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Abstract

For controlled thermonuclear devices of moderate volume employing externally applied magnetic fields, the magnetic energy requirements extend into the megajoule range. A high-voltage series-parallel bank of electrolytic capacitors can supply this energy reliably and inexpensively. The total cost of the bank, including charging supplies, controls, and labor, is less than 14 cents per joule. Required floor space, including access and service area, is about 250 ft^2/Mj. A 5-kv electrolytic bank storing 150 kj has been in routine operation since 1958, and is currently being extended to 1 Mj. The bank is composed of 80 modular 12.5-kj sections, each module being a 12-by-12 series-parallel array of 1000-μf 450-v, standard electrolytic capacitors. Each module has its own charging, switching, and fault-sensing circuits. Including external voltage dividers and internal leakage current, about 24 w/kj is required to maintain the bank at full voltage. Normal one-quarter cycle discharge times are in the millisecond range with repetition rates ranging from one-half to 15 or more per minute, depending on the external circuit. Capacitor life is measured in years, is dependent upon the time required for the electrolyte to dry out, and is virtually unaffected by the operating schedule of the bank. Flexibility in the usage of the bank is ensured by having multiple output-switching ignitrons in each module. Sequencing and control circuitry provides for time-sharing of the bank by up to five users, each having independent control of bank capacity and voltage.

Introduction

In the design of a large energy-storage system for an experimental research facility, some care must be taken that the substantial investment required yields a system flexible enough to serve effectively on different loads throughout its useful life. Energy-storage systems usually outlive the experiment for which they were specifically designed.

A series-parallel electrolytic capacitor bank is an energy storage system that is inexpensive, flexible, and reliable. For pulsed-magnet power applications, which normally require so-called "slow" banks, the range of voltage and capacitance combinations available makes it possible to optimize coil design to an extent not previously possible. The prime advantage of the system described in this paper is that a megajoule of energy, including power supplies and service area, can be installed in less than 250 ft^2 of floor space. The total cost, including charging supplies, controls, and labor, is about 14 cents per joule.

A 5-kv bank has been in operation since 1958 at the Lawrence Radiation Laboratory, Berkeley, supplying magnetic-field energy for a rotating plasma device. Extended to 150 kj (a total of 1728 1000-μf, 450-v capacitors) in 1959, it has operated on a daily basis up to the present without a single capacitor failure due to voltage breakdown or excessive current flow.

The megajoule bank described in this paper is an extension of the modular construction of the 150-kj bank. It has the additional features of time-sharing by multiple output loads, individual reactance-limited charging supplies for each module, and fault-sensing circuitry capable of electrically removing a faulted module from the bank and allowing continued operation at only slightly reduced capacity.

Electrolytic-Capacitor Considerations

Before procedding with the discussion of the bank, we shall discuss some of the philosophy and considerations involved in the use of electrolytic capacitors in this unusual and seemingly severe application.

When an electrolytic capacitor is discharged into an inductive load through an ignitron, the current and time of the first quarter-cycle is simply dependent on L, C, and V. The maximum current, occurring at the quarter-cycle point, is

$$I_{max} = \frac{\pi}{2} \frac{CV}{T/4} , \qquad (1)$$

where

$$T/4 = \frac{\pi}{2} \sqrt{LC} \qquad (2)$$

is the quarter-cycle time. At the quarter-cycle point the capacitor voltage is zero, all energy is stored in the magnetic field, and the inductance becomes a current generator feeding current and energy back into the capacitor. For the second quarter-cycle the voltage across the capacitor must then reverse. The question arises, "Does the capacitor still appear as a capacitance in this reverse direction?"

Figure 1 shows the discharge current and capacitor voltage waveforms generated when one 1000-μf, 5000-v module charged to 2000 v was discharged into a 2.5-mh coil of No. 6 A. W. G., stranded, motor lead wire. One notes a current maximum of about 1250 amp in the quarter-cycle time of about 2.5 msec. The second quarter-cycle time, however, is about 3.5 msec. The ratio of 3.5 to 2.5 is 1.4. Since capacitance scales as the square of the time, it appears that the effective capacitance in the reverse direction has about doubled. This conclusion checks with the fact that the negative peak voltage is only about half that of the positive peak voltage. After the second quarter cycle, the ignitron has extinguished and one notes a decay of the capacitor voltage with a time constant of 15 to 20 msec.

Thus, under conditions whereby the energy is returned to the capacitor, the energy must be dissipated in the capacitor in a period of several tens of milliseconds. Our experience indicates that while electrolytic capacitors cannot sustain a dc reverse voltage, they will sustain a momentary reversal of this type with no adverse effects. We have so far been unable to detect any reverse forming of the capacitors or loss of capacitance.

The limitation in this service is then one of capacitor heating. With the paper jacket removed, this type of capacitor has a thermal time constant of the order of 30 to 50 min. Repetition rates are then limited by the maximum allowable capacitor dissipation of 5 to 10 w. We find we can operate indefinitely at a repetition rate of one per minute with no down time required for capacitor cooling. Forming or leakage currents must then be limited to 10 to 15 ma per capacitor at 450 v, in order to prevent boiling the electrolyte. End of capacitor life is signalled when leakage alone has reached 10 to 15 ma.

