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HIGH-POWER WATER BOILER

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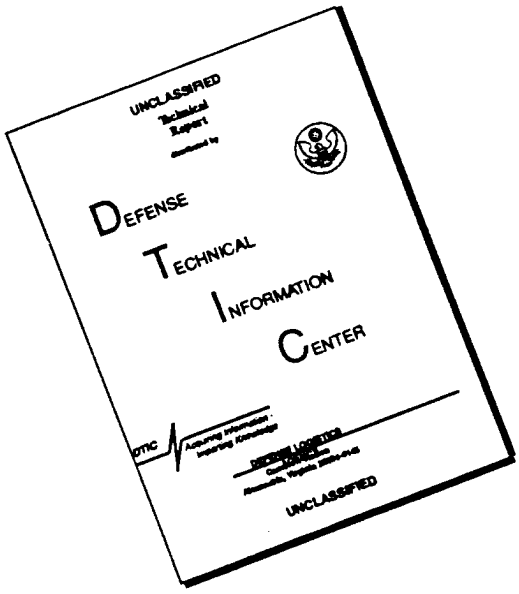

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ABSTRACT

A detailed description of the design and construction of a 5.5-kw water boiler at site Y is given. A 14 per cent enriched uranyl nitrate solution in water is used as the reactor and moderator. The 13.5 liters of solution, containing 870 g of 25*, is held in a 1-ft-diam stainless-steel sphere. The tamper consists of a BeO core surrounded by graphite. A thermal column is connected to one side of the tamper. The operation and performance of the boiler are described.

DESIGN CONSIDERATIONS

General Description

The high-power water boiler or "hypo" is a self-sustaining pile using an enriched uranyl nitrate solution or "soup" in a composite beryllium oxide and graphite tamper. Its primary purpose and use is as a strong source of neutrons which, by use of a graphite thermalizing column, can provide a high flux of slow neutrons.

Plans for a power boiler were first drawn up in the summer of 1943 by D. W. Kerst and his associates, but these plans were put aside in favor of a low-power boiler, or "lopo," which was built and used for the first integral experiments with enriched material during the spring and summer of 1944. A description of this work is given in Report LADC-819. Experience gained with the low-power boiler and experiments made on the effect of added absorbers, changes in tamper material and structure, etc., proved to be very useful in redesigning the high-power boiler. Plans for the hypo were revived and extensively modified in the fall of 1944, and the hypo first ran at power in December.

A power of about 1 kw was selected as a basis for the final design. This power, because of the small size of the reactor, was estimated to give a flux of approximately 3×10^{10} neutrons/sec/cm^2 in the neighborhood of the reactor and of about 10^9 at the inner end of the thermal column, which was adequate for most experiments. A power much higher than 1 kw was not

*Throughout this report, the numbers 25 and 49 are used as abbreviations for U^{235} and Pu^{239}, respectively.

considered feasible for several reasons. The problem of extracting heat from a 12-in. sphere at the rate of, for example, 100 kw appeared rather difficult, and at such a power the tamper and control rods would probably require artificial cooling. In addition, an evolution of hydrogen and oxygen gases formed by ionization from the fission-fragment recoils at a rate of about 2 cc/sec/kw was expected; so there was a strong possibility of the solution frothing at high power.

Experiments made on the low-power boiler with various tampers and measurements of the effects due to the introduction of additional pipes and sheets of stainless steel permitted a rather accurate estimate of the mass of 25 required for the hypo.

The differences in the construction of the hypo and lopo were (1) change from uranyl sulfate to uranyl nitrate, required to permit ether extraction of the fission fragments, (2) elimination of the hydrostatic control system and storage reservoir for the soup, (3) installation of two additional shim rods, (4) introduction of a horizontal 1-in. pipe or "glory hole" through the sphere to permit access to the highest possible neutron flux, (5) introduction of water-cooling and air-flushing systems, (6) construction of gamma-ray and neutron shields, and (7) addition of a graphite thermalizing column.

The two most important simplifications made in the original high-power boiler design were the elimination of the soup-handling system and the substitution of a simple cadmium-lead-concrete shield for the more complex shield needed for high-power reactors.

