High-Voltage Projects
For Fun and Science

BOOK 2

CONTENTS

As time passes, the availability of parts and sundries decreases or price changes occur. Contact the suppliers and distributors listed herein for up-to-date information before you proceed with building or assembling the projects.

By the Editors of Electronics Now and Popular Electronics
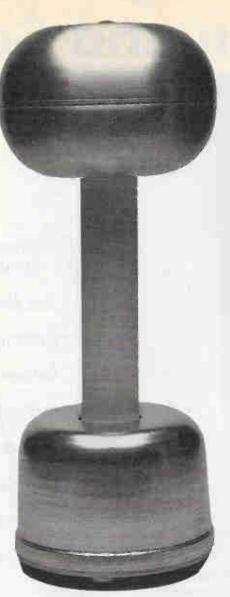
200,000-Volt Van de Graaff Generator

The first known electrical generator was built in 1660 by the German experimenter, Otto von Guericke (also known to historians as the inventor of the air pump). Though Guericke's generator consisted of little more than a revolving ball of sulfur, that frictional device was capable of developing a very strong charge of static electricity.

The generator's ball was made by pouring molten sulfur into a spherical glass container "about the size of a child's head." When the sulfur cooled, the glass was broken open, and the globe removed and equipped with an iron axle. The assembly was then mounted on a wooden frame that allowed the ball to spin freely. When a dry hand was applied to the rotating sulfur sphere, the ball would become electrified, attract small objects, make a crackling sound, and glow faintly in the dark.

Van de Graaff's Generator. Otto von Guericke's machine quickly became obsolete, but the *triboelectric* principles that allowed that generator to operate did not. It is an elementary physical fact that extremely high voltages can be generated by the repeated contact and separation of dissimilar substances, a process that is otherwise known as friction.

In 1927, New Zealand physicist Ernest Rutherford voiced the need for "a copious supply of atoms and electrons ... transcending in energy the alpha and beta particles from radioactive substances." He was talking about an accelerator. Rutherford's wish inspired a young American scholar by the name of Robert J. Van de Graaff.

Van de Graaff knew that charged particles could be moved to high speeds by high voltages. He also knew that conventional methods of electrical transformation might not provide the necessary energy. But the electrostatic characteristics of the atomic nucleus gave him an idea. Van de

Have hours of high-voltage fun when you experiment with this working high-voltage generator.

BY STANLEY A. CZARNIK

Graaff decided to find some way of generating high electrostatic voltages in order to, as he phrased it, "meet the atom on its own terms."
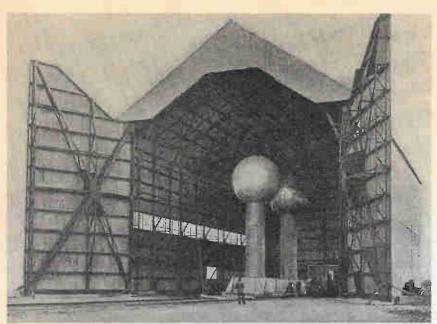
The first Van de Graaff generator was built at Princeton University in the fall of 1929. Van de Graaff built the machine from scrap: a silk ribbon, a small motor, and a tin can. The silk had to be pure; there is a story about how Van de Graaff would visit local fabric shops and set fire to silk samples to see if the cloth was tainted. Van de Graaff's primitive static device developed about 80,000 volts. The high-voltage output was restricted by corona discharge from the edges of the can.

The public became aware of Van de Graaff's new technology in 1931. That's when he demonstrated the creation of over 1,000,000 volts between the spherical terminals of two belt-driven generators. Following that, general interest in these magnificent machines grew very quickly.

Giant Generators. The early success of Van de Graaff's creations was encouraging. Immediately, researchers began making plans for a much, much bigger generator. The size of the machine was to be limited only by the size of the building found to keep it in. A suitable structure was located on the estate of Colonel E.H. Green at South Dartsmouth, Massachusetts. It was the biggest enclosure anyone could find. It was a hangar built originally to house a dirigible, or blimp.

Engineers built two separate machines: one for the positive charge, and one for the negative. The spherical terminals, about 15 feet in diameter, were made of welded aluminum and mounted on two large tubular insulators, each 24 feet high and 6 feet across. The generators were carried on railway track. That allowed technicians to vary the distance between the electrodes. The giant Van de Graaff system was capable of generating nearly ten-million volts.

This giant Van de Graaff generator system was built in Dartsmouth, Massachusetts in the early 1930's. The machine was capable of developing nearly ten million volts. The very large structure in the background was, originally, a hangar built for a blimp.

A Working Model. With a kit of parts from Analytical Scientific, a laboratory supply company in Texas, you can build your own 200,000-volt Van de Graaff static generator in about one hour. (See the Parts List for ordering information.)

The fully assembled machine is about 18 inches high. The spherical aluminum terminal, mounted on top of a heavy plastic tube (PVC pipe), is about 7 inches in diameter. The generator runs on 117 VAC and comes complete with a small electric motor and all the necessary hardware; there's even a spare rubber belt. It's a classic design and an excellent addition to any home-experimenter's workshop.

Building your Model. Once you've obtained the kit, begin by attaching the three rubber feet to the round metal base. Now locate the L-shaped

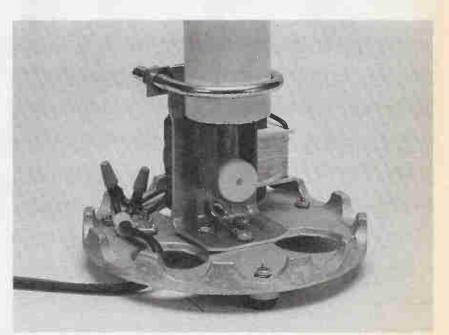motor bracket and the lower brush, which is the short length of stranded wire that's connected to a soldering lug. Push three small screws (8-32 × ½-inch) up through the bottom of the base and the motor bracket. Place lock washers on the screws and secure the assembly with three 8-32 hex nuts. The lower brush goes on the screw furthest away from the 90-degree bend in the motor bracket. The brush should point

towards the vertical section of the bracket. Handle the brush carefully as it is delicate.

The next step is to find the electric motor and mount it by passing the two threaded studs plus the armature shaft through the three remaining holes in the motor bracket. Place lock washers on the threaded studs and secure the motor with a couple of hex nuts.

Now look for the white plastic pulley. Push the pulley over the armature shaft. If you have trouble, tap the end of the pulley very gently with a small hammer or the handle of a screwdriver. The pulley should not come into contact with the motor bracket.

The plastic pipe is held against the upper portion of the motor bracket with a large U-bolt, a metal strip, and two large hex nuts. One end of the pipe has a couple of semi-circular notches cut into it. That end of the pipe should be up; the plain end should be down. The lower end of the pipe should extend about ⅝ inch below the U-bolt. The notches on top should line up with the pulley at the bottom. To check the alignment, simply look straight down through the center of the pipe.

Next, locate the rubber belt and slip it over the metal pulley. Place the pulley into the two notches on top of the insulator and allow the belt to fall through the tube. Pull the lower end of the belt down and place it over the lower pulley. Try to avoid handling the belt too

This is how the inside of your Van de Graaff generator will look just before the lower aluminum shell is placed over the round metal base. Note the arrangement of the stranded wire brush, the rubber belt, and the pulley assembly.

much as skin oils can reduce its effectiveness.

Now, very carefully, adjust the lower brush so that it just barely touches the rubber belt. Spread the strands of wire gently so that as many of them as possible are touching the rubber.

Find the collector support and upper-brush assembly. That's the short length of stranded wire soldered to a V-shaped piece of stiff wire. Push the V-shaped wire into the two small holes at the upper end of the insulator (PVC pipe). And here again, adjust the stranded wire brush so that it just barely touches the rubber belt.
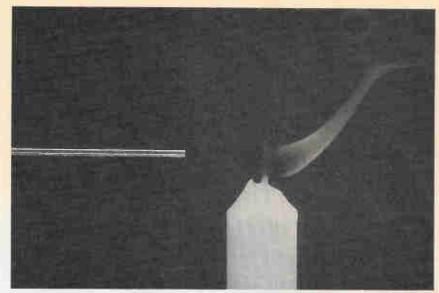
Return to the bottom of the generator and hook up the 117-VAC line cord. Use the wire nuts provided with the kit. The line cord is held in place with a plastic strain relief. Don't forget to connect the little green ground wire. Both the strain relief and the ground wire are attached to the base of the generator with a small screw and a hex nut.

Finally, lower the cylindrical aluminum shell over the plastic tube and push it down over the base. Then place the spherical terminal over the collector support. It should balance perfectly. Now stand back and admire your new Van de Graaff generator. It's a work of electromechanical art!

Testing. Plug your generator in and

The upper brush and upper terminal support fit into the upper end of the tubular insulator. Note how the wire brush is positioned to make contact with the rubber drive belt.

This photograph illustrates the creation of what is sometimes called an "electric wind." Tape one end of a narrow metal rod to the top of your Van de Graaff generator. Turn on the machine and light an ordinary household candle. Now bring the candle close to the free end of the rod. As molecules of ionized air rush from the metal tip, the flame is blown to one side.

the motor should turn. If it doesn't, remove the upper spherical terminal and give the pulley a little spin in the right direction. That should start the generator. Replace the aluminum sphere immediately.

Wait a few moments for a charge to build up on the terminal. Now approach the sphere with a large fluorescent tube. When the tube is three or four inches away from the sphere, the machine will discharge, and the tube will flash. If that doesn't happen, or if the flash isn't very bright, your generator is not working properly.

Unplug the unit and remove the upper terminal and the lower shell. (Please be careful. A small static charge may be waiting for you when you touch the aluminum sphere.) Check the belt and the pulleys for dirt and moisture. They should be clean and dry. Then check the brushes. If the wire strands are too far away from the belt, the generator will operate very poorly, or not at all.

Finally, check both the upper terminal and lower shell for dust and lint. They, too, must be very clean. I was able to improve the performance of my own Van de Graaff generator by cleaning both the shell and the terminal with a bit of good quality metal polish and a soft cloth. That seemed to make a big difference in the machine's operation. In fact, it might be a good idea to polish the aluminum sections before putting the machine together.

MATERIALS LIST FOR THE VAN DE GRAAFF GENERATOR EXPERIMENT

Van de Graaff generator kit
Aluminum-foil strips, very thin
Candle
Fluorescent tube
Foam plastic packing material
Metal polish
Metal rod, 8 to 10 inches long
Tape
The Van de Graaff generator kit is available from Analytical Scientific, Post Box 198, Helotes, TX 78023, Tel. 512-684-7373. The catalog number is MLE-10-065 and the price is $137.75. Include $5.00 for shipping and handling within the continental U.S. The Analytical catalog is $3.00, which is refundable with first order. TX orders must include appropriate sales tax.

Theory of Operation. Here's how your Van de Graaff generator works: The electric charge originates with the friction of the rubber belt moving over the lower plastic pulley. The plastic pulley acquires a negative charge that appears on the outside of the belt while a positive charge appears on the inside. The negative charge is picked up by the ionized air around the lower brush. The positive charge is carried to the upper brush by the belt where it is transferred to the aluminum sphere.

*It's a high-voltage apparatus that has earned a place
in history. Now it's your turn to get in on the fun!*

"**W**imshurst machine? So that's what
it's called!" my neighbor said, his
eyes as wide as half dollars. I
often heard that comment.

I took the Wimshurst machine off the shelf in
my den and placed it on the desk before him. I
turned the handcrank, the black plastic plates
spun, and sparks jumped between the metal
globes. "It will create 75,000 volts," I com-
mented. He leaned away from the machine. As
the plates spun, the machine hummed and
sparks snapped between the globes. The smell
of ozone soon filled the room.

THE
WIMSHURST
MACHINE

BY GREGORY B. PUTZ

I'm sure that you, too, have seen a Wimshurst machine although you may not have known it's name. You probably know more about its cousin, the Van de Graaff generator. Both are electrostatic generators, but that is where the similarity ends. The Van de Graaff generator creates static charges by friction, while the Wimshurst device does it by induction. In the early days of electrostatics, the principle of induction was also known as "influence." In fact, the machine is more correctly called a "Wimshurst influence machine."

The Wimshurst machine played an important role in the early years of electrostatics. It provided high-voltages necessary for experiments in X-ray. But before I tell you how the Wimshurst machine works, let's take a quick look at the science of electrostatics.

Electrostatics. Electrostatics was first noticed sometime in 600 BC when the Greek philosopher Thales discovered that amber attracted light objects when rubbed. The phenomenon not only demonstrated a fundamental concept of electrostatics, but also gave us the word "*elektron*," meaning amber in Greek.

When Italian physicist Alessandro Volta invented the "voltaic pile" (or battery) in 1800, the science of electrostatics changed forever. Volta's new invention provided scientists with a stable, dependable source of moving charges (*i.e.*, DC). This invention was a turning point in electricity because now scientists could study *electrodynamics*, whereas before they were limited to studying *electrostatics*.

Triboelectric Effect. It's been a while since the days of Thales, but we all know a few modern ways to make electricity by rubbing. Shuffling our shoes across the carpet on a dry day causes a spark between our finger and a metal doorknob. Likewise, rubbing a glass rod with flannel and then pulling them apart causes the flannel to hang unnaturally towards the rod. The rubbing action causes the glass to develop an abundance of positive charges and the flannel an abundance of negative ones. Once pulled apart, the difference in charge of the two materials causes the attraction of the flannel to the glass.

The same happens when you rub paper against a plaster wall or wooden door. It sticks to the vertical surface because the rubbing creates opposite charges on the paper and the wall. Try

it with a balloon and you'll see the same effect. In each of these cases, rubbing creates segregated electric charges and static electricity is the result.