Alternatively, one may "crowbar" at the quarter-cycle point; that is, short out the inductance with a triggered ignitron or diode. This clamps the capacitor voltage to zero and allows the coil current to decay with an L/R time constant determined by the resistance placed in the crowbar circuit. Under these conditions, the energy is dissipated in the load. The repetition rate, subject to more stringent charging requirements, may then be 15 or more pulses per minute.

Proper "forming-in" of the electrolytic capacitors in a new installation is important. For example, several capacitors in a single module may fail by arcing at low voltages when an attempt is made to charge the new module to full voltage in a short time, e. g. a few minutes. The sequence used in forming-in the modules described in this paper is as follows: The modules are charged to 1500 v over a period of several minutes and maintained at that voltage for about 30 min. The voltage is then increased in 500-v steps, allowing about 20 min at each step, to the final voltage of 5 kv. Any attempt to shorten the forming-in period results in higher leakage currents and correspondingly higher capacitor heating.

When these capacitors are operated at reduced voltage for periods of the order of a year without intermittent charging to full voltage, reforming to full voltage capability may require several hours. For this reason, in order to have the bank always in a state of full readiness, we charge the bank to full voltage at least once a month.

The maximum peak current deliverable by this type of capacitor is apparently only limited by the number and manner of attachment of the output tabs to the capacitor foils. Our capacitors have double tabs (available from the manufacturer at only very slightly increased cost), each multiply riveted to a foil. Tests show them capable of withstanding at least 2000 shots at a discharge quarter-cycle time of 100 μsec and a peak current of 5000 to 7000 amp with no apparent ill effects. Rather arbitrarily, we suggest 200 μsec as the minimum quarter-cycle time compatible with good reliability and reasonable life. It would seem that a small development program on the part of the manufacturers could result in a multi-tabbed capacitor which would be very competitive with other types of capacitors now employed in "fast" or "semi-fast" banks.

Analysis has shown that hydrogen gas is evolved in the capacitor under the reverse voltage conditions. Most manufacturers now provide their capacitors with an improved vent plug which allows slow diffusion of the gas through a thinned section of the plug. This prevents pressure build-up while still providing a seal for the electrolyte.

Unlike oil-paper capacitors, which are life-rated in terms of dielectric voltage stress, electrolytic capacitors are rated in terms of the time required for the electrolyte to diffuse through the seals and (or) dry out. Operation of the capacitor within its heat-dissipation rating has no real effect on its life. Experience indicates that even in this severe service, the life of these capacitors may well be 5 to 10 yr.

Certainly the most apparent advantage of the electrolytic capacitor is its high energy density. This is typically several times that of other types of capacitors used for energy storage at higher voltages. The small size of the bank we describe bears this out.

The Megajoule Bank

General Description

The megajoule bank is basically 80,000 μf of capacitance, rated at 5 kv and capable of being discharged in a minimum quarter-cycle time of 200 μsec. It consists of eighty 12.5-kj modules of 144 capacitors, each rated at 1000 μf, 450 v, in a 12-by-12 series-parallel array. It is located on top of the nine-foot ceiling of a screen room housing an experimental rotating-plasma device. Figure 2 shows a photograph of half the bank at an uncompleted stage.

Module Description

The modules are assembled in a two-layer drawer having a common front panel. Figure 3 shows a photograph of a single modular drawer and Fig. 4 shows the schematic of a single module. The drawers are supported in a framework constructed entirely of Unistrut structural components. They move on rollers and easily roll out far enough for access to the power supply and ignitron area. The input and output leads must be disconnected, however, to permit rolling the drawer out far enough to service the capacitors. When this must be done, cross-rails with rollers are placed to engage, through holes in the front panel, those rails supporting the drawer. The other ends of the four rails engage the corresponding drawer rails on the other half of the bank, situated across the central aisle. The drawer may then be rolled all the way out for convenient maintenance.

Phenolic strips placed in a criss-cross fashion serve to keep individual capacitors isolated from each other. Thin wooden slats resting on the half-drawer flanges support the capacitors. A polyethylene liner encircling the inside of the half-drawer isolates the high voltage from the ground. The bank, incidentally, floats in potential with respect to ground. Either positive or negative, or neither, output terminal may be grounded. An air-conditioning unit supplying 3000 cfm circulates cool air upward through the bank. This is only necessary under conditions of high repetition rates and (or) high ambient temperatures. Exhaust fans of equal capacity, located on top of the bank, minimize the loss of cool air through unavoidable openings in the front of the bank.

The 150-kj bank had a common charging supply for 12 modules. For isolation, each module had a diode, 10-k resistor, and a fuse in series with the charging line. The diodes were fifteen 500-v, 500-ma silicon types in series. The fuses were ten 3/8 amp, 3AG fuses in series; these were held together by a spring-loaded plunger in one end of the lucite cartridge containing them. These elements provide sufficient protection against discharge current surges through the common charging line for a relatively small system. For a large system having considerable stored energy, it was felt necessary to eliminate even the remote possibility of failure of the series elements with accompanying disastrous and hazardous fault currents through the charging supply. A very large supply is required; moreover, the series resistors result in charging efficiencies of less than 50%.

