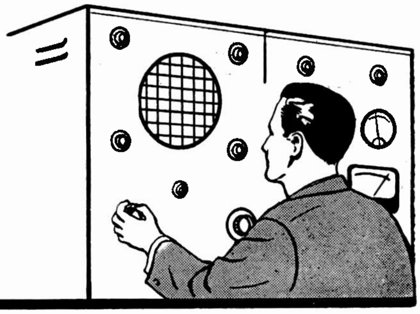
AEROVOX RESEARCH WORKER



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Capacitor Energy Storage

By the Engineering Department, Aerovox Corporation

THE late-middle-aged engineer can remember the capacitor he first met in school: a Leyden jar which had no purpose other than to be charged from a static machine and then noisily discharged in short circuit. The shape and applications of the capacitor have changed considerably since the time of these old demonstrations, but all of its uses have depended in some way upon this ability to store electrical energy.

Such common applications as tuning, phase shifting, time delay, coupling, bypassing, and d-c blocking are not directly concerned with energy storage, although their success depends upon this property of the capacitor. But other uses, increasing in number, are primarily concerned with energy storage. These include pulsing, flash signalling, high-speed flash photography, arc discharge, welding, resistance-capacitance interval timing, and generation of intense magnetic fields.

Operation of a capacitor as an energy storage device is essentially the same as the old-time Leyden jar demonstration: the capacitor is first charged from a d-c source and then is suddenly discharged, to deliver a large amount of energy for a short time to some desired load. The latter may be a flash lamp, gas tube, magnet coil, or similar device.

Both the charge and discharge functions impose uncommon demands upon the capacitor, and these give rise to special design, ratings, and operating requirements. For this reason, the energy-storage capacitor is a distinct component.

STORED ENERGY

The first requirement is that the energy-storage capacitor hold an electrostatic charge. The stored energy

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is a function of capacitance, voltage, and charge:

$$(1) \quad W = \frac{1}{2}CE^2 = \frac{1}{2}QE$$

Where W is the energy in **joules,** C the capacitance in **farads,** E the potential in **volts,** and Q the charge in **coulombs.**

In practice, the energy usually is expressed in **watt-seconds.** (1 **watt-second** = 1 **joule.**) The cgs unit of energy is the **erg.** (1 **erg**=10^{-7} **watt-seconds** or **joules.**)

The amount of charge, as well as the length of time that the capacitor will maintain its fully-charged voltage depend largely upon dielectric properties. The dielectric of the energy storage capacitor is selected for its corona properties, dielectric constant and stress, low leakage, power factor and dielectric absorption (as well as its cost, availability and handling characteristics). Undesired leakage of the charge, however, may also be due to factors other than those inherent in the dielectric, such as surface leakage between capacitor terminals.

