Understanding the Aircraft Magneto

by Kas Thomas

In a world of software-driven electronic ignition, it's something of an anomaly that small airplanes—85 years after the Wright brothers—still rely on whirling magnets and tungsten breaker points to achieve controlled combustion. Even *motorcycles* (for crying out loud) no longer use magnetos. What are we, nuts?

Frankly, we probably *are* nuts for accepting magnetos. Mags (once touted for their light weight) are heavy compared to solid-state ignition, and—much more important—they contain moving parts (some even touching each other). Which means reliability isn't what it should be.

More amazing still, though, is the fact that most pilots don't have the slightest clue as to how a magneto does what it does, or why mags were once considered (and perhaps still are, in certain circles) *the* high-tech solution for aircraft ignition.

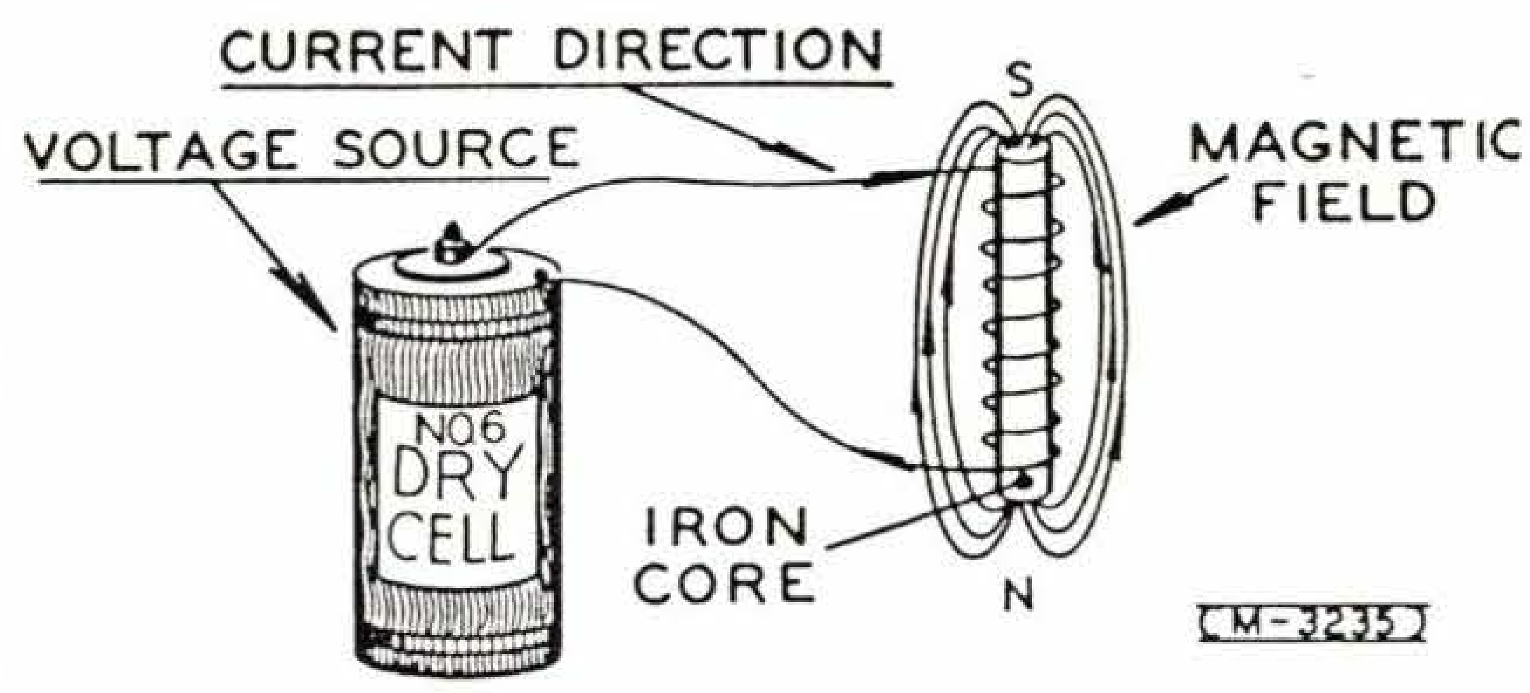

FIG. 1

Current in a wire coiled around an iron bar creates a magnetic field around the bar.

