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Abstract

A series string of electrolytic capacitors has been proven to be a reliable energy-storage unit. Electrolytic capacitor banks have been providing magnetic field energy for Berkeley rotating plasma experiments since 1958.

In this paper, considerations in the theory, design, and usage of low- and high-voltage banks are discussed. Basic electrolytic capacitor properties are reviewed, several particular banks are discussed, then possibilities for future development are examined.

Electrolytic Capacitor Properties

During the manufacture of an electrolytic capacitor, the final process is usually that of "forming-in" the capacitor. The capacitor is charged to a voltage somewhat higher than its rated operating voltage over an extended period of time. This creates the aluminum oxide dielectric, whose thickness is dependent upon the voltage rating of the capacitor. The surface of the electrolyte-impregnated paper serves as an electrode. The presence of the electrolyte subsequently allows a certain measure of self-healing, should minute internal punctures of the dielectric take place.

When a dielectric puncture occurs during the forming-in of the larger capacitors, where 10 to 100 joules may be stored, an audible "tick" is produced. Empirically, it has been determined that the capacitor will heal itself if the energy delivered to the puncture is less than 100 to 200 joules. This is probably one reason why industry has limited the size of the largest units to that corresponding to a stored energy of about 100 joules. Should the energy delivered to the puncture (from paralleled capacitors, say) exceed 200 joules, the chances are high that the capacitor will remain permanently shorted. This points out the need for current-limiting resistors, inductors, or fuses in banks where large numbers of capacitors are simply paralleled.

When a capacitor is discharged into an inductor, the voltage and current during the first quarter-cycle are both, say, positive. During the second quarter-cycle, the voltage goes negative while the current remains positive. During the third quarter, both the current and voltage are negative. A fourth regime exists during the charging period when the voltage is positive and the current is negative. Electrolytic capacitors operate reliably in the first and fourth regimes. Note that in the second regime the polarities are the same ones (voltage -, current +) that exist if one tries to charge the capacitor in the reverse direction. Even though the capacitor would be destroyed under dc conditions, the Berkeley banks have demonstrated that short but frequent excursions into this second regime can be tolerated indefinitely with no apparent adverse effects. Our switches (ignitrons) open at the end of the second regime, when the current is zero and the capacitor voltage is maximum negative. This permits avoiding the third regime, about which there is little information. The negative voltage left on the capacitor is found to decay in a time of the order of a second, dissipating the energy internally in the form of heat. Several factors indicate that the effective capacitance, when the voltage is reversed, is frequently doubled or tripled, and that there is a shunt internal resistance of 100 to 500 ohms for the 1000-μF 450-V units used in our banks.

This ability to "ring negative" for a quarter-cycle can result in significant operational benefits and cost savings. First: high-coulomb crowbars to short the bank at zero voltage are no longer necessary. Second: diodes paralleling the capacitors, sometimes used as brute-force protection against reverse voltage, are no longer necessary. Third: the bulk of the energy is returned to the capacitors where it can be removed by simple air cooling. The cooling requirements on the load inductance are thus vastly simplified.

Present electrolyte impedances are responsible for a minimum R-C discharge time (into a short circuit) of about 70 μsec for the units mentioned above. The high currents generated in this type of discharge create magnetic forces which generally cause the output tabs to break or pull loose from the foils after a limited number of discharges. Experimentally, it has been found that the minimum discharge time compatible with long life is about 200 μsec. This corresponds to a peak discharge current of about 3500 A.

In the second regime, hydrogen gas is normally evolved. The vent plug in the end cap allows this to diffuse out at a rate sufficient to prevent excessive pressure buildup.

For reasonable temperatures, the 1000-μF 450-V units should be operated with an average input power of 5 watts or less. The leakage current can vary from 1 to 12 mA, depending on how well they have been formed-in. The thermal time constant, without the usual paper jacket, is about 45 min.

Some Existing Electrolytic Banks

Probably the largest low-voltage electrolytic bank ever built is the 450-V 800-kJ transportable bank at the University of Washington in Seattle.[1] Fuse wire is used to parallel the individual capacitors in a module. Each capacitor has a small silicon diode in parallel to prevent negative voltage excursions. "Amp-Trap" fuses are used in the output lead of each module. The output switch is a single air-blown circuit breaker which is never called upon to break the load current. Occasional capacitor failures destroy several of the surrounding capacitors, but the bank is generally successful and has been operated for about 3 years. A typical firing rate is once per minute.