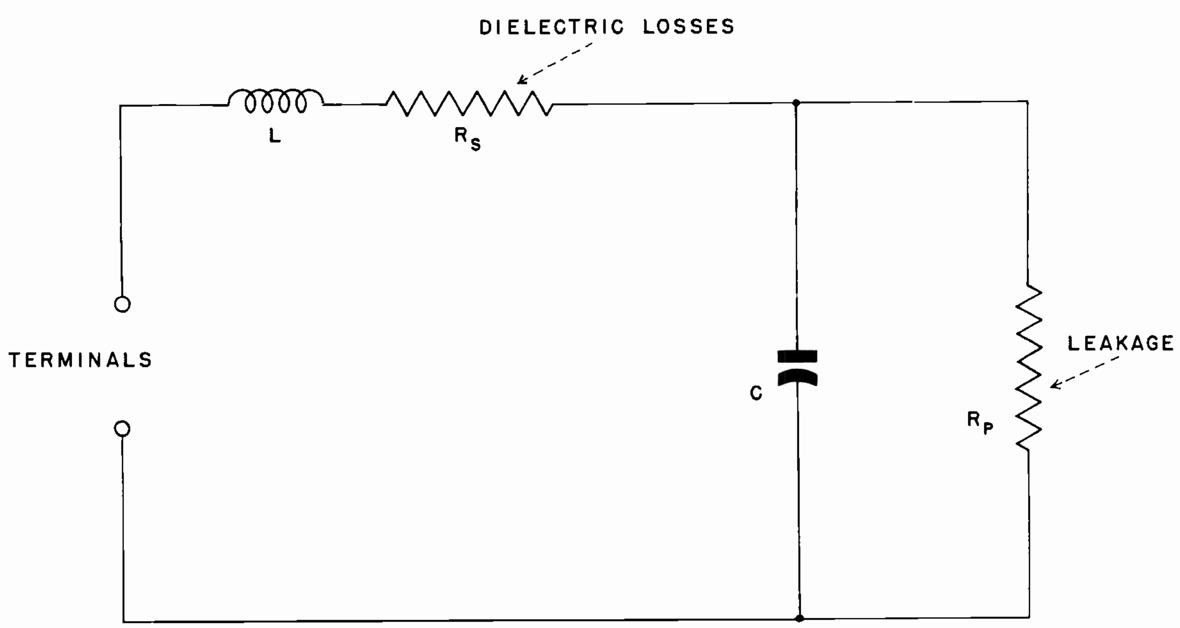
ENERGY-STORAGE CAPACITOR REQUIREMENTS

Equation (1) shows that energy is directly proportional to the capacitance and the square of the voltage. Since large amounts of energy generally are required in energy-storage applications, high capacitances and voltages are chosen.

The capacitance usually is in tens of microfarads (as in a small photoflash unit) but may be hundreds or thousands of microfarads in some instances. Banks of parallel-connected capacitors often are used to obtain the high C values. Thus, the experimental 100,000-joule capacitor bank used for plasma research at U. S. Army Signal Research and Development Laboratory has a capacitance of 480 μfd. And the **Zeus** 20,000-volt capacitor bank for thermonuclear research at Los Alamos Scientific Laboratory has a capacitance of 60,000 μfd (0.06 farad). Forty capacitors are employed in the former and 4032 in the latter. A 7,000,000-joule parallel-capacitor bank developed by General Electric Co. for Boeing Aircraft uses two thousand 6000-volt capacitors to obtain 390,000 μfd (0.39 farad) at 20,000 v for a 5,000,000-ampere arc used to generate shock waves in an air tunnel.

Rapid discharge is required in all energy storage applications. In some instances, the stored energy must be dumped into a load within a few microseconds or less. Since inductance lengthens the discharge time, the internal inductance of the capacitor and also the inductance of the discharge circuit must be minimized.

The effect of a sudden discharge in the RLC equivalent circuit of the energy storage storage capacitor, figure 1, is to produce a damped oscillation (a process known as "ringing"). The rate of discharge, or time for the capacitor current to reach a peak will be a ¼ cycle of the natural ringing frequency. This ringing fre-



EQUIVALENT CIRCUIT OF ENERGY-STORAGE CAPACITORS

FIG. 1

quency may be determined from the relationship:

$$(2)\quad f_R = \frac{1}{6.28}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

Where f_R is in **cycles per second,** C in **farads,** L in **henries** and R in **ohms.**

A high discharge current amplitude is also desirable. The maximum current of the discharge will reach a value given by:

$$(3)\quad I_{peak} = \frac{E}{\sqrt{R^2 + L/C}}$$

Where C is in **farads,** L in **henries,** E in **volts,** I in **amperes** and R in **ohms.**

