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THE PRESENT STATUS OF THE BEVATRON POWER SUPPLY

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ABSTRACT

This report brings up to date the description of the Bevatron power supply. Changes made since the original installation are described, and problems still encountered are treated.

II. POWER SOURCE

12-kv Supply

Power is supplied to the Bevatron at 12,000 volts by underground cables from the University Substation. There are two separate 12-kv buses, each with its own supply. The bus that supplies the main motor generator sets has a voltage regulation of nearly 2% and is designated as the "unregulated" bus. Consequently, this bus carries only such loads as can tolerate this voltage fluctuation. The unregulated 12-kv bus supplies three 12,000/480-volt and one 12,000/2400-volt transformer banks. Two 1,500-kva banks supply building power and one 750-kva bank supplies the generator exciters and auxiliaries. A 3,000-kvar capacitor bank is connected to this bus for power-factor correction.

The other 12-kv bus, designated as the "regulated" 12-kv bus, carries those loads that cannot tolerate the voltage swings due to the main motor generators. These loads consist of general building lights and power, the Bevatron accelerating equipment, electronic control equipment, and experimental setups. This bus also supplies power to other buildings, including the heavy-ion linear accelerator. A 1,500-kva and a 2,500-kva transformer bank supply power at 480 volts. Two 1,500-kw motor generators are supplied directly at 12,000 volts.

Switchgear and Relaying

The switchgear is of the enclosed, air-break type; some is indoor, some outdoor construction. All of the 12-kv bus is enclosed in insulating sleeving; the 480-volt bus is bare. Bus tie breakers are provided at 480 volts to provide for maintenance of the 12-kv buses and the transformers.

The control power for the switchgear and for the main motor generators is 135 volts dc. This is supplied by an 80-amp-hr nickel-cadmium storage battery. The battery is maintained during idle periods by a trickle charger, and when the Bevatron is operating, by a trickle charger plus a booster charger.

We intend to change the source of supply, as the present source is limited to 27,000 kva. The Pacific Gas and Electric Co. plans to install a 35,000-kva 115/12-kv substation on UCRL property. It is expected that this station will be in operation by the winter of 1958. The Campus load, other than the Laboratory load, may then be carried by either the present feeders or by the new substation.

The problem of protecting the motor generators and rectifiers is divided into two categories. The first, known as "total shutdown" includes troubles that require the machines to be stopped. The second, known as "partial shutdown," includes troubles that require only that the generator field be removed and the magnet short-circuited. Emergency trip stations for both categories are provided throughout the motor generator area.

The listing of the individual trip signals, some 25 in number, is adequately covered in earlier publications.[3,4] Two changes were made in category. The ground detector was changed to total shutdown to minimize equipment damage; the generator overtemperature trip was changed to partial shutdown to better utilize the generator cooling fans. In addition, the reverse-phase relay was moved from the 480-volt potential transformers to the 12-kv potential transformers. This change eliminated false shutdowns caused by excessive voltage swings in the 480-volt auxiliary power system.

Additional instantaneous motor-overcurrent relays were added to operate ahead of the time overcurrent relays. In the event of motor overcurrent during rectification, these relays stop the pulser; this puts the ignitrons into inversion, thus reducing the duty on the motors.

It was found advisable to delay the closing of the ignitor shorting relays until after the magnet-shorting switch had closed. This allows the magnet current to commutate among ignitrons rather than to maintain a single path through the converter, which occurs when the shorting relays close.

Particular attention had to be given the inversion arc-through relays, as oscillographs showed as much as 17 cycles operating time. This was too long for the arc to remain in one tube. The entire relay chain was analyzed and, by adjustment of each successive component, the operating time was reduced to 10 cycles from fault to the closing of the shorting switch. In addition, the inversion arc-through relays are gated out during the rectification and step times to permit still closer relay settings.

III. ROTATING SYSTEM

(See Fig. 2)

Generators

The magnet power-supply generators are 12-phase machines rated 46,000 kva, 3195 (L-N) volts, 1200 amp, 837 rpm, and 55.8 cycles. The odd frequency and speed are approximations, as the true speed varies between 890 rpm at no load and 800 rpm at peak load. The maximum pulse rate at full magnet current is 11 pulses per minute.

The 12 generator phases are grouped into four three-phase, wye-connected windings with neutrals. A series-parallel connection of these windings and their associated rectifiers provides 8,400 amp dc at 6,000 volts. (Fig. 1b.)

Each generator phase has two coils in series, with four series groups in parallel, making 96 coils in 96 slots. Each coil spans 12 slots. Opposing phases lie in the same slots to cancel the dc flux in the generator (there are no rectifier transformers).

Each day, before start-up, the generator windings as well as the Bevatron magnet and connecting cables are tested to 4 kv dc to ground. This is sufficient to detect any gross insulation failure to ground. In addition, each generator wye is tested to 30 kv dc annually. The curve of voltage vs leakage current is plotted to determine the "knee" or point of deviation from Ohm's law. The voltage at this point is considered in deciding when to clean and revarnish the generators.

Generator troubles have been many and varied. Electrical troubles have arisen from: moving slot wedges, end-turn insulation failure, rotor coil connection failure, stator coils falling into the air gaps, stator burnout caused by a broken bolt from the rotor (Figs. 3 and 4), and journal etching as a result of bearing-insulation shorts. Mechanical problems have been primarily due to shaft misalignment and to lubricating-oil system and bearing troubles.

Because the generators deliver pulsed loads, the windings are subjected to violent mechanical shocks. The original design provided adequate extra bracing for the end turns and paralleling rings. The slot-wedge construction, however, was of the type used in standard machines, and proved inadequate. Some wedges moved axially (Fig. 5), and in one case released a stator coil which fell into the air gap and struck the rotor (Fig. 6). This failure occurred during start-up and was detected before the field current was built up. Only minor iron damage resulted although the coil was destroyed.

After this fault both machines were rewedged, by use of standard techniques plus a lubricant between wedges and coils. It was necessary to rewedge again within one year. At this time a new technique involving a metal lock was used. The wedges were butted against one another to minimize axial movement. The two end wedges in each slot were locked to the first cooling duct in the stator iron by a T-shaped nonmagnetic locking shim (Fig. 5b). Again, a lubricant was used between the coil and filler strips. The wedges were cemented to the filler strips and to the iron with a plastic cement. This new technique has given excellent results. Eleven months of operation have produced no slot-wedge movement.

Owing to commutation transients, abnormally fast voltage spikes of 5 kv per μsec appear across the generator windings. The end-turn insulation failed in one generator, resulting in a fire and damage to 16 coils. (Fig. 7). (Ten new coils were installed and six damaged coils repaired.) Short-circuit paths for these transients have been provided to prevent future damage. Resistance-capacitance and pure capacitance circuits were tried between phase and neutral, and oscilloscope measurements were made to determine the most effective circuit. The final choice was 0.7 μf to neutral on each phase, which gave a transient rise time of 1 kv per μsec.

The capacitors were fused at first, but the high harmonic current melted the fuses open, allowing them to explode. The solution to this new trouble required a fuse of sufficient interrupting capacity to clear a phase-to-neutral short in case of a capacitor failure, and sturdy enough to last under the harmonic-current heating. The fuses are available, but no method of monitoring for open fuses has been satisfactory. At present the capacitors are not fused, and to date no capacitors have failed. Periodic high-potential tests guard against faulty capacitors.

The bolted and hard-soldered connections between the rotor coils are subject to fatigue failure. Periodic checks of the voltage drop across each joint are made to determine incipient failure, and cracked joints have been successfully detected before they failed in service. Cleaning and resoldering are a sufficient cure.

The bearings are lubricated by a pressure-feed oil system supplied by two pumps--a motor-driven centrifugal pump and a shaft-driven gear pump. The system includes a sump, a temperature-controlled heat exchanger, strainers at each bearing, and a temperature-recording system. Thermocouples in each bearing run to a multichannel Speedomax recorder which monitors each bearing temperature in turn. An alarm is sounded if any temperature reaches 70°C; the motor generators are stopped if the temperature reaches 80°C.

These machines have two insulated bearing pedestals to prevent flow of currents from shaft to bearings. There have been instances when the insulation was bridged accidentally, with resultant etching of journals. Care is taken to keep the bearings clear of ground, and shaft resistance to ground is measured whenever the generator sound shrouds are moved. The most severe case of etching occurred during measurement of the vertical movement of the No. 1 bearing in connection with shaft misalignment studies. The bearing insulation was accidentally shorted by a dial gage. A journal was severely etched and required polishing with crocus cloth and oil. The dial gage movement was welded together.

The bearings are babbitt faces poured on steel shell. After about two years of operation it was found that a bearing would suddenly run hot for a few hours or days and then revert to normal temperature. When these bearings were inspected, it was found that the babbitt had been raised up in blisters and had touched the shaft. The top of the blister had then wiped free of the shaft (Fig. 8). The blisters were drilled and high-pressure hydrogen escaped. The blisters were scraped down, smooth with the original babbitt surface. A pattern of 1/16-in. holes was then drilled through the babbitt to provide a release for future hydrogen accumulation. We conclude that the hydrogen-blister problem is solved.

The lubricating-oil system posed two major problems--that of maintaining a supply of oil in event of power failure, and the removal of entrained air from the circulating oil. The former problem was solved by adding a gear pump belted to the generator shaft and of such size as to deliver sufficient oil down to about 50 rpm. Below this speed the oil rings in each bearing supply sufficient oil. Both oil pumps must be operating satisfactorily before load is applied to the generator. Failure of either pump reduces the system pressure, and both machines are automatically shut down.

The air-entrainment problem became serious when the original supernoisy gear pumps were replaced with quiet centrifugal pumps. Air was mixed with the oil by the rotating shaft, bubbles collected in the suction eye of the centrifugal pump, and the discharge pressure dropped at once to unsafe values. It was necessary to install baffles in the oil sumps to allow air to escape more freely. A bypass was installed from the pump discharge to a jet in the pump suction eye. This jet maintains a higher suction pressure and also mechanically prevents the formation of a large bubble. Even with these modifications the air entrainment problem is still troublesome with cold oil (60°F to 85°F).

Shaft alignment on a five-bearing machine is critical. The shaft-alignment problems at the Bevatron include (1) the pounding of shock loads that impose a reversing torsional stress; (2) a differential vertical movement in the bearing pedestals resulting from temperature changes; (3) a probable, but as yet unmeasured, seasonal distortion of the shale bedrock beneath the foundations, and (4) a possible flexure of the foundation about ventilation openings in the concrete.

The reversing torsional stress must remain below the endurance limit in the critical section of the shaft, the 20-in.-diameter journals between the generator and flywheel. This stress, primarily determined by generator loading, is known and controlled. Shaft torsion is monitored continuously, and any abnormal torsional displacement caused by a rectifier or generator fault is recorded. Thus we know that the normal torsional displacement is 16 to 20 minutes of arc and that abnormal displacements can reach 45 minutes of arc. Shaft stresses resulting from misalignment must not increase the total stress in the shaft beyond the endurance limit.

The problem of shaft alignment and resulting shaft stress has been studied in great detail by both UCRL and the manufacturer. Alignment tolerances have been established, based on a maximum bending stress in the shaft of 2000 psi. The change in bending stress at each bearing has been determined for a 1-mil displacement at a given bearing. From this information it was found that the generator and flywheel shafts must be aligned so that the coupling faces are parallel within 1 mil at the circumference.

Vertical displacement of the bearing pedestals resulting from thermal behavior has both short-time and long-time components. These are a daily cycle owing to the daily starting and stopping of the machines, and a long-time cycle (about a week) which occurs after the machines have been standing idle for maintenance or repair.

The No. 1 generator bearing is supported on two steel H-columns to make room for the generator buses beneath it. These columns were originally exposed to the hot air discharged from the generator, and expanded about 12 mils as they warmed up each day. This meant an increase in bending stress of 430 psi at the No. 2 generator bearing. The columns were shrouded with a thermal insulating board, and cool air is now circulated through these shrouds. The temperature increase in the columns is thus reduced and the thermal expansion is now about 5 mils. The change in bending stress is reduced to about 180 psi.

There is little that can be done about the long-term changes in vertical alignment. Those resulting from heat involve temperature changes in large masses of concrete. These changes are necessarily slow, and affect the other four bearings. The foundations are set on a bench cut into a shale hillside. Because of the pronounced ground-water changes between the dry and rainy seasons, it is reasonable to expect some squirming of the motor generator foundations. So far no correlation has been determined between machine alignment and wet weather.

It is possible, also, that flexure of the foundation at air passages may occur, as the stiffness of the generator foundation may not be uniform along its length. Periodic examinations of the foundation walls are made to detect cracking or other evidence of movement.

The torsional stress of the shaft is near enough to the endurance limit to require frequent journal inspections for incipient cracks. Magnaglo tests are made on each of the two critical journals in each machine, the two between the generator and flywheel. These tests are made at intervals of about 700,000 full-load pulses. A reflectoscope test has been made once, and we intend to repeat this test in the near future. The first reflectoscope test was limited to radial tests because of limited clearance between the coupling halves. Future tests will include axial as well as radial observations.

A final problem encountered was noise. The sources are many, ranging from the balancing weight on the flywheel and a siren effect in the stator air passage to magnetostriction in the stator core. A brute-force method of reducing the noise level was used. Steel shrouds lined with fiber glass bats were placed over the motor and generator air inlets and completely around the coupling. A plain steel shroud was placed around the flywheel. The maximum noise level is about 105 decibels, near the flywheel. Further noise reduction, though desirable, is too expensive to be justified.

Changeover

When the Bevatron power supply changes from rectification to inversion (Fig. 9), there is a full-load torque reversal imposed on the motor generator shafts. This corresponds to the change from generator to motor action. If the load is reversed in properly timed steps, the transient shaft twist can be greatly reduced from the twist obtained when the total load is reversed at once. The two-step method consists of removing the load for a period equal to one-half the shaft natural period (23.5 msec) and at the end of this time applying the reverse motoring torque. The shaft is thus allowed to unwind and wind-up in the opposite direction before the reverse torque is applied. The reverse torque will then hold this opposite wind-up in the shaft, in effect, providing damping.

The means of controlling this changeover from rectification to inversion is an electronic chassis called the pulser.[6] The pulser supplies the thyratron firing tubes (Fig. 10) with the variable portion of their bias (master control) and in this way controls the change from rectification to inversion. There is a variable time delay incorporated in the pulser to adjust the "step" (nominally 23.5 msec).

At times it is desired to operate the Bevatron magnet with a flat-topped current pulse. Attention must be given to the step time delay before this mode of operation is undertaken to insure that the time involved minimizes transient twists in the shaft. Oscillations during this period can be observed from position pickups at each end of the shaft.

If the step is not synchronized separately for each machine, high transient voltages will occur across the interphase transformer of the unsynchronized machine. This will result in saturation of the transformer, allowing the full magnet current to flip to one branch of that machine as shown in Fig. 11. This doubles the current and consequently reduces the margin angle for one-half of the machine. Under these conditions inversion faults and high transient torques at changeover are frequent. The step is now synchronized for each machine separately.

Generator Voltage Control

Excitation power for each generator field is supplied by a double three-phase ignitron rectifier, each with its own transformer. The rectifiers are connected directly to the generator fields through two-pole high-speed circuit breakers. Excitation control is achieved by shifting the firing angle of the ignitrons in response to a signal from the voltage regulator. The response of this system is fast enough to hold constant generator voltage with increasing load until the generator iron saturates.

The voltage regulator is incorporated in an ingenious electronic device known as the synchronizer. This device is designed to hold a constant phase relationship between the two generators, to maintain the total voltage constant, and to hold a balanced division of load between the two generators.