In the megajoule bank, each module has its own reactance-limited charging supply yielding a charging efficiency of about 90%. Each module is essentially a 12.5-kj bank in itself, requiring only primary ac power and ignitron firing-pulse inputs. Voltage-dividing resistors equalize the voltage down the series of capacitors. These draw about 2.5 ma per string or 30 ma per module--about equal to the expected average leakage. Thus, the power required to maintain the bank at full voltage is about 24 w/kj or 300 w per module.

Each capacitor in a series string is connected to the corresponding capacitors in the other eleven parallel strings by nichrome wire. In the event of a shorted capacitor, depending on the module voltage when the fault occurs, this wire either discolors or vaporizes. This provides surge-current limitation for the other capacitors discharging into the faulted capacitor. Additionally, it provides a handy indicator to aid in the location of the faulted capacitor.

Each module has five standard 5550 welding ignitrons to permit switching alternate discharges to five different experiments. There is also a single 5550 ignitron to permit crowbarring, should the user so elect.

Fault Detection

Should the voltage in any two adjacent parallel rows of capacitors differ by more than about 150 v, the neon bulb lights in the fault-sensing circuitry for those rows. These lights are mounted in one end of a lucite block, and a Clairex Cl-3 photosensitive cell is mounted in the other. The Clairex cell senses the light and triggers a cold-cathode 5823 thyratron, which energizes a self-sealing relay. This relay disconnects the primary ad charging power from the module, releases a solenoid plunger that shorts out the bank through two 70-ohm glow coils in series, and lights the fault light on the module front panel and on remote indicator panels. Until repaired or reset, the module remains electrically removed from the rest of the bank. By disconnecting the ignitron trigger leads of the module, the user may continue operation at slightly reduced capacity, rather than take the time to repair the module.

Primary Charging Power

Because of the high-voltage transformer selected, at full voltage each module requires primary ac power of about 1.7 amp at 170 vac. This power is obtained from a motor-driven variable-induction voltage regulator (I. V. R.) operating off a three-phase 480-vac line, with 2:1 step-down transformers on its output. A dc motor on the I. V. R. provides high torque at low speeds. It further allows a controlled slow run-up, enabling an approximate constant-current charging of the bank, with high-speed rundown to minimize operating cycle time.

Output Cabling

There are six pulse output leads for each module: five from the ignitron switches on the negative terminal and one from the positive terminal. Number 6 A. W. G., motor lead wire is used. Tests have shown that its thick neoprene coating is far more than adequate for 5-kv insulation. The bundle of six cables from each module is about 32 ft long and taped at 1-ft intervals with glass-fibre tape to withstand the strong repulsive forces between positive and negative leads. These cables are then connected at a bus panel located at one end of the central aisle separating the two halves of the bank. Should a short occur at the bus panel (a "worst case"), the 32 feet of cable from each module provide sufficient series inductance to limit the minimum discharge quarter-cycle time to 200 μsec or more.

The bank-output load cables typically consist of a bundle of ten No. 0 A. W. G. welding cables for each user. Five are positive leads and five are negative. These are either run in conduit or taped with glass-fibre tape, as dictated by the distance to the load.

Firing Circuits

Control and firing circuits for the bank have been designed to enable any user to select one-quarter, one-half, three-quarters, or full bank capacity. Contactors in the primary bank ac lines provide for charging only the portion of the bank selected. Similarly, the ignitron firing circuits provide for firing only the ignitrons in the modules of the portion of the bank selected. Figure 5 shows a simplified schematic diagram of the firing circuits for one set of output-switching ignitrons. Note that one ignitron fires 20 module-switching ignitrons. The pulse applied to the individual ignitors has a 2 kv, 100-amp peak for several microseconds and a trailing edge of a few tens of milliamperes for several milliseconds. This trailing edge has been found sufficient to provide a "keep-alive" for ensuring continued switching at low anode voltages.

As a matter of interest, we have found that the maximum capabilities of the standard 5550 ignitron, operated under about 12 kv, can be conveniently expressed by the ampere-time product of 20 coul. This can be considered a type of figure-of-merit. For example, it states that the 5550 can pass a maximum current of 20,000 amp for 1 msec. The limitation apparently stems from the time required for the arc of a given current to transfer to the case and do irreparable damage.

Bank Control

Each user has a Station Control console providing him, in his turn, with control over bank capacity, voltage, and firing time. Figure 6 is a photograph of the console. An adjustable timer limits the operating cycle time allotted to any station to a maximum of 5 min. If the bank has not been fired at the end of the cycle time, it is automatically discharged through the glow coils. The Capacitor Bank Control chassis then starts the I. V. R. rundown and sequences all controls to the next user. After the user selects the desired bank voltage at his console, the control chassis causes the I. V. R. to charge the bank automatically to that voltage and maintain it until firing.