The hypo is located in a 30- by 50-ft room and is placed in such a way that neutrons both from the thermal column and from ports leading to the reactor have unobstructed paths for at least 30 ft, thus permitting experiments with collimated beams of either slow or fast neutrons (see Figs. 1 and 2). The other major item of construction was the erection of a fractionating tower and a small chemical laboratory to be used for removal of fission fragments from the soup. This decontamination laboratory is located in a separate building about 100 ft from the hypo. An underground stainless-steel conduit was installed to carry the soup from the hypo to this apparatus.

Control of the reactivity is achieved by means of four rods (Fig. 9), three of which are actuated by safety devices and drop in automatically if the neutron flux exceeds a specified level. The flux is detected by means of ionization chambers located in the tamper, in the shield immediately above it, and in the thermal column.

The hypo is operated from a control station in an adjoining room. The power of the pile may be either controlled manually or held at a specific level by means of an automatic pilot using a modified amplidyne circuit. An accurate indication of the power is given by a sensitive galvanometer connected as a null instrument to an ionization chamber. The power is also continuously recorded on an Esterline-Angus meter and by a calibrated pulse-amplifier-scaler system.

The level of the solution in the sphere, its temperature, the rate of flow of cooling water and flushing air, the position of the various control rods, and similar pertinent information are given at the control station by means of appropriate indicating instruments.

The design of the water boiler, given in detail in later sections, is not considered by the authors to be the final or best construction for a small generator of high neutron flux. It is hoped, however, that it may constitute useful information for future work.

Some changes have recently been made in the boiler because of the unexpected formation of a precipitate after about 1100 kw hr of very satisfactory operation. Tests are in progress to determine the cause and to eliminate future precipitation. Other boiler solutions are under consideration. Any changes or improvements will appear in later publications.

Calculation of M_c from Lopo Observations

A number of experiments were done with the low-power boiler to give information regarding the increase in the amount of 25 required to operate the high-power boiler. Since the total amount of 25 available for the hypo was limited, it was necessary to keep this increase as small as possible.

The lopo tamper was made entirely of BeO bricks. There were two reasons for wishing to replace this tamper with another material in constructing the hypo: (1) A number of the BeO bricks were needed elsewhere, and (2) the gamma-neutron reaction between the fission gamma rays in the solution and the beryllium in the tamper provided a driving source of an intensity dependent on past running history, which was undesirable, particularly if sensitive critical measurements were to be made.

Several tamper combinations were tried with the lopo. A graphite tamper gave a critical mass of 760 g, an increase of nearly 200 g over the BeO tamper. Tuballoy slugs placed in a lattice around the sphere in the graphite did not help appreciably. A graphite core backed with BeO bricks was also very poor. This scheme was tried as a mock-up of a bismuth-core BeO-shell tamper in which the bismuth would act as a gamma-ray shield between the sphere and the BeO. Finally, a thin BeO core and a graphite shell were assembled, and this combination gave a critical mass essentially the same as the complete BeO tamper and was adopted for hypo use. This tamper did not eliminate the gamma-neutron reaction.

The effect of introducing a stainless-steel cooling pipe was measured by placing a short section of the pipe in the sphere and observing the change in control-rod setting necessary to hold the boiler at critical. A similar experiment determined the effect of a glory hole through the sphere. It was planned to increase the wall thickness of the sphere from 0.030 to 0.060 in. The effect of this change was estimated by fitting a spare hemispherical spinning around the existing sphere. In all these measurements it was assumed that the effects were additive, that a measurement could be made on a small absorber, and that this result could be extrapolated to predict the effect of an absorber several times as large. These assumptions are not entirely correct, but the results proved to have sufficient accuracy to be very useful.