Since the internal resistance and inductance of the capacitor and the resistance of the discharge circuit are usually very low, equations (2) and (3), respectively, reduce to the following approximations for practical purposes:

$$2A)\quad f_R \approx \frac{1}{6.28\sqrt{LC}}$$

$$3A)\quad I_{peak} \approx E\sqrt{C/L}$$

Discharge current demands vary with application. In stroboscope, photoflash, and signal light service, the discharge current need only attain a peak value of several hundred amperes to obtain the light required. In the plasma research bank mentioned above, however, the discharge current is 8,000,000 amperes; in the **Zeus** bank, it is 40,000,000 amperes; and in the Boeing bank, it is 5,000,000 amperes. As Buser and Wolfert point out, the quality of a capacitor bank is characterized by its stored energy, its ringing frequency and the maximum available current.[1]

The usual attention to the details of temperature- and voltage-stability of characteristics, of minimizing of the inductive and the resistive parameters in design and manufacture, and of special attention to the problems created by the high physical stresses peculiar to this application, assures a capacitor that fulfills the demands of energy-storage applications: high current and rapid discharge.

Figure 1 shows the equivalent circuit of the energy-storage capacitor. In this diagram, C represents the capacitance, L the inductance, R_p the equivalent parallel resistance (leakage), and R_s the equivalent series resistance (dielectric losses). The inductance is inherent in structural components, such as leads, terminals, tabs, and plates. Electrolytic capacitors often are used for energy storage in small-sized, light-weight portable equipment, in order to obtain the highest capacitance per unit volume. In such capacitors, resistance R_p is kept as low as practicable for the electrolytic dielectric.

1—R Buser and P. Wolfert, "Experimental 100,000 Joule Capacitor Bank for Plasma Research," **Electronics,** August 5, 1960, p. 58.

ENERGY-STORAGE CAPACITOR APPLICATIONS

In energy-storage applications, the capacitor is charged either from batteries (directly or from a battery-operated high-voltage d-c supply using a vibrator or tube — or transistor-type oscillator) or from a line-operated rectifier-type power supply. Then it is discharged through the load. During the discharge interval, the capacitor is usually connected to the load by direct switching, when the current can be handled by contacts, or through thyratron or ignitron switching tubes when the current is very high. The following paragraphs briefly describe some of the applications.

Flash Photography. Photoflash units are available in both stationary and portable models. A stationary unit may be operated from the power line, whereas a portable one has a self-contained battery which powers a transformer-rectifier-type high-voltage d-c supply operated from a vibrator or an oscillator (tube- or transistor-type).

In the photoflash unit, the high-capacitance storage capacitor is discharged through a gas-filled flash tube to give a short flash of intense light. Depending upon type, the flash tube requires a voltage between 120 and 4000 volts, and has a power rating between 100 and 5000 watt-seconds.

Photoflash units are widely used in conventional photography and in such industrial applications as the freezing of motion for photographic observation of machinery in motion.

Spark Gap Operation. The spark gap, as a source of short-interval light is useful in photographically recording hypervelocity phenomena, in connection with the high-speed industrial camera.

In this application, the energy-storage capacitor is charged to high voltage (several tens of kilovolts) and discharged through the gap to give a single, intense spark. High-intensity light pulses of 0.3 microsecond duration, at 2 to 20 joules, have been reported.

Flasher Signalling. In flasher signalling circuits, the capacitor is repetitively charged and discharged. The discharge fires a gas-filled lamp or tube which gives regular flashes of strong light.

Applications of flash signalling include beacons and warning lights for highway, marine, and airport safety, traffic regulation, and hazard marking.

Welding. This is a relatively low-voltage, high-current application. The capacitor is discharged through the metal bodies which are to be fastened together. The weld is made at the interface by the heavy, instantaneous discharge current.

Capacitor-discharge welding is valued in work with wires, foils, and other light metallic bodies.

Magnet Charging. In this application, the heavy, momentary discharge current of an energy-storage capacitor is passed through a coil of wire surrounding the body to be magnetized. The intense magnetic field produced by this current permanently magnetizes the body.

This technique is used both in the production of magnets and in the revitalization of old magnets. It permits recharging a meter magnet without removing the latter from the instrument.

Wire Explosion. In tests involving the exploding of wires, the required destructive current is obtained from the fast discharge of any energy-storage capacitor.