To accomplish this feat, the synchronizer samples the voltage of each machine and adjusts the generator field currents to maintain the sum of the two voltages constant and the difference of the two voltages equal to zero. Because the magnet current is common to the two generators, this action is sufficient to secure equal load division between the two machines. The speed, of course, may vary.

In some applications it is necessary to hold a constant, predetermined phase angle between the two generator voltages. The phase angle is measured by comparing the relative position of the teeth of gear wheels mounted on the motor end of each shaft. These wheels each bear the same phase relationship to their respective generator rotors. Reluctance pickups placed near the gear teeth generate a voltage signal and any phase displacement between the two gear wheels appears as a phase shift between the two reluctance pickup signals.

A phase reference system may be established by the use of two pick-ups on the first machine, spaced 90 electrical degrees apart. It is then possible to match the second machine to any arbitrary phase position of the first machine. The error signal derived when the two machines are out of synchronism is then used to differentially change the field currents (and hence the loadings) on the two machines, driving the machines back into synchronism. During the inversion period, the error signal also acts to shift the firing angle of the 1PJ7 ignitrons and thus to give additional synchronizing power.

One further refinement is necessary. The generator field circuit operates ungrounded; the synchronizer contains grounded electronic components. An ungrounded carrier circuit is then necessary between the two. Such a circuit is used, and it also serves to isolate the two generator excitation circuits from each other.

Driving Motors and Secondary Control

The Bevatron motor generator sets are each driven by a 3600-hp, 3-phase, 12-kv, 837-rpm wound-rotor induction motor. These motors are started across the line with maximum rotor resistance to limit the starting current. The resistance is cut out in successive steps as the machine accelerates to full speed in approximately 6 minutes.

During normal operations the pulse rate is 11 pulses per minute and the speed of motor-generator set swings from 860 rpm between pulses to 800 rpm at maximum magnet current. It is necessary to cut in two steps of resistance during magnet-current build-up (rectification) to limit line current swings. The resistance steps are cut out during the magnet-current decay period (inversion) in the reverse order. This switching sequence is performed by large contactors opening and closing with each pulse. Other contactors are programmed by the operator.

Pulsed operation imposes severe mechanical and electrical duty on the contactors and control relays. The contactors, which interrupt low frequency rotor current, fail because of rapid destruction of the arcing contacts. The solution is to use copper contacts with Elkonite arcing faces, and weekly attention to the arcing surfaces should be given. Care such as this gives about 500,000 pulses per contact pair, and some contacts have lasted 750,000 pulses. This compares favorably with the 200,000 pulse maximum life of solid copper contacts.

The constant jarring of the relay and contactor assembly produces mechanical failure of wires, contacts and some mechanical parts. Bolts break occasionally, and in some cases bolted joints have been replaced with welded joints. Bearings in the pulsing contactors have shown accelerated wear, as have stop lugs. Plain steel-pin bronze-bushing bearings have been wearing excessively on the pulsing contactors. A Laboratory-designed replacement using needle bearings has given excellent results for over three million pulses. Other worn parts are either replaced or rebuilt by brazing and machining.

The control-relay difficulties result from either burned or broken contact assemblies or broken wires. A periodic maintenance and inspection program has been instituted to forestall such failures. Molded bakelite auxiliary contact assemblies on the contactors occasionally break, and are replaced with new ones made from a glass-epoxy sheet having greater impact strength.

The secondary resistors have become a source of trouble. The first two resistor steps used in accelerating and braking are cast-iron grid resistors. Failure of the joints between grids due to rusting and thermal movement has caused two grid assemblies to burn up violently and several more to throw momentary arcs and hot metal. The cure for this shortcoming was to weld connecting bars across all of the joints to give a permanent electrical connection. This was done without dismantling each grid assembly.

Stopping of the motor generator sets is accomplished by dynamic braking. Direct current is fed into two phases of the motor, and the stored energy in the rotating parts is dissipated in the secondary resistors. The resistors and contactors are the ones used for accelerating and pulsing, but different control relays are used. The problems encountered in these braking controls are malfunctioning timers or welded contacts caused by circuit troubles elsewhere.

The brushes on the motor have given more than a normal amount of trouble and the problem of brushes has not been completely solved. They have burned pigtails, have had copper deposits, sparking, extra rapid wear and worn slip rings. A brush of different graphite-copper ratio was chosen to avoid copper deposits and the consequent overcurrent which burned off the pigtails. Some of the brushes lost their pig tails mechanically. Rapid brush wear has been attributed to both light loading and low humidity. Loading has been increased by lifting half of the brushes; the humidity problem is still a whim of the weather. The rings are to be turned this year to smooth out grooves and small accidental nicks. The brush problem is presently under study and moving toward a solution compatible with the wide range of operating conditions.

IV. THE CONVERTER

Series Connection

In the initial installation of the Bevatron power supply, the two 46,000-kva generators operated in parallel. At present the generators operate in series (Fig. 1b).

The magnet current flows through one machine and then one-half the magnet before passing through the second machine and the other half of the magnet. A soft ground of 240 ohms is located at a magnet quadrant so that the voltage to ground is never more than one-fourth the magnet voltage. Spike filters are located on each end of the one-half magnet voltage points to suppress transient voltages to ground so that all quadrants are alike electrically.

Each generator has 4 wye groups connected two in series and parallel through a 360-cycle, 1620-volt, 4167-2084 amp dc interphase transformer. These interphase transformers adequately maintain voltage differences between parallel wye groups during normal operation. During an inversion arc-through, however, they saturate and permit the total magnet current to pass through the parallel branch that is faulting.

The commutating reactance of the generators is nominally about 0.4 ohms. From oscillograms of the converter-current wave shapes (Fig. 12) the commutating angle at 4200-amp phase current appears to be close to 33 degrees during rectification and 17 degrees during inversion. These angles indicate a lower commutating reactance than 0.4 ohms if sinusoidal voltages are assumed. The generator voltage, however, is not sinusoidal (Fig. 13).

Each generator phase is connected to two ignitron tubes through a current balancing reactor (Fig. 1b). This reactor has a rating of 4.5 kva, 1206-603 amp. The parallel anode currents are balanced within a few percent at full load. Current balance is better during rectification than during inversion.

Ignitron Tube

The IPJ-7 ignitron tube is a two-grid, continuously-pumped, water-cooled tube. This 15-inch tube is suitable for applications involving high-current and high-voltage conversion.

It is necessary for the tube to withstand both forward and inverse voltage stress of approximately 10,000 volts. The tap-3 phase-to-phase generator voltage is 17,000 volts peak-to-peak (Fig. 13).

The normal peak current per tube is 2100 amperes. However, there are occasions when the tube currents may double or quadruple because of abnormal circuit operation which unbalances the four parallel current paths.

The most severe case of abnormal tube current results from an arc-back during rectification. This current is in excess of 30,000 amperes peak for a period extending from 1 to 14 cycles.

There are no anode circuit breakers to interrupt this current. During this period the tube carries unidirectional fault current, the arc leaves the mercury pool and travels to the cathode potential parts near the anode. The metal parts are melted from the excessive heat; the glass anode bushing acquires internal surface cracks and, in some cases, the bushing is destroyed.

Inversion arc-backs reach approximately 8,000 amperes peak, but the current periodically goes through zero and thus the arc may not necessarily cause the damage of a normal arc back. The common appearance of an ignitron anode stem assembly after several months operation is shown in Fig. 14. Internal parts of an ignitron also showing signs of arc tracks are pictured in Fig. 15.

Vacuum System

The vacuum system for the pumped ignitron tubes consists of an oil mechanical pump and a water-cooled mercury diffusion pump. The pumps are in tandem and connect to a vacuum manifold. Six ignitrons of one cubicle connect through individual tank valves to the manifold by means of 3/4-inch steel pipe. The pumping speed of the mercury diffusion pump is 5 ℓ/sec at the pump. However, the pumping capacity at the tubes is insufficient to handle any large quantities of gas in a short time. This limits the recovery time of a cubicle after an overload. Degassing must also be done with great care so as to keep the tank pressure low enough to prevent internal damage.

Vacuum monitoring and protection devices include a Pirani gauge and a McLeod gauge connected to the manifold. The Pirani gauge relay is set to trip at 2 microns (μ).

The vacuum leak rate requirements of the IPJ-7 ignitron tube had to be changed from 1μ/hr to 0.1 μ/hr in order to avoid troublesome tubes and to provide satisfactory operation. Tubes with rate of rise in excess of 1 μ/hr have definitely contributed to poor operation.

The main sources of vacuum leaks in a tube are the grid bushings, the anode Kovar seal, and the anode plate-to-tank seal. The anode seals on some tanks were porous and were replaced with new anode seals. The grid bushings had the largest number of leaks and accounted for the highest leak rates. As a temporary measure, a high-temperature insulating varnish was used to seal the leaks. As the tubes are rebuilt the grid bushings are heliarc welded to the anode plate. The anode-assembly vacuum seal consists of two round concentric aluminum "O" rings. This double-ring system is very difficult to check with a helium leak detector because the volume between the rings is inaccessible for monitoring. A double time constant is involved for the helium to pass both seals.

It is believed that thermal cycling of the ignitron tank works the vacuum seals and produces variable leak rates.

Ignitron Cooling System

The cooling system is shown in Fig. 16.

Low conductivity cooling water is required because the ignitron converters are at high voltage. This water is highly corrosive to iron, producing both ferrous and ferric compounds. It is necessary, therefore, to eliminate all iron surfaces either by replacing or by plating the component.

The iron rust settles out on cooling coils producing a thermal insulating layer which affects the cooling efficiency. Therefore, it is necessary to provide periodic flushing of the ignitrons to avoid hot spots on the tank walls. The iron rust also settles out in low spots and must be flushed out to prevent restriction of the water flow. It has been necessary at times to stop the Bevatron operation to correct ignitron overtemperatures.

Low-conductivity water does not necessarily imply that electrolysis cannot occur. It can occur between two dissimilar substances such as iron and copper, particularly if a small leakage current flows. The end bells of the water-circulating pumps required silver plating of the cast iron to inhibit the electrolysis between the brass impeller and the cast-iron end bell. The cast iron dissociates into the water leaving a graphite surface on the end bell.

The severe duty to which the ignitron tubes are subjected because of pulsed loading leaves certain parameters undetermined. One of these factors is the temperature at which the tubes perform most efficiently. Because the merit of each tube is different, the mass analysis is complicated by the interaction of other problems. Operation is definitely better near 50°C than at 40°C. Operation below 40°C is impracticable because the fault rate is excessive. Also below 40°C the current-carrying capacity of the tubes appears to be limited during the fault period. Current limiting in an inductive circuit is not desirable because of the possibility of generating high voltages. The arc tracks on the tank walls indicate that some portion of the anode current terminates on the walls rather than at the mercury pool. This is aggravated by operation of tubes at low temperatures. Operation above 50°C is still being explored because some converter units perform very well at 55°C while others appear to fault more often at high temperatures. The faulting, however, localizes to certain tubes and is not distributed at random. At present the problem is not completely resolved.

The temperature of the ignitron tubes is held to $\pm\frac{1}{2}^{\circ}$C at all duty cycles by a "proportional-reset" temperature regulator. Since the regulator was installed, it is easier to return to rated load after a fault. Previously the temperature changes were sufficient to permit sympathetic inverter faults after an initial fault had occurred.

Tube Failures and Reconditioning

There are two causes of "in-service" tube failure as indicated by excessive faulting:

(a) The tube develops a vacuum leak. This can be detected by taking a rate of pressure rise on the tube and by leak-hunting with a mass-spectrograph type leak detector. Occasionally the leak can be repaired without removing the tube; usually the tube must be removed.

(b) The anode Kovar-glass bushing accumulates a conducting plating of iron and copper on the inside surface (Fig. 14). The coating is spattered on the glass and comes from the iron anode stem and a copper-furnace-braze. Electric-field plots indicate that stresses on the film are approximately 100,000 volts per inch. Occasionally the surface sparks, causing the tube to fault. Some bushings will fail to hold the required voltage, and then the tube must be removed from service and overhauled.

The tubes that fail in operation are overhauled locally. The graphite parts are outgassed in a vacuum furnace at 1800°C for two days. All of the metal parts and the tank are cleaned with iron shot. A new anode bushing and grid bushings are heliarc welded onto the anode plate. All sharp contours are rounded as needed. The heliarc welds are vacuum checked at 29 psi of helium, by the use of a Consolidated leak detector. After assembly, the tube is outgassed at low voltage and high current until the pressure rise is not detectable when the tube is overloaded 300%. In addition, it is necessary to provide high voltage treatment of each tube. High voltage outgassing is necessary before the tube can operate at rated load. This is done by programming the magnet current and voltage in increasing steps until the tube will withstand normal operation. A tube failure represents a loss of at least 7,000 magnet pulses. The failure rate at present is about one tube per month.

Ignitor Firing Circuits

To obtain accurate timing of the ignitor pulses to the converters the ignitor firing circuits are controlled by thyratrons (Fig. 10). The thyratrons used to switch the circuits are triggered by peaking transformers which are excited at generator frequency. Paralleled ignitrons have their firing tubes (thyratrons) triggered by the same peaking transformers so that any jitter at the beginning of the ignitor pulse is several times smaller than normal ignitron-firing jitter.

The primaries of the peaking transformers are cross-connected between parallel branches (Fig. 1b). The peaking transformers for 1A are fed from 3A, etc. This was done to try to equalize the currents through the two parallel branches of the machine. It is surmised that with this cross-connection, commutation notching will advance the peakers of the light current branch and thereby provide a feedback effect to balance the branch currents.

The dc bias windings for the peaking transformers on the two generators are connected in a series loop. During inversion this bias current has three components:

(a) A fixed dc current.

(b) A dc current proportional to load current.

(c) A dc current used for synchronization of the generators. Synchronization is accomplished by differential loading of the generators. The bias current is subtractive through the peaking transformers of one generator and additive through the other. The effect of this is to decrease the counter voltage and hence the load on one generator and to increase the counter voltage and load on the other generator.

It is important that the thyratrons used in the ignitor firing circuits perform reliably. The following troubles are encountered with malfunctioning thyratrons in the ignitor circuits: (a) loss of grid control on an ignitor thyratron can result in spurious firing and inverter faults, (b) failure of the ignitor thyratron to conduct throws a double load on the parallel ignitron with possible consequences of arc-backs and inversion arc-throughs, and (c) if the thyratron is subjected to gas clean-up, high voltage surges can occur in the highly inductive firing circuit, and breakdown of insulation follows.

The ignitor thyratron circuit duty is approximately 1300 volts forward, and 900 inverse, with peak current 40 amp and average current 1 amp.

Ignitron Grid Circuits

The IPJ-7 ignitron has two grids, an inner and an outer grid (Fig. 10). The outer grid must conduct reliably with sufficient current to insure that the tube does not extinguish, particularly at light anode currents. Likewise, the inner grid must be positive and conduct for more than 60 degrees to insure that two ignitrons in series will be picked up.

The voltage applied to the outer grid is obtained from the respective generator. This voltage is distorted by commutating notches (Fig. 13). The nominal sine wave form is hardly recognizable during inversion. To improve the voltage for firing the grids, banks of transformers (Fig. 10) were interposed between generators and ignitron grid circuits to introduce a 15° phase shift. Later a bank of transformers giving a 25% boost (from 60 to 75 volts rms at the grids) was installed between the grid transformers and the 15°-phase-shift transformer bank.

After these changes, grid misfires were counted in an effort to determine the relation between grid misses and inverter faults. While an average ignitron grid might misfire from a few to a dozen times per 16-hr shift, misfires were not indicated as the major cause of inverter arc-throughs.

