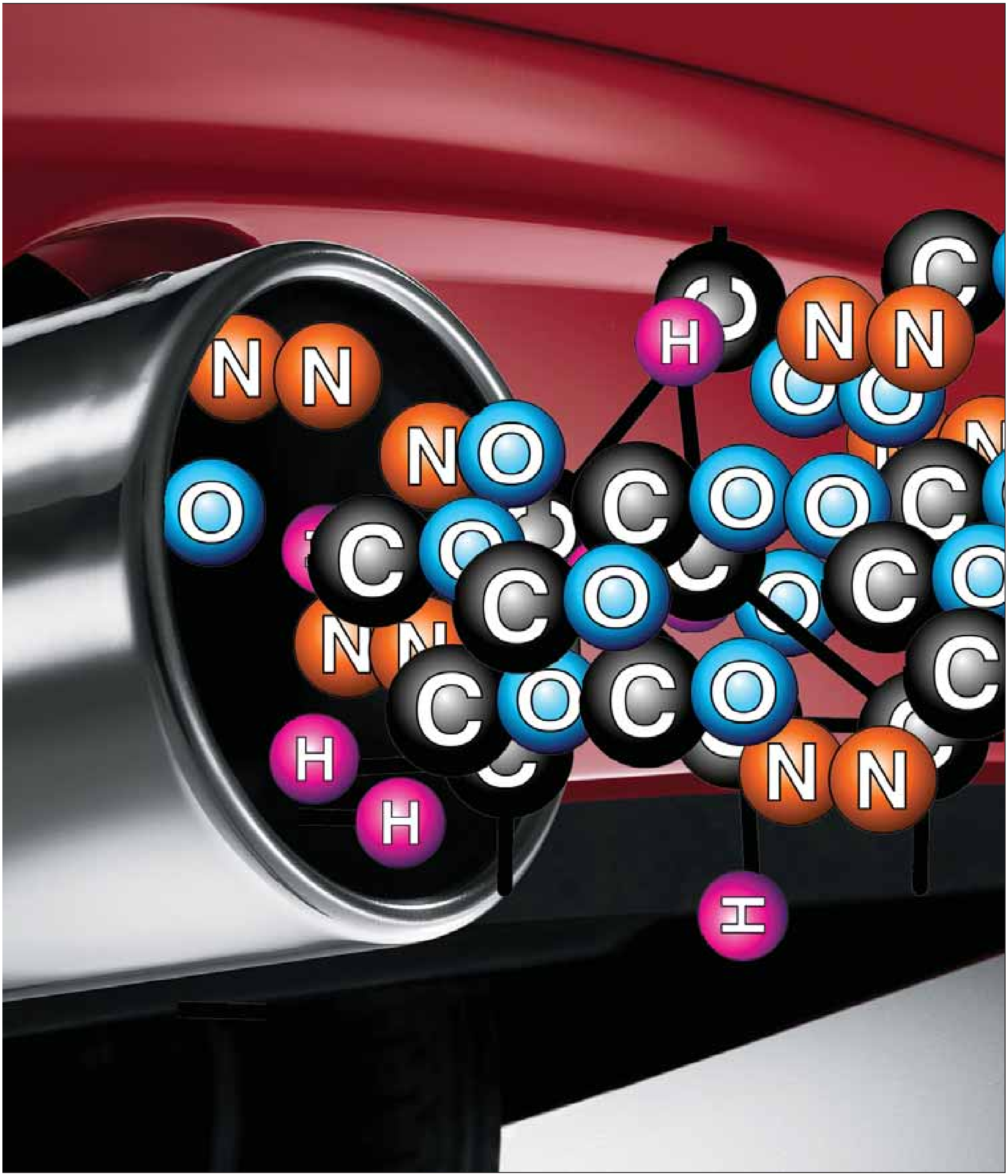
PUT THAT IN YOUR PIPE: 5-GAS ENGINE ANALYSIS

By Bernie Thompson

Understanding the chemical reaction that occurs in the combustion chamber as well as the relationship among the five exhaust gases will allow you to quickly identify the cause of engine running problems.