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[1] Pierre F. Pellissier (Lawrence Radiation Laboratory), private communication.

To date, the Berkeley high-voltage electrolytic banks have been built in 5-kV 12.5-kJ modules. Each module is made up of a 12-by-12 series-parallel array of 1000-μF 450-V capacitors. One size-A welding ignitron (type 5550) is included in each module to switch the shorter, higher currents. These tubes are rated for 20 to 30 coulombs, but pass less than 5 C in this application. To permit inclusion of a fault-sensing circuit (later discarded as unnecessary), one bank was built with the capacitors cross-paralleled with nichrome wire. This caused large capacitor losses during forming-in and was eliminated. The 12 series strings of capacitors are now paralleled only at each end. Very reliable operation has resulted. A 2-W resistor was placed in parallel with each capacitor to aid in equal voltage division down the series string. These conduct about 2.5 mA at full capacitor voltage.

Figure 1 shows the first large electrolytic bank ever assembled. This is a 5-kV 150-kJ 12-module bank built in Berkeley in 1958 for the Geneva Conference. Apparent in the photograph are the charging and firing supplies on top of the bank, the light from monitor neon bulbs across individual capacitors, and the firing and crowbar ignitron mounts. (The crowbar ignitrons are occasionally used to short the bank at zero voltage, extending the duration of the load coil current.) This bank is still in use, and has not lost a single capacitor in the last 5 years of operation. A common dc current-limiting charging supply is employed. Each module has a series 10-kΩ 200-W resistor and a diode in the charging line. This effectively prevents all modules from participating in a disasterous fault should one module become shorted. The ignitrons are fired by discharging a capacitor into the 12 paralleled ignitor circuits. It was built by available Project Sherwood personnel who used perfectly satisfactory inexpensive materials and techniques.

Figure 2 shows a smaller, similar bank rated at 50 kJ and mounted on a transportable pallet. In this application, it is powering a 100-kG pulsed magnet located in the cylindrical aluminum housing. The charging and firing supplies, control panels, and recording oscilloscope are also shown.

Figure 3 shows the largest electrolytic bank yet built, the Berkeley 5-kV megajoule bank. This bank is described in detail in another report[2]--which, incidentally, does not describe several recent refinements mentioned in this paper. Briefly, it consists of 80 modular drawers, each having its own charging supply, firing circuitry, and switching ignitrons. Some of the firing and control electronics can be seen at the end of the aisle, in the photograph, as can the output cabling bus panel. Multiple switching ignitrons in each drawer and appropriate control circuitry provide for the possibility of up to five experiments using the bank on a time-sharing basis. Each user has independent control over bank voltage and bank capacity (in quarter-bank increments).

Figure 4 shows a modular drawer of the megajoule bank when the fault-sensing circuitry and nichrome parallelling wire were still in use.

Even with a common variable ac primary charging supply, the individual module power supplies permit variations in voltage between drawers of up to 100 to 200 volts. Analysis indicates that in order to reliably fire all drawers a long pulse, or burst of pulses, is required at the ignitron ignitors. A 1.2-msec ignitor pulse is supplied to the ignitrons in the megajoule bank. This reliably fires all drawers, providing the bank is well formed-in.

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[2] D. B. Hopkins and P. F. Pellissier, A High-Voltage Electrolytic Capacitor Bank, IRE Trans. Nucl. Sci. 9, 68 (1962).

Note that the switching ignitrons and the power supply transformers provide complete isolation between the modules until the instant of firing. Ignitron prefires are now virtually nonexistent.

The output cabling arrangement is such that the total current is always divided into five pairs of cables, regardless of the bank portion used. This divides the intercable forces by 25 and permits the use of easily manageable output cabling. Sufficient inductance is provided in the module-to-bus panel cables to limit minimum discharge times to 200 μsec or higher, should a fault occur at the bus panel.

In practice, it has been found that the time required for adequate forming-in for operation at the maximum rating of 5 kV is intolerably long (of the order of 2 or more hours daily). Accompanying capacitor losses are high. For this reason, the bank probably should have a practical rating of 4.5 kV, 800 kJ. For a true megajoule rating, it is felt that a 13-by-13 array of 450-V capacitors should be provided for each module, rather than the existing 12-by-12 array.