Fun with Magnets

If you ever played with magnets, batteries, or wires coiled around nails when you were a youngster, you're way ahead of the game when it comes to understanding magnetos. The ancient Chinese could have invented the magneto (and probably would have, if they'd had a need for one); it's that simple.

Start with the fact that if you wrap a wire around a nail and send DC (direct current) through the wire, you get a magnetic field in and around the nail, with a north pole and a south pole and every characteristic of a magnet.

The converse is also true: If you start with an ordinary nail and a coil of wire, and suddenly magnetize the nail, current will be produced in the coil (for the brief time period in which the magnetization takes place).

Suppose you could alternately magnetize the nail in one direction (N-S), then the other (S-N), then the other (N-S), etc., very rapidly. Attach the two ends of the wire to a voltmeter, and you'll find that an alternating current (AC) is being generated in the wire.

Perhaps as a child you played with horseshoe magnets. And maybe you noticed that a nail placed across the ends of the horseshoe would act as a small magnet. (Iron filings sprinkled around the nail will fall into the familiar pattern made by the field of a bar magnet.) You've "induced" magnetism in the nail.

Again, the converse is true: Take a nonmagnetic horseshoe-shaped piece of metal and lay a bar magnet across the ends, and you'll set up a magnetic field in and around the horseshoe.

Now. Imagine that you have a horseshoe-shaped piece of metal and a small bar magnet mounted on a stick so you can spin it with the ends just passing the tips of the horseshoe. Obviously the field in and around the horseshoe will alternate in polarity (N-S, S-N, N-S) as the ends of the bar magnet swap positions.

Next, wind a piece of wire around the curved portion of the horseshoe. Spin the bar magnet, and voila! You've created an alternating current in the wire.

In a magneto, the ends of the horseshoe are called *pole shoes* and the rotating magnet is called a *rotor*. The windings around the horseshoe comprise the *primary coil*. (Starting to sound familiar?) If you can figure a way to harness the AC produced by this little contraption so as to fire spark plugs in an engine, you call the contraption a magneto.

Harnessing the AC

An important fact about the spinning-magnet contraption we just built is that the voltage produced in the coil increases with increasing rotor (magnet) rpm. If you were to grab the loose ends of the coil wire and hold them very close to each other (but not touching), then spin your magnet to higher and higher rpms, you'd observe sparking across the wire ends at some rpm. (Or you'd shock yourself silly, if you touched the bare wire!)

Unfortunately, the coming-in speed of our prototype magneto would be rather high (many thousands of rpms), unless we were to wrap 100,000 or 200,000 turns of wire around our coil core. Obviously that's out of the question. We don't have all the wire in the world, and we don't want to spin our magnet at relativistic speeds.

There's a fairly easy way out, though, and that's to get a spool of very fine wire and wrap a *second* coil around the first coil. The alternating current in our original (primary) coil will induce an AC flow in the secondary coil, and the voltage in the secondary will be proportional to the ratio of turns of wire in the two coils. If we use 100 times as many turns in the second coil as in the first, the AC voltage produced in the secondary will be 100 times the AC voltage in the primary. We won't have to turn our magnet so fast to get a spark, because we've *transformed* the low voltage of the primary into a high voltage in the secondary.

It makes little difference whether we actually transform the magneto's voltage at the magneto, or at the spark plugs. If we want, we can run the primary voltage all the way out to the cylinders and put dedicated transformers at each spark plug. Exactly this scheme was used in the ignition systems for many high-flying piston aircraft of the 1940s and 50s. It's called a *low-tension* magneto system, because the magneto itself puts out very mild AC voltages. Internal arcing is unlikely with such mags (which is what makes them so well suited to high-altitude work).

When the secondary and primary windings coexist inside the magneto itself, the result is a *high-tension* ignition system—so called because the output of the mag is (potentially, at least) very-high-voltage indeed.

Spark Timing

Transformer action can give us the voltages we need for firing our spark plugs. But unfortunately, the magneto device we've been describing has a serious drawback in that it doesn't allow us to hold a constant relationship of spark timing to crankshaft (and piston) position. We noted earlier that the AC voltage output of the magneto goes up or down with magnet rpm. Say it takes 5,000 volts to cause gap arcing in our spark plugs (a not untypical value for a spark plug in cruise conditions). The problem is this: magneto output reaches 5,000 volts *quicker* at high rpm than at low rpm. If you set the mag so it'll fire your plugs at, say, 20 degrees before top center (BTC) of piston travel at 2,000 rpm, you may find that your plugs are firing at 30 degrees BTC at 2,500 rpm.