Photo illustration: Harold Perry; waveforms, charts & illustrations: Bernie Thompson

The time: the height of World War II. The place: North Africa. After many defeats in the African desert at the hands of Rommel and his armored division, we could now experience the sweet scent of victory. Filled with uncertainty one night, I couldn't sleep, and walked around the camp thinking of what was to come at



daybreak. I noticed an officer across the camp reading by a faint light and walked over. It was our new Field Commander, General Patton. He was reading Rommel's book on warfare. *Wow!* I thought to myself. *He's reading the enemy's book!* Hearing me approach, Gen. Patton paused for a moment and looked up. Noting my surprise, he explained, "In order to win against your opponent, you must first study him. You must understand him. Then and only then can you predict his actions on the battlefield."

As I emerge from my reminiscence, I realize it's the same (almost) with a problem automobile engine. Every day in your service bay you must fight an all-out war, you against the vehicle! And in order to be victorious, you, too, must know your opponent.

A chemical reaction powers the internal combustion engine. In order for this chemical reaction to take place, many things must occur in the correct order. When any of these events fails, this reaction will change.

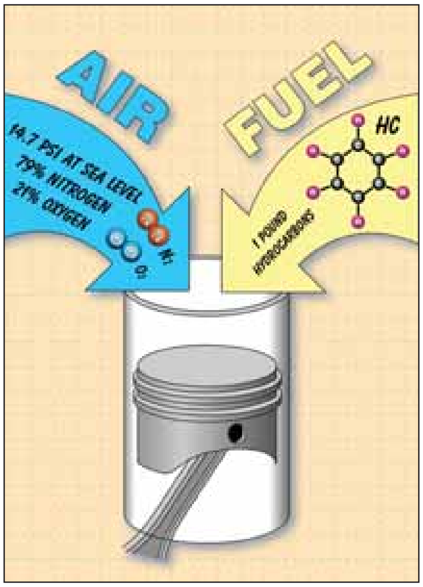


Fig. 1

Knowing what these changes are, and why they occur, will guide you in successfully repairing the vehicle.

A spark ignition (SI) engine draws air into the cylinder by creating a pressure differential. It does this by the downward movement of the piston with the intake valve in the open position. Air enters the engine at 14.7 psi (at sea level). Atmospheric air is composed of approximately 79% nitrogen (N_2) and 21% oxygen (O_2). The fuel control system then adds a hydrocarbon (HC)—in this case gasoline—into the intake or directly into the cylinder (Fig. 1). The intake valve then closes and the piston starts its upward movement. As piston movement increases, the volume in the cylinder becomes smaller. This creates energy in the form of heat.

The mechanical force of the piston stroking upward causes the gas and air molecules to accelerate inside the cylinder. As these molecules accelerate, they collide with each other. These collisions are perfectly elastic, so when the molecules collide, the energy is transferred from one molecule to another. This creates heat energy that's transferred to the gases within the cylinder. Some of this heat energy is transferred to the cylinder walls. If the walls are the same temperature as the gas, then some gas atoms lose energy and some gain energy, the average temperature staying the same. If the walls are hotter than the gas, more atoms gain energy than lose energy and the temperature of the gas increases. If the compression occurs faster than the energy can dissipate into the cylinder walls, the temperature of the gas mixture will rise. This heat energy will be gained by the hydrocarbon chains, which, under the right conditions, will cause complete combustion to occur.

You can see that this heat energy is very important; it's crucial when igniting the air/fuel mixture. This heat energy reacts with the hydrocarbon chain to excite the bonds between the carbon and hydrogen atoms and causes them to become unstable. The hotter the HC bond, the more unstable it becomes and the easier it is to break.