To initiate bank firing, the user supplies a pulse of about 25 v to the Initiate Firing Pulse Input on the console, or he may simply push the Initiate pushbutton. The Control chassis causes the primary ac to be removed from the bank and generates a 60-v, 1 msec pulse at the Initiate Sync Pulse Output on the console. This pulse is generated 150 msec after receipt of the Initiate pulse. The user may channel this pulse into the Firing Pulse Input to fire the bank, or he may use this pulse to trigger external circuitry. This circuitry must then supply about a 50-v pulse to the Firing Pulse Input to fire the bank. The user may delay the firing of the bank by up to about 5 sec after receipt of the Initiate Sync Pulse; however, it is advantageous to minimize this delay time since the bank decreases in voltage by about 30 v sec at full voltage with the primary ac removed. It is not possible to fire the bank without first providing an Initiate pulse.

After firing, the sequencer delays for 5 sec to permit observing a lighted fault light, should a fault occur, at the consoles and a main status-light panel. The sequencer then switches all controls to the next user.

Conclusion

It is felt that operation in a series-parallel arrangement establishes a relatively newly opened field for electrolytic capacitors and energy-storage banks. The increased demand for this type of capacitor has already resulted in higher quality capacitors being produced, improved design of the vent plug and output tabs, and a significant simultaneous lowering of price. It is to be hoped that this trend continues. The advantages of size, cost, and flexibility have already been mentioned. For applications necessitating portability, it would be entirely possible to construct a 25-or 50-kj bank on a pallet or cart, or a 100-to 200 kj bank in a truck van. Large sustained currents are possible: with a 600-μs quarter-cycle time, the megajoule bank generates one megampere peak current. Past experience leads us to be optimistic about the long-term reliability of the megajoule bank.

We hope others considering construction of energy-storage systems will benefit from some of the techniques and "rules of thumb" mentioned in this paper.

Acknowledgments

The contributions of Mr. William R. Baker, in charge of the Berkeley Sherwood group, to all phases of design philosophy, development, and particularly inspirational support cannot be overemphasized and are gratefully acknowledged. It is also a pleasure to acknowledge the untiring efforts of Mr. Roy W. Brentlinger in countless tasks of developmental support, bank construction, and maintenance.

Footnote

*This work was done under the auspices of the U. S. Atomic Energy Commission.

Figure Legends

Fig. 1. Waveforms for single-module discharge into 25-mh inductance.

Fig. 2. Photograph of one-half of the megajoule bank at an uncompleted stage.

Fig. 3. Photograph of a modular drawer.

Fig. 4. Schematic diagram of a single module.

Fig. 5. Simplified firing circuits for one set of output-switching ignitrons.

Fig. 6. Photograph of a station control console.