The estimates of increased mass for each of the above items were

Thicker sphere	20 g
Cooling pipes	80 g
Glory hole	30 g
Total	130 g

A final consideration was an estimate of the allowance to be made for temperature rise in the solution and for excess reactivity to allow the introduction of absorbers into or near the sphere. A negative temperature coefficient of about 0.75 g of 25 per degree Centigrade had been measured on the lopo. Of this amount, about 0.2 g was due to the displacement of 25 from the sphere by the expansion of the solution. In the case of the hypo, this effect would not exist, since as it was planned to leave a free space above the solution to allow for expansion and for escape of gas bubbles. The remainder of the coefficient is largely due to the increased mean free paths for the neutrons with increasing temperature. The effect, expressed in terms of grams of 25, was expected to be roughly proportional to the total mass of 25, so a coefficient of about 0.9 g/°C was expected. The actual coefficient proved to be 1.33 g/°C. A total allowance of 60 g of 25 excess was taken to be sufficient for normal operation. The possibility of borrowing foils or slugs of 25 and inserting them in the tamper near the boiler as boosters for special experiments was thought feasible.

A conversion of the uranyl sulfate to uranyl nitrate was considered necessary because of the problem of removing the fission fragments. The ether-extraction process for the nitrate was a well-known procedure, but a corresponding process for the sulfate had not been developed, and it did not appear feasible to initiate a major research project on this problem. When the thermal cross sections were taken to be of 0.5 barn for sulfur and 1.75 barns for nitrogen, a comparison of uranyl sulfate and uranyl nitrate soups indicated that a decrease of reactivity of about 3.4 per cent was to be expected. Experiments with the lopo established the relation that 1 per cent in K was equivalent to 20 g of 25, so this would indicate that the conversion from the sulfate to the nitrate would cost approximately 70 g. This amount was at first underestimated by a factor of 2, since at that time it was thought that 1 per cent in K was equivalent to 11 g in the lopo.

The changes in the solution and the structure of the sphere thus add up to 200 g, making the estimate of the new critical mass 765 g. The actual critical mass would have been about 773 g had there been enough material with 14.6 per cent enrichment. The estimates described above thus proved to be quite accurate. The available material of this enrichment amounted to 767 g, and an additional 102 g of 25 procured was only of 10.8 per cent enrichment; so after mixing to a concentration of 14 per cent, the final critical mass was 806 g.

Decontamination of Active Boiler Solution

The chemical method chosen for decontamination is ether extraction. This process depends on the possibility of obtaining a favorable distribution of UNH (uranyl nitrate hexahydrate) between water nearly saturated with a soluble nitrate and diethyl ether. It has the advantage over other methods in that it is a simple continuous process, comparatively easy to carry out by remote control. The latter consideration is very important from the operator's standpoint, since there will probably be several hundred curies of γ activity in the boiler when decontamination becomes necessary. It was originally thought that this situation would arise after a few months of operation, but after 1000 hr of operation, no decontamination has been needed.

The practical distribution coefficient

$$D \equiv \frac{\text{concentration of UNH in ether phase}}{\text{concentration of UNH in water phase}}$$

for a pure water-ether system depends on the initial concentration of UNH in the water. For concentrated solution (1.4M), D is about 0.3; at 0.1M it has fallen to 0.003. Because the distribution coefficient is unfavorable to start with and becomes more so as the extraction proceeds, it is not possible to extract all the UNH from pure water into ether. In fact, just the opposite is feasible: The UNH can be completely extracted from the ether with pure water. If, however, the water phase is nearly saturated with a second soluble nitrate, such as NH_4NO_3, $Ca(NO_3)_2$, and $Zn(NO_3)_2$, the distribution coefficient is much higher,[4] as high as 150, and remains essentially constant down to very dilute UNH solutions. Under these conditions it is possible to extract the UNH quantitatively into the ether.

In this process the fission products are not extracted into the ether to the same extent as the U and should concentrate in the water phase or waste. Preliminary experiments indicated decontamination factors of 70 to 500 -- i.e., the total β and γ activity was decreased by a factor of 70 to 500 after one ether extraction using NH_4NO_3 as the salting-out agent. $Ca(NO_3)_2$ gives a factor of 20 to 30 for gammas alone, but because the distribution coefficient for UNH when using $Ca(NO_3)_2$ is about 10 times greater than when using NH_4NO_3, the pumping rate using $Ca(NO_3)_2$ can also be 10 times that possible using NH_4No_3. Therefore the active boiler material introduced into the extraction column is a solution of 1M HNO_3, 3.4M $Ca(NO_3)_2$, and 0.7M $UO_2(NO_3)_2$. In hand extractions using an equal volume of diethyl ether, this gave a distribution coefficient of 5. The column has been operated with this solution, and no loss of U has been observed.