The purpose of the spark ignition engine is to break the hydrogen-carbon and carbon-carbon bonds. The hydrogen is using energy to hold onto

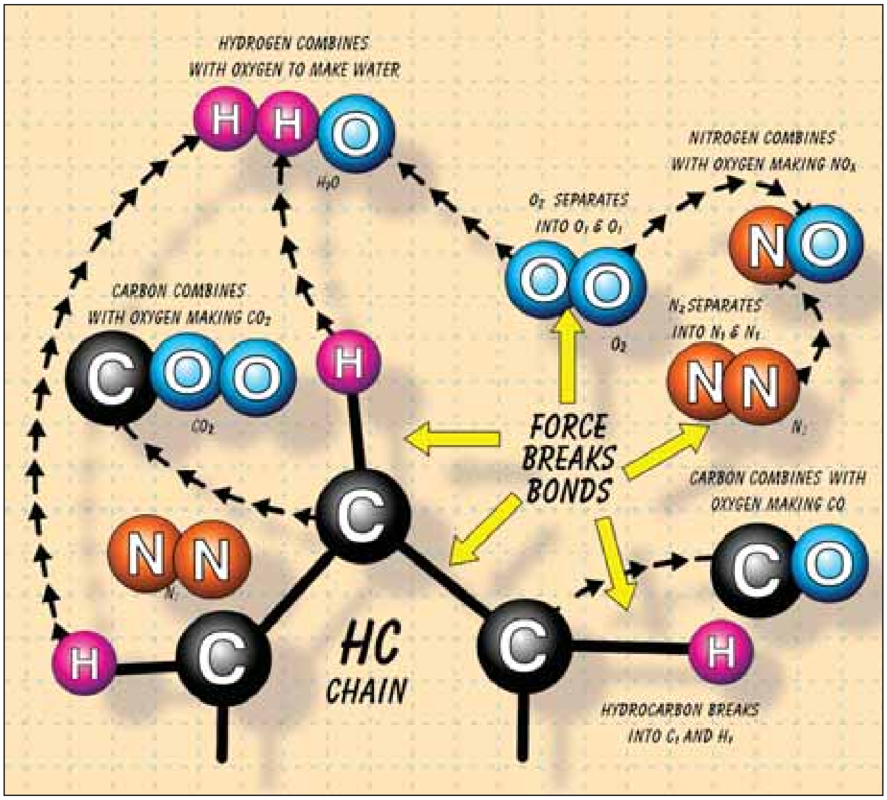


Fig. 2

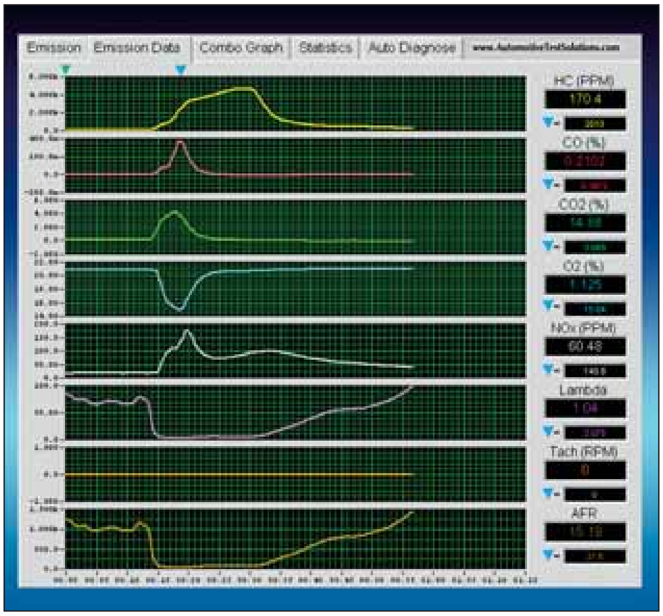


Fig. 3

	Maximum	Minimum	Average	Standard Deviation
HC (PPM)	4662	72.91	1792	1776
CO (%)	0.3716	-0.00869	0.03141	0.08314
CO2 (%)	4.269	0.007156	0.6664	1.175
O2 (%)	20.95	14.87	20.07	1.655
NOx (PPM)	176.9	15.86	64.91	43.77
Lambda	86.08	2.547	31.68	31.45
Tach (RPM)	0	0	0	0
AFR	1257	37.19	465.4	459.2

Note: Statistics are calculated on data between the two sliders ▼&▼

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Fig. 4

the carbon atoms and the carbon is using energy to hold onto other carbon atoms. If these bonds are broken, then this energy is no longer needed to hold together the HC chain. This energy being freed from the HC bond is what powers the internal combustion engine.