That's not all. Suppose some of your plugs are worn out, dirty, or gapped wrong (and maybe you have a leaky ignition lead or crusty terminal here or there, too). Some of your plugs are going to require 5,000 volts to fire, others will require 6,000, others 7,000, maybe 10,000. Each of these voltages falls on a different portion of the magneto's AC output curve. What it means is that your spark plugs are going to fire at different times in the Otto cycle!

This is clearly unacceptable. Reciprocating engines demand precise timing of the ignition event for proper operation. Some way must be found to allow precise adjustment of ignition timing.

The thing to do is suddenly, within a split second, step up the voltage output of the mag at *exactly* the moment you want ignition to occur (rather than simply wait for voltage to build to the required threshold level). We can do this by interrupting the current flow in the primary coil (in a precisely timed way), causing a sudden—near-instantaneous, in fact—collapse of the magnetic field associated with the primary coil. The secondary coil, sensing this enormously fast *flux change*, will respond by momentarily experiencing an astronomic voltage level. This voltage spike will, of course, spark the plug without hesitation.

The mechanics of this setup are shown in the accompanying simplified drawing of a magneto (Fig. 2). In this case, the magnet is actually a double magnet (four poles on one rotor); modern magnetos contain just a two-pole rotor. Notice that on the same shaft as the magnet is a cam with lobes (or ramps) that rub against a breaker finger. The contact breaker contains two *points* which in turn serve the same function as the contacts on a switch. The breaker assembly is little more than a glorified switch.

The primary, as we've seen, doesn't develop much voltage (compared to the secondary). But there is certainly a possibility of arcing across the breaker points when they open. To prevent this, a capacitor (or condenser) is wired across the points, providing a different "path of least resistance" than the air gap between the contacts.

The Lenz Effect

What about this flux-change business, anyway? How does it work? And what's this about "astronomic voltage levels"?

First let's back up a step or two and recall that it's the *change* of a magnetic field's strength that induces a voltage in a coil. (This is why voltage is proportional to

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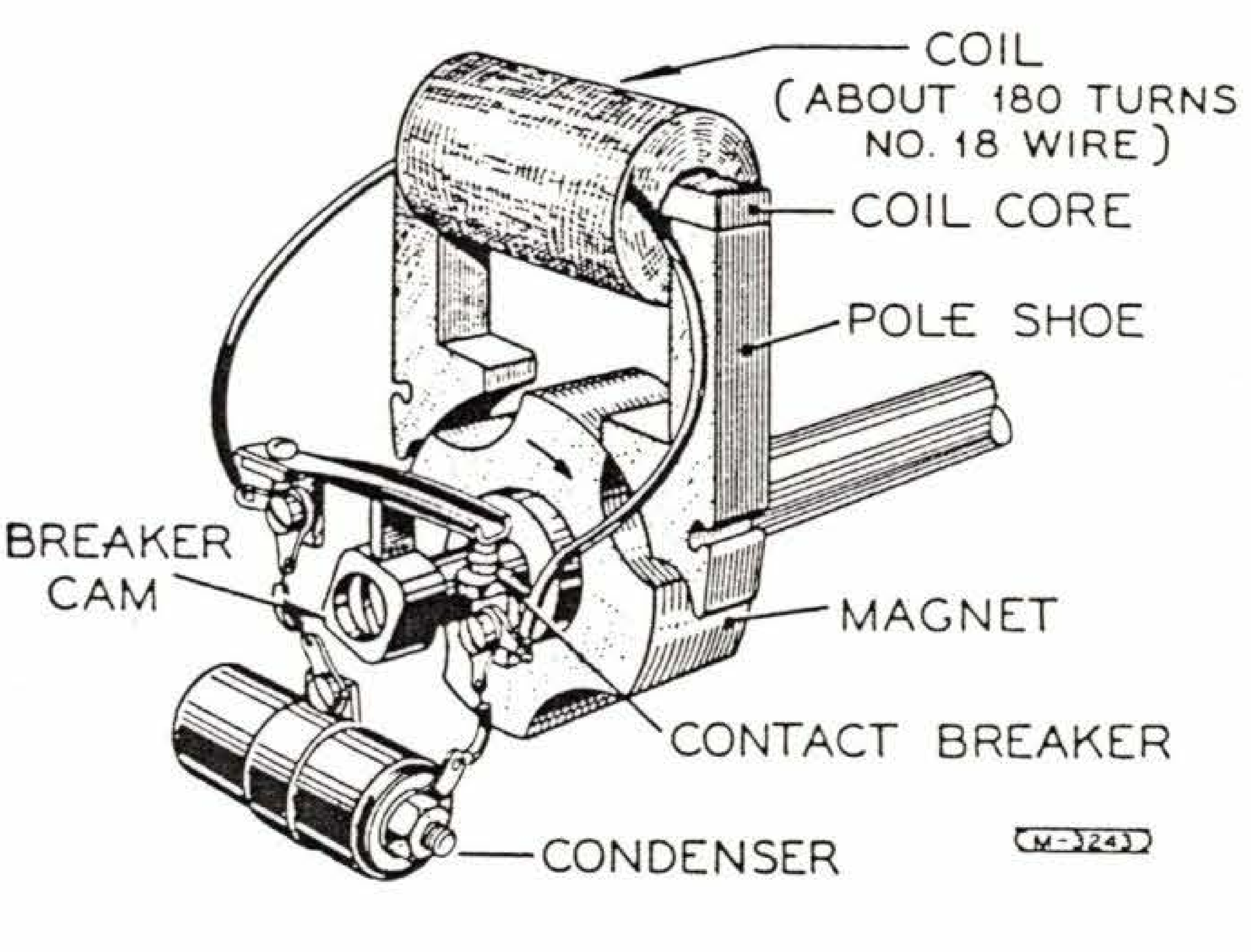
FIG. 2