Bank Philosophy and Speculations

The above-mentioned banks have demonstrated that a series string of several electrolytic capacitors forms a reliable energy-storage unit. As they are being charged, should one or more capacitors suffer a temporary dielectric puncture and assume a lower voltage, the excess voltage would simply be distributed among the other capacitors in the string. The main energy delivered to the puncture is just that stored in the punctured capacitor. Note that the voltage "slack" to be taken up by the other capacitors in the string decreases as the number of capacitors in the string increases. In other words, the higher the voltage rating of the bank, the less the bank is likely to be affected by momentary punctures in individual capacitors, and the higher the overall reliability is likely to be.

A situation can exist whereby when a capacitor punctures, causing more voltage to be impressed across the others in the string, the others are overvoltaged to the extent that their leakage current greatly increases. A sort of "chain reaction" is set up which can end in one of two ways. If it progresses fast enough, the energy stored in the other parallel strings is "dumped" into the faulted string, perhaps causing permanent damage to several of the capacitors in the string. The most likely result, as seen in the megajoule bank, is simply that the leakage current increases to the point where the fuse in the power-supply primary blows. The likelihood of a complete string failure of this type is also reduced by having more capacitors in the string.

Consider a capacitor in a string operated near its rated voltage. Should it be overvoltaged in the manner mentioned above, its leakage current would increase, implying a lower shunt resistance than it had before. This would cause the capacitor to partially discharge, reducing its voltage. The capacitors in a string should therefore show a first-order tendency to self-equalize, or equally distribute, the voltage down the string. This effect should be strongest when the capacitors are operated near their rated voltage. Initial tests have been performed, and it appears likely that the voltage-equalizing resistors placed in parallel with each capacitor of the Berkeley electrolytic banks are unnecessary.

To date, a disadvantage of electrolytic banks has been their relatively large assembly costs due to the large number of components (the megajoule bank contains 11,520 capacitors). Elimination of the parallel resistors results in large savings in assembly costs. It is felt that if two remaining obstacles can be hurdled, electrolytic banks have every possibility of being competitive with the oil-paper capacitor banks used in most pulsed-magnet applications.

The first requirement is a different capacitor terminal arrangement. If the capacitor could be made to have one terminal on one end and one on the other, similar to those on a flashlight battery, these could then be loaded into inexpensive insulating racks or tubes and simply pressed together. Discharge currents per string are low, typically less than 500 A. A pressed-type contact should reasonably handle these currents. Alternatively, many series sections could be placed in long insulating containers having terminals at each end. These configurations would permit vastly reduced assembly costs.

The last remaining obstacle is one of capacitor cost. Recent development efforts by the engineering staff of the Los Alamos Sherwood Group soon will result in the availability of 10-kV fast oil-paper capacitors for a price between 2 and 3 cents per joule. This is probably the stiffest existing competition for electrolytic capacitors in this application. These presently cost about 3.5 to 4 cents per joule in large quantities. It is felt that if the electrolytic capacitor manufacturers can lower their unit cost electrolytic banks will find widespread usage. An increasing number of experiments require multiple large banks for energizing several coils at different times. Electrolytic banks, with their higher energy density, would permit smaller installations with attendant savings in required building space.

The major capacitor manufacturers have been questioned about these possibilities and their recommendations should be forthcoming.

Figure Captions

Fig. 1. 150-kJ 5-kV bank.

Fig. 2. 50-kJ 5-kV bank.

Fig. 3. Megajoule 5-kV bank.

Fig. 4. 12.5-kJ module of megajoule bank.