It's important to understand that the atoms are being held together with force. In order to break this bond, more force must be applied to the bond than the force that's holding the atoms together.

In an SI engine, when the compression is at its peak pressure, the HC bond loosens for a split second. At this precise point, the spark needs to ionize across the spark plug electrodes. When the spark occurs, it applies more force than the HC bond was held together with. The hydrogen and carbon atoms will now be separated from one another.

However, if the hydrocarbon chain is completely broken down to its individual atoms and there's no oxygen to reform with, the hydrogen and carbon will reform into the same HC molecule it had been before it was broken apart. In this case, no energy would be released.

This is what happens in the combustion process. The oxygen and hydrocarbons are heated and become unstable. The HC bond is then broken by the shock wave of the spark ionizing across the spark plug electrodes. The carbon being freed from the hydrogen is attracted by the oxygen and bonds with it, forming new compounds (see Fig. 2 on page 42).

As we said, the atmosphere is comprised of 21% oxygen and 79% nitrogen. Nitrogen is not a reactant. Its sheer mass has to be accounted for because it produces heat energy during compression. During the reaction inside the combustion chamber, the nitrogen will not release energy, but as the reaction between the oxygen and hydrocarbons occurs, the oxygen and hydrogen will push against the nitrogen in the cylinder. The reactants that will release the energy upon ignition are hydrocarbons and oxygen. In a chemical reaction, it's important to have the proper weight ratio of the compounds reacting with one another. If the weight ratio of the reactants is correct, then at the end of the reaction, neither chemical that you started with will be present. This is a balanced reaction.

In an internal combustion engine, total combustion efficiency is not possible. Hydrocarbon chains will be forced into crevices such as ring lands and valve pockets. Metal surfaces—such as the cylinder wall—will also take on heat, allowing some of the HC chains to escape combustion. In this case, the hydrocarbons and oxygen molecules will break apart and recombine as carbon monoxide (CO) and carbon dioxide (CO_2). The hydrogen will combine with oxygen to form H_2O—water. Low levels of HC will also be present. Under these conditions, oxides of nitrogen (NO_X) will be produced as well.

When gasoline burns, the proper weight ratio is 14.7 lbs. of air (or the air pressure at sea level) with 1 lb. of fuel. This is considered to be the proper chemical ratio, or stoichiometry. This is also referred to as a Lambda of 1. If by weight the air is greater than the fuel, Lambda will increase. For example, a lean mixture by 10% would equal 1.10 Lambda. If by weight the air is less than the fuel, Lambda will decrease. A rich mixture by 10% would equal .90 Lambda.

An example of a rich mixture would be a burning candle (fuel) with a drinking glass over it. The candle would use up all of the oxygen in the glass and stop burning, leaving most