In high school, you probably saw a Van de Graaff generator. It made sparks fly, fluorescent tubes glow, and your hair stand on end when you touched its dome. The Van de Graaff generator works in a way that is similar to rubbing glass with flannel, except
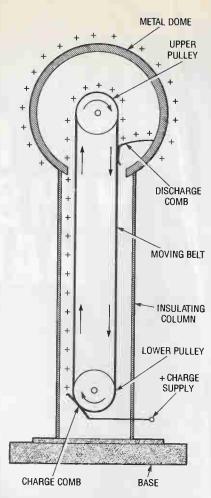

METAL DOME

UPPER PULLEY

DISCHARGE COMB

MOVING BELT

INSULATING COLUMN

LOWER PULLEY

+ CHARGE SUPPLY

CHARGE COMB   BASE

Fig. 1. A Van De Graaff generator places a high-voltage charge on its metal dome by friction, whereas a Wimshurst machine charges via induction.

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that the rubbing is made continuous by using a moving belt inside the generator (see Fig. 1). As an electric motor turns the belt, metal combs in the generator's dome and base strip charges from the belt. As a result, the dome and base develop opposite charges. Small, classroom-sized Van de Graaff generators produce 200,000 volts. Larger ones, like those used for sub-atomic particle research, create several-million volts.

Glass rubbed with flannel, and paper, or balloons sticking to a wall, and the Van de Graaff generator are all examples of creating static electricity using friction. That is also known as *triboelectric* charging. As we mentioned, there is another way to create static electricity and that is by induction.

Induction. John Canton, in 1753, was the first to put forward the concept of induction of charge. He demonstrated that when a charged body is brought close to a neutral body, the neutral body develops a charge of equal magnitude but opposite polarity. One of the earliest devices to demonstrate induction was the "electrophorus." The electrophorus is the simplest electrostatic generator.

Later in 1787, Abraham Bennet, the inventor of the gold-leaf electroscope, developed the first simple machine to induce electrostatic charges. The device was called a "doubler" because of its ability to progressively accumulate static charges. His doubler did not use friction, but used Canton's induction concept to generate separate positive and negative charges.

New varieties of doublers, or "influence machines" as they were soon called, were developed by Nicholson in 1788, Belli in 1831, and Lord Kelvin in 1860. Also in 1860, Varley built the first successful high-voltage influence machine. Other induction devices were subsequently developed by August Toepler and Wilhelm Holtz. But it wasn't until 1878 that British engineer James Wimshurst invented the first dependable device to inductively generate static electricity. The Wimshurst influence machine was born.

The Machine Itself. Before we explain how a Wimshurst machine works, its a good idea to describe its structure. The Wimshurst machine has three major parts: rotating parallel plates, neutralizing rods, and collecting combs

(see photos). Today's bench-sized demonstration units typically have 12-inch diameter plates. During the heyday of electrostatics, larger Wimshurst machines (used for research or powering early X-ray machines) had multiple pairs of plates several feet in diameter.

Each Wimshurst machine develops a maximum electrostatic potential based on the number of plates used, their diameter, and the spacing between them. Interestingly enough, increasing the rotating speed of the plates does not increase the maximum discharge voltage. Only increasing the number of pairs of plates increases the discharge voltage.

The plates can be any sturdy, non-conducting material, such as glass or plastic (see Fig. 2). The plates are mounted in pairs, separated by a quarter-inch gap, on a horizontal shaft. The closer the plates are mounted to each other, the better the machine will operate. The plates are turned by belts and pulleys from a common crankshaft, but they rotate in opposite directions. A difference in pulley diameters causes the plates to spin several times faster than the handcrank.

Metal-foil strips called "sectors" are

evenly spaced along the outer surface of each plate. Those help extract excess charges from the non-conductive plates.

The charges that accumulate on the sectors are removed by pairs of collecting combs made of tinsel threads. Each pair of combs is mounted on a U-shaped bracket, with one brush touching the front plate and the other brush touching the rear plate. The two U-shaped brackets are mounted opposite one another. They carry the accumulated charges to the machine's discharge balls.

There are two "neutralizing rods" that span the diameter of each plate and also have metal tinsel combs on each end. The front and rear rods are perpendicular to each other and are positioned at an angle of 45° to 60° from the machine's base.

In addition to the three basic parts of a Wimshurst machine, they typically have two built-in Leyden jars, which are very simple glass and foil capacitors. Each Leyden jar can be electrically connected to a collecting comb by means of a hinged rod. If the Leyden jars are not connected to the collecting combs, then a continuous arc jumps between the discharge balls when the handcrank is turned. If the connecting rods are lifted to touch the collecting combs, then a sharp (and intense) snap of electricity jumps between the discharge balls every few seconds.

It is important to notice that all the metal parts of a Wimshurst machine are built with rounded edges. A fundamental rule of electrostatics is that charges find it much easier to "jump" from a pointed surface than from a rounded one. Any sharp points on the machine would allow the charges to dissipate quickly.

How it Works. Remember that the Wimshurst machine is an induction device. It doesn't depend on friction to make an electrostatic charge. As you'll see, quadrants of negative and positive charge are created across the plates by induction between the front and rear plates. As the plates rotate, these positive and negative charges are syphoned off through the metal sectors by the collecting combs.

As you may recall, the principle of induction requires that an object be initially charged before you can use it to induce a charge in something else. That holds true for the plates on the Wimshurst machine. Even before you crank the handle the plates have some static charges on their surface. The charge is created from the incidental rubbing and handling of the machine, and the machine actually amplifies this initial imbalance of charge.

DISCHARGE BALLS

1/4" TO 3/8"

FRONT PLATE

FRONT NEUTRALIZING ROD

CENTER HUB

"A"

DRIVE BELT (FRONT)

SWITCH(LEVER TO CONNECT LEYDEN JAR TO DISCHARGE (LIFT UP TO TOUCH BAR "A")

PULLEY (FRONT)

HANDCRANK

LEYDEN JAR 1 OF 2)

BASE

COLLECTING COMB (FRONT)

The Wimshurst machine is composed of many parts. However, not all Wimshurst machines have Leyden jars although this one does.

Looking at Fig. 2 let's say that quadrant CD of the rear plate had a slight negative charge before the crank was turned. That would induce a small positive charge on the front plate in the same sector. As you turn the crank, electrons on the front plate sector at point C are repelled by the electrons built up on the rear plate. That pushes them up the neutralizing rod to A, which is a more desirable place to be because the rear plate has a positive charge there. That leaves electron-starved quardrant CD with a net positive charge, and electron-rich quardrant AB becomes more negatively charged.

Note that the rear plate—rotating in the opposite direction—works in a reciprocal fashion: Electrons move through the rear neutralizing rod from B to D. So on the rear plate, quadrant AB becomes more positive and quadrant CD becomes more negative. That permits the front neutralizing rod to scoop up more repelled electrons and so on.

In the region of the collecting combs, the front and rear plates have the same charge. The charges on the plates repel each other in those areas. That permits the collecting combs to scoop up the excess charges and send them to the discharge balls. The charges will continue to accumulate until surface leakage or a spark between the discharge balls dissipates them.

You can see the charge leakage by placing the device in the dark, setting the discharge balls a good distance apart, and looking at its corona discharge radiating from the edges of the plates. You'll also see tiny, purple arcs around all combs.

Setting the gap between the discharge balls an inch or two apart, causes a continuous shower of sparks to jump between the spheres. Connecting the Leyden jars to the discharge spheres allows you to separate the balls by a larger distance to produce big crackling sparks.

Demonstrations. Here are some demonstrations that you can try with a Wimshurst machine. For instance, with the Leyden jars disconnected, move the discharge balls far enough apart so that there is no spark when you turn the handcrank. Light a candle and hold it close to one ball and then the other. At the positive ball, the flame will be attracted toward it, and at the negative one, the flame will be repelled.

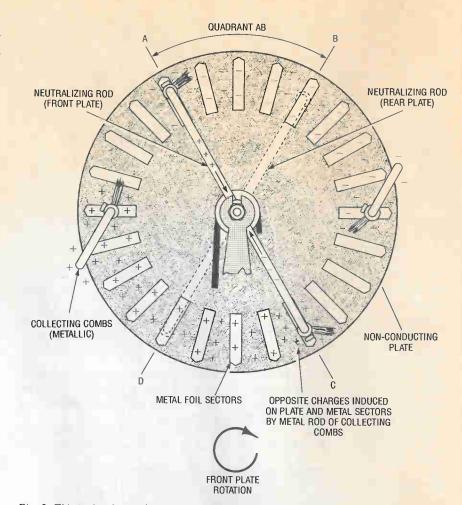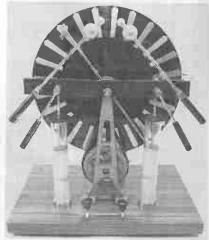For another experiment, hold a piece of cardboard between the dis-

Fig. 2. This is the charge distribution on the front plate. Front and rear neutralizing rods scoop the charges up and move them to more desirable quadrants. The collecting combs can then wisk them away.

Here you can plainly see the Leyden jars and discharge spheres. The jars are connected to the spheres by lifting up the levers attached to them.

charge balls (again with the Leyden jars disconnected). Allow the shower of sparks to jump through the cardboard. Inspect the cardboard and notice that the hole caused by the spark is bulged on both sides. That shows that sparks act like AC current, they oscillate between the discharge balls.

For a different effect, start by cutting some kind of shape out of a piece of aluminum foil. A good example is a letter, such as T or L. Paste the aluminum design to a piece of cardboard. Using a knife or razor blade, cut the design in several places to create discontinuities in the foil (don't let the cuts exceed $\frac{1}{32}$ inch wide). Connect each end of the shape to one of the discharge balls. Run the machine and watch the arcs as the charges jump the cuts in the foil.

Safety. You must respect the potential of any electrostatic generator. Under normal use, they are safe, but you should not let that lull you into a false sense of security. **You must never attempt to condense, or store, the charge they produce without full knowledge of its dangers. Simply said, avoid connecting any capacitor to any electrostatic generator.** ■

Build the Lightning Bulb

Create an electrical storm in a light bulb with this easy-to-build project

BY VINNY VOLLONO

Since the dawn of civilization, mankind has been fascinated by lightning. And is was that fascination with lighting and electricity that has brought about many of the high-tech novelty items—like the Tesla Coil, *Eye of the Storm,* Jacob's Ladder, and the Van DeGraph Generator, for example—that are showing up in the market place.

Similar effects can be produced by the *Lightning Bulb,* which creates a stunning display, yet consists of little more than a modified clear incandescent lamp and a high-voltage power supply. The lamp is modified by taping a piece of aluminum

foil to the back half of its glass envelope, forming a sort of makeshift capacitor. The electrode inside the lamp forms one plate of the capacitor, the glass envelope of the lamp serves as the dielectric, and the aluminum foil is used as the second plate.

The aluminum foil, like the negative plate of a polarized electrolytic capacitor, is grounded. A high voltage is discharged into the lamp through its inner electrode, ionizing the thin gas that remains in the envelope, creating a visual effect similar to an electrical storm.

Circuit Description. The Lightning Bulb circuit uses a quadrac (see Fig. 1)—a device that combines a triac and a diac trigger in a single package—to control the supplied current. Figure 1A shows the schematic symbol for the quadrac, while Fig. 1B shows the pinout for the unit used in our circuit. Note that quadracs are becoming increasingly more difficult to come by; if one can not be located, a discrete diac/triac combination of
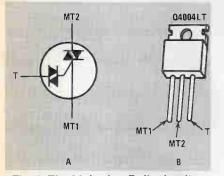

Fig. 1. The Lightning Bulb circuit uses a quadrac—a device that combines a triac and a diac trigger in a single package—to control the input power source. Shown in A is its schematic symbol for the quadrac, which B is the pinout for the unit used in our circuit.

equal or higher rating can be used in its place.

Figure 2 shows a schematic diagram of the Lightning Bulb circuit. The heart of the circuit is a 12-volt automotive ignition coil, T1, which is used to deliver a high-voltage charge of sufficient magnitude to ionize the gases within the glass envelope of lamp I1.

Power for the circuit is taken directly from the AC line and applied through a phase-shift network (consisting of capacitor C1 and resistor R1) to the trigger input (T) of quadrac TR1, causing it to conduct.

With TR1 conducting, a short burst of energy is applied via C2 to the primary winding of T1. (Recall that when power is first applied to a capacitor, the capacitor acts as a short, and then the capacitor begins to charge to the applied voltage.) That burst of energy creates a magnetic field around the primary winding of T1, causing a high voltage to be induced in its secondary.

When capacitor C2 begins to charge to its highest level, the AC signal begins to collapse. As the signal collapses, the current needed to maintain triac conduction dips below the holding level (I_H), the triac turns off, and the second half of the AC signal begins.

As the AC signal becomes more negative, a signal is again applied to the triac's trigger input, causing it to conduct. Triacs conduct during both the positive and negative half cycles of an AC waveform, and can be activated by either a positive or negative trigger source. (For a better understanding of the operation of triacs and other thyristor devices, see *All About Thyristors*, which appeared in the March and April 1988 issues of *Hands-on Electronics*.)

With TR1 now conducting in the opposite direction, the charge on C2 is bled off, via TR1, and a burst of energy (of opposite polarity) is applied to the primary winding
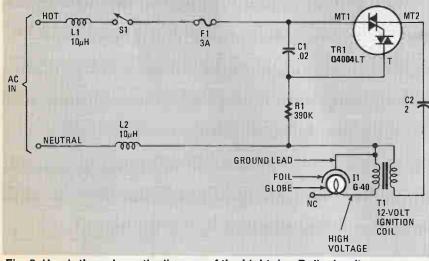
of T1, causing a voltage to be induced in its secondary winding. The high-voltage output (about 20,000 volts) at the secondary of T1 is applied to the lamp, I1, creating an electrical storm-like effect.

The value of C2 must be limited to between 2–2.5 µF to prevent damage to ignition coil T1. On the other hand, if the value of C2 is too small, the display will be somewhat insufficiently pronounced. Inductors L1 and L2 were added to block any switching transients from entering the AC line.