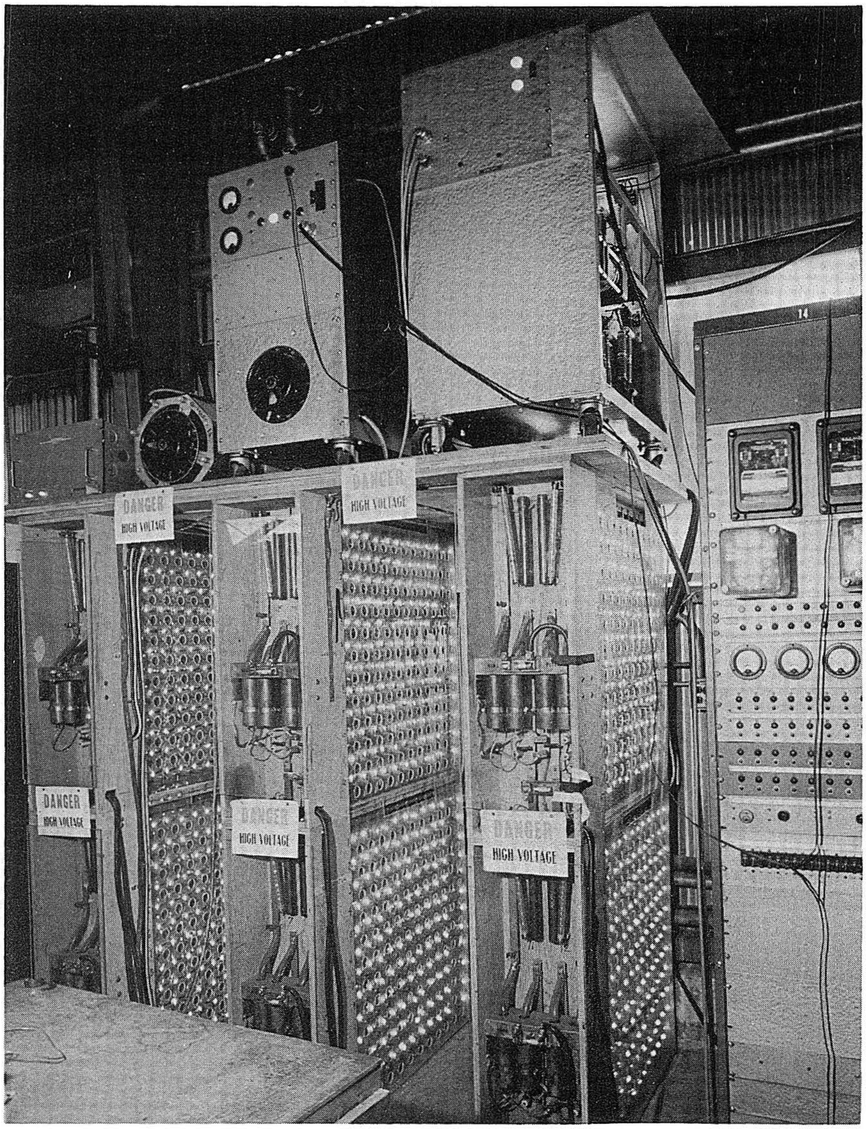
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Fig. 1

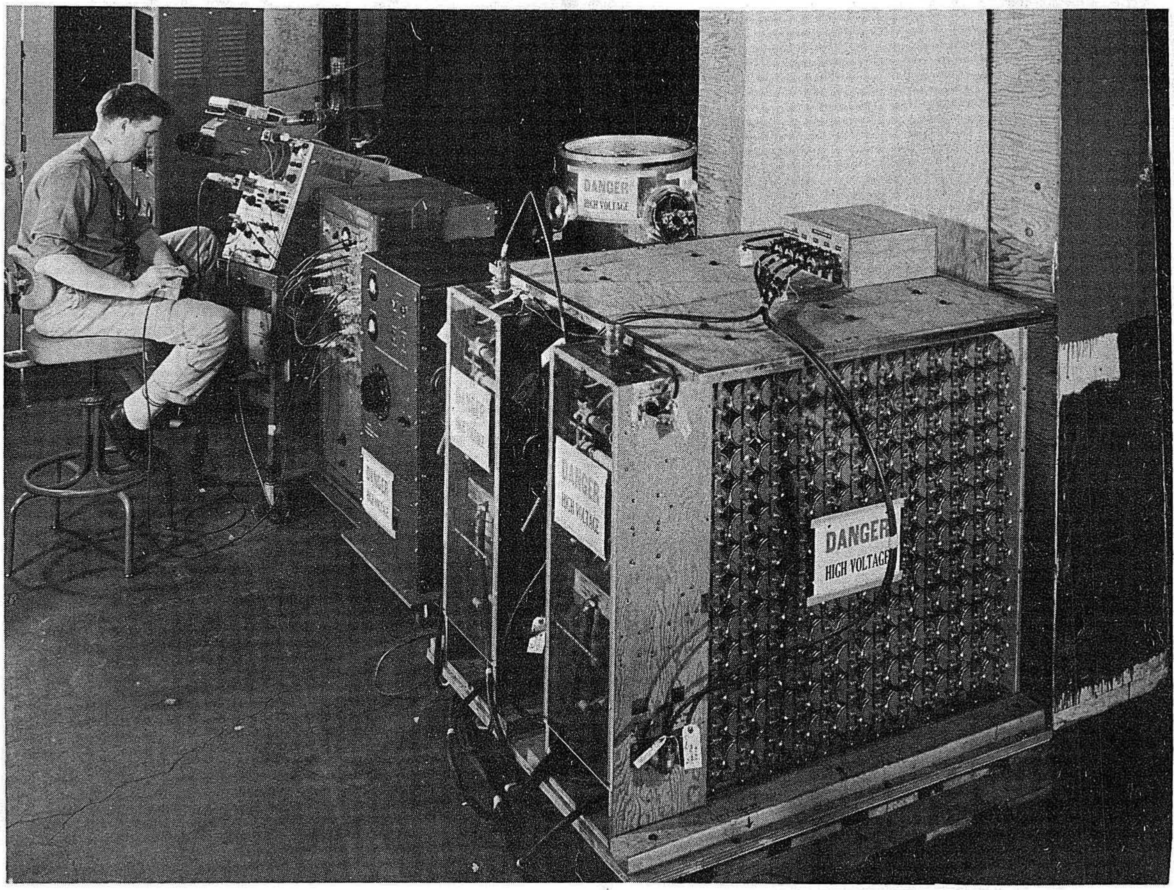
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Fig. 2