The apparatus is shown in the accompanying flowsheet (Fig. 3). The soup and washings from the water boiler are stored in the main tank in the underground vault. The necessary chemicals are added to it here with the aid of the 3-in. pipe extending above ground. The small soup reservoir in the cubicle is filled with solution from the tank in the vault by means of compressed air. The UNH solution nearly saturated with $Ca(NO_3)_2$ is then pumped

(by means of sylphons) into the top of the extraction column, where it meets the ether pumped in at the bottom. Because of the difference in densities of the two phases, flow will be countercurrent. To ensure good contact between the phases during this stage, the lower 7 ft of the extraction column is packed with 8-mm pyrex beads. The U is quantitatively extracted by this process into the ether. The waste-water phase is taken out from the bottom of the column and discarded after testing for U.

The ether, which now contains the uranium, is taken out from the top of the extraction column and introduced into the bottom of the stripping column. In rising, the ether phase here meets distilled water falling through the 4 ft of beads. The extraction is now reversed and the uranium is quantitatively extracted into the water and is drawn out from the bottom of the stripping column as decontaminated UNH solution. The ether, now free of uranium, is taken out from the top of this column and recycled, being pumped back into the bottom of the extraction column. These processes can be followed in detail on the flowsheet.

All these operations are controlled at a distance, from the ground level in the case of the vault and through 1 1/2 ft of concrete in the case of the cubicle. When the columns are operating satisfactorily, there is no need to enter the vault after the soup is in the storage tank. Only a small portion (approximately 3 per cent) of this solution, and therefore of the activity, is in the cubicle at one time; the waste containing the major portion of this activity is removed from the cubicle at once. At the time of this report, it is being stored at a distance down canyon from Omega, awaiting the construction of a gravel pit and final disposal. The decontaminated UNH is brought out into the chemical laboratory if the activity is low enough, and there it is evaporated to remove ether and to restore the proper U concentration for water-boiler operation. If the activity is still too high, the decontaminated UNH solution can be returned to an auxiliary storage tank in the vault. After proper chemical treatment, it can again be ether extracted. This can be repeated until the activity is sufficiently low to meet requirements of health safety and efficient water-boiler operation.

As the result of an accident, it became necessary to purify a portion of the active boiler soup. This was an opportunity to test the apparatus and method with activity in the order of magnitude expected in the ultimate decontamination. The solution put through the columns was less than 0.7M in UNH and contained about 20 curies of γ activity; otherwise, conditions and operations were as previously described. Over-all results were satisfactory, a decontamination factor for gammas of 20 to 30 being obtained with no loss of U in the columns.

Materials of Construction of Ether-extraction System. Materials used in construction of column may be summarized as follows:

1. Pipes: Pipes carrying UNH solutions, water, and waste are 1/8 in. 18-8 stainless-steel pipe. Pipes carrying pure ether, air, and vacuum are 1/8-in. normal steel.
2. Valves: Valves on stainless piping are 1/8-in. stainless globe valves. Valves on normal steel piping are 1/8-in. brass needle valves.
3. Tubing: Flexible tubing used on setup is 1-in. Saran tubing, joined to pipes by expansion fittings.

4. Columns: Columns are standard 1 1/2-in. commercial pyrex pipe with a flanged end, and are fitted to stainless plates by a screwed joint against a Koroseal gasket.

5. Column packing: Columns are packed with 8-mm solid pyrex beads.

6. Tanks: All tanks are constructed of 18-8 stainless plate with welded joints. Tops of main and auxiliary storage tanks are removable and are held in place by a bolted joint with a rubber gasket.

7. Floor pan: The pan is constructed of 18-8 stainless plate, which is welded.

8. Risers: Risers are of 3-in. 18-8 stainless tubing with a stainless bottom and side arm welded on.

9. Pumps: Pumps are constructed of 18-8 stainless sylphon bellows coupled to commercial stainless double-check ball valves and operated by a 1/20-hp "Boston" ratio motor.

