FIRE IN THE HOLE

Understanding Ignition Waveforms

By Bernie C. Thompson

The ignition waveform is a window that allows you to see what's occurring in the combustion chamber. Join us for a closer look.

From its humble beginnings, the internal combustion engine has been transformed many times over to produce more power and to be more efficient. Today's internal combustion engine comes in two forms: compression ignition (diesel) and spark ignition. We will analyze the spark ignition (SI) system here. At this point, it's still the dominant system in use in this country.

It's important to understand how energy is released in the SI engine. In an internal combustion engine, the air/fuel mixture is drawn into the cylinder, where it's compressed. As the air/fuel mixture is compressed, the molecules are forced into a smaller space. This causes them to run into each other, which creates friction and heat.

It takes energy to hold together the different atoms that form the molecular chain of the fuel molecules. In order for the fuel to release this energy, the fuel molecules must separate, or break apart, then reform into a different molecular structure with a lower energy state. Once the fuel molecules are broken apart, the energy used to hold everything together is no longer needed. This freed energy is what powers the internal combustion engine.

In an SI engine, cylinder compression alone does not provide enough energy to separate the fuel molecules. The heat that's transferred into the fuel molecules makes it unstable, but more force must be applied to separate the atoms contained in the fuel molecules. It would not be easy to separate two wrestlers locked together in combat. To separate them you'd have to apply more force than they're using to hold on to each other.

A stun gun that applied a spark of 100,000 volts would do the job. The potential energy supplied by the stun gun

Photo courtesy General Motors; illustrations: Roy E. Thompson, Jr. & Blue Soroos

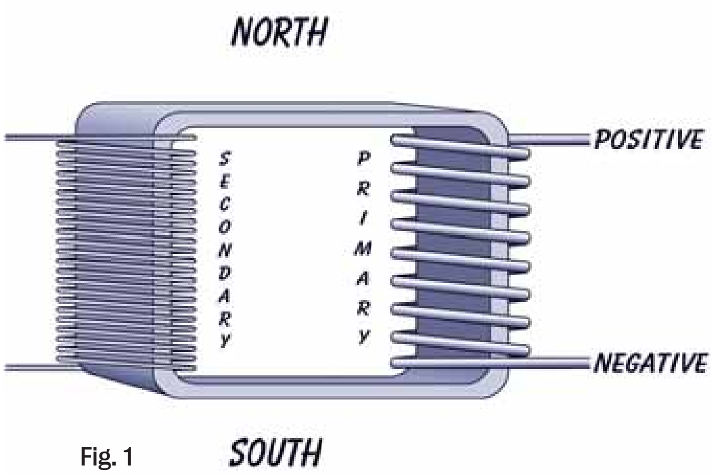

Fig. 1

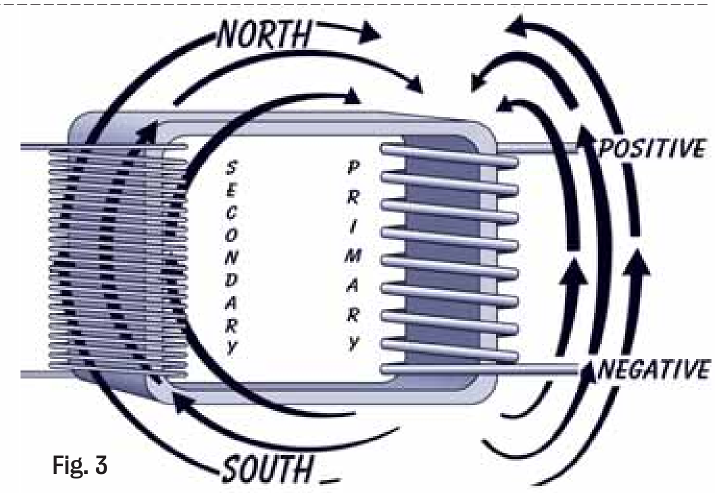

Fig. 3

is greater than the energy the wrestlers are using to hold on to each other, so they would let go and separate. Even though the cylinder compression creates heat energy, more force is needed to separate the fuel's molecular structure and release its energy. That force is supplied by a high-energy spark from an ignition system.