The components of a crude magneto would include a coil of wire wrapped around an iron core, a rotating magnet, and a breaker assembly to interrupt the flow of current in the primary coil circuit. (A four-pole magnet forms the rotor in this diagram. In real life, two-pole rotors are used.) Note that a capacitor (or "condenser") has been wired across the breaker to prevent contact arcing.

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magnet rpm.) But when we talk about the primary coil in a magneto, we've got more than one magnetic field to concern ourselves with. On the one hand, there's the field produced by the rotor magnet, which alternately changes strength and direction in the coil core as the rotor spins. This is what induces current in the primary coil. The field strength of the magnet in the core is plotted at the top of the accompanying graph (Fig. 3) as the "static flux curve."

Magnet rotation induces a current in the primary coil. This current, in turn, gives rise to *another* magnetic field, since a magnetic field always accompanies current flow. It turns out that the direction of this induced-current field is such as to *oppose or resist* the original flux change that gave rise to the current in the first place. What it means is that the *net* field strength in the vicinity of the primary coil is nothing like what the static flux curve of Fig. 3 would suggest. Instead, the resultant or net flux wants to stay high for a while when the originating flux is decreasing, and it wants to stay low when the original flux is on the way up. (See the "resultant flux" curve, Fig. 3.)

The flux interactions just described are summed up by *Lenz's law* (which says that an induced current is always in such a direction that its magnetic field opposes the flux-change that induced the current). The reason this is important is that it has the effect (in a magneto) of keeping the *total* flux of the coil-and-core *high* until well after the magnet has swapped ends. (Note: "Flux" here refers to imaginary magnetic lines of force. It does *not* imply a dynamic change of anything. In other usages, the word "flux" implies flow or dynamic change, but in magnetism it merely implies static lines of force.)

The effect of this flux-change lag is to make point-opening a very dramatic event, electromagnetically speaking. Thanks to Lenz, a coil (or core) can in effect *store up* magnetic-field energy while the rotor of the magneto is undergoing a reversal of direction. Then, *bang!* The breaker points open and the stored energy has to be dissipated.