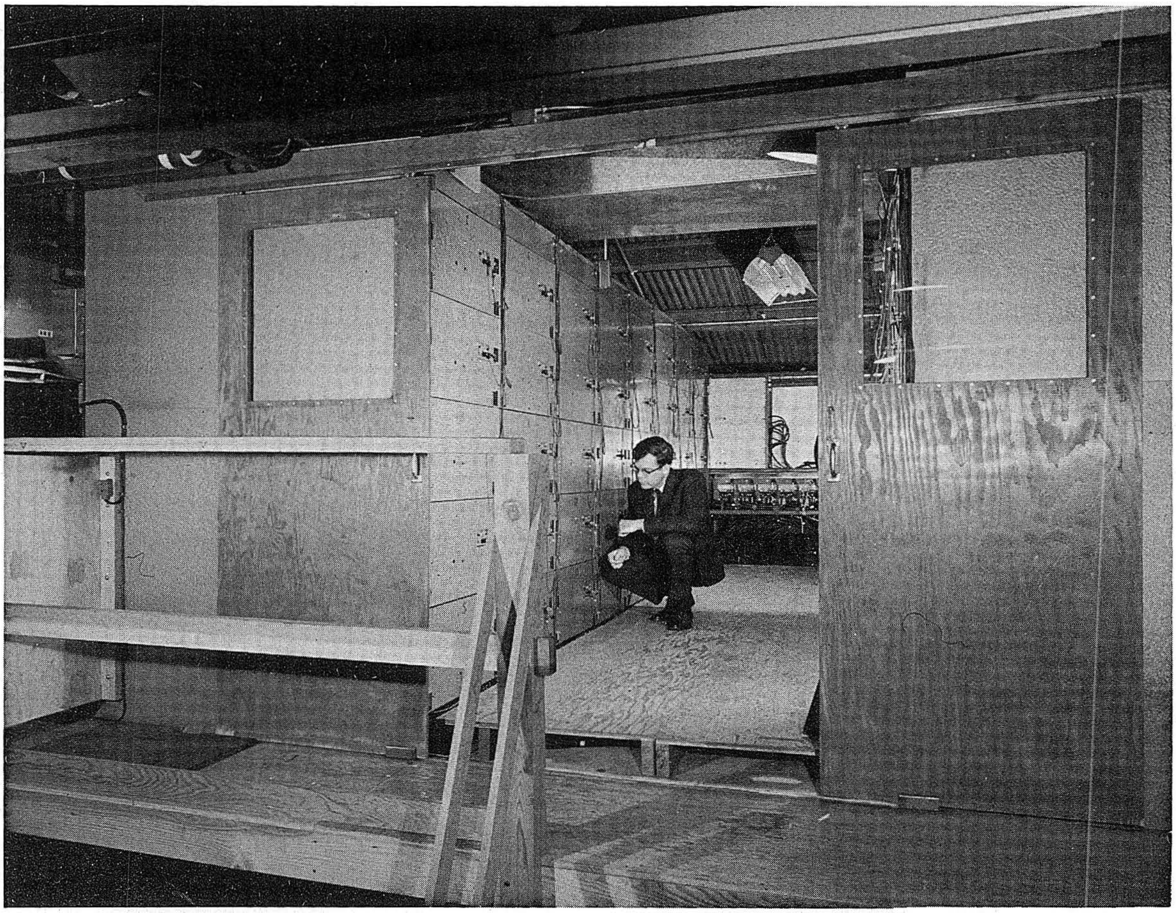

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Fig. 3