Pictures of inverter faults indicate, however, that some faults start with a forward fire in which an ignitron fails to hold off forward anode voltage before an ignitor pulse is received. If the outer grid is kept negative instead of positive until the ignitor pulse is received the chance of these forward fires may be reduced. This is accomplished by biasing the outer grid at -50 volts and then applying a positive voltage through a thyratron at the time of ignitor firing.

During rectification the firing angle of the ignitron with respect to its anode voltage is fixed. This allows the selection of a single optimum phase for the plate of the controlling thyratron. During inversion however, there is a swing of 45° in inverter firing angle. To keep the instantaneous grid voltage during firing at high level, two thyratrons and two phases are used during inversion.

At the beginning of the magnet pulse, during the first cycles of rectification, arc-backs have been much more frequent than at other times. This greater frequency of arcing back of the ignitrons possibly stems from the following sequence: (a) During rest the ignitron grids are fired at their inversion angle. Consequently the ignitrons are ionized by the grids during a period of negative anode voltage. (b) When rectification is started the ignitrons that are being ionized in this manner are now in a condition to arc-back. Unless precaution is used this condition has been found to produce an average of one arc-back per one-to two-thousand magnet pulses. A method for preventing these arc-backs has been found to be the removal of the inversion firing one or two cycles prior to the beginning of rectification.

"Customer's Rheostat" Relays

Normally the inversion period should be as short as possible. The duration of inversion, however, has a lower limit set by the margin-angle requirements of the converter. It is the purpose of the inverter phase-shift circuits to approach this limit.

The inverter phase-shift circuits use a signal current proportional to magnet current to control the firing angle of the ignitrons. A fraction of this signal current is passed through the bias windings of the inverter phase-shift transformers. The size of the fraction passing through the bias windings is selected by a rheostat mounted by the purchaser of the converter and consequently designated as the "Customer's Rheostat". This bias-winding circuit is highly inductive and introduces a lag in the circuit response. To correct for this lag, "C-R" relays are used to make the signal current more nearly in phase with the magnet current. Thus, firing angle is varied according to magnet current. The end result is that sufficient margin angle can be maintained while the inversion period is reduced.

Figure 17 shows the effect the "C-R" relays have on the signal current and the resultant effect on the converter dc counter voltage.

V. OPERATION AND MONITORING[7]

Requirements of Operation

The purpose of the Bevatron power supply is to provide the Bevatron magnet with a unidirectional triangular wave shape of current. A square wave of voltage applied to the magnet fulfills this requirement. During the positive portion of the voltage, the current should increase exponentially according to the equation

$$i = \frac{E}{R}\left(1 - e^{\frac{-Rt}{L}}\right).$$

The rate of change of magnet current with respect to time increases for currents above 6000 amp because saturation of the magnet iron reduces the inductance. At crest current the voltage on the magnet is reversed and the current decreases to zero. The positive and negative square-wave voltage is obtained from two asynchronous alternators and ignitron converters. The ac voltage of the generators is rectified by ignitrons to cause the current to increase and the ignitrons are fired as inverters to cause the current to decrease. The changeover period of 23 msec from rectification to inversion is done in two steps to minimize the mechanical oscillation of the shafts.

The present operation of the Bevatron requires crest magnet-current values between 2000 and 8490 amp. The repetition rate varies from 4 to 17 pulses per minute because maximum duty is required for any specific operating condition. For instance the repetition rate would be 17 ppm at 4500 amp, 12 ppm at 7200 amp, or 11 ppm at 8490 amp.

A minimum of 1-sec rest time between pulses is required for other electronic components in the Bevatron to function.

Certain ignitron control circuits require generator frequency power. This power is provided by four 30-kva, 3-phase transformers connected to the generator bus, two on each generator. These transformers are equipped with motor-driven tap changers for voltage control. The voltage regulator maintains 270 volts on the secondary by adjusting the generator-terminal voltage. Fused disconnects provide primary protection. There is a 30° phase difference between the two transformers on each generator (Fig. 1b).

Magnet Voltages

The magnet voltage is variable in the following steps:

Excitation-transformer taps	No-load magnet voltage	Generator line-to-line voltage
1	18000	6660
2	17000	6310
3	16000	5940
4	15150	5600
5	14200	5250
6	13500	4980
7	12720	4700
8	12050	4450
9	11350	4190
10	10700	3950
11	10100	3720

There is also a 5% vernier adjustment for each tap.

The magnet voltage must not exceed 16 kv because of the limitations imposed by the magnet cable insulation and corona discharge. The corona discharge is noticeable when the rate of change of magnet voltage is fast at the higher voltages.

The leading edge of the magnet voltage should be identical from pulse to pulse. Because the magnet voltage is derived from two separately controlled 12-phase generators, the phase displacement between the first ignitrons to conduct on each machine is not constant. This changes the configuration of the leading edge of magnet voltage and thus affects the injection of the proton beam 30 msec from the beginning of rectification. Synchronization of the two generators is necessary if this condition is to be eliminated.

The peak-to-peak ripple of the magnet current should not exceed 0.035 amp at 100 amp and should be no more than 2 amp at 8500 amp. The undesirable effect of current ripple is noticeable in the structure of the proton beam.

The magnet current should not exceed 8490 amp, but must be at least 15 msec past 8333 amp. This is necessary because of the experimental physics requirements.

At very small values of magnet current, the converters tend to operate as a 6-phase rather than 12-phase system. This mode of operation is objectionable because of (1) the excessive ripple during injection time and (2) the high transient voltages caused by erratic ignitron conduction. This effect can be minimized by providing a ballast resistor across each ignitron 3-phase unit capable of conducting approximately 10 amp. It is also necessary to maintain a permissive gate signal on the grids of the ignitrons, approximately as long as the anode conduction period. This keeps the ignitron conducting even though the anode current may be too low to maintain a cathode spot.

Inversion Arc-Throughs

Inversion arc-throughs have been the most frequent source of interruptions to magnet pulsing. These faults may be classified according to the manner in which they start. The following types have been noted on the Bevatron converter:

(a) Arc-throughs following an arc-back. The arc-back occurs after conduction stops and at the instant of initial inverse voltage. Figure 11b shows how an ignitron might "lock-in" to this type of faulting. In examining the current transformer traces, allowance should be made for the poor positive current-pulse traces due to the high dc level through the transformer at peak current. This is the most frequent type of arc-through on the Bevatron power supply. At this time the ignitron is subjected to an inverse voltage of 7500 volts with a rise time of 100μsec and a decay of tube current from 2100 amp to zero in 800 μsec. In the spring of 1958, cushioning circuits consisting of a series capacitor and resistor were connected from anode to cathode of each ignitron. To minimize power loss the values of capacitance and resistance are being optimized. Present units are 3 μf and 30 ohms per phase.

This change produced a significant reduction in the fault rate. Commutation reactors were considered instead of the cushioning circuits but the RC network appeared promising and was easier to install.

(b) Arc-throughs starting with a forward-fire. In this case the ignitron does not deionize sufficiently to hold off forward voltage. To assist deionization, close attention is paid to grid circuit operation, and the ignitron temperature is controlled.

In case the grid receives a spurious signal from the control circuits, conduction may start and produce an inversion arc-through. The occurrence of such signals can be prevented by avoiding marginal operation of the grid and ignitor firing circuits as described in their respective sections.

(c) Arc-throughs caused by incomplete commutation. These had been observed to occur quite frequently when a large voltage unbalance appeared between branches of a machine, causing one branch to take full magnet current. Such a condition and its correction is described in the last paragraph under Changeover (p. 12). In Fig. 11a the transductor signal shows that the current through one branch doubles, resulting in incomplete commutation in a pair of ignitrons. One of this pair (Trace 2) continues to arc-through while the other (Trace 3) clears after the first cycle of faulting.

(d) Arc-throughs resulting from failure to fire:

(1) Both parallel ignitrons miss. This misfiring must result in an arc-through on the preceding phase since the current cannot commutate.

(2) A single ignitron of a pair misses. An arc-through could possibly result when this condition persists at heavy currents. Observations, however, indicate that occasional misfires or short periods of misfiring are not likely to produce arc-throughs of the overloaded tube.

The Section entitled Ignitron Grid Circuits indicates the steps taken to evaluate and prevent misfires.

Arc-Backs

The most severe fault to both the generator and the ignitrons is an arc-back (Fig. 18). Occasionally arc-back currents reach values of over 30,000 amp for as long as 14 cycles. The fault starts in one tube but may cause a 3-phase arc-back on one ignitron frame. An arc-back occurs on the average of once every four shifts. After an arc-back it is necessary to wait for 15 minutes for the vacuum system to return to normal so as to minimize any sympathetic faults. Arc-backs are detrimental to the generator windings and shaft. (Refer also to the last paragraph under Ignitron Grid Circuits.)

Magnet-Current Flat Top

For certain physics experiments it is desirable for the magnet current to remain at the crest value for 150 msec. During this period the rate of change of current should be adjustable from 0 to ± 138 amp per sec. In order to reduce the slope of the magnet current, it is necessary to lower the magnet voltage. The magnet voltage is reduced to a small value by inversion firing of half the cubicles, and the precise voltage is controlled by inverter phasing.

The magnet-current ripple should be as low as possible at this time and can be minimized by synchronization of the two generators.

Long Injection Period

A 10-Mev proton beam is normally injected for 500 μsec when the magnet current is 100 amp. For the injection period to be extended it is necessary that the magnet current rise very slowly. It is necessary to avoid large magnet-current ripples; these can be minimized by synchronization of the two generators.

Here, again, control of the ignitron firing can reduce the magnet voltage while synchronization and phasing of the two generators will reduce the ripple voltage.

Pulsing Control System

Two sets of peaking-transformer signals are available to the firing tubes. The larger pulses cause inversion and are available continuously. The smaller signals can be gated on by a bias pedestal which causes rectification, after which the inverter signals again become effective. The bias pedestal is controlled by an electronic chassis called the pulser, which determines the repetition rate and the duration of rectification.[6] The inversion time continues until the magnet current reaches zero.

Because of the speed variations of the motor-generators the contactors that control the secondary resistors of the 3600 horsepower, wound-rotor motors are controlled by the signal from the magnet pulser in order to program the line current.

The bias pedestal is generated by a coincidence between a time base and a generator phase signal. This starts rectification at the same electrical period for each magnet pulse, thereby providing better repeatability in the magnet-voltage wave shape.

Rectification is terminated for each converter separately by synchronized signals referenced to each generator. This allows the changeover of each machine to be independently controlled to provide the correct phase and sequence of ignitron firing. If the sequence of changeover is incorrect, there is a greatly increased tendency for the magnet current in the parallel branches to become unbalanced. Without the synchronized turnoff, the current unbalances 25% of the pulses and increases the fault rate. (See also the last paragraph under Changeover.)

Monitoring the Bevatron Power Supply

Most of the power-supply electrical apparatus is interconnected in such a manner that failure of but one small component can stop magnet pulsing. The power supply has already been pulsed eight million times. The next eight million pulses should occur within a much shorter period (Fig. 19). To accomplish this will require increased maintenance. For some apparatus, such as the high-voltage rectifiers, good preventive maintenance checks have yet to be found.

Because routine maintenance is not yet 100% effective, it is necessary to be prepared to anticipate, locate, and correct troubles as quickly as possible. This requires the use of a comprehensive and reliable monitoring system. The monitoring system in use at present consists of:

(a) Voltage and current monitors:
  (1) High voltage compensated dividers connected phase-to-ground and cathode-to-ground on the ignitrons.
  (2) Isolation transformers for observing ignitron grid voltages.
  (3) Voltage dividers for observing total machine or magnet voltages.
  (4) Current transformers for observing phase currents.
  (5) Movable current transformers for observing individual ignitron anode currents.

(b) Outer grid misfire lights and misfire counters.

(c) Inversion-fault counters which read out on solenoid-operated registers the number of times the associated ignitron started an inversion arc-through.

(d) Arc-back indicators which are magnetically operated flags attached to the bus bars of the ignitron units in such a way that heavy reverse currents cause the flags to indicate which ignitron has arced back.

(e) Beam "plexer" for indicating up to 10 different voltage waveforms and displaying them all simultaneously (in chopped form) on a cathode-ray tube screen.

(f) A Ry-com, multichannel oscilloscope with a 17-inch screen that allows the viewing of twelve waveforms. Attached to this oscilloscope is a hood and 35-mm camera with its shutter released to catch transient phenomena on the long persistence screen.

(g) An Ampex, two-channel tape recorder which can be put into service very quickly to record transient phenomena.

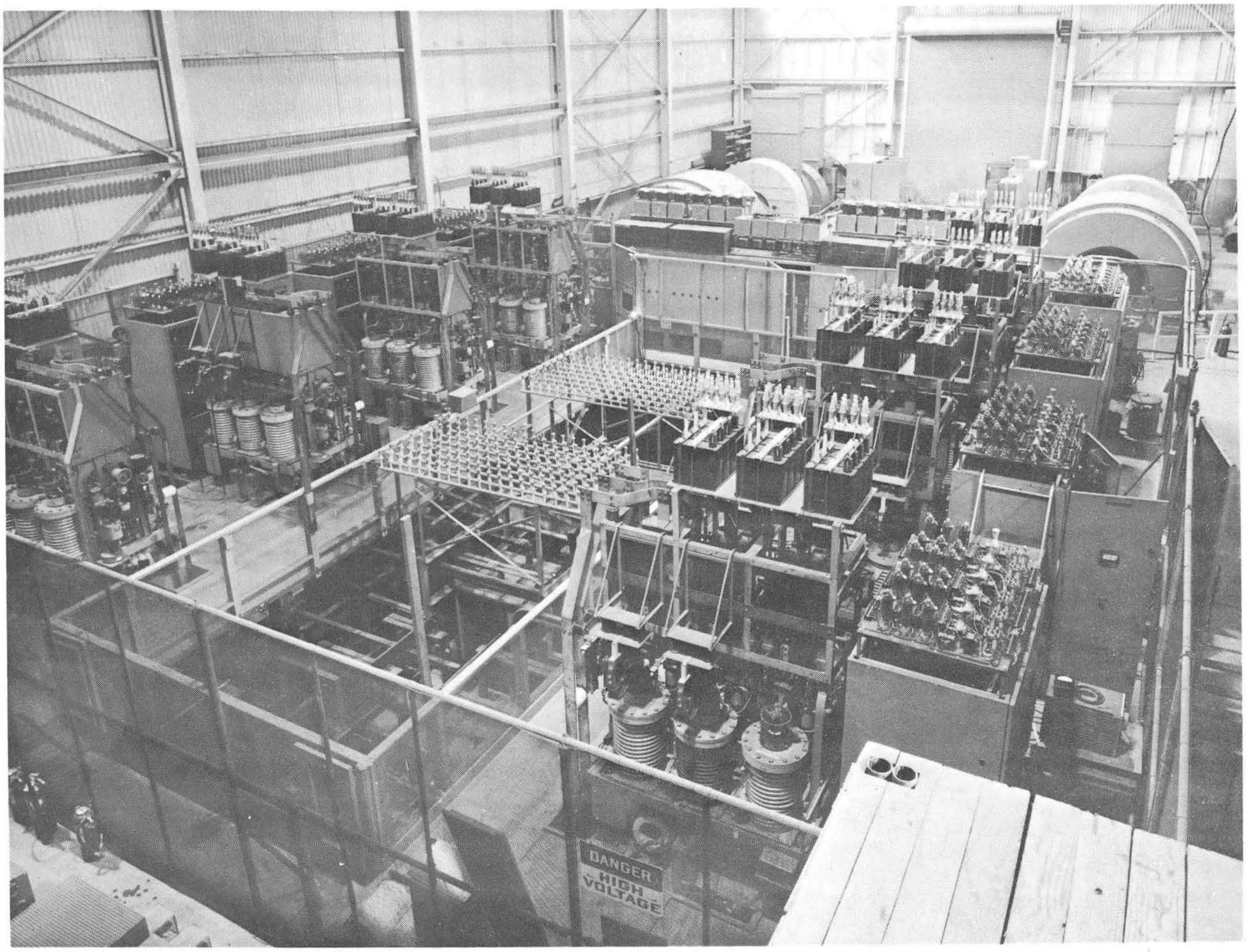
Besides providing help on troubles of immediate concern, these monitors have furnished much information as to the nature of the ignitron faults of this power supply. Changes based on this information are at least partially responsible for the increased number of pulses per year.