Many different types of ignition systems have been used to supply the high-energy spark necessary to ignite the air/fuel mixture. The most popular system in use today is the step-up transformer, which uses a low-voltage, high-current pole to create a high-voltage, low-current pole. This is accomplished with two different coils, or windings, of wire. The first coil is the primary and the second coil is the secondary (Fig. 1). The primary is wound around a core for magnetic amplification. In newer transformers, this core is composed of many plates of a ferrous metal (usually soft iron), layered or laminated together. This gives better amplification than a solid core.

The primary winding uses larger diameter wire with fewer windings. This allows the primary to have a very low resistance value. The secondary uses smaller diameter wire with many more windings to produce a higher resistance value. The automotive coil is usually wound at a ratio of approximately 1:100. In other words, for each turn of the primary winding, the secondary has 100 winding turns. The primary winding resistance is normally in the range of 1 to 4 ohms, while the secondary winding usually has a resistance of 8000 to 16,000 ohms.

The primary and secondary windings are insulated from each other via transformer oil or epoxy. Transformer oil can hold off a breakdown voltage of only 20kV to 25kV, so in newer high-energy transformers, vacuum-sealed epoxy that can hold off a breakdown voltage of 50kV is used instead. The primary and secondary are electromagnetically coupled, so anything that affects one winding is mirrored in the other.

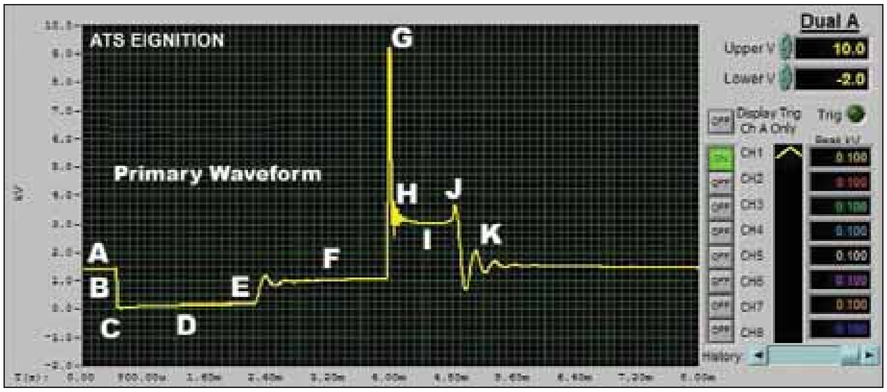

Fig. 2

The step-up transformer uses electromagnetic induction to produce the necessary spark energy. To understand how the transformer works, let's look at the waveform produced by this device, beginning with waveform segment A in Fig. 2 below. (We'll keep referring to this waveform.) This is the open-circuit voltage, or source voltage, because the circuit has not been completed. There's no current flowing through the primary circuit at this point. The voltage then drops abruptly when the module driver is turned on, thus completing the primary circuit to ground (waveform segment B). This voltage drop will come very close to ground.

The initial voltage drop depends on whether the driver used to control the current is a transistor or a MOSFET. If a transistor is used, the voltage drop will be .7 to 1 volt. This is due to the resistance across the transistor's gate. A MOSFET has less resistance across its gate, causing a lower voltage drop of about .1 volt to .3 volt. The initial voltage drop is the voltage that remains in the circuit to push the current across the resistance of the module driver or gate (waveform segment C).

Once the module closes the driver, current starts to flow through the primary winding circuit. When current flows through a coil winding, all of the current is used to create a magnetic field around the winding (Fig. 3). This magnetic field buildup is called inductance. The magnetic field is proportional to the inductance and the current. In other words, the larger the current, the larger the magnetic inductance.

As the magnetic field builds, it moves across the primary and secondary windings, inducing voltage in both. However, the effect of this induction is different within the two windings. As the magnetic field builds and moves across the secondary winding, it induces electromotive force (emf) and frees electrons. This can be seen in the secondary waveform when the module driver closes. There are voltage oscillations when the circuit is first completed (Fig. 4). This is caused by the magnetic field moving across and inducing voltage in different windings contained within the secondary coil winding.

Capacitance exists between the coil windings. It occurs when two conductors are separated by space and current is flowing through them. Electrical potential builds between the two conductors. The size of the conductors and the distance between them determines the amount of capacitance.

Ringing occurs in the circuit as energy changes between electrical and magnetic energy. These ringing oscillations diminish into a steady curve that flattens out when the coil has become saturated. The saturation point will vary depending on the amount of current flowing through the primary, the amount of resistance and the number of turns within the winding.