Safety First. As shown in the schematic diagram (Fig. 2), you'll be dealing with a high-voltage transformerless power source. Because of the possible safety hazard associated with projects of this type, it is strongly recommended that you use an isolation transformer when testing and troubleshooting the circuit. For an extra margin of safety, always be sure to discharge the capacitors before performing any work on the circuit. A capacitor can store a charge large enough to melt a copper penny.

Caution: In assembling the Lightning Bulb, *do not* omit the protective plexiglass tube that covers the lamp. The clear ⅛-inch thick plexiglass tube helps to prevent an accidental shock. The high voltage can penetrate the glass and you could get a shock or worse. The safety cover is an absolute must.

Construction. Because of the simplicity of the circuit, the author's prototype was built on a piece of perfboard (measuring about 3 × 4 inches), and the connection between the components were made using point-to-point wiring. Note that for those who wish to use a printed-circuit board, one is offered by the supplier given in the Parts

Fig. 2. Here's the schematic diagram of the Lightning Bulb circuit.

PARTS LIST FOR THE LIGHTNING BULB

U1—Q4004 4-amp, 400-volt quadrac, or triac/diac combination (see text)
C1—0.02-µF metal-film capacitor
C2—2-µF, 400-WVDC metallized polyester or polycarbonate capacitor
F1—3-amp 3AG fuse
I1—G-40 clear incandescent lamp with 5-inch envelope
L1, L2—10-µH hash choke
R1—390,000-ohm ½-watt resistor
S1—single-pole, single-throw toggle switch
T1—12-volt automotive ignition coil
Perfboard materials or printed-circuit board, plastic enclosure, 6-inch OD plexiglass tube, 1½-inch OD plexiglass tube, high-voltage cable, fuse holder, aluminum foil, electrical tape, wire, solder, hardware, etc.

List. However, printed-circuit board construction will not be discussed in this article.

Assemble the circuit board using Fig. 2 as a wiring guide, making the interconnections between the components as the components are installed on the board. Just about any 12-volt automotive ignition coil should do for T1. The .02-μF capacitor specified for C1 can be replaced by two .01-μF units connected in parallel, which is what the author used in his prototype.

When the circuit-board assembly is complete, set it aside for a while and begin modifying the lamp. The lamp used in the author's prototype is a 25-watt designer's bulb with a 5-inch clear-glass envelope. Contrary to common belief, the area within the envelope—particularly where larger envelopes are concerned—is not a total vacuum. Some gas still remains within the envelope even after the evacuation process. Lamps having large envelopes produce a more impressive display because of the higher concentration of gas (in comparison to standard household lamps) within the envelope.

Start the modification process by placing black electrical tape on what will be the back half of the lamp. Place a layer of aluminum foil over the tape and then add a second layer of tape over the aluminum foil to hold it in place. Starting from the outer edges of the foil, apply the tape, working your way inward toward the center. Leave a small portion of the foil exposed so that a wire can be attached. The author used aluminum solder to the attach a lead to the aluminum foil, but gluing or taping should work. Once the wire is attached, it should be connected to the ground terminal of T1 as shown in Fig. 3. Then cover the exposed aluminum and the wire with tape.

The author used a regular plug-in lamp socket to connect the lamp to the high-voltage output of T1. A high-voltage cable is connected across the two contacts of the lamp socket. The type of lead wire used in TV sets to bridge the high-voltage output of

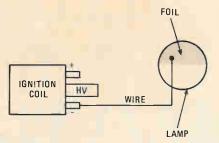Fig. 3. A wire is connected from the ground lead of T1 to the aluminum foil that's been placed on the glass envelope of the lamp.

When applying the second layer of tape, leave a small area of aluminum exposed, and connect a wire to the foil.
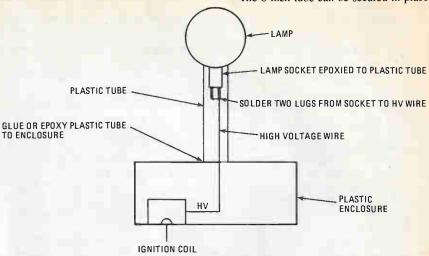

Fig. 4. Mount the lamp-and-socket assembly to its support column, and then mount the entire assembly on the project's plastic enclosure.

the flyback transformer to the anode of the CRT is ideal. Once the wires to the lamp are in place, mount the lamp and socket to their support column. It's a good idea to devise some sort of identification method for the leads; that will cut down on the confusion that may arise during the final electrical-assembly process.

The lamp-support column is a 5- to 6-inch length of plastic tubing with an outside diameter (OD) of 1½ inches. After threading the wires from the lamp-and-socket assembly through the tube, secure the lamp-and-socket assembly to the tube with glue or epoxy. (See Fig. 4.) Once the glue has dried, re-enforce the assembly where the lamp-and-socket assembly meets the support column with one or two wraps of tape.

The support-column assembly is then secured to the project box with glue, or is held in place with screws and "L" brackets. The two leads from the lamp are then connected to the circuit-board mounted components.

The "hot" side of T1's secondary is connected to the bridged lamp-socket terminals (as shown in Fig. 4), and the negative side is connected to the lead coming from the aluminum plate on the lamp. Feed a line cord through the enclosure wall to the circuit board. Connect one lead from the line cord
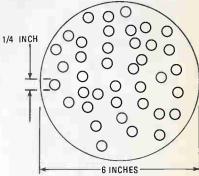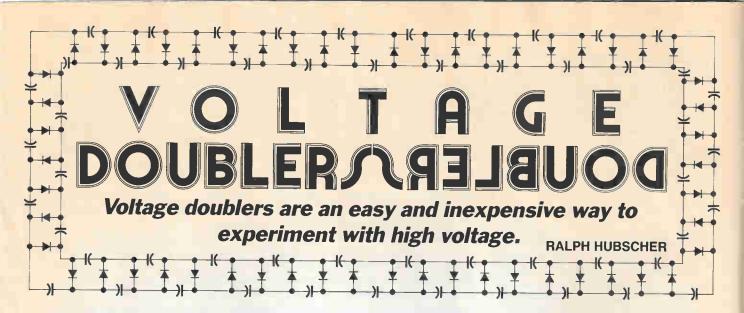
directly to the circuit board. The other lead is then connected through S1 to the circuit board.

Once that is done, check your work. If everything looks okay, seal the board in its enclosure and place a 6-inch OD plexiglass tube over the lamp and column assembly. (The actual length of the protective tubing depends on the physical height of the lamp/support-column combination.) The tube provides the user with some measure of protection from high voltage that's present in the circuit.

The 6-inch tube can be secured in place

Fig. 5. A 6-inch diameter lid is fashioned from a piece of clear plexiglass. Quarter-inch holes are then drilled into the lid to help ventilate the lamp.

with ½-inch wide angle brackets. (See photos.) A lid for the tube can be fashioned from a piece of clear plexiglass. Holes, about ¼ inch in diameter, should be drilled in the lid for ventilating. The lid can then be glued to the top of the protective tube.

You are now all set to give your Lightning Bulb a test run. As with all other projects of a similar nature, ambient light detracts from the visual effect of the display. The Lightning Bulb gives a much more impressive display in a darkened room. ∎

VOLTAGE
DOUBLERS

Voltage doublers are an easy and inexpensive way to experiment with high voltage.

RALPH HUBSCHER

IF YOU'VE BEEN LOOKING FOR A WAY to generate high voltage, you've undoubtedly run across the voltage doubler. Voltage doubling using diode-capacitor combinations is a common practice. However, whole banks of doublers, called cascades, can also be used for producing extremely high DC voltages from moderate to high AC voltages. Such high DC voltages may be needed for TV sets, lasers, air purifiers, industrial smoke-stack dust removers, negative-ion generators, and, of course, for experimenting, on which we'll concentrate here.

Half-wave doubler

Figure 1 shows a half-wave voltage doubler; we'll assume that C1 and C2 are initially discharged. During the first half-cycle shown in *a*, the upper input terminal is positive and the bottom negative, so D1 conducts and C1 charges to about 170 volts peak. Diode D2 can't conduct, since it's back-biased, so C2 discharges through R_L. In the second half-cycle (*b*), the analysis is similar, except that D2 conducts and C2 charges.

The circuit is really a transformerless voltage amplifier. While T1 can provide isolation, as well as increase the AC voltage initially going into the doubler, the amplification due to the doubling action would occur without it. When the polarity reverses, both the input voltage and the charge across C1 are in series like two batteries, producing about 340 volts peak. One problem, though, is that a half-wave doubler can't be used with a load that draws much current.

Full-wave doubler

Let's see how a full-wave voltage doubler is related to and built from both positive and negative half-wave rectifiers. Figure 2-*a* shows a half-wave rectifier with a positive output, Fig. 2-*b* shows the same version with a negative output, and Fig. 2-*c* shows the two combined into a full-wave voltage rectifier.

The full-wave voltage doubler shown in Fig. 3 has been redrawn for greater clarity; it has better regulation than a half-wave version, and is easier to filter. The circuit produces nearly double the peak AC voltage of 170 volts, or about 340 volts peak across R_L. For the first half-cycle (*a*), D2 is cut off and D1 conducts, so that V_{C1} equals approximately 170 volts DC. On the next half-cycle (*b*), the positive voltage is replaced by a negative voltage, so D2 conducts and D1 is cut off. R_L goes across C1 and C2 in series, effectively creating a doubled level of about 340 volts DC.

Warning!! This article deals with and involves subject matter and the use of materials and substances that may be hazardous to health and life. Do not attempt to implement or use the information contained herein, unless you are experienced and skilled with respect to such subject matter, materials, and substances. Neither the publisher nor the author make any representation as for the completeness or accuracy of the information contained herein, and disclaim any liability for damages or injuries, whether caused by or arising from the lack of completeness, inaccuracies of the information, misrepresentations of the directions, misapplication of the information, or otherwise.

Unlike the half-wave voltage doubler, the full-wave version has two capacitors across R_L rather than one. Whereas C1 shown in Fig. 1 is cut off and unsupplied for half of every cycle, C1 and C2 in Fig. 3 are supplied on alternate half cycles. When the capacitor corresponding to the diode that's cut off discharges, it can only do so through the capacitor being supplied, slightly decreasing both its current and the maximum voltage it reaches.

Measuring high-voltage DC

Voltage measurements will be possible only to about the second or third stage of a cascaded voltage doubler with most voltmeters. Beyond that, you'll need to use either a high-voltage DC meter or an external voltage divider for use with a standard high-impedance voltmeter (10 megohms or more).

A good voltage divider that can be used for the purpose of high-voltage measurements is the RCA SK3868/DIV-1, a high-voltage DC divider; it's used in TV's to reduce the final anode voltage going to the CRT to the level required for the focus voltage. It consists of resistors R1 (200 megohms) and R2 (40 megohms) in series, as shown in Fig. 4. There are three leads, one for the free ends of each resistor, and the other at their juncture. If you put both a 10-megohm meter (shown as Z_M in Fig. 4) and a 2.7-megohm resistor (R3) in parallel with the 40-megohm resistor (R2), you can achieve almost exactly 100:1 range multiplication, for a full-scale deflection of 20 kilovolts DC.
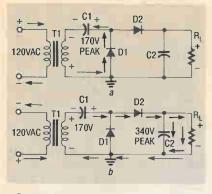
FIG. 1—HALF-WAVE VOLTAGE DOUBLER. During the first half-cycle (*a*), D1 conducts, D2 cuts off, C1 charges to 170 volts peak, and C2 discharges through R$_L$. For the second half-cycle (*b*), the input polarity is reversed, and both the input and C1 are in series, producing 340 volts peak. Now D1 cuts off while D2 conducts, and the current divides between C2 and R$_L$; the cycle then repeats.
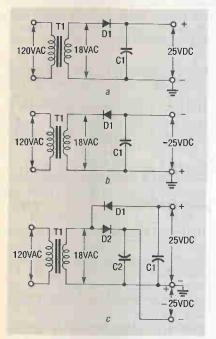

FIG. 2—TWO HALF-WAVE RECTIFIERS, one with a positive output (*a*) and one negative (*b*), combine to make a full-wave voltage doubler (*c*).

FIG. 3—FULL-WAVE VOLTAGE DOUBLER, redrawn for greater clarity. For the first half-cycle (*a*), D2 is cut off and D1 conducts, producing about 170 volts DC across C1. On the next half-cycle (*b*), D2 conducts and D1 is cut off. The output voltage is now across C1 and C2 in series, doubling the level to about 340 volts DC.
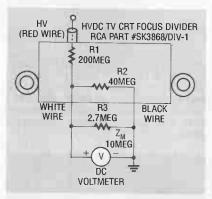

FIG. 4—TO MEASURE HIGH VOLTAGES with an ordinary 10-megohm meter, you can use the RCA SK3868/DIV-1 high-voltage divider. The circuit provides a 1:100 voltage division, allowing 20 kilovolts to be measured on a 200-volt scale.
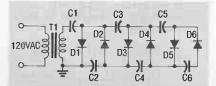

FIG. 5—THIS CASCADED DOUBLER uses 1N4007 diodes rated at 1 kilovolt PIV, and capacitors from 0.068–0.1µF with a 400-volt DC working voltage.

FIG. 6—THIS VOLTAGE DOUBLER is the same as the one shown in Fig. 5, although it's drawn differently. You should be able to recognize both versions.

Cascaded voltage doublers

Figures 5–8 show four additional voltage doublers. The one shown in Fig. 5 is the most straightforward. If you build it, use 1N4007 diodes with peak inverse voltage (PIV) ratings of 1 kilovolt for D1–D6, and 0.068–0.1 µF capacitors with working voltages of 400 volts DC. Figure 5 is electrically identical to the one in Fig. 6, so keep that in mind if you should come across either format. Figure 7 shows an extended version that's better

stabilized for moderate-current applications; it's called either a Cockcroft-Walton or Greinacher cascaded voltage doubler.