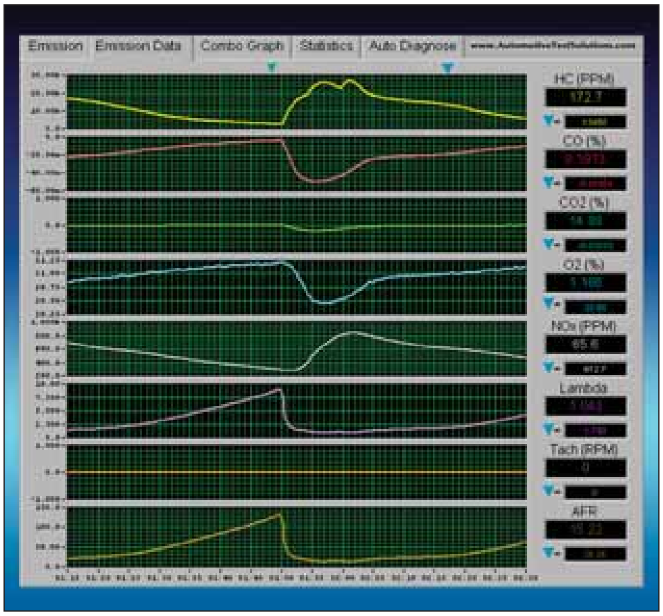

Fig. 5

	Maximum	Minimum	Average	Standard Deviation
HC (PPM)	27030	2703	17590	6393
CO (%)	-0.003663	-0.05001	-0.02897	0.01325
CO2 (%)	0.001811	-0.2058	-0.07866	0.06434
O2 (%)	21.22	20.44	20.84	0.2325
NOx (PPM)	840.8	281.7	621.3	184.7
Lambda	9.047	0.8771	1.95	2.001
Tach (RPM)	0	0	0	0
AFR	132.1	12.81	28.47	29.22

Note: Statistics are calculated on data between the two sliders: ▼&▼

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Fig. 6

of the candle (a large amount of fuel) in the glass unburned.

An example of a lean mixture would be a single match (fuel) burning with a drinking glass over it. The match would burn completely but there would still be oxygen left in the glass.

An example of a stoichiometric mixture would be several matches (fuel) burning with a drinking glass over them. In this case, all of the matches would burn completely and would use all of the oxygen in the glass. As the air/fuel mixture changes, the burn rates also change. A rich mixture burns much faster than a lean mixture. This will change the gas traces at the tailpipe.

The abundance of fuel makes a very hot flame front that rapidly burns the hydrocarbons. The burning hydrocarbons use up all of the oxygen before all of the hydrocarbons burn. This leaves partially burned hydrocarbons, or CO, in the combustion chamber. In a rich condition, the tailpipe readings show high levels of CO, low levels of O_2, slightly higher levels of hydrocarbons and lower levels NO_X.

NO_X forms at temperatures greater than 2500°F or at very high pressures. In a slightly rich condition, the flame front is at its highest peak temperature and the NO_X is at a lower level. This is because the flame front is moving very rapidly, which does not allow enough time to break the nitrogen down so it can combine with oxygen. In a rich condition, the lack of oxygen also contributes to the low level of NO_X produced.

An example of a lean condition would be a prairie fire. Since the grass is sparse, the flame front moves across the grasslands slowly, missing many clumps of grass. Inside the cylinder a lean air/fuel mixture burns the same way. The flame front moves slowly, missing many of the hydrocarbon chains completely. This lean condition leaves the cylinder with high levels of HC, high levels of O_2, low levels of CO and low levels of CO_2. Since the flame front is moving slowly, there's more time for the nitrogen to break apart, and with the abundance of oxygen, it easily combines to form high levels of NO_X. The effects of engine variables such as load, speed, ignition timing and injector timing will all have an effect on tailpipe emissions. It's not possible to cover all of these variables in this article, but if you understand the basis of the chemical reaction, you'll have the basic tools you need to understand the emissions problems in your service bay.

Now that we have a better understanding of the combustion process, let's look at three no-starts, a hard hot start and a misfire on a six-cylinder engine.

No-Start 1. An exhaust probe was placed in the tailpipe and the engine was cranked for 8 seconds. The gas traces were then put into two formats: The first (Fig. 3 on page 44) is a graph of the gases and the second (Fig. 4) is a statistics chart of the gas traces. During this no-start, HCs climbed to 4662 ppm. This may seem high but actually is quite low. During a no-start condition, the HC concentration can reach a level of 30,000 ppm. The CO level is also low, at .3716%. The CO_2 level is also low, at 4.26%. The O_2 level has not dropped very far, moving from 20.95% to 14.87%. The NO_X level has climbed to 176.9 ppm, while Lambda dropped to 2.54 and the air/fuel ratio dropped to 37.19:1.