Figure 19 indicates the increasing number of pulses per year produced by the Bevatron. This increase reflects both the longer operating hours and the improvements in the over-all accelerator. From the standpoint of the power supply the most frequent and elusive trouble, the inversion arc-through, has been greatly reduced. This is indicated by the number of pulses per fault, which has increased from about 1000 to 7000 during the past year. There now remains the task of making these standard power-supply components withstand up to five million pulses per year.

ACKNOWLEDGMENTS

The authors are indebted to Dr. Edward Lofgren, who is in charge of the Bevatron, for his consistent interest and assistance in correcting the problems of the Bevatron power supply. The authors also wish to express their appreciation to George Farly of the Electronics Engineering Department for his assistance and encouragement in preparing this report.

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



ZN-2086

Fig. 1a. Bevatron power supply: view from south end.

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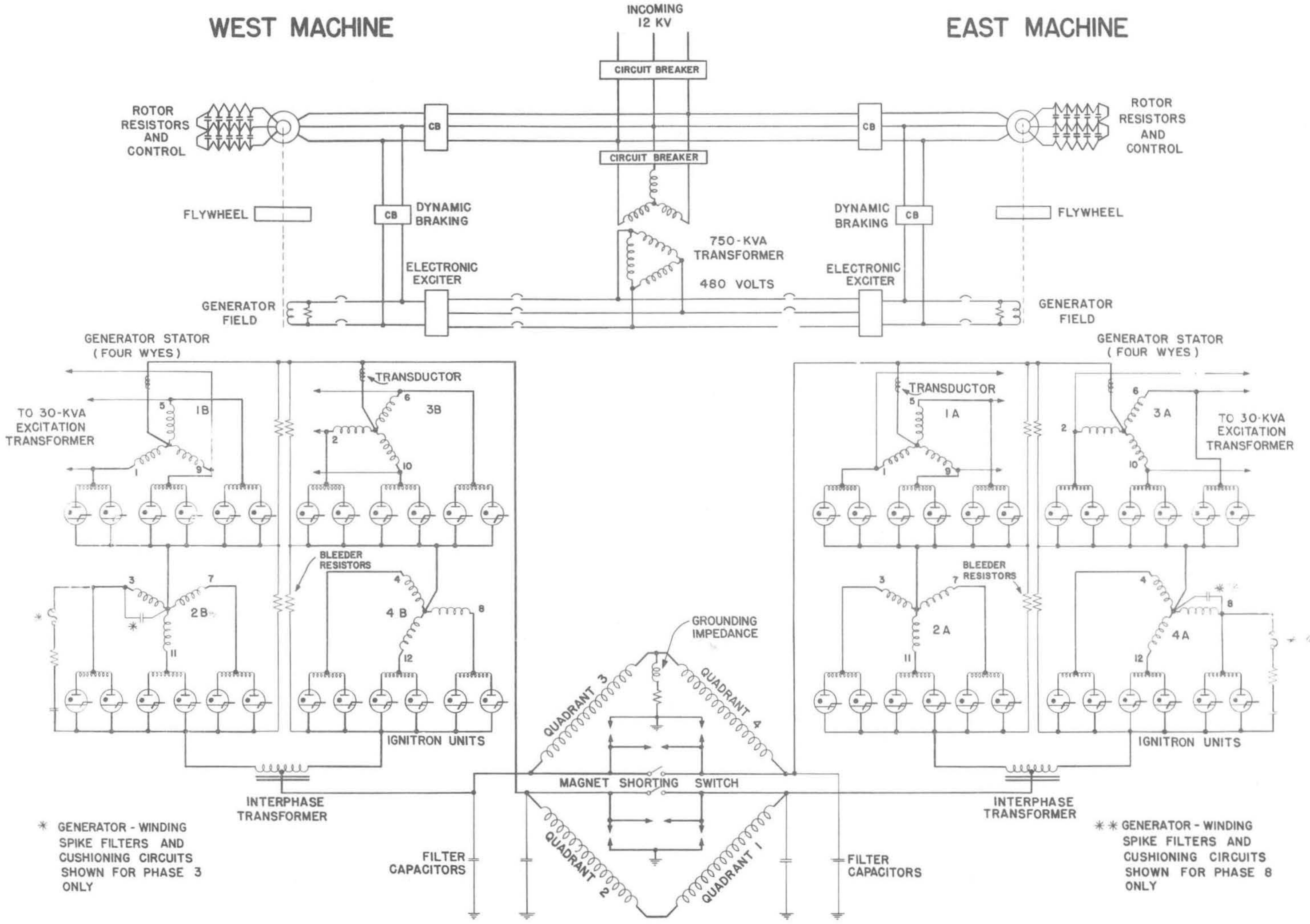


MUB-257

Fig. 1b. Bevatron power supply and magnet: simplified diagram.

WEIGHTS	POUNDS
MOTOR ROTOR	13200
MOTOR STATOR	21900
GEN. ROTOR	98750
GEN. STATOR	116560
FLYWHEEL	134900
TOTAL ALL COMPONENTS	504000

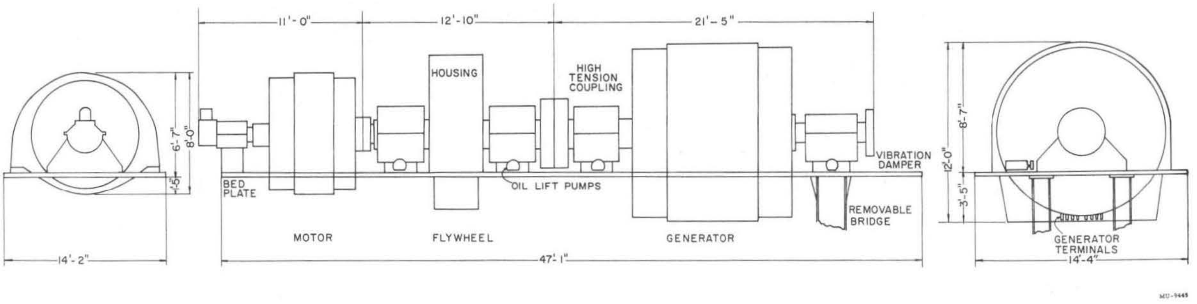
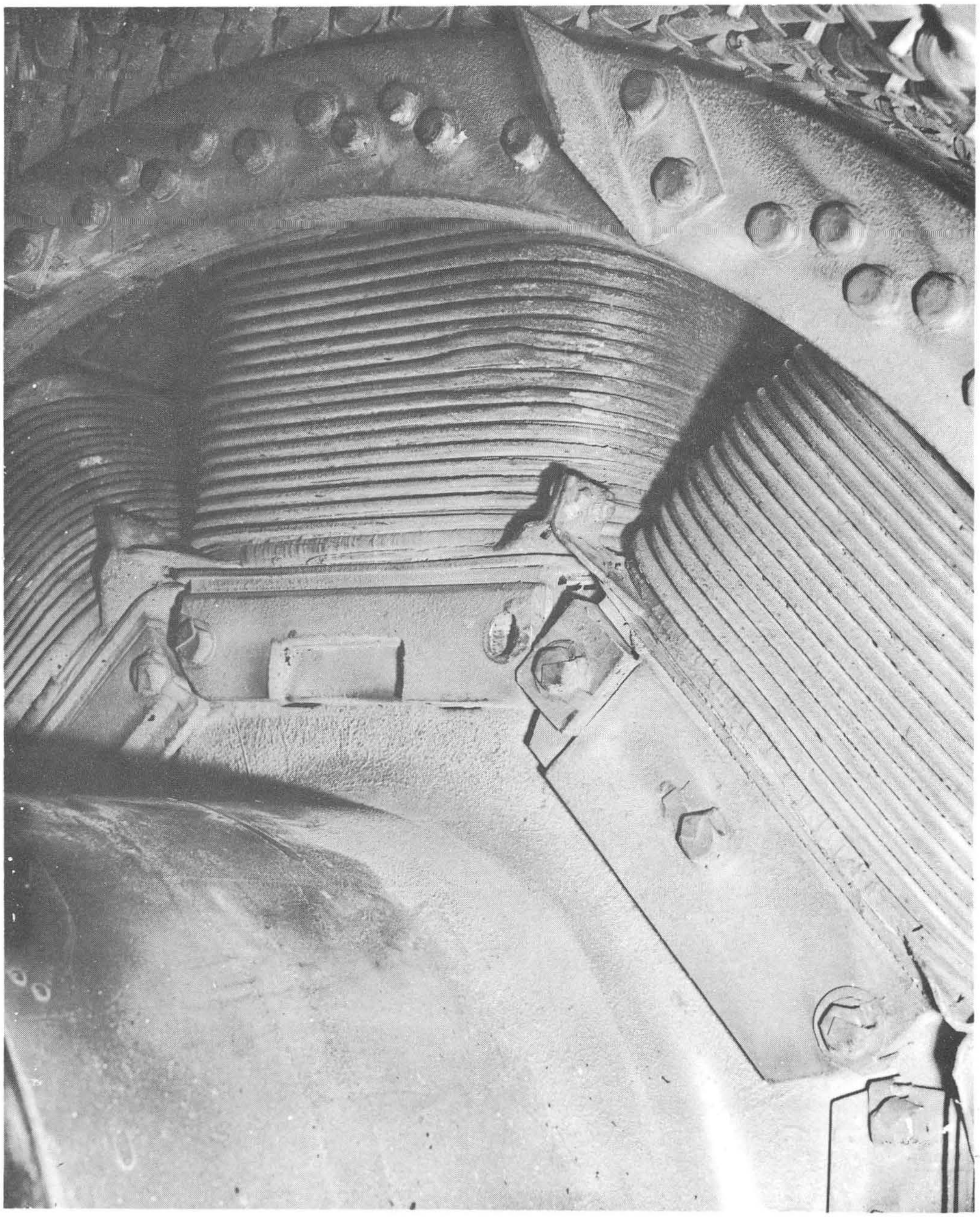
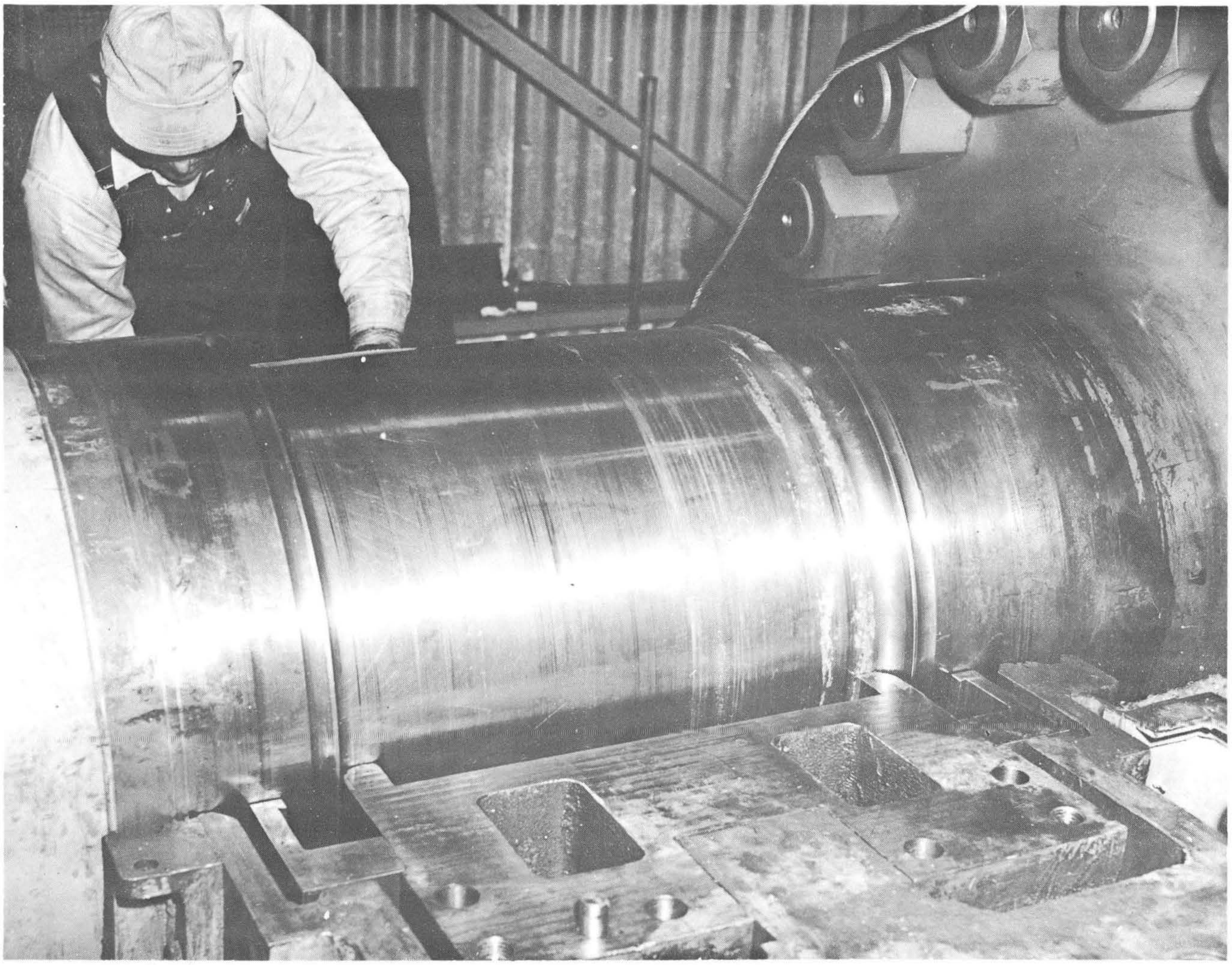


Fig. 2. Entire motor-generator set.