You can use a sewing needle as an emitter for the doubler shown in Fig. 8 to generate "corona wind." That will sound like a his-
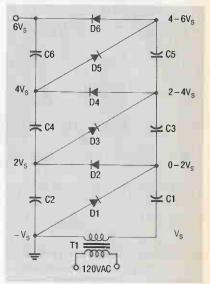
sing noise. (We'll shown you how to demonstrate the "wind" later on.) The circuit delivers 3.75 kilovolts DC when powered from 120 volts AC, or 7.5 kilovolts DC when powered from 240 volts AC.

The output of a cascaded voltage doubler should be terminated with no less than 200 megohms, and only then be allowed to extend beyond a protective plastic case, for safety. Voltages as high as 5 megavolts DC have been generated using

-13-

cascaded voltage doublers, especially when operating in a pressurized atmosphere. The biggest advantage to using voltage doublers is that they use inexpensive low-voltage parts. Otherwise, if all the parts had to be of the high-voltage variety, you would have to use expensive and rather large capacitors like the one shown in Fig. 9.

If you have problems with the circuit in Fig. 8 (or any other high-voltage circuit), you must discharge *every* capacitor (we'll tell you how in a minute) before you check for malfunctions. When examining the circuit for problems, closely check the solder connections, and then the diode directions and continuity. The 1N4007's should have a resistance of 1.1K when forward-biased and be open when reverse-biased, while the capacitors

should all have infinite resistance.

To properly discharge capacitors, build a discharging wand like the one shown in Fig. 10. Use a 2-foot wooden (or plastic) dowel, and connect a stiff wire tip

FIG. 9—HIGH-VOLTAGE CAPACITORS. A 0.25 μF, 7.5-kilovolt capacitor is on the left; a 100 pF, 15-kilovolt capacitor is in the middle; and 0.0005 μF, 5-kilovolt capacitor is on the right.
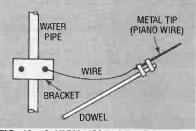

FIG. 10—A HIGH-VOLTAGE GROUNDING wand is used to discharge capacitors. A 2-foot wooden dowel is attached to a stiff wire tip. The metal tip must be connected to an earth ground, such as a cold-water pipe.

FIG. 11—HOMEMADE SWITCH for high-voltage DC. The line filter at left is a safety measure to keep high-voltage DC out of the house wiring.
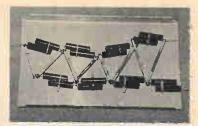

FIG. 12—A TYPICAL CASCADED voltage doubler. Note the wide spacings between the diodes, the long connecting wires, and the smooth solder joints.
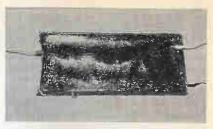

FIG. 13—THIS IS THE DOUBLER from Figure 12, after being sealed in candle wax. For better protection, you can immerse it in pure paraffin oil.

(piano wire works well) to a cold water pipe as earth ground with a good electrical connection. Discharge all capacitors twice, since they generally either hold charge, or tend to recharge from other capacitors. Don't use an AC line ground or chassis ground instead of an earth grounded water pipe, or you may blow a fuse or damage parts.

Figure 11 shows a switch for high-voltage DC that you can use with any of the cascaded voltage-doublers shown here; standard switches may present a shock hazard. Also, use an electromagnetic interference (EMI) line filter like the one seen at left in the photo to keep high-voltage DC out of house wiring, and to prevent shock from static charge. The EMI filter is from Corcom Corp. (1600 Winchester Road,

FIG. 7—THE COCKCROFT-WALTON, or Greinacher cascaded voltage doubler, has improved performance for moderate-current applications.
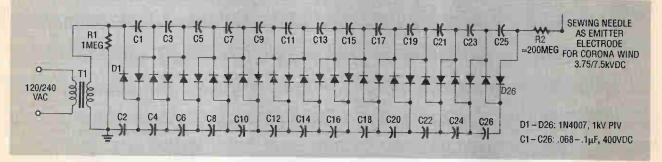

FIG. 8—THIS 25-STAGE VOLTAGE DOUBLER will generate "corona wind." It delivers 3.75 kilovolts DC when powered from 120 volts AC, or 7.5 kilovolts DC when powered from 240 volts AC.
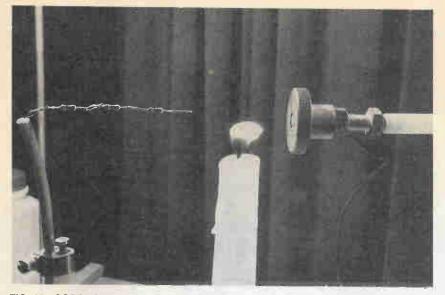
FIG. 14—CORONA WIND DEMONSTRATION. The flame will deflect toward the ground plate. Note the black ground wire attached near the screw threads.
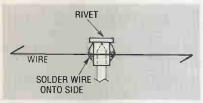

FIG. 15—THIS ION-MOTOR ROTOR, when placed on top of the sewing-needle emitter, will spin in a circle.
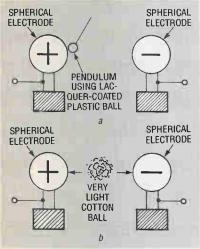

FIG. 16—TWO CHARGED DOOR KNOBS cause a suspended, lacquer-coated plastic ball to behave like a pendulum (a). A light cotton ball will bounce back and forth without being suspended on a string (b).

Libertyville, IL 60048, tel. 312-680-7400), Model 2061 is rated at 20 amps, 250 volts, and 50–400 Hz. The high-voltage DC switch in Fig. 11 also uses an old 100-amp fuse box, shown on the right; it may look like an antique, but it will prevent any shocks.

When you build a cascaded voltage doubler, you can encase the circuit in pure paraffin oil or candle wax to reduce the chances of getting shocked. It will also minimize corona loss, so the high-voltage DC arrives where it's needed. Figures 12 and 13 show a typical ladder-type voltage doubler before and after being sealed in wax.

Experiments

There are many experiments that can produce observable effects due to the high-voltage DC produced by voltage doublers.
• With a high-voltage emitter pointed at a ground plate (used to attract ions), with a burning candle placed in between them (see Fig. 14), you'll see the candle flame deflect toward the metal plate.
• You can make a rotor for an ion motor, using a light pivot made from a rivet with thin, stiff wire (like piano wire) attached, as shown in Fig. 15. The rotor must be balanced on top of the sewing-needle emitter (much as in a compass) used for the doubler shown in Fig. 8. (We ran a similar construction project in **Radio-Electronics**, February, 1991.) When powered up, the rotor will spin and a hissing sound will be heard. Both ends of the wire are bent at opposite right angles, so the emitted electrons propel the wire in a circle. You should sharpen both ends of the rotor wire to provide a sharp surface

good for corona generation and electron emission. The sharpened ends will have a small radius of curvature (a tight curve or bend), giving rise to a highly distorted electric field at its surface. The high electric field is what tends to ionize air molecules in the vicinity.

• Another experiment you could try involves holding a fluorescent tube near the emitter. The tube will glow, but be careful not to touch the terminals on the ends, or you'll get a shock.
• Lines of force of an electrostatic field can be demonstrated by placing the electrodes (the high-voltage DC output and ground) in a tray covered with castor oil containing some farina. The farina will produce the pattern of the electric field lines; similar to iron filings shaken lightly on a piece of paper in the presence of a bar magnet.
• If you place two round door knobs on insulated stands made from plastic cups filled with candle wax, and then charge them, then a plastic ball suspended from a string will be drawn to and touch the positive electrode, and fall back to center when the spheres are discharged (see Fig. 16-a). A plastic ball coated with conductive lacquer swings toward the positive electrode like a pendulum; when the ball and doorknob touch, the ball becomes positively charged, so they repel one another. It then swings toward the negative side, absorbs electrons, becomes negatively charged, and is repelled back to the positive. The process repeats indefinitely as long as the high-voltage DC is present, and it will continue to operate for some time after it's shut off. The charge exchange is slow, and there'll be arcing at the positive electrode.
• A grounded metal ball alternates between both electrodes, like the conducting plastic ball. However, the arcs are smaller due to its greater weight, and should be observed at both ends, but more on the positive side.
• A light cotton ball should be drawn to the positive electrode and hang there by itself, as shown in Fig. 16-b. It's then repelled 0.5-inch toward the negative electrode, and the process should repeat indefinitely. ■

Make Kirlian Photographs

John Iovine

In this article we explore the mysteries of Kirlian photography and show you how you can investigate the phenomenon yourself!

LABORING IN RELATIVE OBSCURITY, Seymon Kirlian (pronounced keer-lee-an) began his work in electro-photography in 1939. Over 40 years later, that work is still the source of much speculation and controversy. That's because it has been claimed that Kirlian was able to use auras that surrounds the objects in his electro-photographs to detect illness in plants and animals before any other outward symptoms were visible. Whether those claims are true or not, they sparked a good deal of interest in the field of electro-photography; so much so that electro-photography is today commonly called Kirlian photography.

What is it?

In Kirlian photography, a variable-frequency high-voltage source is use to produce images on photographic film. It does so without the benefit of a camera, lenses, or light, so it can, in some ways, be likened to X-ray photography. The resulting photograph is a recording of the cold electron emission created by the high-voltage source. How the emission is modified by the subject or object used in making the photographs is the focal point of Kirlian photography.

Many of the theories used to explain the effect read like excerpts from a science-fiction novel. One theory put forth by Dr. F Cope, who was investigating the Kirlian aura at the Bio-Chemistry Laboratory at the Naval Air Development Center, in Warminster PA, felt that all substances and, in particular, living organic matter, contain and are surrounded by what can best be described as a matter energy field. When a high-voltage charge is introduced into that field, it becomes or behaves like a superconductive plasma. The laws of physics that pertain to such a plasma are complex, involving an extended form of Einstein's Theory of Relativity. It's possible that the aura recorded around objects may be a physical manifestation of that matter field.
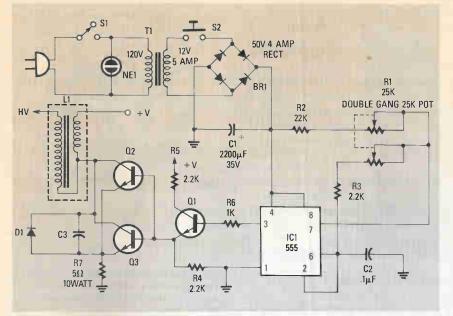
FIG. 1—YOU CAN MAKE YOUR OWN Kirlian photographs using this circuit. Coil L1 is an automotive ignition coil that can be obtained cheaply from an automotive junkyard.

FIG. 2—THE "CABINET" for L1 can be fashioned from a cardboard tube. The end caps can be made of plexiglass.

Unfortunately, when Dr. Cope died, the research unit disbanded. While Dr. Cope was alive, though, he was one of a few scientists with the courage to do research into what is considered, at best, a fringe science.

It is that fringe-science category that impedes research into the field, in addition to quickly becoming associated with the quacks, psychics, and pseudo-scientists that permeate the field. It is easy to see that any scientist wanting to seriously investigate electro-photography is going to be met with serious opposition, and could possibly lose their standing in the scientific community.

But is the opposition justified? Is it possible that the procedure has no merit whatsoever? I don't think so and, to make my point, allow me to draw a few analogies. We analyze light from stars to determine their composition, and their doppler shift to determine speed. Those two facts have created a foundation upon which modern cosmology in the last century stands. We typically perform spectrographic and colormetric analysis to determine a compound's composition. It is therefore my belief that the Kirlian effect may provide a tool with which we can probe nature.

Despite the opposition to electro-photographic research, Kirlian images have been used experimentally, as a diagnostic tool, in medicine, and for non-destructive testing of materials in engineering. One interesting aspect of electro-photography is that, while all objects appear to produce an electro-photographic aura, the aura of inanimate objects appears constant over time, while living creatures give off an aura that is time varying. In humans, emotional stress, illness, and alcohol or drugs all appear to have an effect on the aura.

One of the U.S. government's studies in the area involved using the Kirlian aura to ascertain the physical and mental health of military personnel, and to determine their level of fatigue. That was done by measuring the diameter of the aura or corona, at the fingertip. At the end of the test, the results were analyzed and two statistically valid conclusions could be drawn. One was that the corona of those suffering physical stress (exercise) was larger in diameter than the test average; the other was that those suffering mental stress (fatigue, etc.) had coronas that were smaller in diameter than the test average.

It may appear obvious than those test results could be due to the dilation or constriction of the blood vessels. Another study proves that assumption incorrect. Compounds given to individuals to dilate or constrict blood vessels do not produce a statistical difference in the corona diameter, according to a report.
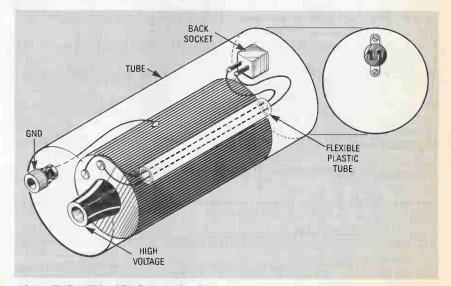

FIG. 3—THE AUTOMOTIVE IGNITION COIL is mounted inside its cabinet by gluing it to one side. Make the ground connection by soldering a wire to the side of the coil housing and connecting the other end to the cabinet-mounted binding post.
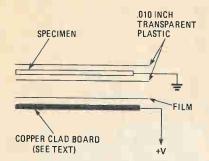
FIG. 4—THE SPECIMEN to be photographed should be sandwiched between two sheets of thin (0.01-inch) transparent plastic.
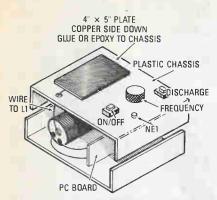

FIG. 5—TO MAKE THEM EASIER TO FIND in the dark, cluster the unit's operating controls around NE1.

While the results of the tests were interesting, there is still not enough data to hail Kirlian photography as a "fool-proof" diagnostic test. Although other similar tests have been reported, the results have been incomplete. For instance, in one study, the fingertip coronas of 120 adult humans were photographed. Of the sample, 20% had a corona diameter that was markedly below the average. It was later determined that 50% of that 20% suffered from some sort of medical problem.