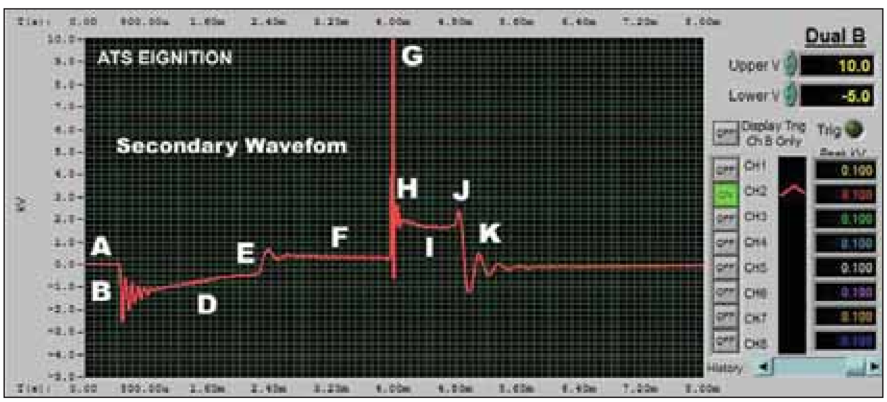

Fig. 4

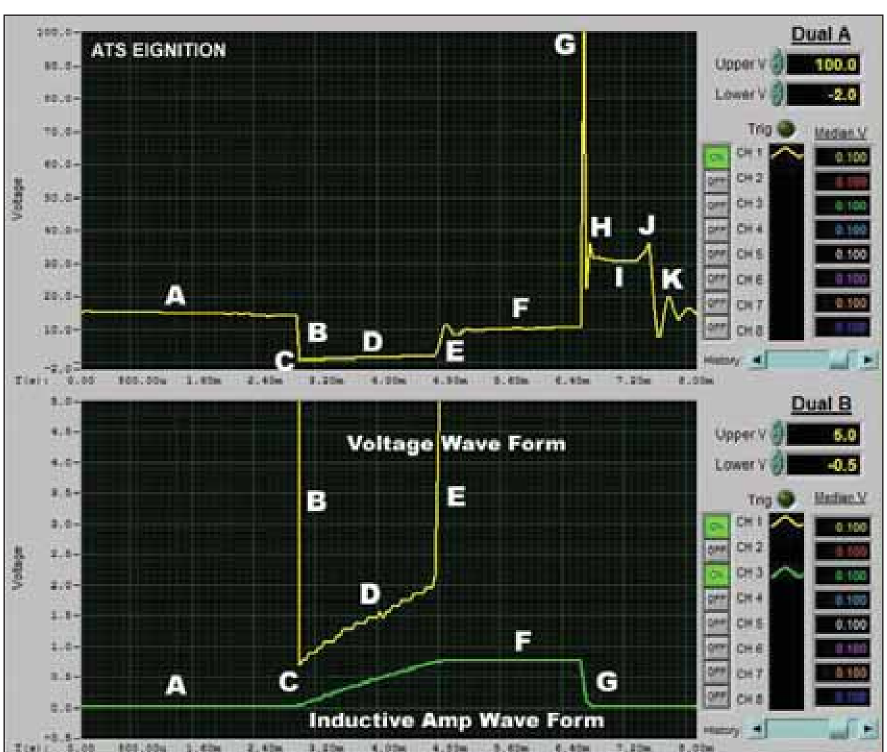

Fig. 5

As the magnetic field builds and moves across the primary winding, the voltage that's induced into the primary winding frees electrons. However, since current is flowing through the primary winding, these free electrons impede the current flow. In my previous article on fuel injectors (January 2005), I gave the example of a school hallway packed shoulder-to-shoulder with children to illustrate this problem. The example also works for ignition coils.

Imagine the children running down the hallway as fast as they can run. Now imagine more children entering the hallway from classrooms located along this hallway. The children leaving the classrooms can't change the flow of children already running down the hallway without increasing the pressure. Just like the children entering the hallway, the induced voltage (pressure) in the primary winding creates resistance to the change in current flowing through the primary circuit. This resistance is called counter electromotive force, or counter voltage.