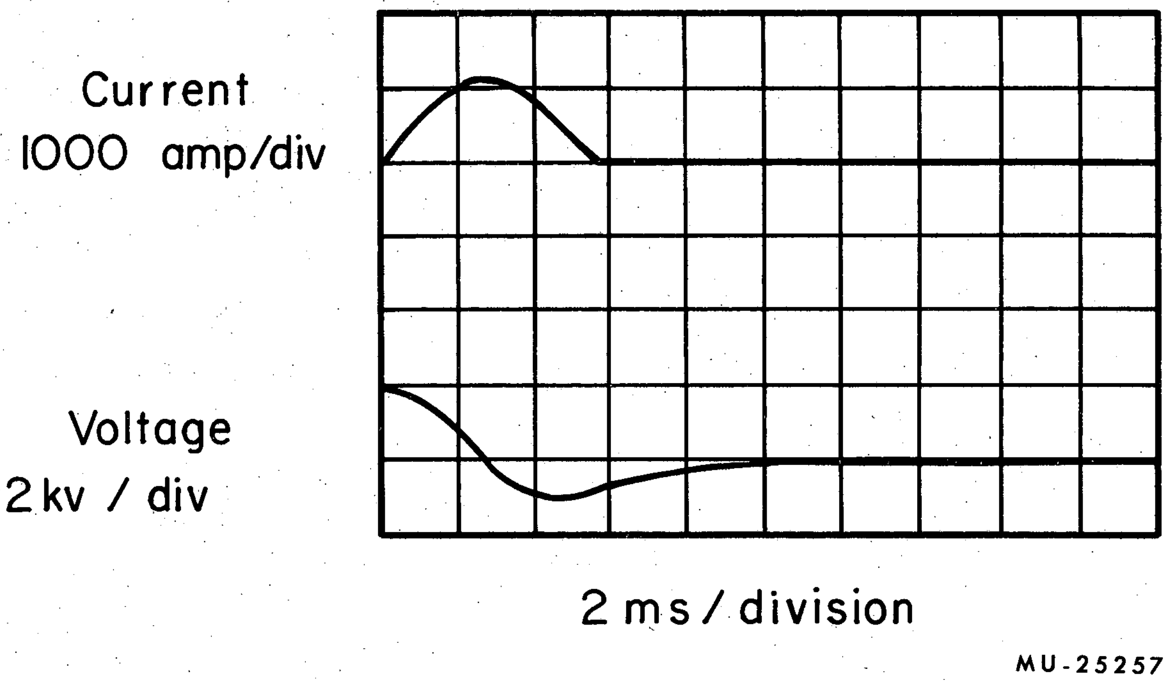
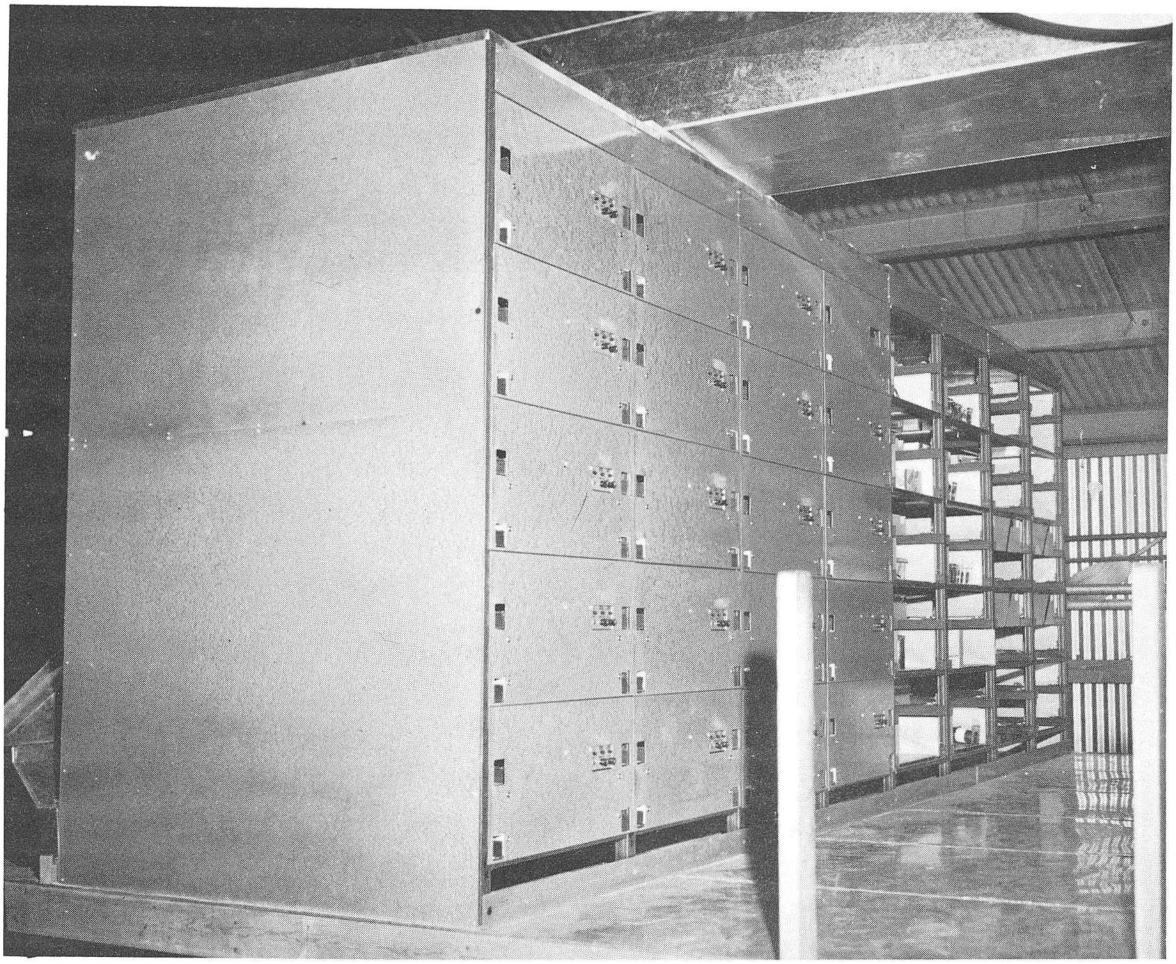