There are several obvious flaws with that study. For one, no report was made on the health of the 80% whose corona diameter was not reduced; it would have been informative to know what percent of those, if any, also suffered from some medical problem. Also, no follow-up appears to have been done on those whose corona diameters were decreased and who had no ascertainable medical problems. It would have been interesting to see how many of them developed some kind of difficulty, and in what time frame following the experiment.

The most dramatic experiment in Kirlian photography, and one that has garnered the most attention, is the so-called phantom-leaf phenomenon. In that experiment, a small part (approximately 2% to 10% of the total surface area) of a leaf is cut off. Electro-photographs subsequently taken will sometimes show the energy pattern or aura of the missing section. The reason for that is unknown, and it is the subject of much speculation, and although the effect is exceptionally rare, it has been demonstrated enough times by different people to prove its existence. One important fact must be kept in mind if you wish to attempt to replicate the phantom-leaf effect. The leaf must still be attached to the parent plant when shooting the photograph.

Making your own

There are probably quite a few doubters still out there. To those we offer the following challenge: Why not build your own Kirlian-photography unit and prove or disprove the existence of the effects yourself? The worst-case scenario is that you will

FIG. 6—ALTHOUGH THE RESULTS are not visually striking, Kodalith film is easy to work with. Here is a Kirlian aura captured on that film.

build a device that takes exceptional, beautiful, and exotic photographs of the most-common items lying around. In the balance of this article we will present a simple set up that will allow you to do just that. Although the equipment is not on par with that used in research labs, it is still more than sufficient to provide startling results. The color photographs that accompany this article showing the Kirlian aura of some common leaves, were produced using the apparatus as described.

The circuit for the setup is shown in Fig. 1. The heart of the circuit is a 555 timer in astable mode whose frequency is controlled by a double-ganged pot. The output of the timer is fed into Darlington-transistor T1. The Darlington transistor controls two TO-3 power transistors that switch the current on and off to a three-terminal automotive ignition coil, L1.

Construction is straight-forward, and the circuit is simple enough that a PC board is not required—although you can use one if you wish. Note that the transistors can get hot, so they should be heat sinked. The only other point that merits special mention is that a plastic chassis is essential, to provide adequate shock protection from the coil and is also essential to properly mount the exposure plate on top of the chassis (see Fig. 2).

Figure 3 shows the internal mounting of the components. The ignition coil is epoxied or glued to one side of the chassis so that the high-voltage

SOLID-STATE TESLA COIL

Build an updated version of Nikola Tesla's most-famous experiment.

By Charles D. Rakes

IKOLA TESLA IS CONSIDERED BY SOME TO BE THE greatest inventor of our modern electrical age, and many experts consider him to be the true father of radio. However, today he is best remembered for his fascinating wireless power-transmission experiments, using his famous Tesla coil.
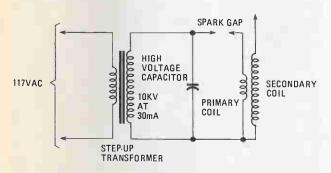
The high-frequency air-core, oscillating Tesla coil is just as exciting today as it was back in 1899, when he used it to successfully transmit electrical energy over 25 miles, without wires, to light a large number of incandescent lamps. The Tesla coil is ideal for demonstrating and exploring the unusual phenomena that occur with high-frequency high-voltage energy.
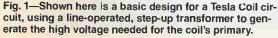
Most Tesla coils designed for educational and experimental purposes use a line-operated, step-up transformer—in setups like that shown in Fig. 1—to generate the high voltage needed for the coil's primary circuit. While there's nothing technically wrong with that approach, it can place the operator in harm's way if the coil's primary circuit is accidentally touched. A shock from the high-voltage winding could prove extremely dangerous and may be fatal.
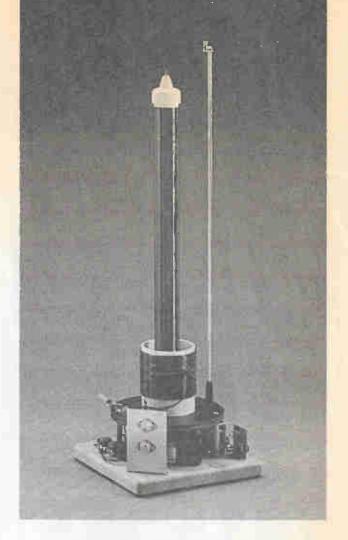
Our version, the *Solid-State Tesla Coil* (see photos), eliminates the line-operated, high-voltage transformer, making it a safer project to build and to experiment with. Even so, wise operators will keep their digits out of the wiring while the coil is under power.

Solid-State Tesla Coil

The schematic diagram for the Solid-State Tesla Coil is shown in Fig. 2. In that updated version of the Tesla experiment, an 18-volt, 2-ampere transformer (T1), a bridge rec-
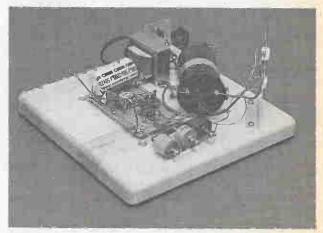

tifier circuit (consisting of D1-D4), and filter capacitors (C1 and C3) supply operating power for the coil circuitry.

A 555 oscillator/timer (U1) is configured as a self-oscillating pulse-generator circuit. Resistors R1 and R2 make up a voltage-divider network, which is used to lower the 24-volt DC output of the power supply to a safe operating level for U1. The 555's narrow output pulse at pin 3 supplies drive current to the base of Q1. Transistor Q2 supplies sufficient

Fig. 1—Shown here is a basic design for a Tesla Coil circuit, using a line-operated, step-up transformer to generate the high voltage needed for the coil's primary.

Here is the author's prototype of the Solid-State Tesla Coil with the 9-inch circular deck removed. The two heavy wires running the length of the top and bottom of the board serve as the ground and + V bus.
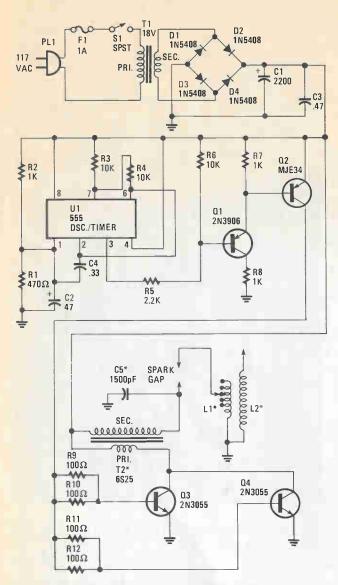
Fig. 2—Our updated version of the Tesla experiment uses an 18-volt, 2-ampere transformer (T1), a full-wave bridge rectifier (consisting of D1-D4), and filter capacitors (C1 and C3) to supply operating power for the Coil's circuitry.

current to transistors Q3 and Q4 to drive those components into full saturation.

The primary winding of T2 (an automobile-ignition coil) is connected in series with Q3 and Q4, and across the power supply. Transistors Q3 and Q4 operate like a toggle switch, connecting the coil across the power source at the rate and on-time set by U1.

That high-current pulse generates a rising and collapsing field across the primary winding of T2. The field causes a current to be induced in the secondary winding of T2. The secondary output of T2 is fed across three 500-pF, 10-kilovolt doorknob capacitors (collectively designated C5) that are parallel connected and tied across the high-voltage output of T2 as an energy-storage device. Those capacitors charge up to T1's secondary voltage and are then discharged through the spark gap and the primary (L1) of the Tesla coil, producing higher voltage in the secondary of the coil (L2).

The secret of producing a successful Tesla coil is in the tuning of the primary coil to the natural resonance frequency of the secondary coil. Because variable 10-kilovolt capacitors

are about as common as Condor eggs, some other means must be used to tune L1. The simplest method is to tap the primary coil on every turn and select the tap that produces the greatest voltage at the hot end of L2.

Perfboard Assembly

The author's prototype was built breadboard style on an 11 × 11 × 1-inch wooden cutting board (see photos), but any similar non-conducting material (perhaps plastic) will do. The majority of the small components, as shown in the photos, were mounted on a 3 × 5-inch section of perfboard, and point-to-point wiring techniques were used to complete the connections. Refer to the schematic diagram (in Fig. 2) and the photos for wiring and general parts-layout details. Note: Components T1 and T2, C5, Q3 and Q4, F1, and S1 are not mounted to the perfboard (see photos).

Figure 3 shows the positioning of the perfboard and off-board components on the baseboard. Mount the fully-populated perfboard assembly to the baseboard using four ¼-inch plastic spacers and wood screws. The location of the sub-assemblies on the baseboard isn't too critical, so long as the general layout is followed. Keep all wire leads as short as possible, especially around the high-voltage circuitry.

A 2½ × 2-inch piece of aluminum is formed into an "L" bracket, which is used to hold S1 and F1 (see photo), and is mounted on one corner of the baseboard. A 5 × 3-inch piece of aluminum mounts to the opposite corner and functions as the heat sink for the two power transistors (Q3 and Q4). A simple band is formed from aluminum to hold T2 in place.
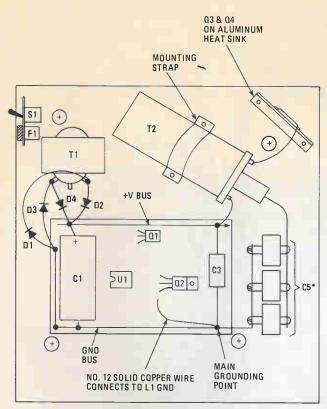
Recall that C5 is really three 500-μF doorknob capacitors.

Fig. 3—The author's prototype was built breadboard style on an 11 × 11 × 1-inch wooden cutting board, and most of the components were mounted on a 3 × 5-inch piece of perfboard.

Two brass strips, about ⅜-inch wide by 3-inches long, are used to tie the three high-voltage capacitors together. If doorknob capacitors cannot be located (often they can be salvaged from older black-and-white TV's), a substitute can be made from window glass and aluminum foil.

To fabricate C5, take a 10-inch square piece of glass, like that of a picture frame, and glue a 9-inch square piece of aluminum foil to the center of the glass on both sides, leaving an equal border around each aluminum plate. Cut two 6-inch lengths of #22 insulated stranded wire. Strip about 3-inches of insulation from one end of each wire and tape the stripped end to each of the aluminum plates.

Shown here is the 9-inch circular deck supported by four dowel rods, and an end cap positioned at its center.

The Deck

Figure 4 and the photos show the top deck of the author's prototype, where the two air-core coils (L1 and L2) are mounted. The top deck consists of a 9-inch diameter circle cut from ½-inch thick fiber board. Four 3¾-inch lengths of ⅜-inch dowel hold the 9-inch coil base above the perfboard.

Select a drill bit slightly smaller than the dowel rod's diameter and drill the four mounting holes in the 9-inch circle to match the illustration. Position the 9-inch circle on the baseboard at about the center, and mark the location of each hole. Drill each location on the baseboard with the same bit to a depth of about ½-inch.

If the two-layer Tesla coil seems like too much bother to

9-INCH DIAMETER, 1/2-INCH THICK
FIBER OR WOOD CIRCLE
ALL DIMENSIONS IN INCHES

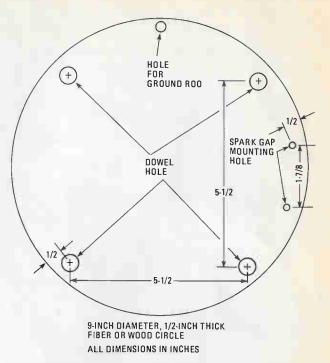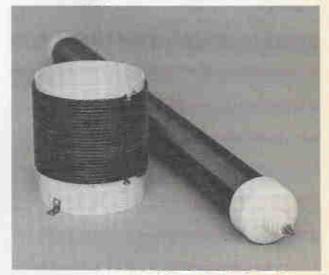Fig. 4—Shown here is the general layout of the top deck of the author's prototype, which supports coils L1 and L2. Four 3¾ × ⅜-inch wooden dowel rods hold the 9-inch circular base above the perfboard and other components.
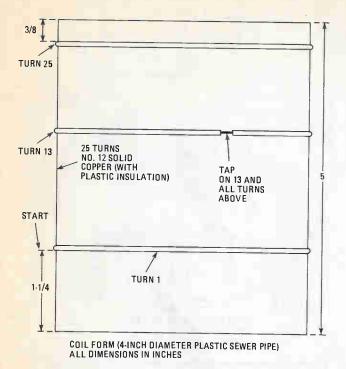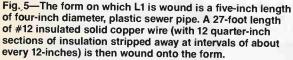

Here is what L1 (left) and L2 (right) should look like once completed. Although winding L2 may appear difficult, it can be done in an hour by hand or in 15 minutes by lathe.

duplicate, then build a single-level unit on a larger wooden base to suit your own needs. Actually, any good layout scheme that respects the dangers of high voltage should do quite well.

Winding the Primary Coil

The primary-coil (L1) is wound on a form cut from a 4-inch diameter, plastic sewer pipe to a length of five inches (see Fig. 5). Take a 27-foot piece of #12 insulated solid-copper wire and strip away a ⅛-inch section of insulation at about every 12 inches, continuing for one-half the length of the wire (12 times total). Those stripped areas serve as tap points for tuning the coil.

Fig. 5—The form on which L1 is wound is a five-inch length of four-inch diameter, plastic sewer pipe. A 27-foot length of #12 insulated solid copper wire (with 12 quarter-inch sections of insulation stripped away at intervals of about every 12-inches) is then wound onto the form.

Wind the coil starting at the top of the coil form (see Fig. 5) with the end that has the 12 tap points. In other words, turn 25 is the first winding to be made. That gives a tap on every turn from turn number 13 to turn number 25. Drill two small holes in the coil form where the winding starts and ends. Those holes are used to secure the ends of the windings (see photos).