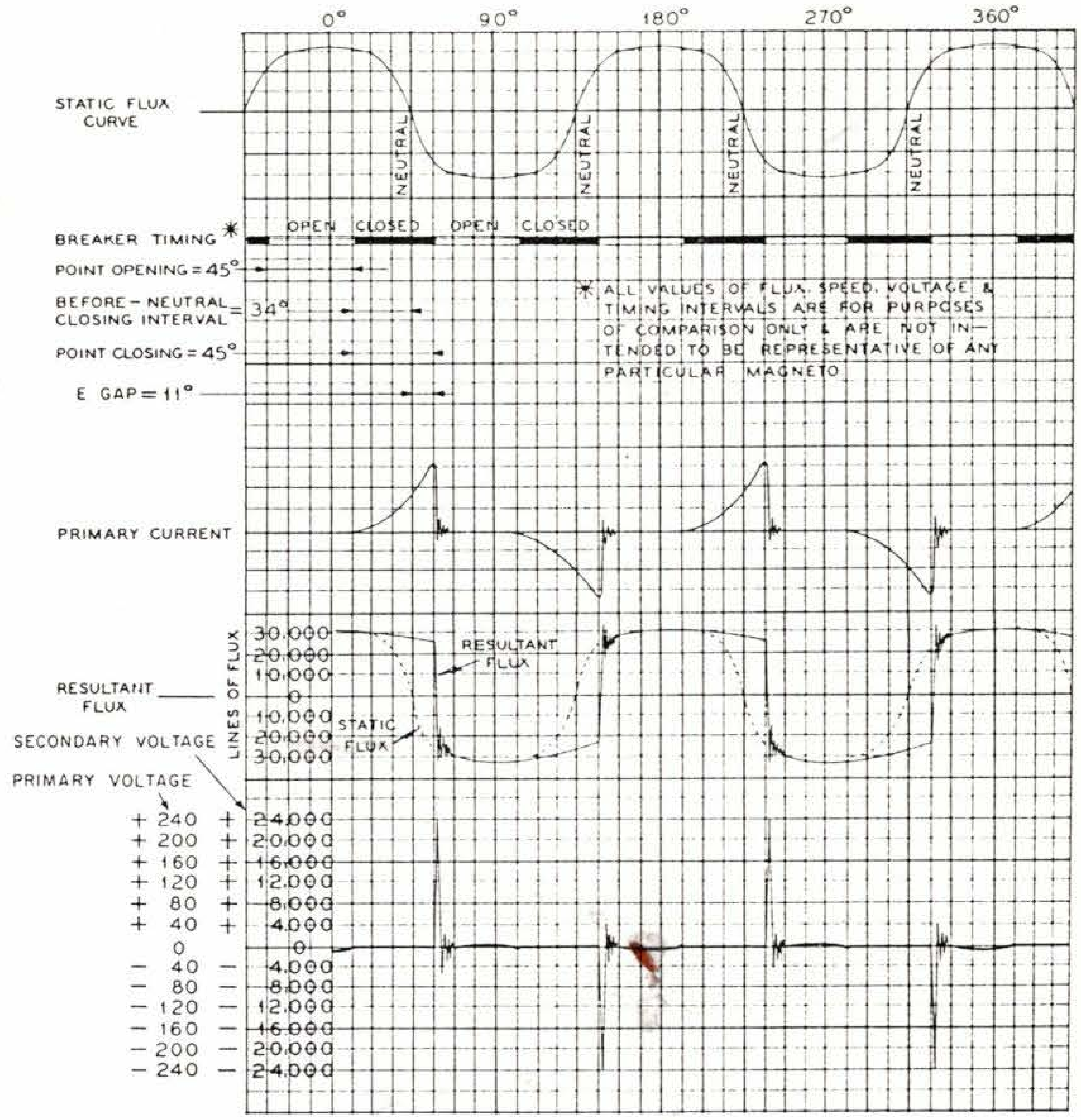


FIG. 3

The flux and current relationships for a magneto with an open-circuited secondary. (In an engine, spark plugs would dissipate the energy in the secondary, preventing the voltage spike from taking the form shown in the bottom plot.) Note the relationship of point opening to magnet neutral position. Also note the lag in resultant flux caused by the Lenz effect. Resultant flux stays high even as static flux is going from positive to negative. The sudden change of flux that results when points open is what causes the voltage spike in the primary and secondary. With a quick enough flux change, the voltage spike could (in theory) go to infinity.

Flyback Action

Where does that stored electromagnetic energy go? Well, again, recall what happens when a coil of wire is exposed to a *change* of a magnetic field's strength. A voltage is induced in the coil proportional to the rate of change of the magnetic field, right? In this case, when the points open, the current is going to stop flowing (instantly) in the coil, and the associated magnetic field is going to collapse.

What happens then is, the collapsing field "cuts" the turns of the primary winding. As some people like to say, the coil *self-induces*—a voltage spike appears in the primary.

This is like a gift from God (or from Lenz, at least) for magneto designers, since a voltage spike in the primary automatically means one heck of a voltage spike in the secondary (which, remember, has 100 times as many turns of wire in it).

The rapidity of the field collapse means that the voltages induced can be very, very high indeed. In fact, an instantaneous collapse of the field would mean an infinite voltage in the coil(s). This is the so-called *flyback effect*.