Whenever there's inductance in a circuit, a counter emf will be produced by a change in current in a way that resists the change in current. And whenever there's resistance in a circuit, there will be a voltage drop proportional to the resistance. This voltage drop can be seen as the slight rise at the bottom of the primary waveform. If the oscilloscope voltage setting is lowered to magnify the bottom of the ignition primary coil waveform, the voltage drop can be seen more clearly (waveform segment D in the upper pane of Fig. 5 and magnified in the lower pane).

Since the current flowing through the winding makes the resistance for the voltage drop, it mirrors the primary ignition coil waveform made with an inductive amperage clamp (lower pane of Fig. 5). Once the current rises to the point of full coil saturation (magnetic field not in movement), the magnetic field completely surrounds the secondary windings. The ignition coil's saturation point is based on the current flowing through it. The larger the current, the larger the magnetic lines of force. Likewise, the smaller the current, the smaller the magnetic lines of force.

The circuit then limits the current flowing through the primary winding (waveform segment E in Fig. 2). However, the magnetic field still remains at full strength. Notice that when current limiting is switched on, the voltage is still below the open-circuit voltage (waveform segment F). To accomplish this, a resistor is switched into the circuit to limit the current flowing through it. If the primary circuit has unwanted resistance, the time for the current limit to switch on will be increased. If the coil is shorted or has lower-than-normal resistance, the time for the current limit to occur will be reduced. If the design characteristics of the system are known, variations in the expected time to limit current will be an indicator of a problem.

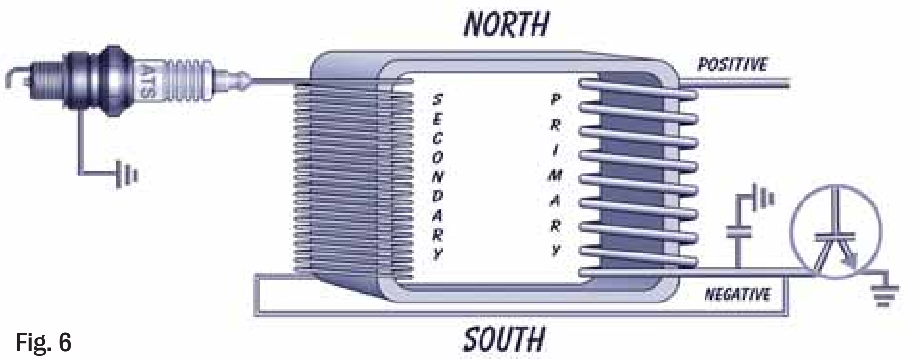

Fig. 6

As engine rpm is increased, the time between cylinder firing becomes shorter, the time to saturate the coil decreases and current limiting will cease. (Not all ignition systems have current limiting.) The PCM then commands the module driver off. This ends the current flowing through the primary winding. The magnetic field then begins to fall across the secondary winding.

When a magnetic field moves across a wire or winding, voltage is induced into that wire or winding. This induction makes electromotive force, which frees electrons and pushes them through the circuit until they return to the secondary winding where they were produced. The amount of induction is proportional to the size of the magnetic field and the speed with which the magnetic field falls across the secondary winding.

A condenser or capacitor is used to promote a faster collapse of the magnetic field. Neither component will allow direct current to pass through it to ground; however, alternating current is able to pass through. A direct current that pulses very fast becomes alternating current and can pass through the condenser or capacitor. This allows the current in the primary coil circuit to pass through either of these components to ground.

The condenser is connected to the primary winding (Fig. 6). Once the current stops, the magnetic field falls back into the primary winding to stabilize the current within the winding. The faster the current in the primary winding dissipates through the condenser, the faster the magnetic field will collapse. The rapid movement of the magnetic field increases the induction within the secondary winding and the current, being pushed by a high voltage of up to 50kV, will look for a pathway or circuit.

The ignition coil's secondary is connected to the spark plug. The electrons move to the spark plug gap; however, this is an open circuit. When high voltage is trying to push electrons across an open circuit, it will first form a corona, or a low-energy field, across the spark plug electrodes (Fig. 7A on page 38).