Winding the Secondary Coil

The secondary coil form (see Fig. 6) is cut from a section of 1½-inch diameter, plastic water pipe (which actually measures 1⅞-inches in diameter). So when selecting your secondary coil form, take a ruler with you and be sure to come home with the correct-diameter pipe. You'll also need two plastic end caps that snugly fit the ends of the tubing.

Make a mark on the coil form about one inch from each end. That sets the starting and ending points for the winding. Fill the space between marks with a neat solenoidal winding of #26 enamel-covered copper wire. Winding the coil by hand shouldn't take over an hour, and if a lathe is handy, you should be able to complete the job in about 15 minutes. Leave
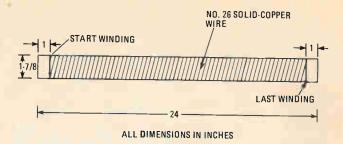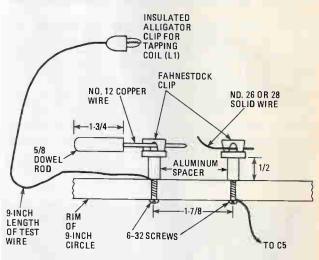

Fig. 6—Using #26 enamel-coated copper wire, L2 is wound on a 24-inch length of 1½-inch diameter, plastic water pipe, either by hand or (if available) using a lathe.

about 6-inches of wire at both ends of the winding for making connections.
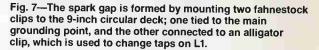
Spray several coats of Krylon clear #1301 acrylic on the coil for added insulation and protection against moisture. Always let each coat dry completely before applying the next. Two or three coats are sufficient.

It's Coming Together

Mount one of the 1½-inch, plastic end caps to the center of the 9-inch circular deck with a 1-inch long #8-32 screw, washer, and nut. Take two small metal "L" brackets and mount the primary coil centered around the end cap on the 9-inch base. Drill a small hole through the end cap and baseboard near the rim of the cap. Take the secondary coil and push one end of the coil's lead through the hole in the end cap, and then set the coil in the end cap.

Fig. 7—The spark gap is formed by mounting two fahnestock clips to the 9-inch circular deck; one tied to the main grounding point, and the other connected to an alligator clip, which is used to change taps on L1.

Take the other end cap and drill a hole in the center to clear a #8-32 screw, and mount a feed-through insulator (see photo) on top. Select a #8-32 screw long enough to stick through the top of the insulator by about ½-inch, and grind the end to a nice sharp point. Connect the top end of the secondary coil to the bottom of the #8-32 screw with a small solder lug and tighten in place. Place the cap on top of the coil.

The spark gap is shown in Fig. 7. Two holes are drilled to clear a #6-32 screw to match the drawing in Fig. 4. Two

STUN GUN

ROBERT GROSSBLATT, and ROBERT IANNINI

This experimental high-voltage generator can produce 75,000 volts at a peak power of 25,000 watts.

MAN'S FASCINATION WITH high voltages began with the first caveman who was terrified by a bolt of lightning. In more recent times, electronics experimenters and hobbyists have found the Tesla coil and the Van de Graaff generator equally fascinating. In this article we'll show you how to build a hand-held high-voltage generator that is capable of producing 75,000 volts at a power level as high as 25,000 watts. The stun gun can be used to demonstrate high-voltage discharge and as a weapon of self-defense. Before building one, however, you should read and pay very close attention to the warning in the accompanying text box, as well as to the description of physiological effects that follows.

WARNING

THIS DEVICE IS NOT A TOY. We present it for educational and experimental purposes only. The circuit develops about 75,000 volts at a maximum peak power of 25,000 watts. The output is pulsed, not continuous, but it can cause a great deal of pain should you become careless and get caught between its output terminals. And you should never, repeat, NEVER, use it on another person! It may not be against the law in your area to carry a stun gun in public, but, if you use it on another person, you may still be liable for civil action.

To help you build, test, and adjust the device safely, we have included a number of tests and checks that must be followed strictly. Do not deviate from our procedure.

Physiological effects

So that you may understand the danger inherent in the stun gun, let's discuss the physiological effects first. When a high voltage is discharged on the surface of the skin, the current produced travels through the nervous system by exciting single cells and the *myelin sheaths* that enclose them. When that current reaches a synapse connected to a muscle, it causes the muscle to contract violently and possibly to go into spasms.

The longer contact with the high voltage is maintained, the more muscles will be affected. If the high voltage maintains contact with the skin long enough to cause muscle spasms, it may take ten or fifteen minutes before the brain is able to re-establish control over the nerve and muscular systems.

How much power is required to cause such spasms? That's not an easy question to answer because, although it is relatively easy to make precise measurements of the power produced by a high-voltage device, it is difficult to rate the human body's susceptibility to shock accurately. Some obvious factors include age and diseases such as epilepsy. But the bottom line is simple: *The only one who fools around with a stun gun is a fool.*

The amount of energy a device delivers is actually the amount of power delivered in a given period of time. For our purposes, it makes sense to talk about energy in joules (watt-seconds). Using a fresh 9.8-volt Ni-Cd battery, the stun gun is capable of delivering peak power pulses of 25,000 watts. Actually, pulses start out at peak power and then decay exponentially. The length of the decay time depends on the components used in the circuit, the ambient temperature, the battery's capacity, and the positioning of the output contacts with respect to each other.

Assuming that the decay rate is purely exponential, the stun gun can produce about 0.5 joules of energy, provided that the battery is fully charged. Let's put that number in perspective.

Both the Underwriter's Laboratory (in Bulletin no. 14) and the U. S. Consumer Product Safety Commission state that ventricular fibrillation (heart attack) can be caused in humans by applying 10 joules of energy. Since the stun gun only generates about half a joule, you might think that a device that produces only one twentieth of the critical amount has a more-than-adequate margin of safety. *Don't bet on it.* A brief contact with the stun-gun's discharge hurts a great deal, but it takes only about five seconds of continuous discharge to immobilize someone completely.

Let's compare the stun gun's output with a similar device, called a Taser gun, which appeared on the market a few years ago. You may have seen a film demonstrating just how effective the Taser could
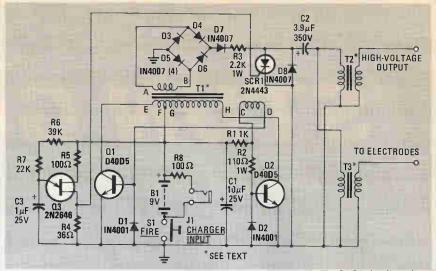

FIG. 1—THE STUN GUN'S CIRCUIT is a multi-stage voltage step-up circuit. The Q1/Q2 circuit produces a squarewave output of about 10 kHz, and Q3 produces 15-μs discharge pulses at a rate of about 20 ppm. Those pulses fire SCR1, which induces a voltage in the windings of step-up transformers T2 and T3.

be as a deterrent. A foolhardy volunteer was paid an enormous sum of money to have the Taser fired at him. No matter how big, strong, (and stupid) the person was, as soon as the Taser's "darts" hit him, he would collapse to the ground and go into uncontrollable convulsions.

The energy produced by the Taser is only 0.3 joules—about 60% of what our stun gun produces! Even so, the Taser has been officially classified as a firearm by the Bureau of Tobacco and Firearms because it shoots its electrode "darts" through the air. Even though our stun gun doesn't operate that way, the Taser puts out considerably less energy than the stun gun. Keep those facts and figures in mind as you assemble and use the device.

How it works

The schematic diagram of the stun gun is shown in Fig. 1. Basically, it's a multi-stage power supply arranged so that each succeeding stage multiplies the voltage produced by the preceding stage. The final stage of the circuit feeds two oppositely-phased transformers that produce extremely high voltage pulses. If that description sounds familiar, you've probably studied capacitive-discharge ignition systems—the stun gun works on the same principles.

The first section of the power supply is a switcher composed of Q1, Q2, and the primary windings (connected to leads E, F, G, and H) of T1. When FIRE switch S1 is closed, R1 unbalances the circuit and that causes it to start oscillating. Since base current is provided by a separate winding of T1 (connected to leads C and D), the two transistors are driven out of phase with each other, and that keeps the circuit oscillating. Resistor R2 limits base drive to a safe value, and diodes D1 and D2 are steering diodes that switch base current

from one transistor to the other. Oscillation occurs at a frequency of about 10 kHz.

The switching action of the first stage generates an AC voltage in T1's high-voltage secondary (leads A and B). The amount of voltage depends on the battery used, but a battery of seven to nine volts should produce 250 to 300 volts across T1's secondary.

That voltage is rectified by the full-wave bridge composed of diodes D3–D6. Capacitor C2 charges through D7 at a rate that is controlled by R3.

The value of capacitor C2 affects the output of the stun gun. The greater the capacitance, the more energy that can be stored, so the more powerful the discharge will be. A larger capacitor gives bigger sparks, but requires more charging time, and that gives a lower discharge rate. On the other hand, a smaller capacitor gives smaller sparks, but a faster discharge rate. If you wish to experiment with different values for C2, try 3.9 μF (as shown in Fig. 1), 7.8 μF, and 1.95 μF. Those values were arrived at by using one 3.9 μF capacitor alone, two of the same capacitors in series, and two in parallel.

Meanwhile, UJT Q3 produces 15-μs pulses at a rate of about 20 ppm. That rate is controlled by C3 and the series combination of R6 and R7. When a pulse arrives at the gate of SCR1, it fires and discharges C2. That induces a high-voltage pulse in the primary windings of T2 and T3, whose primaries must be wired out of phase with each other. The result is a ringing wave of AC whose negative component then reaches around and forces the SCR to turn off. When the next pulse from Q3 arrives, the cycle repeats.

The outputs of the stun gun appear across the secondaries of T2 and T3. The hot leads of those transformers connect to
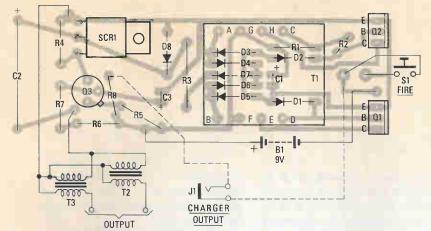
FIG. 2—MOUNT ALL COMPONENTS ON THE PC BOARD as shown here. Note that T2 and T3 are mounted off board, and that J1, C1, and D7 mount on the foil side of the board. In addition, a number of components mount beneath T1: D1–D6, R1, and R3. Those diodes and resistors must be installed before T1.
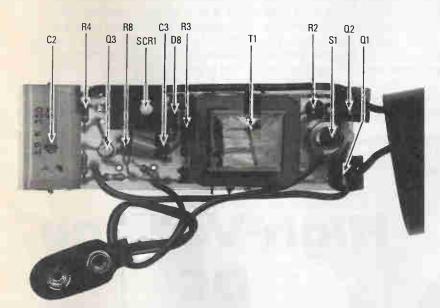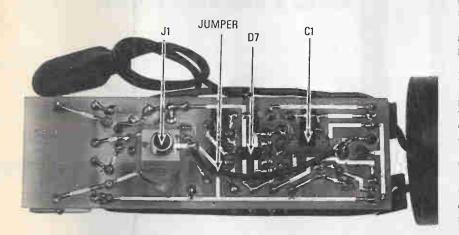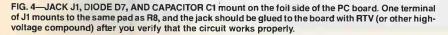

FIG. 3—BEND SCR1'S LEADS 90° so that the nomenclature faces up and then solder the SCR to the board. Also note that C3 must be bent over at a 90° angle, and that R2 is mounted vertically.

FIG. 4—JACK J1, DIODE D7, AND CAPACITOR C1 mount on the foil side of the PC board. One terminal of J1 mounts to the same pad as R8, and the jack should be glued to the board with RTV (or other high-voltage compound) after you verify that the circuit works properly.

the output electrodes, which should be held securely in position about two inches apart, and which should be insulated from each other and from the environment with high-voltage potting compound.

Batteries

The stun gun can be powered with almost any battery that can supply at least seven volts at one amp. A Ni-Cd battery would be a good choice; R8 and J1 will allow the battery to be recharged without removing it from the case.

The higher the battery's voltage, the higher the stun-gun's output voltage. Most nine-volt Ni-Cd's actually have a maximum fully-charged output of only 7.2 volts. However, batteries that deliver 9.8 volts when fully charged are available from several sources.

Construction

Keep in mind the fact that the stun gun produces dangerously high voltages, and don't approach the construction of the stun gun with the same nonchalance with which you might build a light dimmer.

The circuit can be built on a PC board or on perfboard. The foil pattern for a PC *(Continued on page 31)*

Voltage, by definition, is the electrical pressure that causes current to flow through a conductor. When that pressure is sufficiently high, a high voltage is produced. But how do we define high voltage? Is 100, 1000, or 10,000 volts considered high voltage? When compared to 10 volts, they all can be considered high voltage.

As far as safety goes, high voltage can be considered any voltage that endangers human life. It's obvious that 1000 volts poses a greater hazard than does 100 volts, but that does not mean that 100 volts is safe to handle. As far as safety goes, 100 volts is still considered high voltage—and that fact must be understood.

The *Miniature High-Voltage DC Generator*, presented in this article, is capable of generating around 10,000-volts DC. So high a voltage can ionize air and gases, charge high-voltage capacitors, and can also be used to power a small laser or image tube, and has many other applications that are useful to both the experimenter and the researcher.