One key here is that oxygen was converted with hydrocarbons to form CO and CO_2. This means a spark had to be present in the cylinder. In order to break the hydrogen-carbon bond, a force must be applied that's greater than the force holding the molecules together. This force is generated by the ignition coil. If the spark fails to ionize across the spark plug electrodes, the hydrocarbon chain will not break down.

	Maximum	Minimum	Average	Standard Deviation
HC (PPM)	16490	5947	13210	3225
CO (%)	0.07075	0	0.01777	0.0263
CO2 (%)	2.147	0.5252	1.372	0.5679
O2 (%)	19.91	18.42	19.05	0.4923
NOx (PPM)	119.7	40.97	85.11	26.99
Lambda	2.821	1.279	1.645	0.4522
Tach (RPM)	0	0	0	0
AFR	41.19	18.67	24.01	6.602

Note: Statistics are calculated on data between the two sliders: ▼ & ▼

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Fig. 7

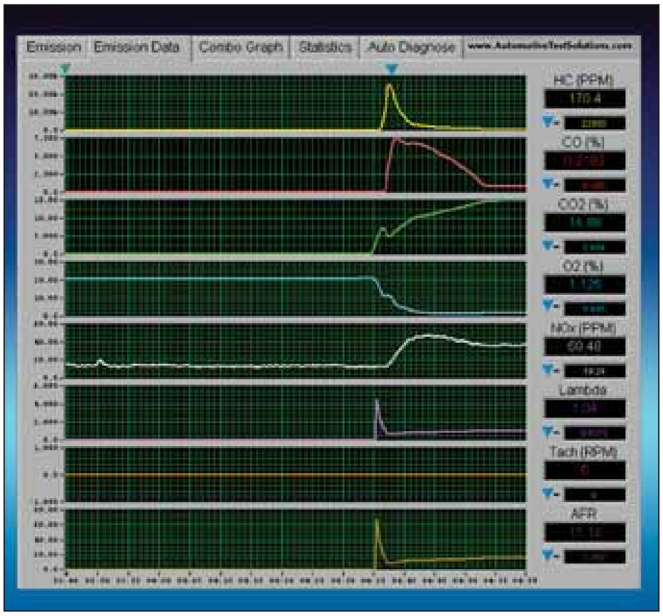

Fig. 8

A second key is that Lambda is 2.54. This is 2.5 times too lean. This engine has a low fuel delivery problem. The fuel pressure and volume or the injector ON-time or flow rate should be checked.

No-Start 2. An exhaust probe was placed in the tailpipe and the engine cranked over. The gas traces were then put into two formats: The first is a graph (Fig. 5 on page 48) and the second is a statistics chart (Fig. 6). HC climbed to 27,030 ppm. CO reached only .003663%. CO_2 max is only .001811%. O_2 dropped from 21.22% to 20.44%. NO_X rose to 840.75 ppm. Lambda dropped to .877, with an air/fuel ratio of 12.81:1.