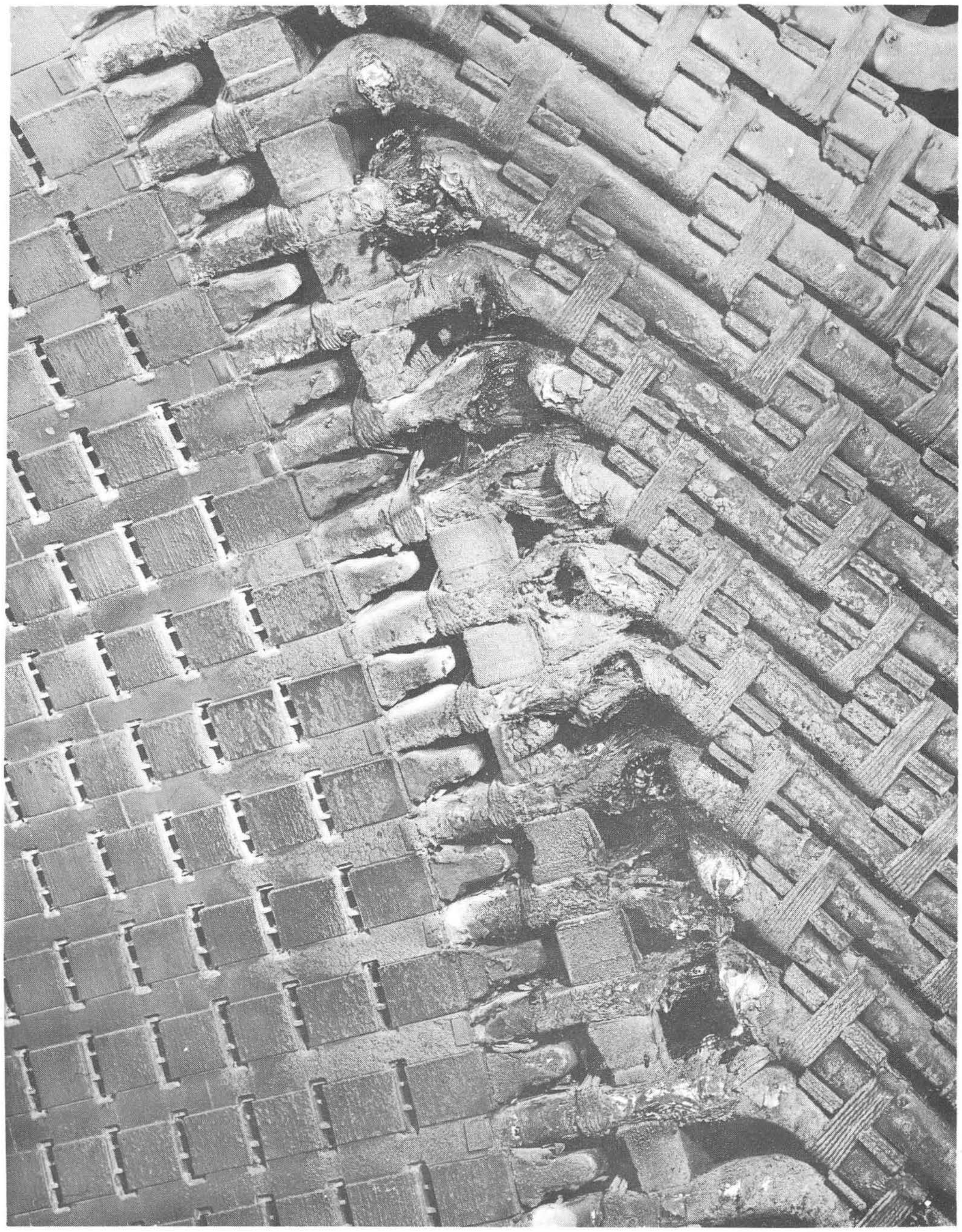
ZN-1992

Fig. 3a. Power-supply damage: broken bolt on generator rotor.



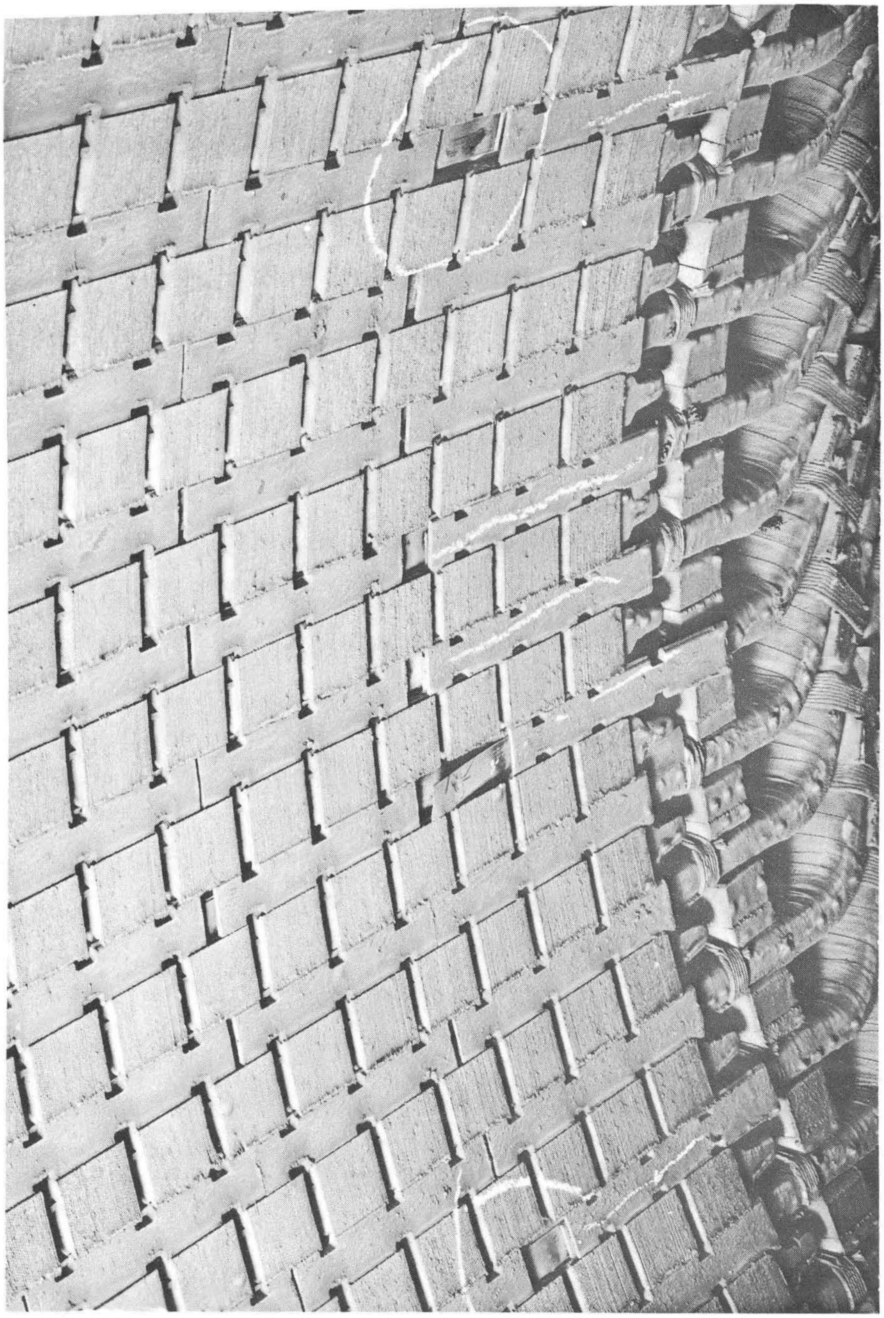
ZN-1993

Fig. 3b. Power-supply damage: damage to generator journal from short-circuit currents caused by broken bolt.



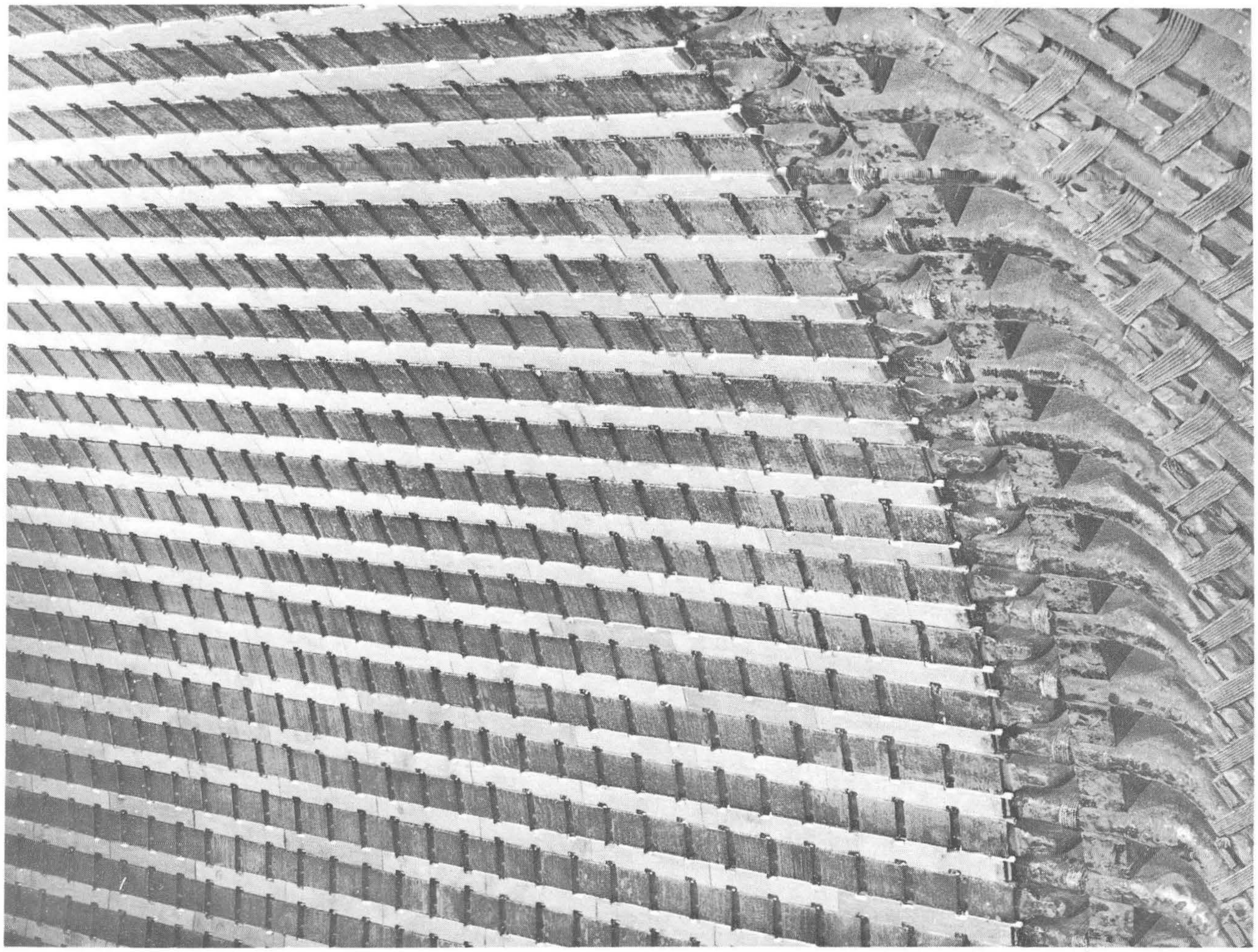
ZN-1994

Fig. 4. Generator stator damage.



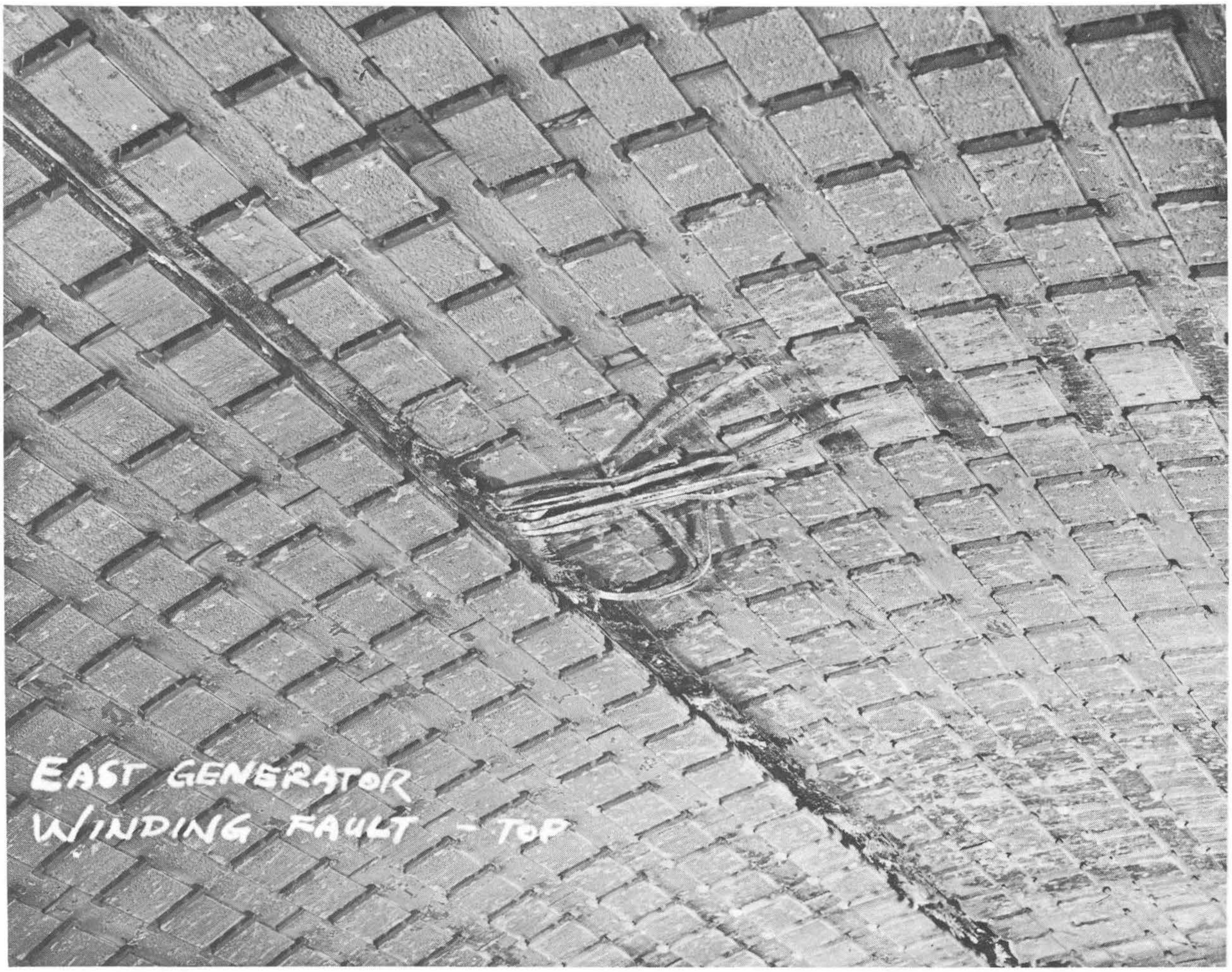
ZN-1995

Fig. 5a. Generator stator: wedge movement.



ZN-1996

Fig. 5b. Generator stator: new stator wedge locks.