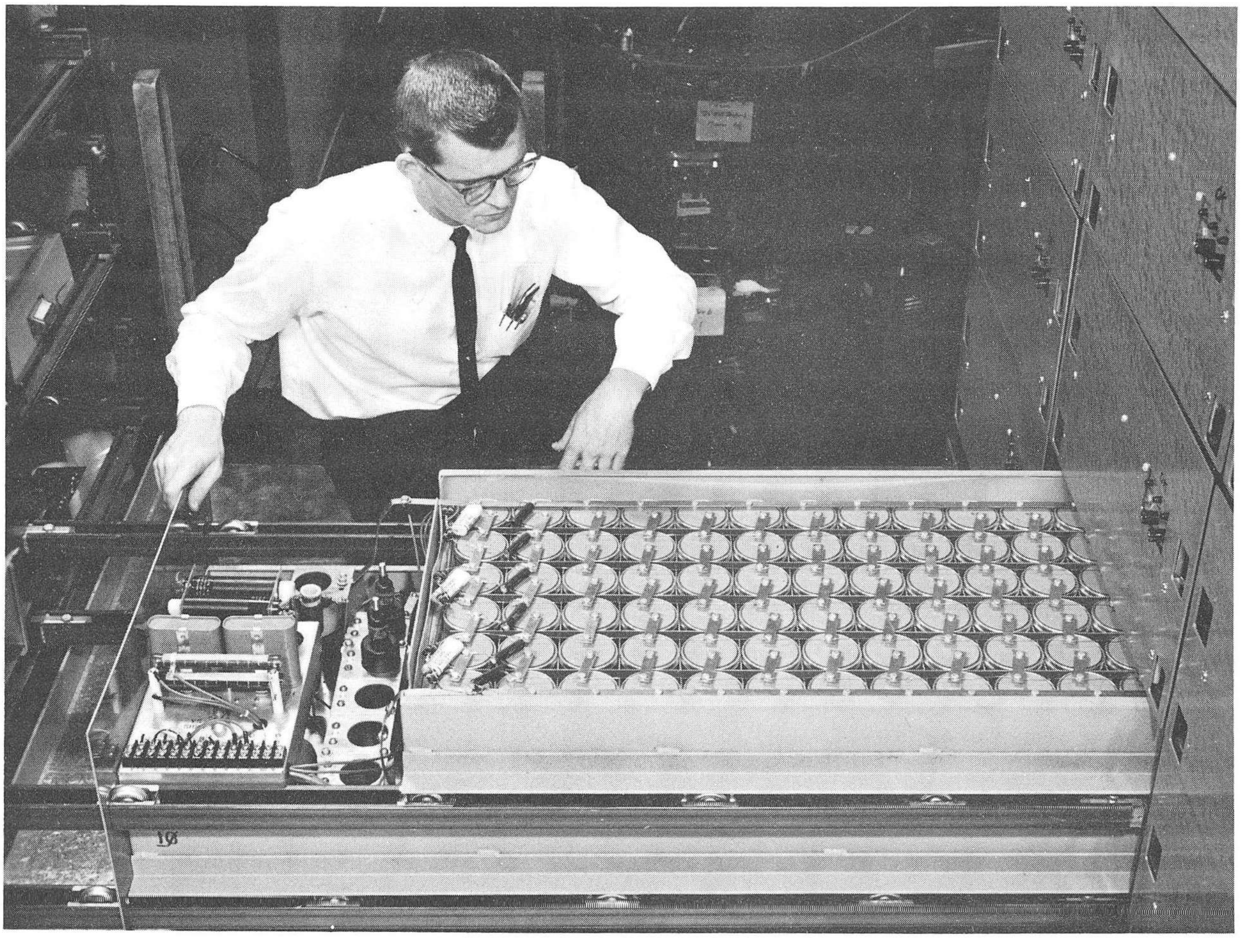