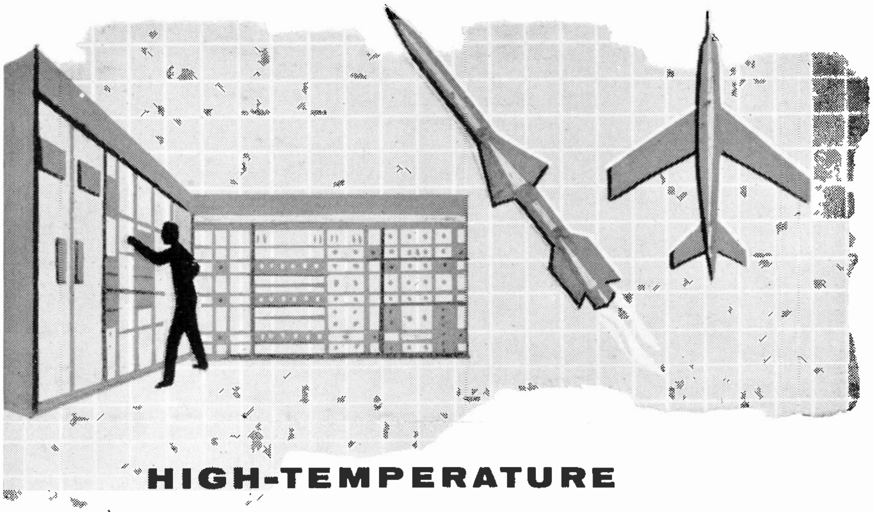
SUMMARY

In general energy storage capacitors differ from conventional capacitors in that they are designed for short-term application of voltage, very high discharge currents, (sometimes in excess of 20,000 amperes per mfd.), low internal inductance and, in the larger sizes, in heavier cases to withstand the forces developed during discharge.

The application of energy-storage capacitors requires a careful analysis of the application and generally requires special capacitors for each job.

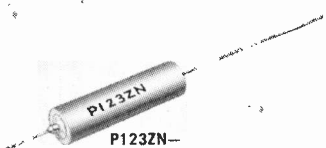
AEROVOX

CAPACIBILITY*

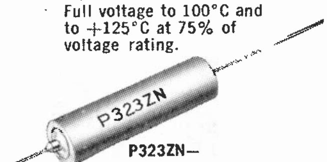


HIGH-TEMPERATURE

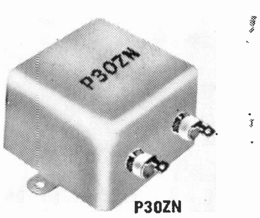
METALLIZED PAPER CAPACITORS



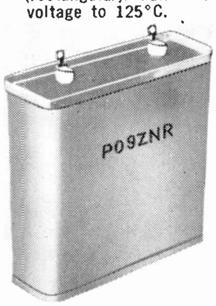
P123ZN—
rated at 50 VDC. Full voltage rating to +100°C. Rated from 150 VDC to 600 VDC. Full voltage to 100°C and to +125°C at 75% of voltage rating.



P323ZN—
full rated voltage to 125°C.



P30ZN (bathtub) and **P09ZN** (rectangular). Full rated voltage to 125°C.



Designed specifically to meet critical operating requirements, Aerovox metallized paper capacitors offer many important advantages, including minimum size for space-tight applications... reliability and long service life... low radio frequency impedance... and a wide range of case styles for operation to +125°C **without voltage derating.**

Aerolene® impregnated units are available in the temperature ranges shown at left:

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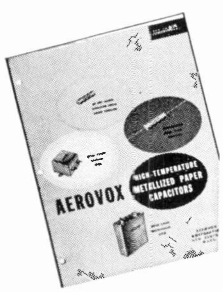

***Capaci-bility** An Aerovox characteristic. Capability to design, develop, and manufacture capacitors to best meet customers' requirements.

AEROVOX CORPORATION

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Technical Leadership — Manufacturing Excellence