CONSTRUCTIONAL DETAILS

The major components of the hypo, which will be be described in detail in the following sections of this report, are the following (see Fig. 2):

The reactor (1) is a 12-in.-diam. steel sphere containing the solution. It is surrounded by a tamper consisting of a core of BeO bricks (2) supplemented by a shell of graphite (3). Accessories to the reactor are the cooling coil (4) and the pipes for the flushing air and level indicators (not shown in Fig. 2). The sphere is pierced by a horizontal pipe (glory hole) (5) to permit access to the highest flux of neutrons.

Between the tamper and the thermal column (6) is a bismuth wall (7) which provides gamma-ray protection for workers when holes are made in the thermal column. A removable cadmium curtain (8) can be used as a shutter for thermal measurements. The shield around the entire assembly consists of 4 in. of lead (9), 1/32 in. of cadmium, and 5 ft of concrete (10).

Sphere Assembly

(There is a 1/16-in. wall of 18-8 type 347 stainless steel throughout. All joints exposed to solution or vapor have stainless-steel welds made in an inert atmosphere.)

Sphere. A 1-ft-diam. stainless-steel sphere contains the active solution. The sphere consists of two spun hemispheres with a 1 1/2-in.-ID tube welded into the top and a 3/4-in. tube welded into the lower hemisphere. The wall thickness varies from 1/16 in. at the poles to 3/64 in. at the equator owing to the spinning operation. A 1-in.-ID tube is welded horizontally through the sphere to permit irradiation at the highest possible flux. The hole is slightly off center in order not to pass through the weld joining the hemispheres. This weld, the last to be done in the assembly, was made by flowing the narrow flared lips of the two hemispheres together with an acetylene torch. A helium atmosphere was maintained inside the sphere to prevent oxidation (see Corrosion Study in LADC-819). Figure 4a shows details of the sphere assembly.

Cooling Coil. A six-turn stainless-steel cooling coil 1/4 in. in inside diameter and an effective length of 157 in. is wound in the form of a helix. Figures 4a and b show the appearance of the coil. Calculations for natural convective cooling indicated that 50 cc/sec of water through a 72-in. length of such a tube should give adequate cooling for operation at 1 kw with an approximate rise of 30°C above room temperature. A schematic sketch of the complete cooling system is shown in Fig. 4c. Electrolysis of the water in the solution was expected to produce 2 cc/sec of hydrogen and oxygen because of the heavy ionizing particles in the sphere. Tests with a mock solution indicated that the cooling efficiency of a coil might be cut in half by bubble formation. The cooling tube was designed to take care of this possibility. The inlet- and outlet-water pipes are arranged so that the coil will not drain by gravity. A water bucket in the outlet (Fig. 5) serves as an indicator to show that water is flowing at 50 cc/sec and also turns the water-cooling units on. These units lower the inlet-water temperature to 8°C and permit 5.5-kw operation independent of season. The outlet water flows through a tank with several compartments before leaving the shield. This permits the short-lived radioactivity of the water to die out before the water gets to the creek about 100 ft from the building.

Flushing-air and Level Indicator. Because of the explosive nature of the gas released by electrolysis and the highly concentrated radioactivity of the gases produced in the solution, a means of diluting and flushing out these gases was required. Approximately 50 cc/sec of air is admitted through a 1/4-in.-ID tube which is pointed at the end and serves as a solution-level indicator as well as an air inlet (Fig. 4a). The tube is 11 ft long and is held concentric to a 3/4-in. tube by means of a single lavite insulator 7 ft from the sphere. It can be raised or lowered by a selsyn-controlled gear. A revolution counter gives the pointer position, and a neon light in conjunction with a thyratron circuit, requiring a fraction of a microampere, indicates the liquid contact. The level can be read to 0.003 in.