Once the corona has formed, ioniza-

Fig. 7A

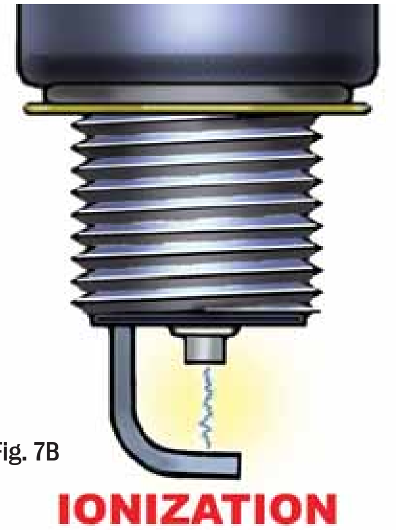

Fig. 7B

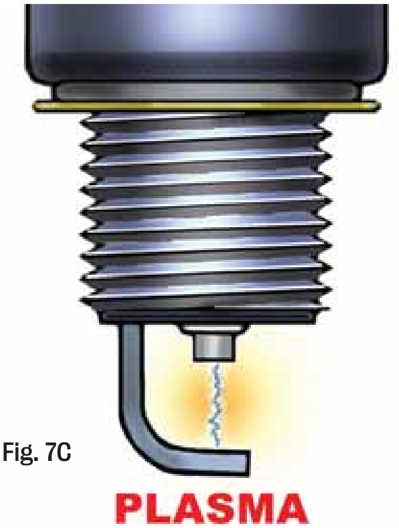

Fig. 7C

tion will begin. A very high voltage is required to start ionization. The electrical potential will apply enough force on the atoms between the spark plug electrodes to rip electrons free (Fig. 7B). Atoms having an electron ripped from them become positive ions. (An ion is a positively or negatively charged atom and is the result of the atom having lost or gained one or more electrons.) This is the breakdown voltage, or the amount of voltage that was required to push the electrons across the resistance.

In this case, the resistance is the spark plug gap (waveform segment G in Fig. 2). The wider the spark plug gap or the greater the resistance between the spark plug electrodes, the higher the breakdown voltage will be. This breakdown voltage is read as kV and is the amount of energy required to overcome the total resistance within the circuit. Once the electrons have bridged the spark plug gap, ionization is complete.

Notice the oscillations that occur as the electron flow starts after the breakdown voltage (waveform segment H in Fig. 2). This ringing, or oscillation, is created by the induction occurring across the windings and the capacitance between the turns. The transformer makes it very easy for the energy to change between electrical energy and magnetic energy. The breakdown voltage that starts the arc is very fast (about 2 nanoseconds). This fast energy spike starts the energy change between electrical and magnetic. The harder the spike to start the arc, the more oscillations that will follow.

These oscillations are analogous to a child on a swing. The child begins in a stationary position on the swing. A strong push causes the swing to move. The harder the push, the higher the swing will go. The swing will then oscillate back and forth until the energy has dissipated. The ignition coil changes electrical energy into magnetic energy and vice versa in much the same way. The swing, being a mechanical device, needs a "push" or energy in order to move, just like the coil's discharge, or "push," causes an energy spike. Once the electrons establish flow, the voltage is stabilized and the oscillations will diminish into an even voltage (waveform segment I in Fig. 2).

Once ionization occurs, the free electrons and the positive ions form a pathway across the spark plug electrodes. This occurs at a point where the number of electrons flowing equals the number of positive ions and the spark plug gap "plasmas" (waveform segment H in Fig. 8). Plasma is a hot ionized gas that enshrouds the electrons flowing through it, thus lowering the resistance across the spark plug electrodes (Fig. 7C). The resistance of the plasma is affected by the gas and the pressure that comprise it. The plasma will decrease the voltage required to maintain the