Fig. 1



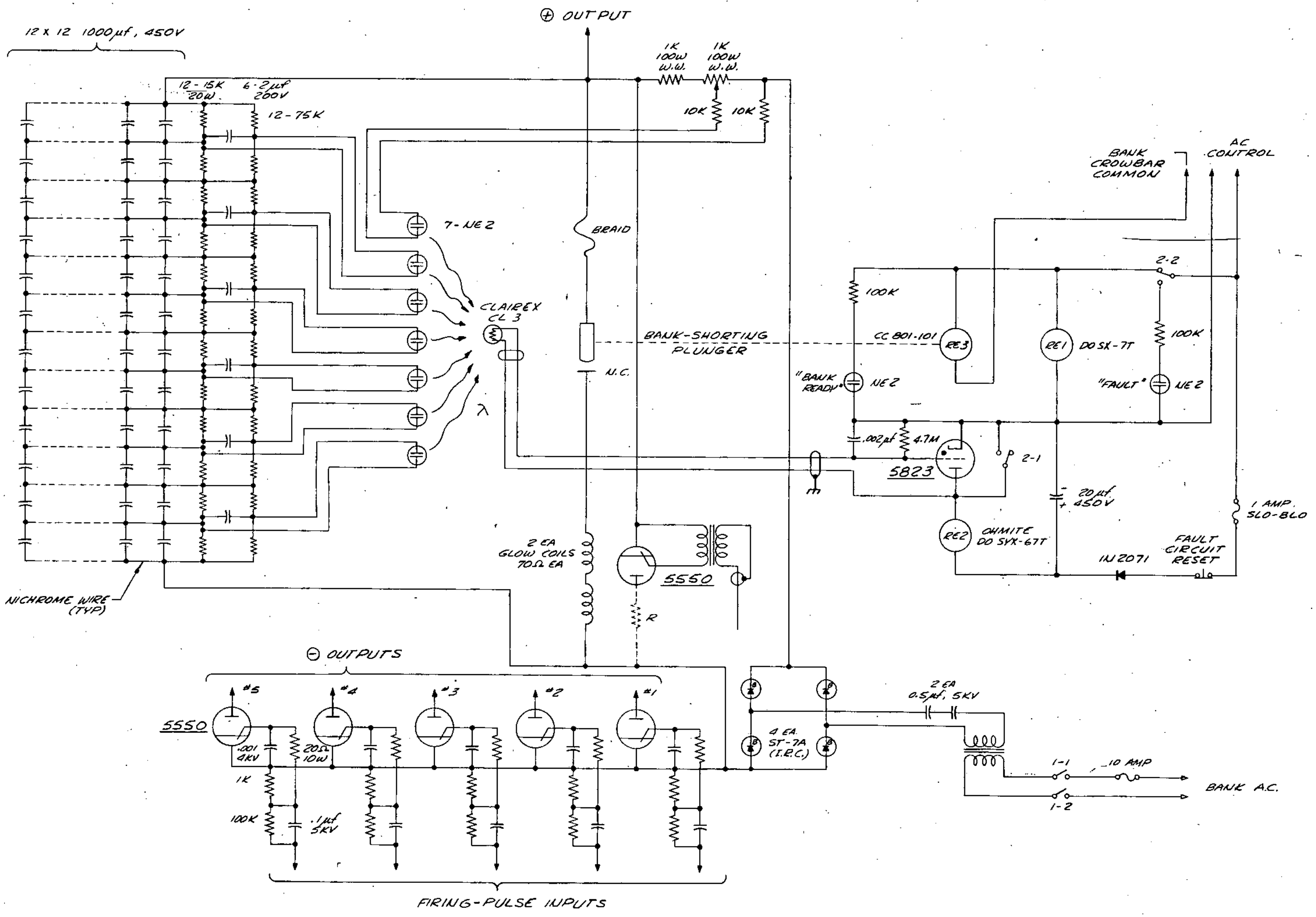
ZN-2984

Fig. 2



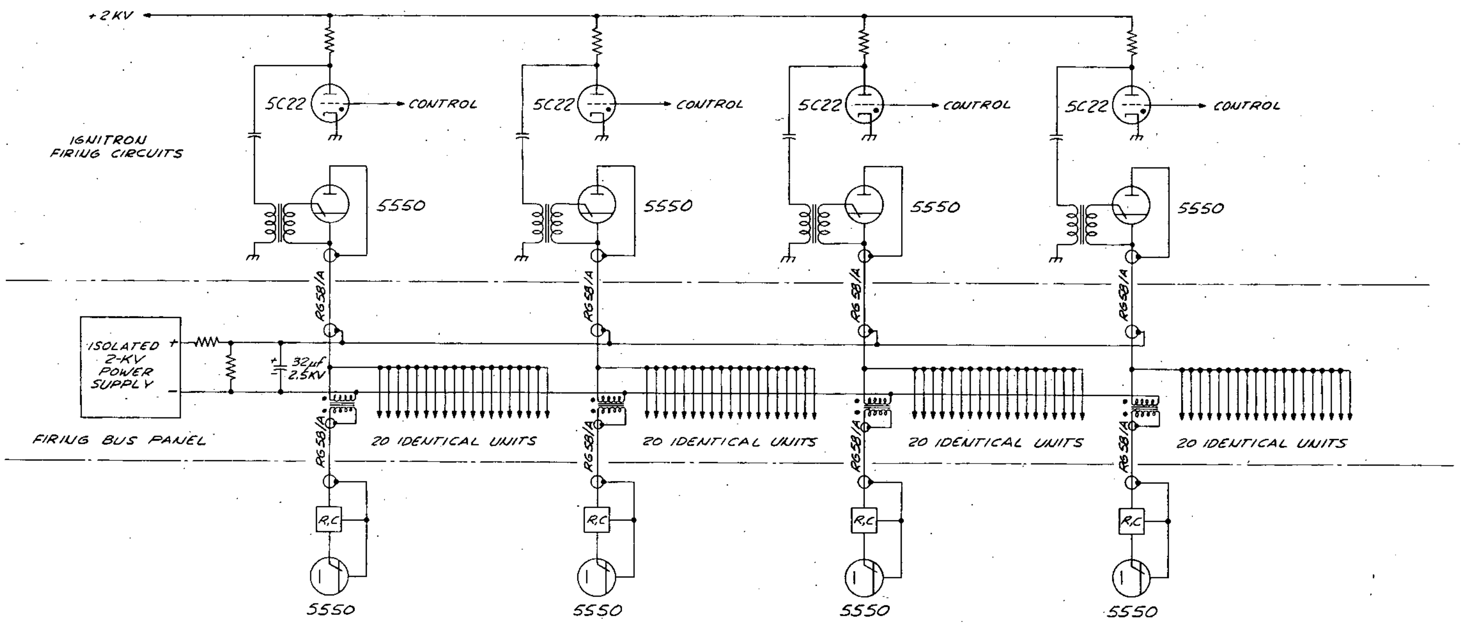
ZN-2985

Fig. 3


12 x 12 1000μf, 450V
12 - 15K 20W.
6 - 2μf 200V
12 - 75K
NICHROME WIRE (TYP)
⊕ OUTPUT
1K 100W W.W.
1K 100W W.W.
10K
10K
BRAID
7 - NE 2
CLAIREX CL 3
λ
BANK-SHORTING PLUNGER
N.C.
2 EA GLOW COILS 70Ω EA
5550
R
BANK CROWBAR COMMON
AC CONTROL
2-2
100K
100K
CC 801-101
RE3
RE1
DO SX-7T
"BANK READY"
NE 2
"FAULT"
NE 2
.002μf
4.7M
5823
2-1
20μf 450V
RE2
OHMITE DO SYX-67T
1 AMP. SLO-BLO
FAULT CIRCUIT RESET
1N2071
⊖ OUTPUTS
5550
#5
#4
#3
#2
#1
.001 4KV
20Ω 10W
1K
100K
.1μf 5KV
FIRING-PULSE INPUTS
4 EA. ST-7A (I.R.C.)
2 EA 0.5μf, 5KV
1-1
10 AMP
1-2
BANK A.C.