In a real engine, of course, magneto output doesn't go infinite, because sparking will occur across the plug electrodes at anywhere from a few thousand to 10,000 or 20,000 volts, depending on cylinder pressure and gap dimensions. If the plug is defective, presenting an infinite resistance to the mag, arcing will occur somewhere else along the circuit, possibly inside the mag itself.

Right away we can see why it's so important to keep plugs clean and correctly gapped in a high-altitude ignition system (e.g., Turbo Arrow, Turbo Saratoga, Mooney 231, P210, Seneca II/III, Skymaster, or other aircraft flying above 10,000 or 12,000 feet). Air acts as a dielectric inside the mag. That is to say, air is insulating. But air is only half as dense at FL 180 as it is at sea level. In a turbocharged plane, manifold pressure continues to increase at high altitudes (thus continuing to insulate the spark plug electrodes), but magneto air thins out (unless you have pressurized mags). Arcing is therefore increasingly likely to occur inside the mag—rather than at the plug(s)—in a high-flying aircraft.

Points Are Optional

The keen reader will note that breaker points aren't strictly necessary in a magneto turning at high speed. In fact, the crude magneto device we constructed very early on in this article operated satisfactorily, without breaker points, when spun at sufficiently high rpm. There are even occasions on record where aircraft magnetos have continued to operate without breaker action. We know of one case in which both sets of points (from both mags) fused in a six-cylinder helicopter engine, yet the pilot continued to fly under full power. It was only when he landed and performed a low-rpm mag check that the engine quit altogether!

This is a good time, perhaps, to digress for a moment and take note of the fact that two-pole magnetos turn at one-and-a-half times crankshaft speed in six-cylinder engines (and at exactly crank speed in four-cylinder engines). In a six-cylinder, four-stroke-cycle (Otto-type) engine, there are three power events for every 360 degrees of crank travel. Accordingly there has to be three flux reversals (or point-opening events) in every turn of the crank. Since a two-pole mag gives one flux reversal every 180 degrees, it follows that the mag rotor must turn one-and-a-half revs per single crankshaft revolution.

In a four-cylinder engine, two cylinders fire with every complete crankshaft revolution. That means two flux reversals in the mag, and (at 180 degrees per reversal) one full turn of the rotor per crank revolution.

Helicopter engines, incidentally, normally operate at very high rpms (by fixed-wing standards)—usually on the order of 3,000 to 3,400 crankshaft rpm. This means a magneto rotor rpm of 4,500 to 5,100 rpm for a six-cylinder engine. At such rpms, breaker action isn't strictly necessary. Flux reversal is rapid enough to give sparkworthy voltages without precisely timed flyback action.