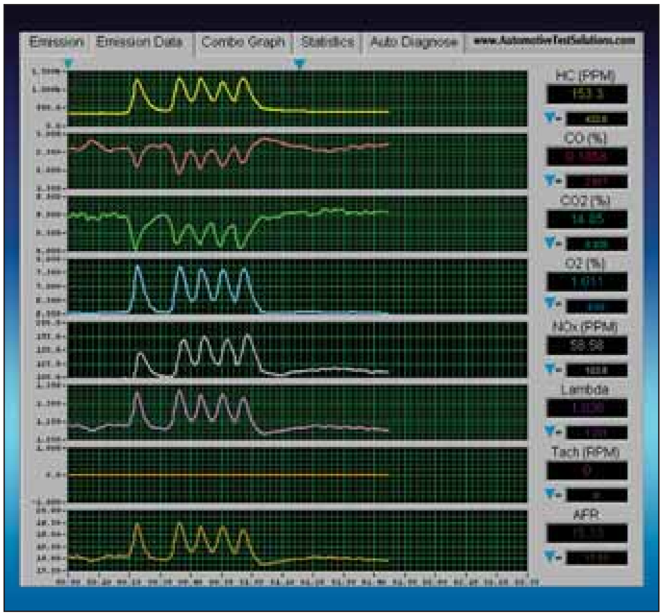

Fig. 9

What can we learn from these numbers? The HC level of 27,030 ppm is good during a no-start. This is confirmed by the Lambda reading of .877. This is approximately 12% rich, which would be correct for a cold start. The key to this puzzle is the CO and CO_2. The O_2 did not combine with carbon, because there wasn't enough force to break down the hydrocarbon chain. If the spark does not ionize across the spark plug electrodes, the hydrocarbon chain will not break apart. Under this condition, the carbon molecules will not be released, so neither CO or CO_2 will form. If the engine was running and then died, there would be trace amounts of CO and CO_2 left in the tailpipe.

Crank the engine for 8 to 10 seconds to clear the exhaust system. Let the starter cool and then crank the engine over for 8 to 10 seconds to run the test. In this example, the ignition system should be checked.

No-Start 3. An exhaust probe was placed in the tailpipe and the engine was cranked (Fig. 7). HCs reached 16,490 ppm. The CO level climbed to .07075% and CO_2 to 2.14%. The oxygen exhibited very little change. NO_X reached 119.7 ppm. Lambda dropped to 1.27, with an air/fuel ratio of 18.67:1. At first this appears to be a lean air/fuel mixture. With a Lambda of 1.27, this is 27% too lean. The keys to unraveling the puzzle with this no-start are the HC and CO. With a reading of 2.14% CO_2, you know that spark occurred. The HC delivery at 16,490 ppm under good ignition would produce a higher CO reading than .07075%. For good ignition to occur, there are many things that must happen in the correct order. If spark does not occur at the correct time, complete ignition cannot happen. This engine has a timing error. The ignition timing, firing order or cam timing must be checked.

Hard Hot Start. An exhaust probe was placed in the tailpipe and the engine was cranked over until it started (Fig. 8, opposite page). HCs climbed to 25,280 ppm. The CO level rose to 7.49%, CO_2 to 14.98%. The O_2 reading dropped from 21.15% to 1.39%. NOx rose to 47.44 ppm. Lambda dropped to .60, with an air/fuel ratio of 8.835:1.

What do these numbers mean? Both the HC and CO readings are high. Lambda is the key to unraveling this mystery. At .60, the air/fuel ratio is 40% too rich. Notice the bump in the CO_2 and O_2 traces. The CO_2 started to climb, then dropped, then started to climb again. This shows that the overfueling problem existed only at start-up. The question here is, where did the extra fuel come from? To find out, once the engine starts, allow it to run until the gas traces stabilize, which is after about 10 to 15 seconds. Now shut the engine off and wait about 2 minutes, then restart it. If the mixture is still very rich, the problem is in the fuel injection system. The engine coolant temperature sensor is a likely culprit. If the mixture is now good, additional fuel is leaking into the intake manifold. The injectors, fuel regulator or fuel line should be checked to find this leak.

Misfire. In Fig. 9, the six-cylinder engine was running with the exhaust probe in the tailpipe. The cylinders were then killed one at a time by removing spark from the cylinder. HC and O_2 are the traces to check. Since these are the chemicals reacting with each other, if spark does not occur in the cylinder, these gas traces will be the best reflection of the bad cylinder. Note that there was little change when the second cylinder spark was killed. HC rose only 60 ppm. This is HC residue left over from the first cylinder killed. What this means is that HC did not change during the cylinder kill. The O_2 level was 6% before the kill sequence and during the second kill, the oxygen was still at 6%. HCs and O_2 remaining unchanged during the kill indicates this cylinder has no fuel being injected. The fuel injector and/or the injection circuit must be checked on this engine.

Understanding the gas traces and the chemical reaction that occurs in the combustion chamber is critical to targeting engine problems very quickly. These are only a few examples of how an exhaust gas analyzer can be used in your service bay. M