled to the engine, it's critical to test the coil winding resistance while injectors are in a "powered-up" or loaded condition. Some units automatically test injector windings for shorts or opens while flowing current through the coils. If any injectors fitted to the rail are noted to be out of the normal resistance range, an alarm will sound and those injector(s) will be displayed on the control panel before flow testing begins.

Next, multiple spray pattern and flow volume bench tests can be performed (photo 6). All of the injectors should be flow-tested in both static (wide open) and dynamic (pulsed) modes. A series of timed tests that range from 15 to 120 seconds to cover a wide pulse-width delivery rate are necessary to ensure that injectors will be capable of delivering good volume and spray patterns before reinstallation.

Now that you know the facts, it's up to you. Explain to your customers that decarbonizing the combustion chamber and servicing injectors can not only deliver an immediate reduction in their overall fuel consumption (and cost) but also reduce their long-term costs (and vehicle down time) in diagnosing driveability faults. Ignoring these two vital PM services will also inevitably create the need to repair intake valve carbon damage and cause unnecessary lambda sensor and catalytic converter failures and replacements.

Don't let a dark cloud of carbon buildup conceal the reality of its silver lining. M

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