E-Gap

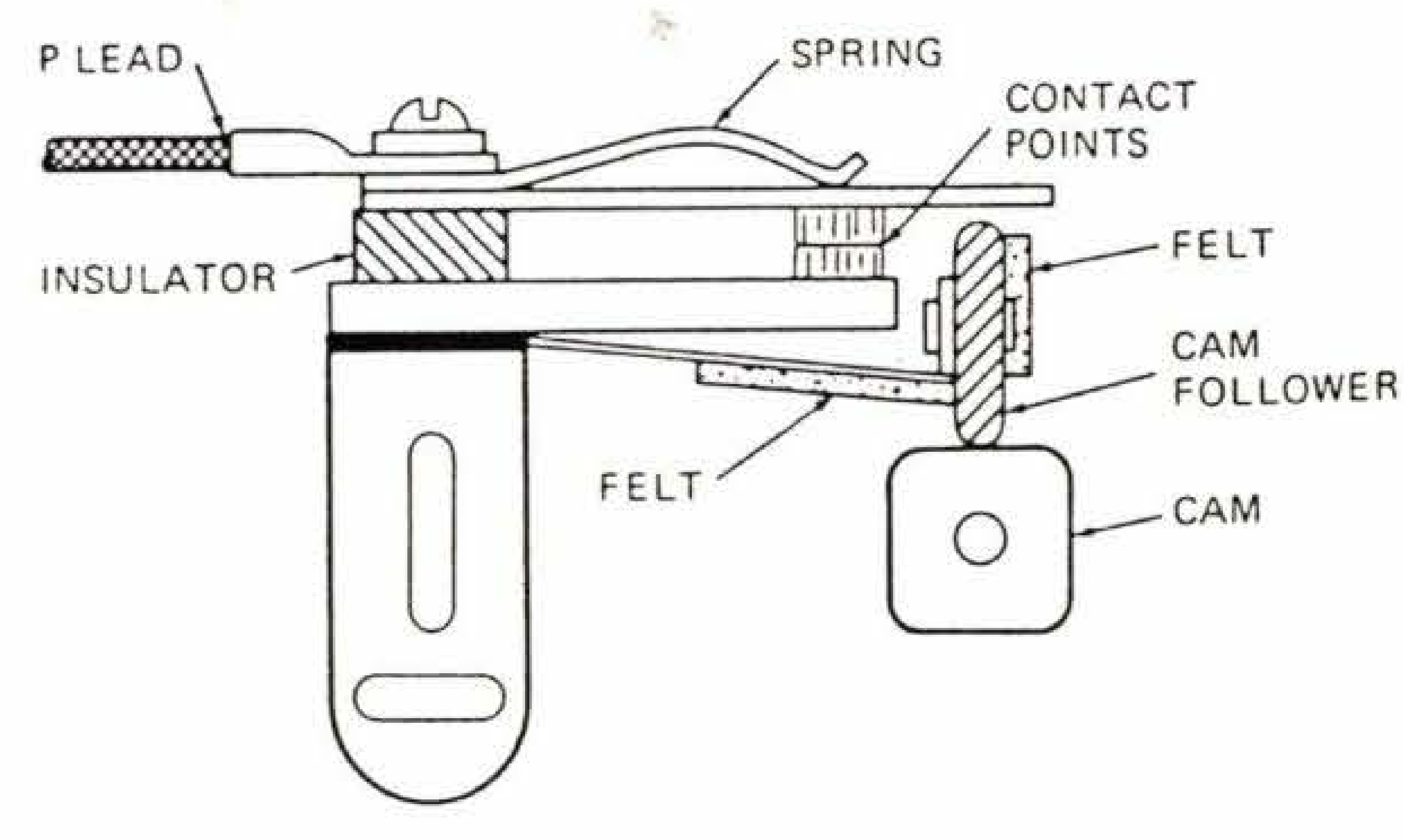
If you're going to use points to control ignition timing, you might as well set things up so that point-opening occurs precisely when the electromagnetic stress in the mag is maximal. This is easy enough to do. We know that current in the primary peaks when static flux (from magnet rotation) is undergoing reversal. That is, when the magnet goes through its neutral point (where the poles are aligned neither in one direction along the coil axis nor the other direction), we know that the magnetic field in the coil core is about to reverse—going from N-S to S-N (or vice versa).

Offhand you'd think that this would be the time to open the points—right at the moment of max-flux-change, where the magnet is reversing itself. But we're forgetting something. Our old buddy Lenz says that the induced current in the primary is going to set up a magnetic field that will cause a lag in the net flux change. What it means is that we'll get a far more dramatic zap if we wait until the magnet has actually turned an extra few degrees beyond neutral, *then* break the circuit.

It's a simple matter—if you're a scope-head—to hook an oscilloscope up to a mag and determine the optimum moment of breaker-point opening empirically. When you do this, it turns out that the *most efficient* angular gap (E-gap) for point opening is 10 to 15 degrees past neutral, for a two-pole mag. (Some actual published specs are: 10 degrees plus-or-minus 4, for the Bendix S-20/200 series; 15 plus-or-minus 2 for the 1200-series; 8 degrees for the D-2000/3000 series.)

Setting the E-gap angle is also called setting the mag's *internal timing*, as distinct from external, mag-to-engine timing. The former is concerned with the relationship of breaker opening to magnet position. The latter is concerned with the relationship of breaker opening to piston position.

FIG. 4



A typical breaker assembly. Points are tungsten-alloy. (In radial-engine mags, platinum was sometimes used.)

E-gap specs are fairly narrow, not because a magneto won't function if the internal timing drifts (it will), but because the distributor finger lines up with the output towers of the harness cap over very tiny angular travel ranges. If points open too early or too late, the distributor finger may not be lined up with the output tower. When distributor finger coverage is poor, the spark may well find an easier path to ground than via the towers, in which case distributor arcing occurs and you land with an uneasy stomach.

Note: This concludes the "theory" portion of our tour of aircraft magnetos. Next month we'll go inside an actual magneto and look at the mechanics of magneto assembly, inspection, and operation.—Ed.