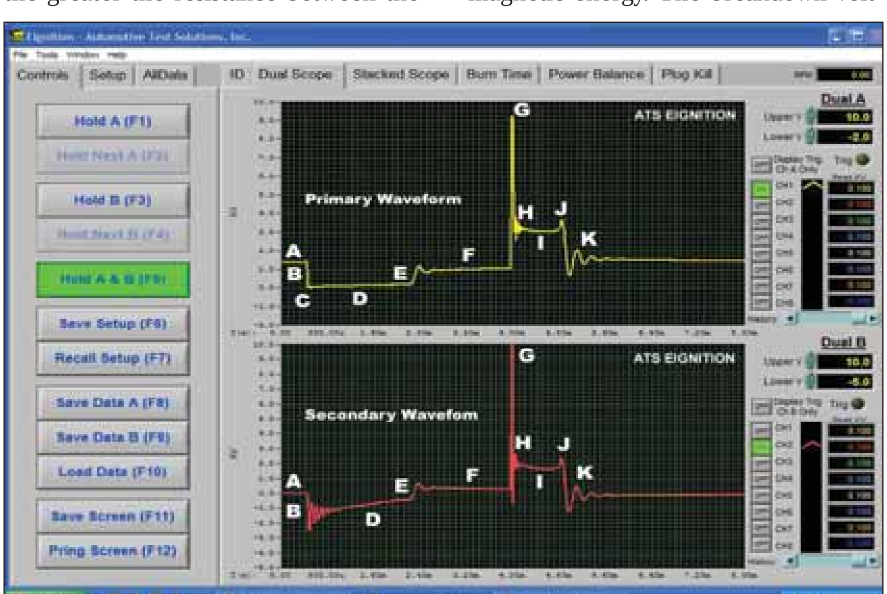

Fig. 8

electron flow across the spark plug gap.

The voltage level at which the ionization turns to plasma is a very important point to analyze. Since the breakdown voltage is not stable, but moves up and down on various discharge cycles, it's necessary to check the voltage level of the plasma. This plasma voltage is more stable than breakdown voltage and will show resistance values that cannot be seen in breakdown kV. The point at which the ionization turns to plasma will be affected only by resistance in the circuit.

In Fig. 9 below, the yellow trace has a 20k resistor placed in the ignition wire. The red trace is the companion cylinder and the point of plasma is normal. The point of plasma on the yellow trace is 2.3kV higher than normal, indicating resistance in the circuit.

In Fig. 10, the yellow trace has a .20-in. gap between the ignition wire and the spark plug. The red trace is the companion cylinder and the point of plasma is normal. On the yellow trace, the point of plasma is 1.2kV higher than normal, indicating resistance in the circuit.

In Fig. 11, the injector is unplugged, allowing no fuel delivery to the cylinder. Note the point that the ionization changed to plasma did not differ between the yellow and red traces, indicating normal resistance in the circuit. However, the plasma waveform has more resistance due to the lack of hydrocarbons in the plasma gas. This creates the very steep voltage rise in the burn time that exceeds 10kV.

Once the electron flow is established across the plug gap, it will continue until the secondary energy is depleted. As the transformer runs out of energy near the end of the burn time, there's a slight rise in voltage as the spark burns out (waveform segment J in Fig. 2). This is caused by the plasma breaking down. The electrons from the transformer start to decrease in number, causing an imbalance between the positive ions and the electrons, allowing the plasma to break down. Since the plasma creates an electrical pathway that has less resistance, this plasma breakdown allows the resistance to increase, causing the voltage rise at the end of the burn time.

Fig. 9

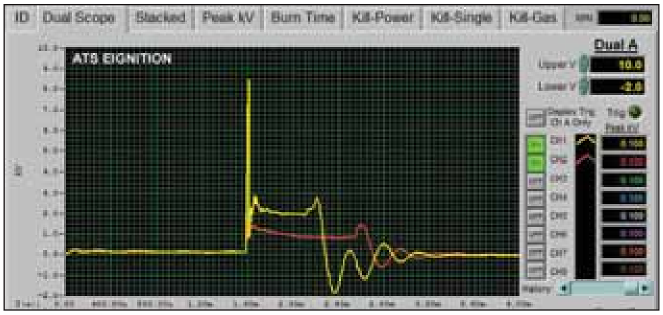

Fig. 10

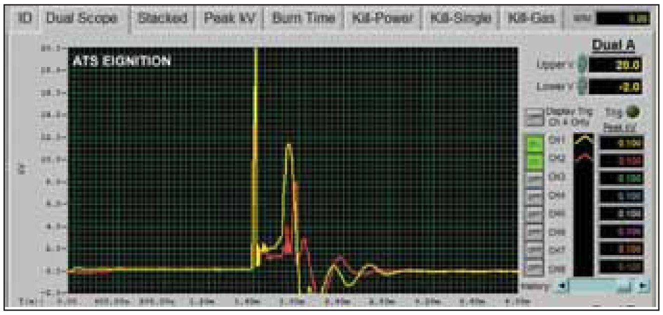

Fig. 11

The induction that put electrical energy into the secondary coil winding is limited. An ignition coil that's fully saturated is like a water bucket that's totally filled. If a water pump were used to pump the water out of the bucket under pressure through a fixed orifice, then the higher the pressure, the quicker the water would be emptied. Once the water is gone, the pressure would also be depleted. In the secondary ignition coil, the greater the voltage or pressure the coil needs to push the electrons across the resistance in the circuit, the quicker the electrons are used up.