Circuit Description. Figure 1 is a schematic diagram of our Miniature High-Voltage DC Generator. The circuit is fed from a 12-volt DC power supply. The

input to the circuit is then amplified to provide a 10,000-volt DC output. That's made possible by feeding the 12-volt output of the power supply to a DC-to-DC up converter. The output of the up-converter is then fed into a 10-stage, high-voltage multiplier to produce an output of 10,000-volts DC.
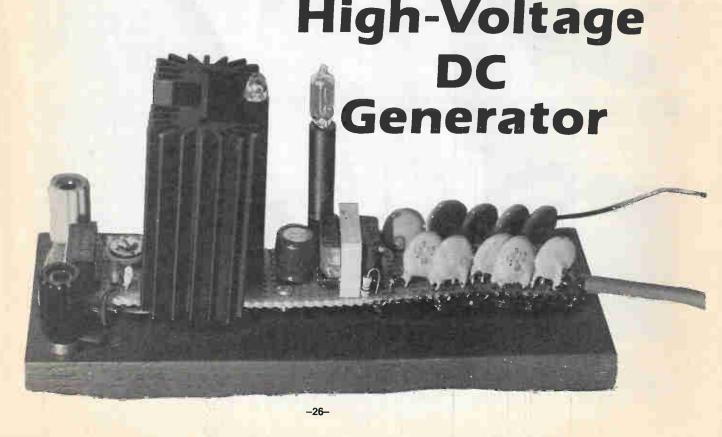
Let's see how the circuit works. First, let's start with U1 (a 14584 hex Schmitt trigger). Gate U1-a is set up as a square-wave pulse generator, which provides a very clean square-wave (pulsating DC) output. The output of U1-a is fed to the inputs of U1-b to U1-f, which are connected in parallel to increase the available drive current.

The pulsating output of the paralleled gates is fed to the base of Q1, causing it to toggle on and off in time with the oscillations of U1-a. The collector of Q1 is connected in series with the primary winding of T1. The other end of T1 is connected directly to the positive terminal of the battery or power supply. This produces a driving wave in the primary winding of T1 that is similar to a square wave.

The on/off action of the transistor, caused by the pulsating-signal applied to Q1, creates a rising and collapsing field in the primary winding of T1 (a small ferrite-core, step-up transformer). That causes a pulsating signal, of op-

Learn how very-high voltages are generated from relatively low power sources and apply the same techniques to your own experimental circuits

BY VINCENT VOLLONO
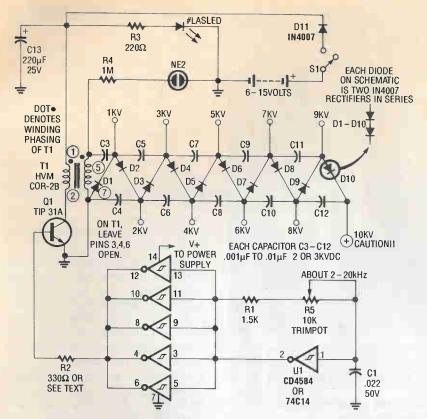
High-Voltage DC Generator

Fig. 1. In the High-Voltage DC Generator, the input to the circuit, taken from a 12-volt DC power supply, is magnified to provide a 10,000-volt DC output. There's no C2.

posite polarity, to be induced in T1's secondary winding.

The pulsating DC output at the secondary winding of T1 (ranging from 800 to 1000 volts) is applied to a 10-stage voltage-multiplier circuit—consisting of D1 through D10, and C3 through C12. The multiplier circuit increases the voltage 10 times, producing an output of up to 10,000-volts DC. The multiplier accomplishes its task by charging the capacitors (C3 through C12), through the diodes (D1 through D10); the output is a series addition of all the capacitors in the multiplier.

In order for the circuit to operate efficiently, the frequency of the square-wave, and therefore the signal applied to the multiplier, must be considered. The output frequency of the oscillator (U1-a) is set by the combined values of R1, R5, and C1 (which with the values specified is approximately 15 kHz). Potentiometer R5 is used to fine tune the output frequency of the oscillator. The higher the frequency of the oscillator, the lower the capacitive reactance in the multiplier.

Light-emitting diode LED1 serves as an input-power indicator, while neon lamp NE1 indicates an output at the secondary of T1. A good way to get the maximum output at the multiplier is to connect an oscilloscope to the high-voltage output of the multiplier, via a high-voltage probe, and adjust potentiometer R5 for the maximum voltage output. If you don't have the appropriate test gear, you can place the output wire of the multiplier about a half-inch away from a ground wire and draw a spark, while adjusting R5 for a maximum spark output.

Caution: The output of the multiplier will cause a strong electric shock. In addition, be aware that even after the multiplier has been turned off, there is still a charge stored in the capacitors, which, depending on the state of discharge, can be dangerous if contacted. That charge can be bled off by shorting the output of the circuit to ground. (In fact, its a good idea to get in the habit of discharging all electronic circuits before handling or working on them.)

Also, U1 is a CMOS device and, as such, is static sensitive. It can handle a maximum input of 15 volts DC. Do not go beyond the 15-volt DC limit or the IC will be destroyed. Diode D11 is used to prevent reverse polarity of the input voltage source.

As far as the voltage multiplier goes, the diodes and the capacitors must be rated for at least twice the anticipated input voltage. So, if we have a 1000-volt input, all of the diodes and the capaci-

In the author's prototype, LED1 and NE1 were mounted to 1½-inch stand-offs, and the entire circuit (minus the power supply) was mounted to a block of wood. The wood block helps to isolate and insulate the circuit board from any metallic objects.

tors must be rated for at least 2000 volts each. Because diodes with that voltage rating can be hard to find and expensive, D1 through D10 are each really two series-connected 1-amp, 1000-volt rectifier diodes.

Construction. The unit can be assembled on perfboard, as is the case with the author's prototype shown in the photo/ Transistor Q1 must be properly heat sinked or it will overheat quickly and self destruct.

The multiplier must be assembled in such a way so as to prevent any ion leakage. When a high-voltage source is terminated at a sharp point, the density of charge is concentrated at that point. The ions both on the point and near the point are like charges, so they repel each other and quickly leak off. So it is very important when soldering the multiplier to keep all connections rounded by using enough solder to make a smooth, ball-like joint.

The solder side of the multiplier should be insulated to prevent contact with any metallic object. On the author's prototype. A high-voltage insulating compound was used on the solder side of the board. High-voltage putty can also be used. Also in the prototype, the output of the circuit is simply a heavily shielded wire, like that used to feed high voltage to the anode of a TV picture tube. That type of wire can safely handle voltages in the 15,000- to 20,000-volt range, and will also help to prevent leakage.

Positive and Negative Ions. The polarity of the diodes in the multiplier will determine the polarity of the ions. In the author's prototype, the multiplier is set up to generate positive ions. If the diodes were reversed, negative ions would be produced.

In a positive-ion generating multiplier, like that used in the author's prototype, which generates approximately 10,000 volts DC, the output is a shock hazard. A negative-ion generating multiplier with a −10,000-volt DC output, offers the same shock hazard as the positive +10,000-volt output.

Experiments. If you place the high-voltage output wire about ½ to ¾ inch from a ground wire, you will draw a spark of 10,000 volts. But remember, the oscillator is built around a CMOS device, which is static sensitive, and any high-voltage kickback will toast the unit. So when experimenting with the spark, do not use the circuit ground. A more reliable method would be to draw a spark to an earth ground.

Flash Lamp Electric Storm. When the output of the Miniature High-Voltage DC Generator is connected to a small flash tube, the high voltage ionizes the Xenon gas in the tube, creating a small electrical storm within the tube's glass envelope.

Getting Different Voltages. By tapping the multiplier circuit at various stages you'll get output voltages ranging from 1,000 volts to 10,000 volts DC. For instance, by placing a tap at the cathodes of D2, D6, voltages of 2000, and 6000 volts are made available.

Troubleshooting. If you get no output or a low output from the circuit, check that the input to logic gates is below 15 volts. The application of an input voltage exceeding that limit will blow out the IC. Also check the signal (with an oscilloscope) that you get a square-wave output of approximately 12 kHz at pin 6 of U1.

The switching transistor must be mounted on a heat sink or it will overheat. Make sure the heat sink is of a suitable size to keep the transistor cool.

If a 2-kilovolt (kV) diode is placed at the output of transformer T1, you should get an unloaded output of approximately 800 to 1000 volts DC.

If you have a problem with the output of the unit, it is best to disconnect the multiplier from the oscillator and check the output of the transformer. In that way you will know if the problem lies in the oscillator or the multiplier.

The multiplier components must be rated for at least twice the input voltage. The diodes and capacitors used in the multiplier circuit should be rated at 2000 volts. However, you may choose to do as the author did; use two series-connected 1-kV units for each diode in the multiplier to give an effective rating per pair of 2 kV.

Safety. The output of the circuit is high-voltage DC, which will cause an electric shock if touched. So use caution. Also with the circuit turned off, the capacitors in the multiplier are still charged, and will discharge through the path of least resistance—your body—if you comes in contact with the circuit. So discharge the circuit by connecting the output lead to ground with the power off.

The Miniature High-Voltage DC Generator emits a fair amount of ozone. If the circuit is to be operated for a long period of time, make sure that you do so in a well ventilated room. Ozone is harmful in moderate to large quantities.

When drawing a spark discharge, the circuit emits radio and television interference. That can be seen as static lines on your television set or heard as noise on your AM radio. ∎

HIGH-VOLTAGE ZAPPERS

It doesn't take much to generate enough high voltage to curl your hair

CHARLES D. RAKES

THE TWO CIRCUITS WE'VE GOT HERE ARE for the experimenter having a touch of Ben and Nikola's fascination for working with high voltage. But unlike those two brave pioneers who flirted with lightning and gigantic spark coils, our high-voltage circuits are mild in comparison, having outputs of less than 50 kilovolts (kV). Even so, don't ever become careless when working with high voltage. To do so could be dangerous to your health and your good nature. So please take care.

A circuit that generates a high voltage by discharging the energy stored in a large-value capacitor through the primary winding of a high-turns-ratio step-up transformer is known as a *Ca*-*pacitor-Discharge* (CD) system. It's the same concept used by many of the high-performance auto-ignition systems to produce a super-hot spark. It's also the same kind of system used by some of the top-of-the-line electric fence chargers. And let us not forget one of the most popular personal-defense devices now on the market, the electronic Stun Gun, which also generates its zap with a capacitor-discharge circuit.

How we make the zap

As shown in the circuit of Fig. 1, step-down transformer T1 drops the incoming line voltage to approximately 48 VAC and, in the process, adds a degree of safety through the transformer's primary-to-secondary isolation from the power line. T1's 48-volt secondary is rectified by diode D1; the resulting DC charges capacitor C1, through current-limiter R1, to a voltage level pre-set by R4. When the voltage on R4's wiper reaches about 8.6 volts, Q1 begins to turn on, drawing current through R7 and the base-emitter junction of Q2. Then Q2 turns on and supplies a positive voltage to the gate of silicon-controlled rectifier
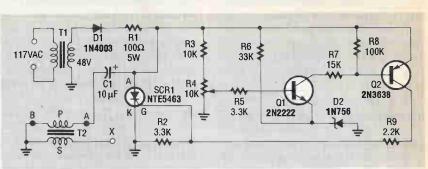

FIG. 1—BE SURE TO KEEP EVERYTHING, especially yourself, away from the high-voltage output at point "X."

Q3. The positive gate voltage causes Q3 to conduct, thereby discharging C1 through the primary winding of step-up transformer T2; the end-result is a high-voltage arc at the output terminal (X).

The value of the high voltage developed at T2's output is determined by the value of C1, the voltage across C1, and the turns ratio of T2. The frequency or pulse rate of the high

PARTS LIST
FIG. 1
All resistors are ½-watt, 5%, unless otherwise noted.
R1—100 ohms, 5 watts
R2, **R5**—3300 ohms
R3—10,000 ohms
R4—10,000 ohms, potentiometer
R6—33,000 ohms
R7—15,000 ohms
R8—100,000 ohms
R9—2200 ohms
Capacitors
C1—220- or 440-µF, 75–100 volts, electrolytic, or 10-µF 220-VAC motor capacitor (see text)
Semiconductors
D1—1N4003 silicon rectifier
D2—1N756, 8-volt Zener
Q1—2N2222 NPN transistor
Q2—2N3638 PNP transistor
SCR1—NTE5463 10-amp, 200-volt silicon-controlled rectifier
Other components
T1—Step-down transformer, 48 VAC, 300 mA
T2—Auto ignition coil, or substitute (see text)

voltage is determined by the resistance of T1's primary and secondary windings, the value of R1, and the value of C1. The lower the value of each item, the higher the output pulse rate; the peak output voltage will remain unchanged only if C1's value remains unchanged.

Building the CD system

The circuit shown in Fig. 1 is non-critical, so any parts layout and mounting can be used; perforated wiring board will probably make for the easiest assembly. But no matter what kind of construction is used, keep T2's output terminal (labeled X) at least three inches clear of all circuit components, yourself, and anything else that can conduct electricity.

The transformer used for T2 can be almost any 6- or 12-volt auto-ignition coil, but one designed with a high turns ratio for a capacitor-discharge ignition system will produce the greatest output voltage. The CD coil that we used produced a spark 1¼ inches in length from the output terminal to the coil's common terminal.

An old (but good) TV flyback transformer can also be used for T2. Simply wind about 10 turns of test-lead wire around the transformer's ferrite core and connect the free ends of the wires to the points labeled "A"
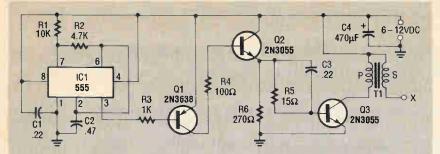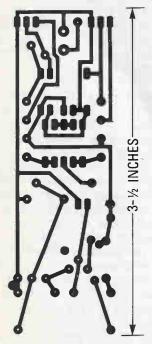
FIG. 2—THE SPARK DURATION is controlled by a 555 timer in this circuit.

and "B" in Fig. 1. Some experimenting with the number of turns may be necessary to obtain good results with that type of transformer. Our experiments with the TV flyback produced a voltage that would jump a ¾-inch gap.

If a small-engine repair business is located in your area, see if the owner or mechanic will give you a few of the old ignition coils. If you obtain several old coils, one or more should be usable. To produce a high voltage with a small-engine ignition coil, connect the primary leads to terminals "A" and "B," and a ½ to ¾-inch spark should be possible.