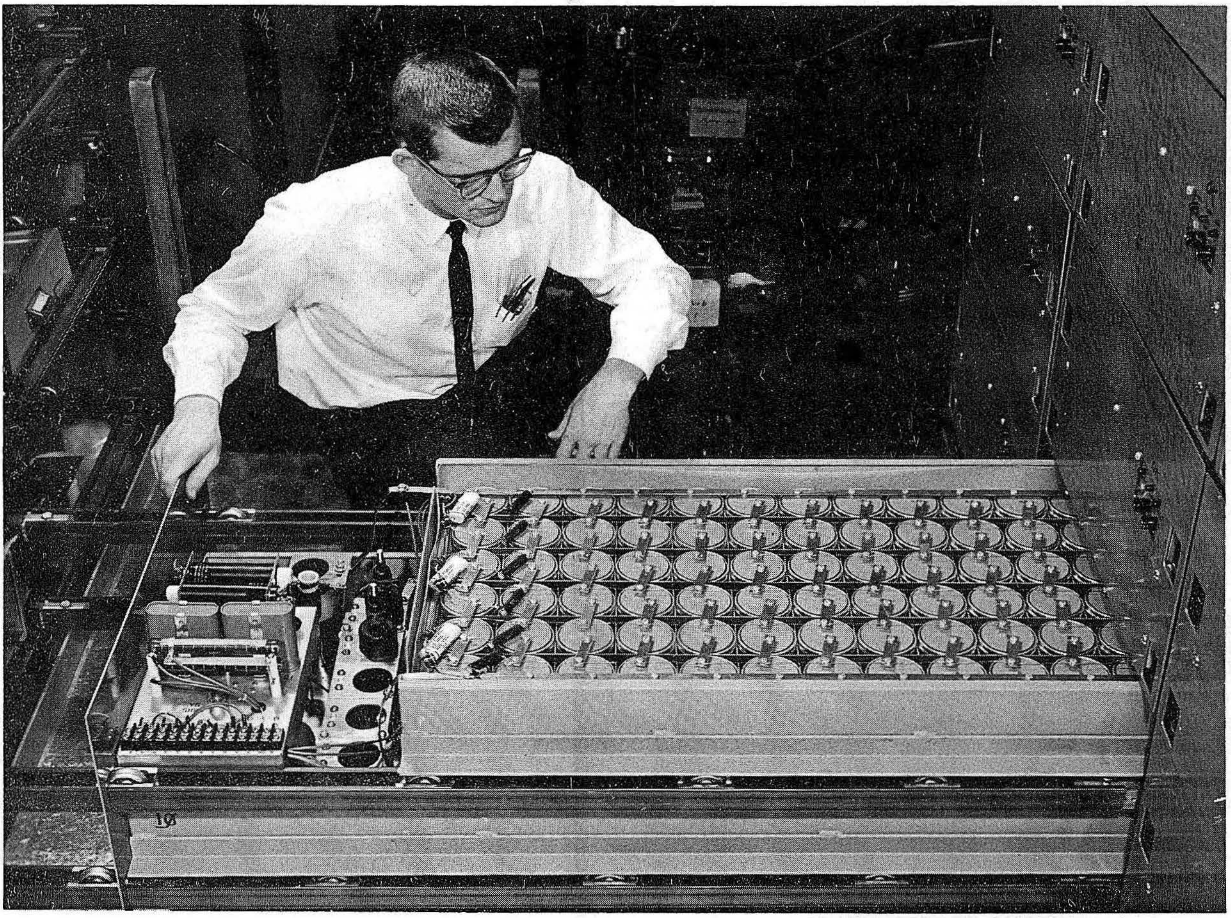

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Fig. 4