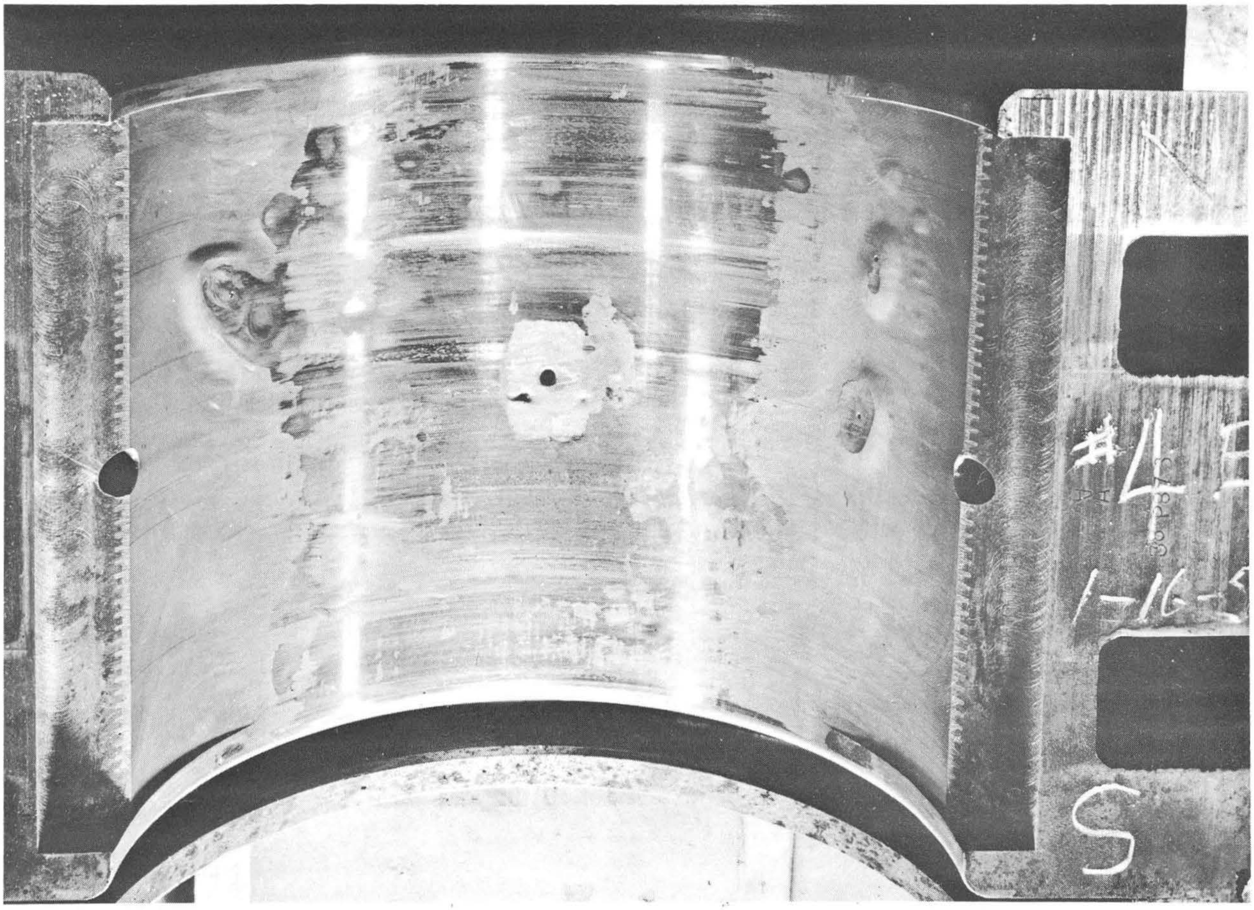


ZN-1997

Fig. 6. Coil turns protruding from generator stator.

ZN-1998

Fig. 7. Coil knuckle damage in generator stator.



ZN-1999

Fig. 8. Hydrogen blisters on lower half of generator bearing.

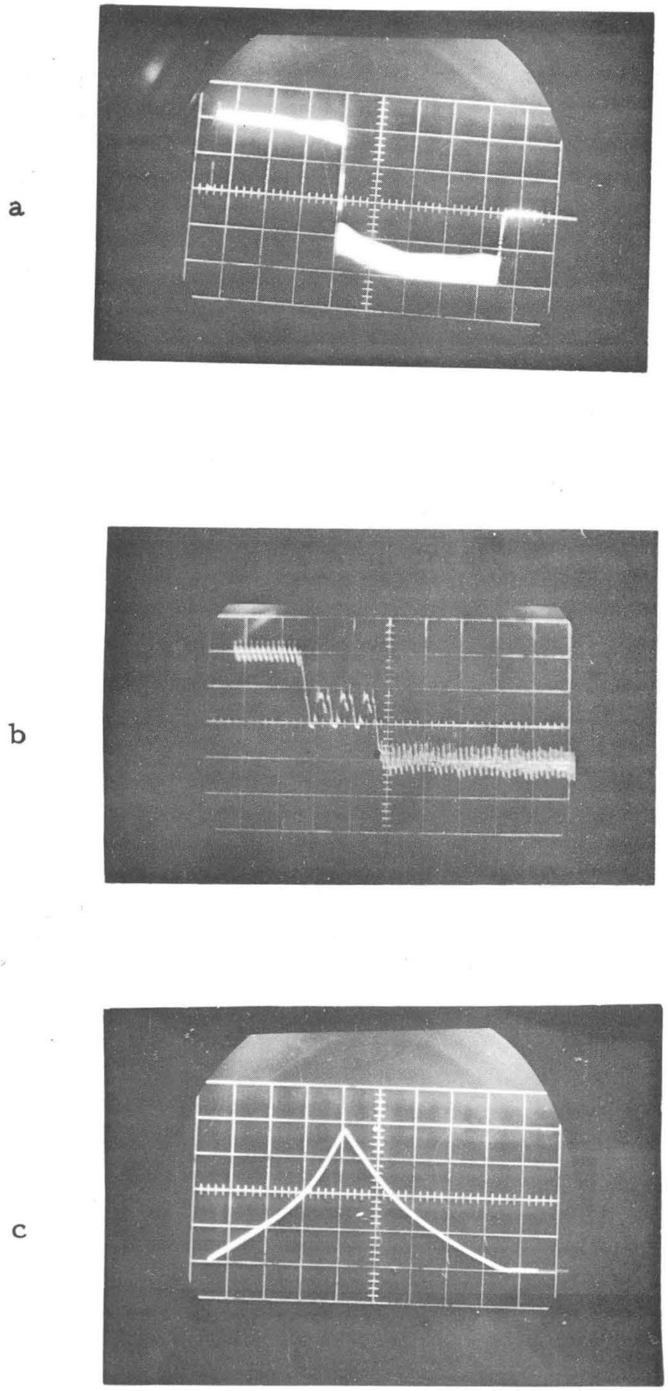
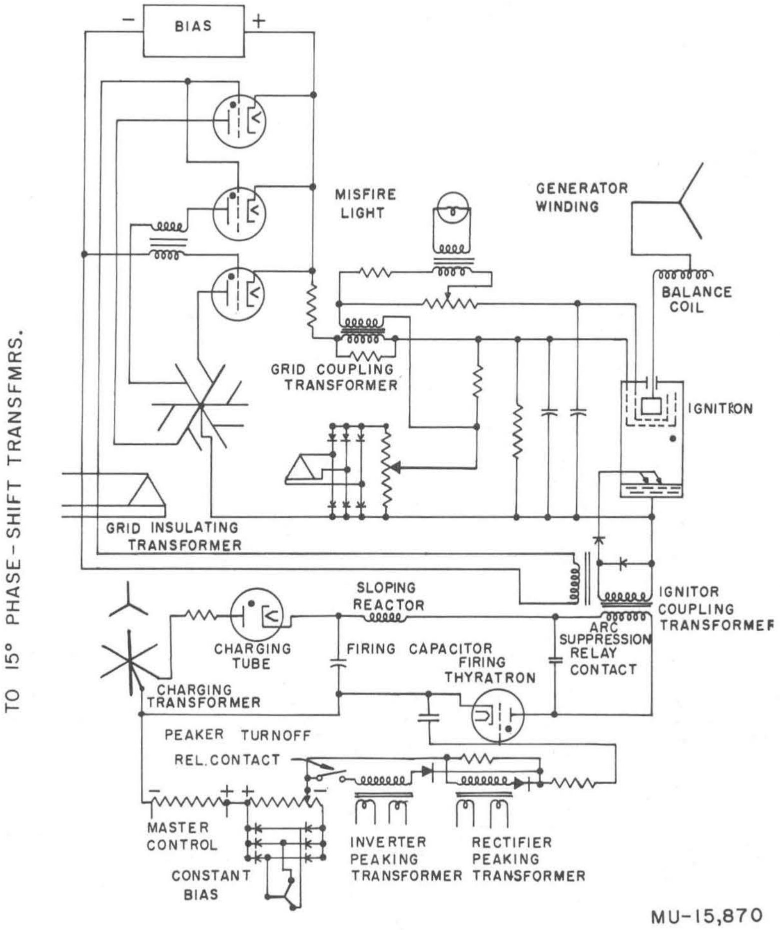


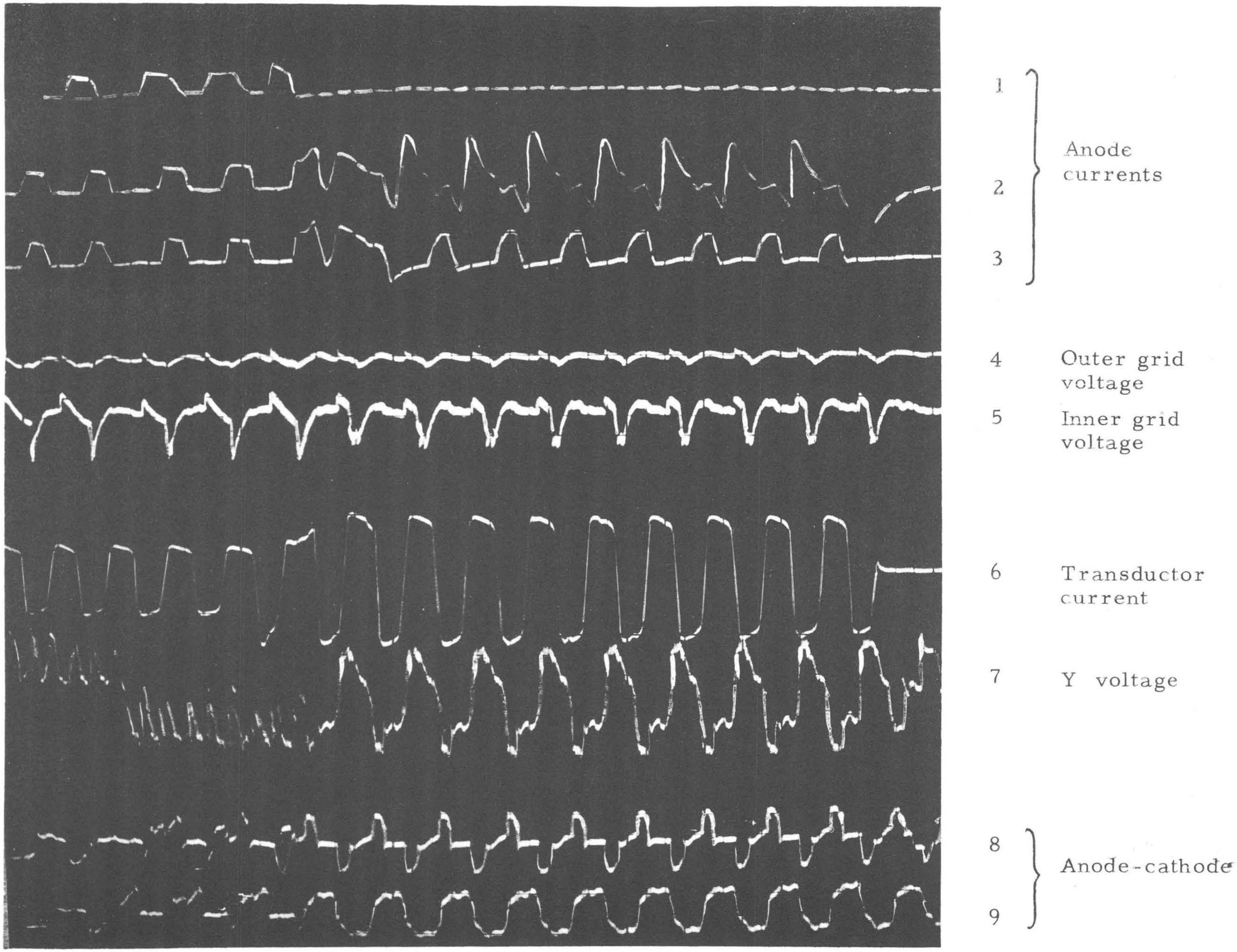
Fig. 9. Single pulse of Bevatron magnet, showing voltage and current wave shapes: (a) magnet voltage during rectification and inversion; (b) magnet voltage at change-over; (c) magnet current--8400 amp crest.

ZN-2087



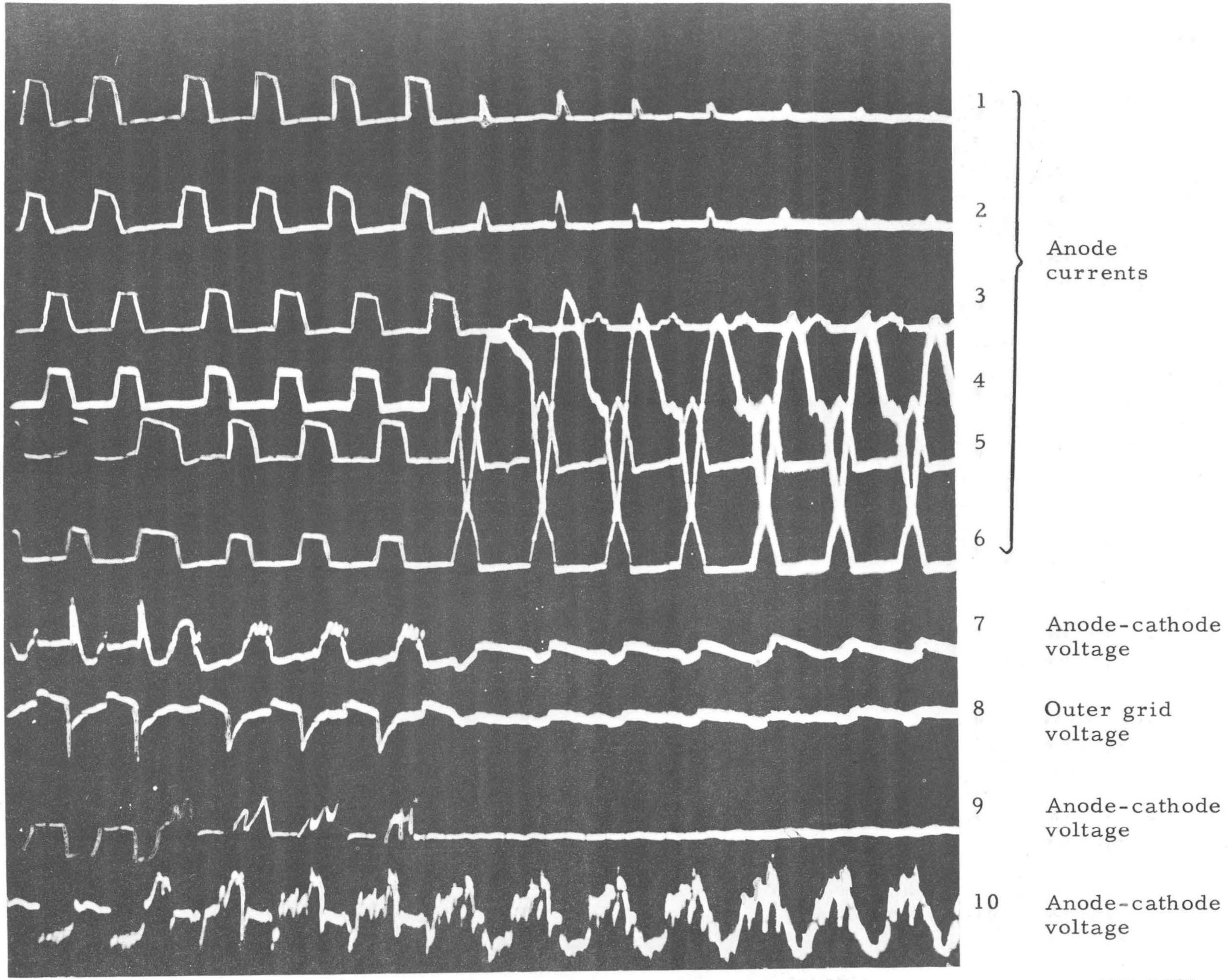
MU-15,870

Fig. 10. Bevatron ignitron converter-excitation circuits.