To make a "magnetic charger," select one of the ignition coils that has a good primary winding and carefully remove the secondary winding from the coil's core. Connect the primary wires to terminals "A" and "B." Position any object that you want to magnetize on the exposed core laminations and apply power; you should hear a "Zap" sound as the magnetic pulses hit the metal object.

Maximum spark

If you want to achieve a maximum spark, select a CD ignition coil, and use a 440-μF, 75- to 100-WVDC electrolytic capacitor for C1. Using a DC voltmeter, monitor the voltage across C1. Adjust R4 so that the Q3 fires when the charging voltage across C1 reaches between 50–55 volts. That setting should produce a spark 1¼ to 1½ inches long every second or so.

To obtain a faster pulse rate, with some reduction in the output, change C1 to a 10-μF, 220-VAC motor capac-itor (or any other lower value with a rating of 75 volts or more). Experiment with different component values to obtain the desired results.

An excellent electric fence charger can be made by building the CD circuit in a suitable case and selecting a 220-μF capacitor for C1. Adjust R4 for one to two pulses per second.

Battery-powered high voltage

A high-voltage generator circuit that can operate from a battery or other low-voltage DC source is shown in Fig. 2. Output voltage great enough to jump a 1-inch gap can be obtained from a 12-volt power source, and with a higher pulse rate than the circuit in Fig. 1.

A 555 timer IC is connected as an astable multivibrator that produces a narrow negative pulse at pin 3. The pulse turns Q1 on for the duration of the time period. The collector of Q1 is direct-coupled to the base of power-transistor Q2, turning it on during the same time period.

The emitter of Q2 is direct-coupled through current-limiter R5 to the base of power-transistor Q3. When Q3 turns on, there is a minimum resistance between its collector and emitter. That causes a high-current pulse through the primary of T1, which generates a very high pulse voltage at T1's secondary output terminal (labeled X). The pulse frequency is determined by the values of R1, R2, and C2. The values given in the Parts List were chosen to give the best possible performance when an auto ignition coil is used for T1. Here too, a CD-type ignition coil will produce the greatest output voltage.

Perforated wiring board construction is a good choice for this circuit, but remember to be careful when working near the output terminal of T1 while the power is on.

Getting parts

Radio Shack is a prime source for most of the components used in this article. Digi-Key Corp. (701 Brooks Ave. South, P.O. Box 677, Thief River Falls, MN 56701-0677) is another good source. A good selection of unusual components, such as photo-flash capacitors and telephone transformers, is available from All Electronics Corp. (905 S. Vermont Ave., PO Box 20406, Los Angeles, CA 90006). ∎

STUN GUN PRINTED-CIRCUIT BOARD DIAGRAM

3-½ INCHES

The original Stun Gun printed-circuit board diagram is shown here. Allegro Electronic Systems has a modified board diagram that appears to be less susceptible to arc-over. You can obtain a free copy of the Allegro diagram by sending a self-addressed, stamped, business-size envelope to Allegro Electronic Systems. Their address is given in the Parts List for the Stun Gun.

PARTS LIST

FIG. 2 All resistors are ½-watt, 5%, unless otherwise noted.
R1—10,000 ohms
R2—4700 ohms
R3—1000 ohms
R4—100 ohms
R5—15 ohms, 5 watts
R6—270 ohms
Capacitors
C1, C3—0.22 μF, 100 volts, Mylar
C2—0.47 μF, 100 volts, Mylar
C4—470 μF, 25 volts, electrolytic
Semiconductors
IC1—555 timer
Q1—2N3638 PNP transistor
Q2—2N3055 NPN power transistor
Q3—2N3055 NPN power transistor with heatsink
Other components
T1—Auto ignition coil (see text)

board is shown in "PC Service" on page 30; alternatively, a PC board can be purchased from the source mentioned in the Parts List. If you build the circuit on a perfboard, follow our parts layout closely; otherwise you may have problems with arcing.

Due to the critical nature of the three transformers, we are not providing details on winding them. They are available from the source mentioned in the Parts List.

Referring to the parts-placement diagram in Fig. 2, and the photos in Fig. 3 and Fig. 4, mount all components except C2, T1, T2, and T3 on your board. Note that several components mount on the foil side of the PC board: C1, D7, and J1. Do not install those parts yet either.

After all components (except those mentioned above) are installed, check your work very carefully, especially D1–D6, R1, and R3, because T1 will be installed above them, and there will be no chance to correct errors later. After you're absolutely sure that they're installed correctly, install T1 with the black mark on the windings mounted toward C2.

Foil-side components

One of J1's tabs shares a hole on the PC board with resistor R8, which should be mounted already. Solder the tab of J1 that corresponds to the tip (not the barrel) of an inserted plug to the indicated pad. Then mount C1 and D7. Last, solder a 1¾-inch piece of 18-gauge wire to the barrel pin of J1, and connect the opposite end of that wire to the appropriate pad beneath S1, the FIRE switch.

Preliminary check-out

WARNING: While measuring voltages and currents, keep your face, hands, and all metallic objects away from the high-voltage end of the stun gun. If if you want to prod a component, use a non-conductive rod such as a plastic TV alignment tool. High voltage behaves very differently than low voltage. Any material that retains moisture can serve as a discharge path. THAT INCLUDES WOOD! Also, never work on or use the unit when your hands are wet.

Connect a voltmeter (set to a 1000-volt DC range) to ground and to the output of the D3–D6 diode bridge. Then power up the circuit using either a freshly-charged battery or an external supply capable of delivering 9.8 volts at one amp. If everything is working properly, you should measure about 400-volts DC at the output of the bridge when you press S1.

If you don't measure that voltage, connect an oscilloscope to the collector of Q1 or Q2. You should see a squarewave with a period of about 100 µs. If that waveform is not present, the switching circuit is not operating correctly. *Remove power* and check your wiring again. *Do not debug the circuit with a battery connected.*

Resistor R6 controls the rate at which the UJT (Q3) discharges, and R3 controls the rate at which C2 charges. You can experiment with the values of those components if you are not satisfied with the circuit's high-voltage output. R3 can vary from 2.2 to 4.7K. You can also experiment with the value of C2. See Table 1.

After the circuit is operating correctly, attach J1 to the board with high-voltage potting compound or RTV. And before you mount the circuit in a case, make sure there's no arcing on the PC board. If there is, you can stop it with a liberal application of RTV, paraffin, or epoxy.

Conclusion

The stun gun's discharge is very impressive. The spark is highly visible and each discharge produces a sharp, resounding crack. The circuit can teach you much about voltage-multiplying circuits and power supply design. But don't ever forget that the stun gun is not a toy. It can cause much damage to both you and others. Never leave it lying around where children, pets, or anyone unfamiliar with how to use it can handle it. It's a good idea to remove the battery before storing the stun gun. Above all: be careful! ∎

fahnestock clips are mounted to the board on ½-inch aluminum spacers, using #6-32 hardware. A 1¾-inch length of #12 solid-copper wire is fitted in one end of a 1¾-inch piece of dowel rod to produce the adjustable terminal of the spark gap. The other gap wire must be made from a #26 or smaller wire for the gap to perform properly.

Place the four dowel rods in the baseboard, position the 9-inch deck on top, and press down until all four dowel rods are even with the top of the circle. Connect the bottom of L1, using a short length of #12 wire, to the main grounding point (see Fig. 3). Also connect the bottom end of L2 to the same point.

A separate vertical ground rod can be positioned on the deck (see photos) for additional experimenting. The vertical ground was made from a 29-inch length of ¼-inch threaded rod, and covered with a section of aluminum tubing to give a neat appearance. At the top, a binding post was mounted for versatility. That allows the ground rod to accept a number of different experimental items.

Checking It Out

Before we start this stage of construction, a word of warning is in order:

Do not touch or make any adjustments while power is applied to the Solid-State Tesla Coil. Remember that you'll be dealing with high voltages, so caution is the watchword.

With the power off, set the spark gap for a ⅛-inch gap and connect the tap clip to turn 15 or 16. Plug in the power cord and turn S1 on. A loud electrical discharge should be heard, and a blue brush discharge should be seen at the top of the pointed screw that's connected to L2.

Turn the power off and move the tap wire (that's connected to L1) up or down one turn at a time until the greatest blue discharge is obtained at the top of L2. Form a 1½ to a 2-inch vertical gap between the ground rod and the top of the coil to aid in tuning up the coil. When the Tesla coil is properly adjusted, it should produce a 2-inch arc between the top of L2 and the ground terminal.

The coil discharge is most dramatic in a darkened room, and you should be able to light a fluorescent lamp at a distance of about two feet from the secondary coil. A clear incandescent lamp moved to within a few inches of the secondary coil will produce a beautiful blue lightning array from the lamp's filament to the outer edge of the glass envelope. Neon lamps glow around the coil without wires. Experimenting with the coil can be an almost endless adventure. But remember, always put safety first! ∎

terminal is lying underneath the copper-clad board on top. A single-sided copper-clad board measuring 4 × 5-inches is mounted on top of the unit (see photo), copper side down. Before gluing the board in place, solder a wire to the copper side, and then drill a hole through the top of the chassis for the high-voltage terminal on the ignition coil.

Three-terminal ignition coils can be obtained from any automotive supplier or an automotive junkyard. Just about any 12-volt, three-terminal coil will work.

The most-costly component in the assembly is the plastic chassis. The overall dimensions are 3.25 inches high, 6.25 inches deep, and 8.0 inches wide. If you wish, the chassis, as well as wired and tested units, can be purchased from the supplier mentioned in the Parts List.

The setup used in making a Kirlian photograph is shown in Fig. 4. The film is placed on the board mounted to the top of the unit, and the specimen is placed on top of the film. If the specimen to be "photographed" is inanimate, such as a leaf or a piece of metal, it should be grounded for best results. Any earth ground that you can connect a wire to will work fine. In any event, the specimen is placed between two sheets of thin (0.010-inch) transparent plastic, and the "sandwich" is then placed on the film.

Never ground a living creature, including yourself. Doing so can subject the "specimen" to a very nasty shock. When dealing with living creatures, take special care to prevent any contact with a ground.

One note about the ignition coils high voltage terminal: To the uninitiated, the location of that terminal may not be apparent at first glance. It is located within the tube-like protuberance at the top of the housing. When the coil is used in it's normal application, a spark-plug wire is placed in the opening at the top of the tube so that it makes contact with the terminal inside; the wire is held in place by friction. For our application, the lead from the copper-clad board must make good contact with the high-voltage terminal.

You will note from Fig. 1, that the circuit uses two ON/OFF switches, S1 and S2. Switch S1 is the unit's main power switch; when it is in the ON position, power is supplied to the neon lamp, NE1, and the circuit is placed in standby mode. The neon lamp does more than give a visual indication of the state of the unit. Since we are working with photographic film, the circuit must be used in a relatively dark, light-tight room. Obviously, that can present problems in using the unit. If the controls are clustered around the lamp (as shown in Fig. 5), the lamps gives off just enough light to make identification of the controls possible in a dark room without adversely affecting the Kodalith film. When you use color film, you should block the light from the film. Switch S2, the discharge switch, is a normally open momentary. It is used to control the balance of the circuit.

To make a Kirlian photograph, turn on the unit using S1, turn out the lights, place the film and specimen on the top plate as discussed previously, and make the exposure using S2. As a guideline, start with an exposure time of 10 to 15 seconds. It is likely that you will do a lot of trial-and-error experimentation with both the exposure time and frequency (which is adjusted using R1) before you will obtain satisfactory results.

The author has had good results with two types of film: Kodak 6118 Ektachrome and Kodalith 2556. The Ektachrome film will give you spectacular color transparencies, such as the one accompanying this article. However, it can be difficult to work with and to develop. Unless you have a photographic darkroom and are equipped for developing that type of film, you will probably want to take it to your local photo-developing store.

Kodalith 2556 ortho film type-3 is a high-contrast, black-and-white graphics-art film that may be familiar to those who make their own PC boards. The results are less spectacular, as shown in Fig. 6, but that film's light requirements are less exacting (a photographic safelight or the red neon lamp on the unit can be left on when handling the film), and the processing is much simpler, requiring just three basic chemicals. The author found the right exposure using the Kodalith first, and Ektachrome for the final exposure. ∎

A powerful static charge builds up on the spherical terminal. In a dark room, you will be able to see long, thin, bluish bolts of artificial lightning jump between the upper terminal and the base. It's a fantastic sight!

Experiments. Gaseous tube illumination and spark production are only two of the many interesting things you can do with your Van de Graaff generator. Here are just a few of the others:
● Obtain some foam plastic packing material and break it up into small pieces. Turn on your generator and allow it to run for a few moments. Now, drop the plastic bits, one by one, on top of the spherical terminal. They land on the aluminum, sit there for a second, and then shoot off! Some of the plastic may fly for a distance of one or two feet. When the material makes contact with the terminal, it picks up an electric charge. Since like charges repel, the plastic is thrown off the surface of the sphere.
● Find some very thin aluminum foil and carefully cut it into strips about ¼- to ½-inch wide and about 8 inches long. Tape the strips to the top of the terminal. Make sure the foil is making good electrical contact with the aluminum sphere. Turn on the generator. The strips will be repelled from the terminal and from each other. Now approach the sphere slowly with the palm of your hand. The strips will be attracted magically to your fingers!
● You can also use your generator to create what is sometimes called an "electric wind." Locate a narrow metal rod about 9- or 10-inches long. Tape one end of the rod to the top of the spherical terminal. Make sure that this end of the rod is entirely covered with tape, and, once again, check for a good electrical contact. Turn on the machine. Next, light a household candle and approach the free end of the rod with the candle flame. As molecules of ionized air rush from the metal tip, the flame will be blown to one side.

These experiments just scratch the surface of what you can do with your generator. The book, *Nature's Electricity* by C.K. Adams (Tab Books, Blue Ridge Summit, PA 17294) contains many other interesting experiments that can be performed with your Van de Graaff generator, as well as other static-electricity experiments. ∎