The period when the electrons bridge the spark plug gap is called burn time (waveform segments G-J in Fig. 2). Burn time will change according to the pressure it took to start the electrons flowing through the circuit. If the pressure is low, the burn time will be longer; if the pressure is high, the burn time will be shorter.

Let's use a piece of rope to demonstrate this principle. Assume the rope is a set length, and is positioned to represent the pattern that the breakdown voltage and burn time make (Fig. 12 on page 44). If the rope used to make the vertical line is longer, the horizontal line will become shorter. Conversely, if the horizontal line becomes longer, the vertical line will become shorter. If the entire length of rope is shorter, just like when the ignition coil's magnetic field is not fully saturated, the vertical and horizontal sections will also be affected, due to the reduced amount of stored energy available.

The breakdown voltage and burn time are influenced by the pressure or compression and the content of the gas that's in the cylinder. Under normal conditions, the cylinder is filled with a gas comprised of ambient air (approximately 21% oxygen and 79% nitrogen) and C_4H_8 hydrocarbons (gasoline) in a ratio of 14.7 parts air to one part hydrocarbons. The gas mixture in the cylinder is composed of atoms that will ionize or allow the spark to jump across the spark plug electrodes.

We know these atoms will ionize. But if conditions change, their ability to ionize will change. The amount of pressure or compression will change the density of the mixture, which will have an effect on ionization. The turbulence within the cylinder will also change the characteristics of the ignition waveform. If any of these variables changes—compression or pressure, turbulence, gas content, fuel or water vapor—then the ionization that forms the plasma will change. This, in turn, affects the spark waveform.

Spark stops when the electrical energy is not strong enough to keep the electrons flowing across the spark plug gap (waveform segment J in Fig. 2). Whatever energy is left within the coil must be absorbed by the windings. The absorbed energy is dissipated by changing between electrical and magnetic energy. This is what causes the oscillations in the waveform at the end of the spark duration (waveform segment K). This ringing can be used to see how much energy was used or not used during the ignition coil discharge. A large voltage change and a large number of ringing oscillations at the end of the waveform indicate the amount of energy left in the ignition coil. If there are no oscillations, the ignition coil's energy has been totally dissipated.

The ignition waveform is a window that allows the technician to see what's occurring in the combustion chamber. Once you learn how to view the waveform during the breakdown voltage and burn time, you'll see how the waveform reflects what's occurring within the cylinder. Examples of conditions that can be identified via the ignition waveform include lean air/fuel ratio, rich air/fuel ratio, preignition, turbulence caused by cam timing or valves, turbulence caused by exhaust backpressure, EGR, water vapor caused by an engine coolant leak, worn spark plugs, carbon tracking, resistance within the circuit, etc. There's more information within the ignition coil's waveform than in any other waveform produced on the vehicle.

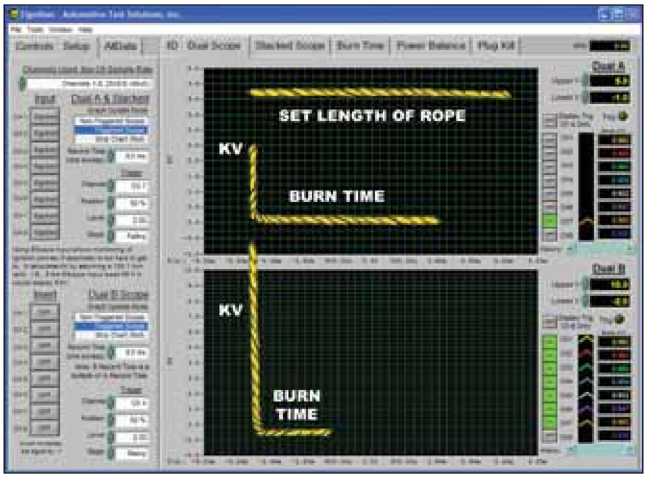

Fig. 12

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