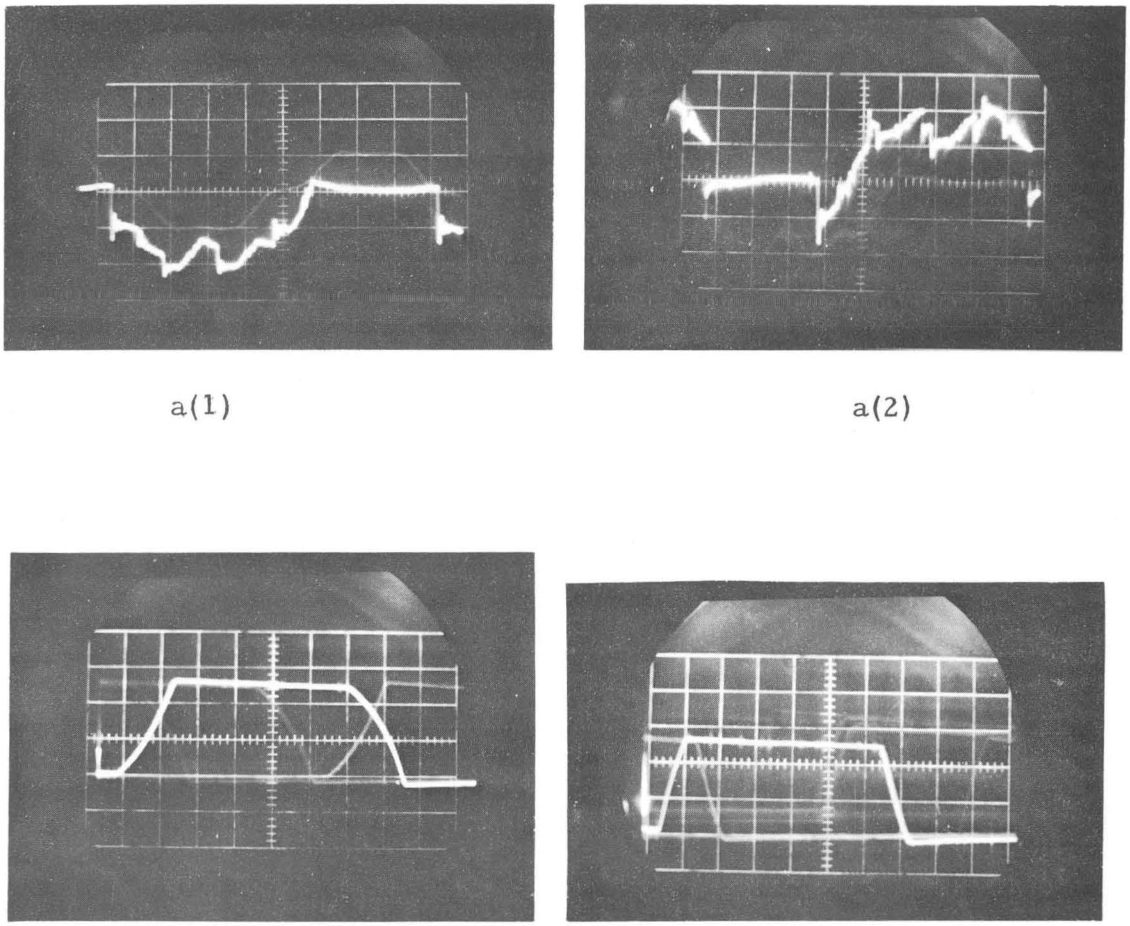
ZN-2088

Fig. 11a. Inversion faults: following current flip.



ZN-2089

Fig. 11b. Inversion faults: on anode 4, starting with inversion arc-back.

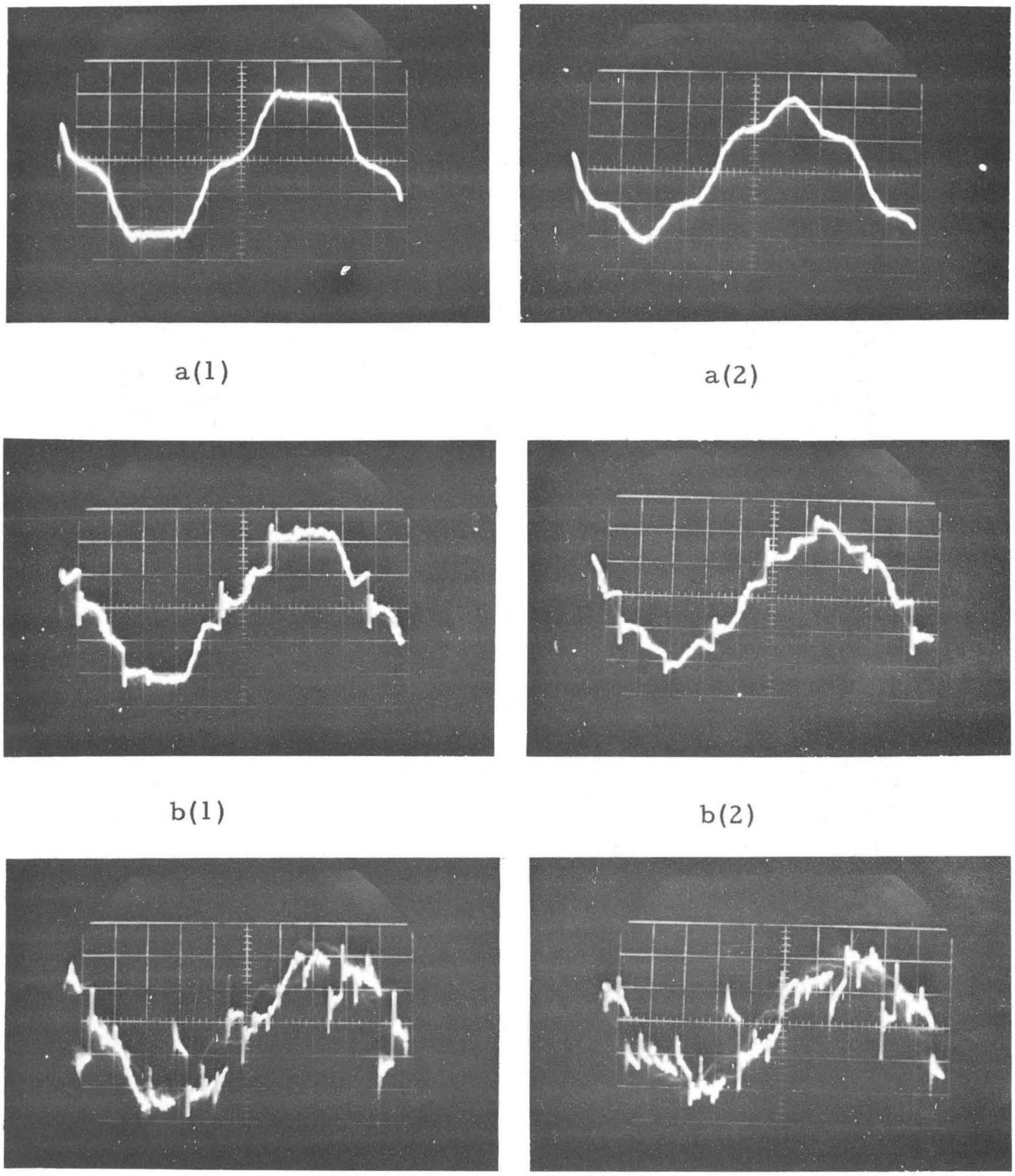


a(1) a(2)

b(1) b(2)

Fig. 12. Ignitron wave shapes: (a) ignitron anode-to-cathode voltages--(1) rectifying, (2) inverting; (b) ignitron anode current--(1) rectifying, (2) inverting.

ZN-2090



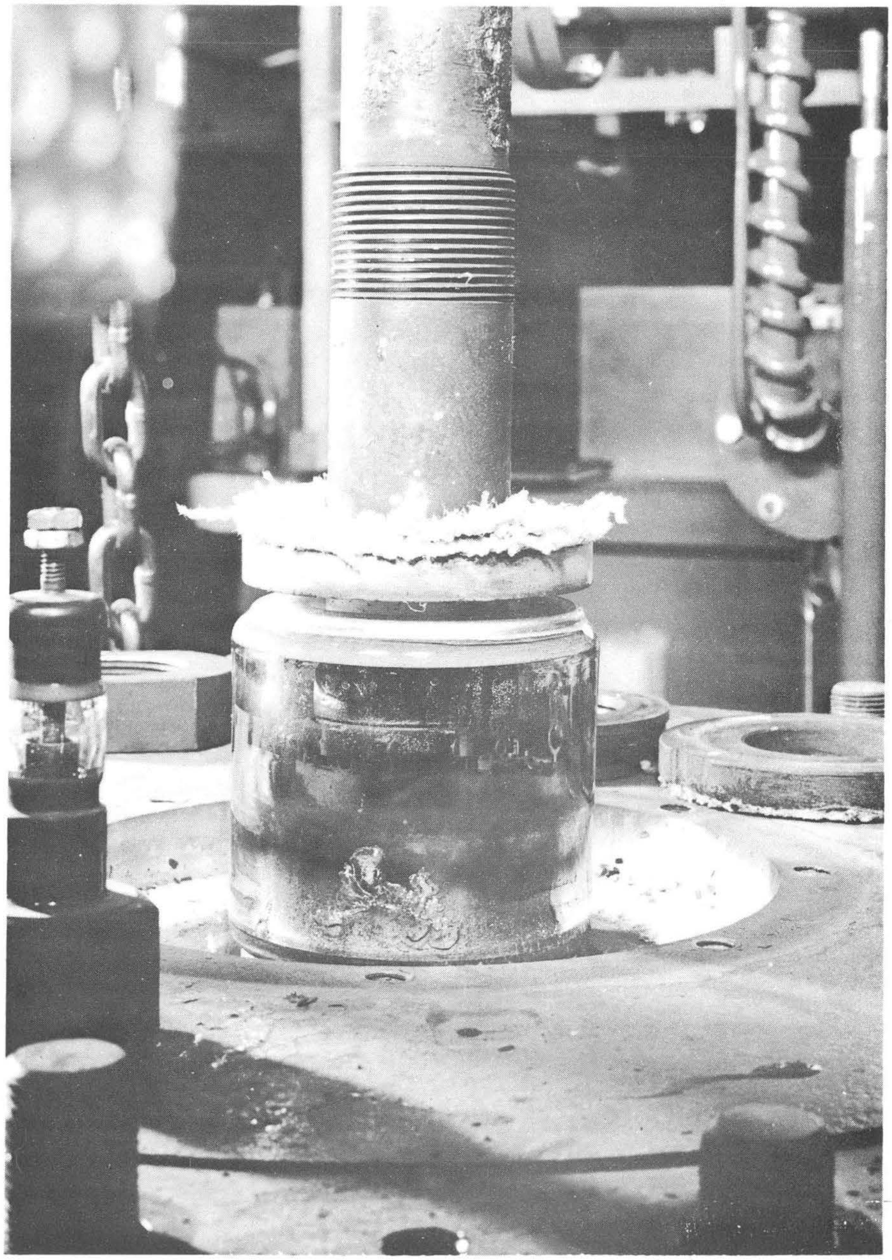
a(1)　a(2)

b(1)　b(2)

c(1)　c(2)

Fig. 13. Generator voltages: (a) no load--(1) phase to neutral, (2) phase to phase; (b) rectification--(1) phase to neutral, (2) phase to phase; (c) inversion--(1) phase to neutral, (2) phase to phase.

ZN-2091

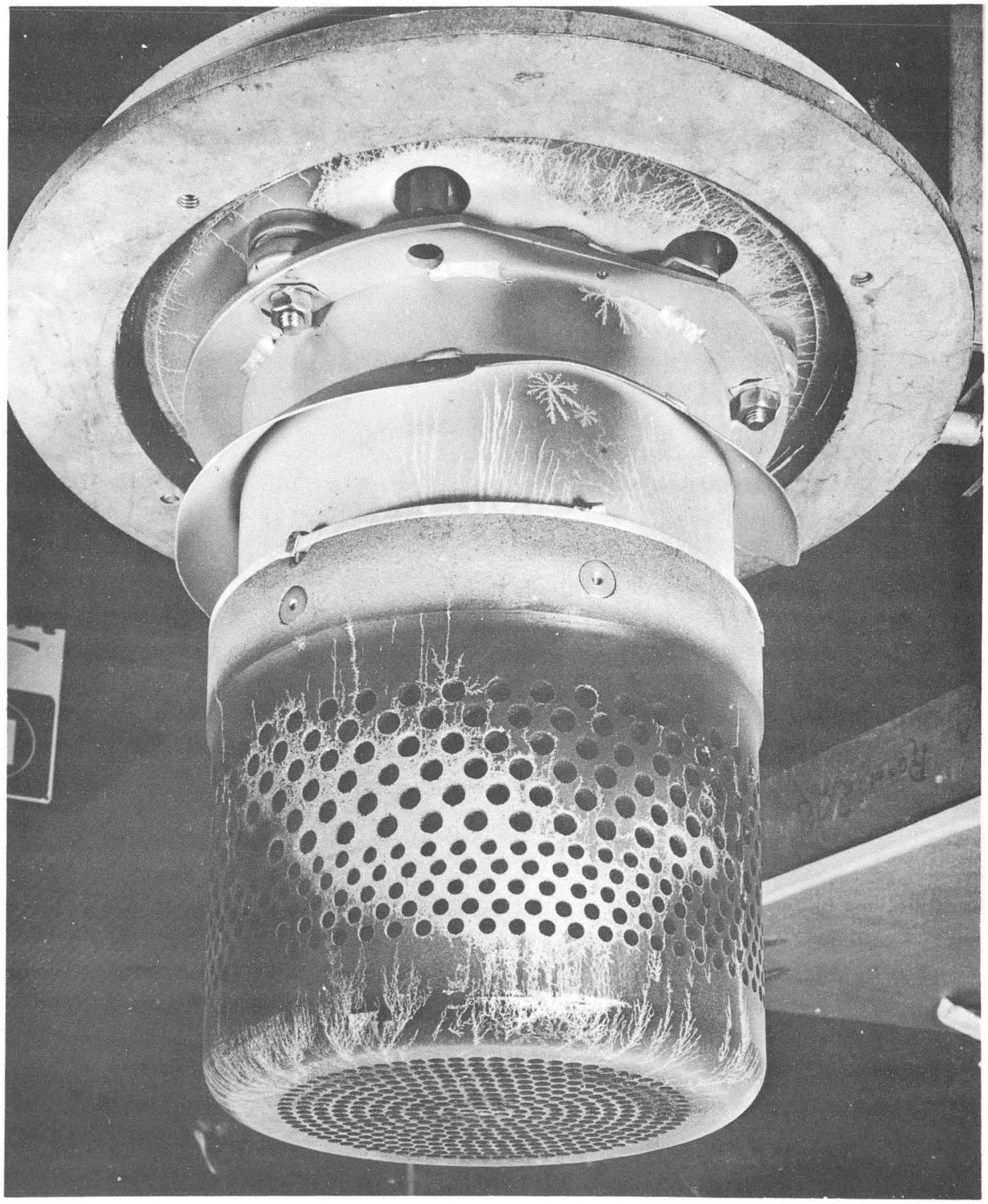


ZN-2000

Fig. 14a. Ignitron anode-stem insulator: spalling and plating of glass anode bushing--grid bushing to left of anode bushing.