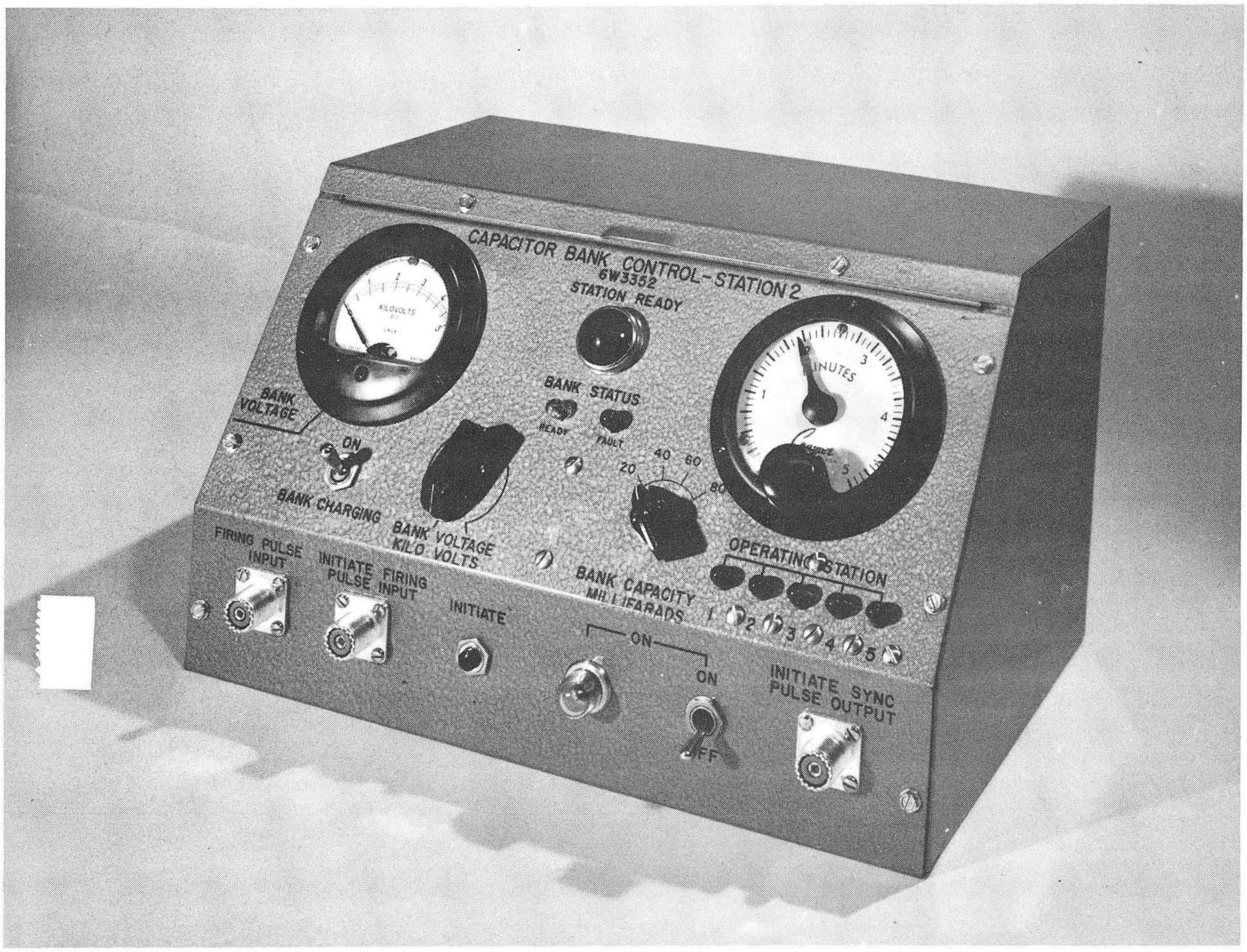
MUB-886

Fig. 4


+2KV
IGNITRON FIRING CIRCUITS
5C22
CONTROL
5550
RG58/A
ISOLATED 2-KV POWER SUPPLY
32μf 2.5KV
FIRING BUS PANEL
20 IDENTICAL UNITS
R,C

MUB-887

Fig. 5


CAPACITOR BANK CONTROL-STATION 2
6W3352
STATION READY
KILOVOLTS
BANK VOLTAGE
ON
BANK CHARGING
BANK STATUS
READY
FAULT
BANK VOLTAGE KILO VOLTS
20
40
60
80
MINUTES
BANK CAPACITY MILLIFARADS
OPERATING STATION
1
2
3
4
5
FIRING PULSE INPUT
INITIATE FIRING PULSE INPUT
INITIATE
ON
ON
OFF
INITIATE SYNC PULSE OUTPUT

ZN-2986

Fig. 6