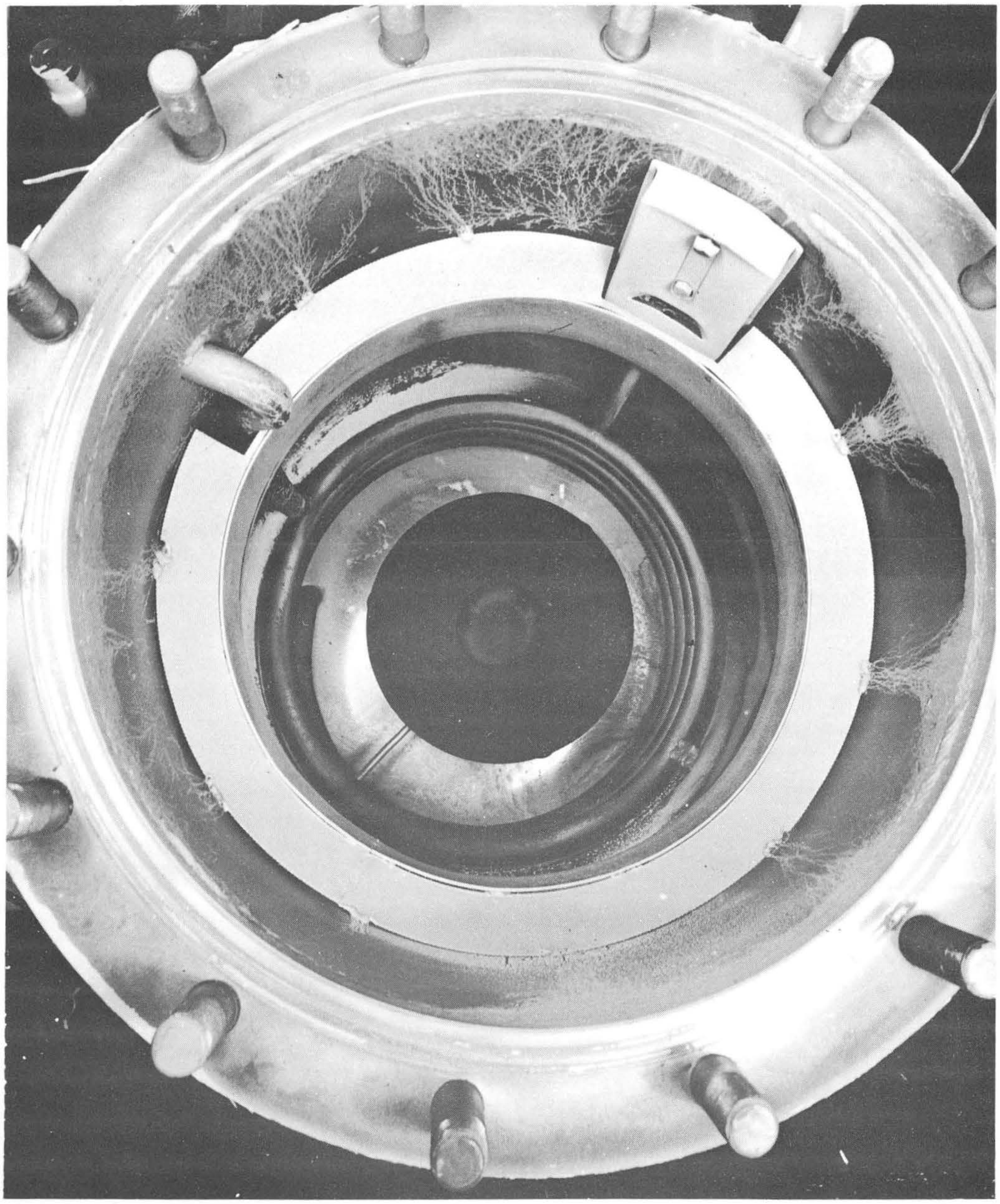
ZN-2001

Fig. 14b. Ignitron anode-stem insulator: arc tracks on anode stem and shield.



ZN-2002

Fig. 15a. Interior parts of ignitron: outer graphite grid.



ZN-2003

Fig. 15b. Interior parts of ignitron: ignitron tank, showing cooling coils and blast bubble at center and vacuum connection at upper right.

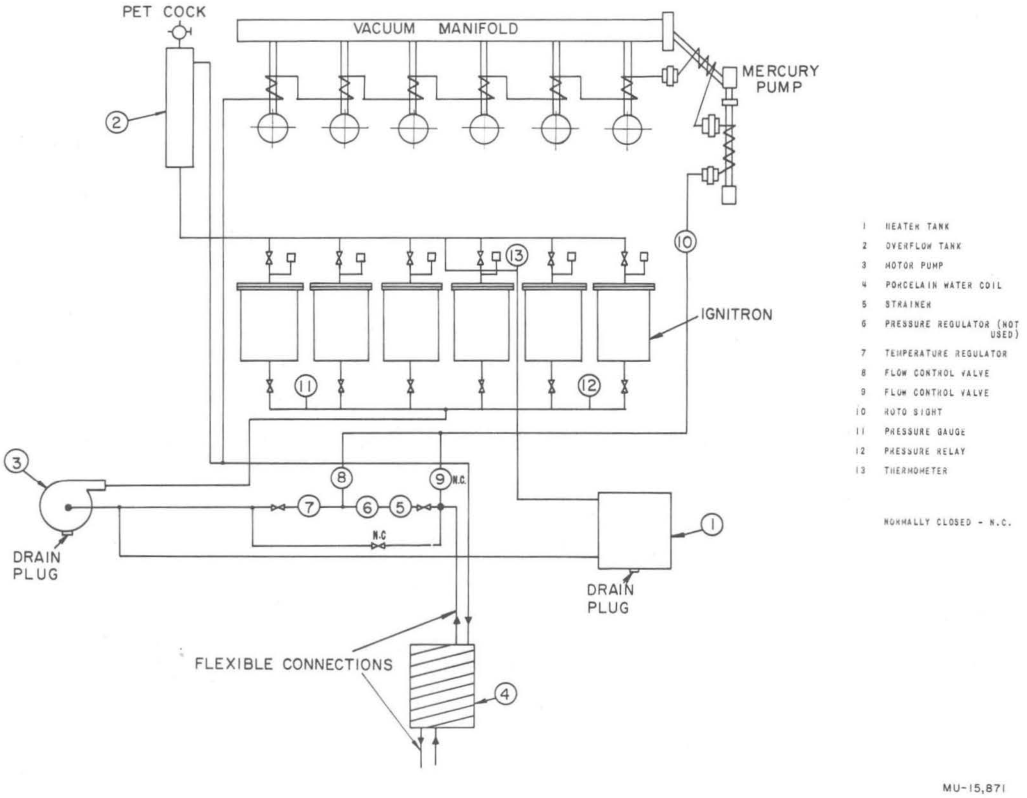
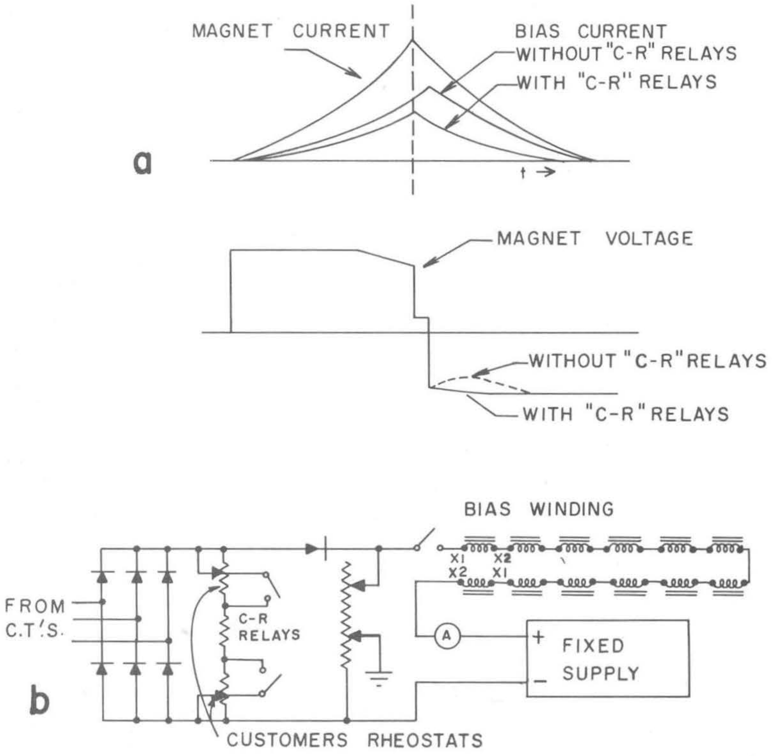
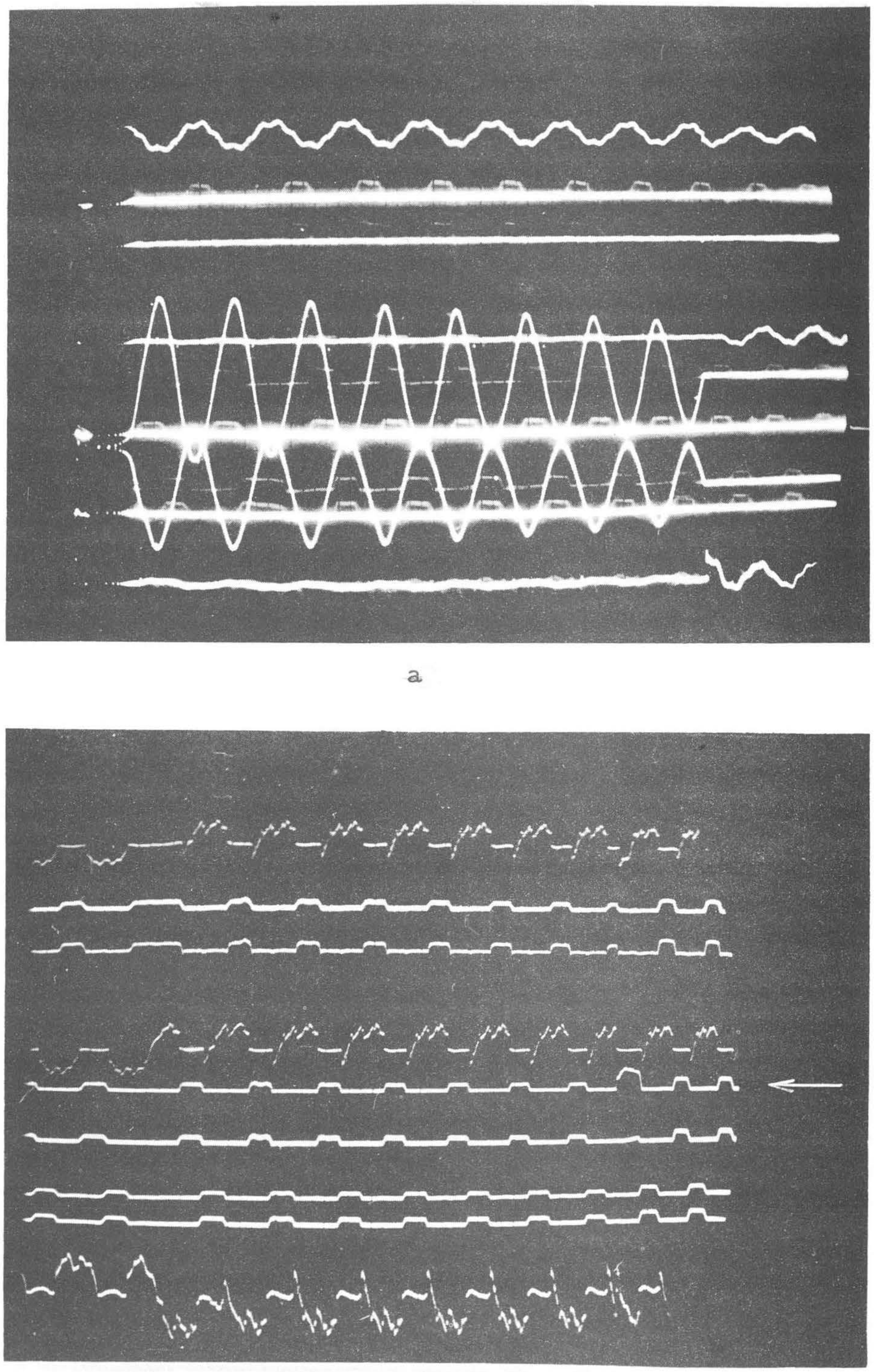


Fig. 16. Ignitron-stand cooling system.



MU-15,869

Fig. 17. Customer's rheostat: (a) effects of c-r relays on current and voltage; (b) schematic of c-r rheostat and relays circuit.



a

note one-cycle arc-through

b

ZN-2092

Fig. 18. Arc-back involving two phases: (a) arc-back pulse; (b) first pulse following arc back.

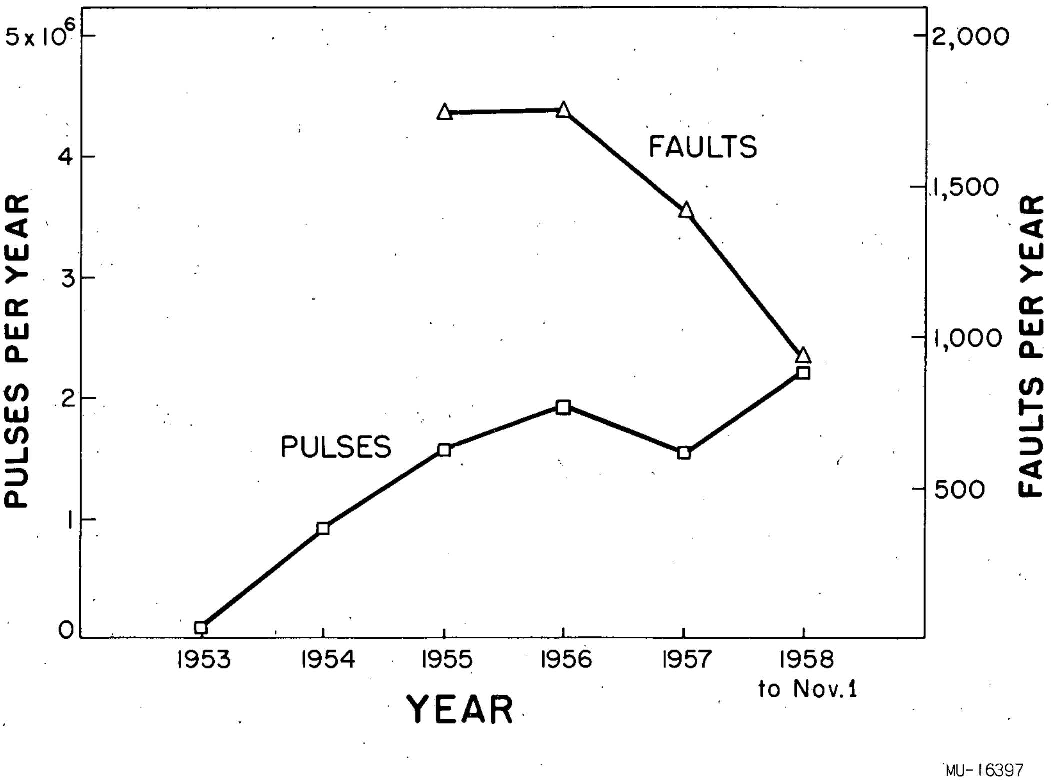


Fig. 19. Bevatron pulses and faults by year.

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