Air Outlet. A 3/8-in.-OD air-outlet tube is welded into the top of the 1 1/2-in. upper sphere tube. This is connected to a small chamber outside the boiler shield which acts as a safety catcher for the boiler solution. The presence of liquid in the air-outlet line is shown by a contactor and panel light. Some platinum gauze in an enlarged section of the tube acts as an explosion stop in case the flushing-air flow should stop, and one of the contactors should cause a detonation. Beyond the safety catcher the air goes underground for 200 ft to a large silica gel drying tank, which can be reactivated by remote control. The drier, which is shielded by an earth wall, is necessary to prevent the moist air from condensing and freezing in the tube during the winter months. From the drier, a 200-ft copper tube extends underground, and then an 1800-ft Saran tube takes the highly active gases a sufficient distance from the building to reduce the radiation to less than 0.01 r/8 hr. This Saran line is strung 15 ft aboveground between trees.

Tests of the soup have shown that much of the fission activity is carried out with the flushing air, resulting in a smaller gamma activity in the boiler than anticipated. The outgoing air, however, is extremely active, and special precautions must be taken to avoid the slightest leak in the system.

The maximum γ activity of soup samples removed immediately after boiler operation has been 25 mc/cc. The gases must be released at a considerable distance to prevent G-M-counter background difficulties, and it was necessary to post signs warning people to keep away from that part of the tubing carrying the waste gases which is above ground.

Bubbler-level Indicator. A 3/8-in.-OD tube extends 4 cm down into the sphere and acts as a minimum solution-level indicator. If the solution is above the tube end, the pressure changes due to bubbling produced by a small air flow through the tube are amplified and can be made audible or visible at the control panel by means of a loud-speaker and neon light. To permit an easy escape for the bubbles and to leave space for expansion and possible frothing formed by electrolysis, the sphere is not completely filled with solution. A maximum solution level of 3 cm from the top and a minimum of 4 cm from the top are used.

Temperature Indicator. A copper-constantan thermocouple in a 3/16-in.-OD stainless-steel sheath extends through the bubbler tube into the center of the sphere. Thermocouples are connected also to inlet and outlet water. The temperatures are read directly on a panel meter. A cold-junction box is automatically maintained at 28°.

Drain Tube and Dump Valve. The 3/4-in. tube extending out of the bottom of the sphere is closed off by a remotely controlled valve (Fig. 5). If the valve is opened, the solution is dumped to the chemists' decontamination equipment.

Tamper, Thermal Column, and Radiation Shield

Surrounding the sphere, as just detailed, is the tamper. This tamper, or reflector, is a rectangular parallelepiped of BeO 24 by 24 by 27 in., surrounded by graphite to complete a rectangular parallelepiped 60 by 48 by 60 in. (Figs. 2, 6, and 7). Two drip pans have been installed to prevent the loss of solution in the event that a leak should develop in the sphere. The first is a 0.020-in. stainless-steel pan placed between the graphite and the BeO, and the second is a 3/16-in. Pb pan beneath the graphite (see Fig. 7). Both drip pans have drains leading to the storage vault.

The tamper is designed to permit removal of various blocks of graphite (see Fig. 8) for the purposes of obtaining neutron beams, inserting absorbers, irradiating samples, etc. Two of these horizontal ports extend through the graphite to the BeO, and the third extends to the sphere and is drilled with a 1-in.-diam hole coaxial with the 1-in.-diam glory hole welded into the sphere. In addition to these experimental ports, design demanded that there be openings left for control, safety and shim rods, monitors, and sphere attachments. These ports are all vertical and are shown top view in Fig. 9, in which use, size, and location can be seen.

Horizontally adjacent to the tamper is the thermal column, a 5-ft cubical pile of graphite. To protect personnel working in front of the thermal column, an 8-in.-thick pier of Bi was placed between the tamper and thermal column. This results in a substantially reduced γ flux without a serious neutron loss. As in the tamper, experimental ports have been provided. The transverse ports

(see Fig. 8) extend through the column. The longitudinal ports can be varied almost at will, but normally these extend to the cadmium curtain. The largest port obtainable without complete remodeling of thermal column is 34 by 34 in., extending 4 ft into the thermal column.

As an added feature for experimental convenience, a cadmium curtain has been placed across the thermal column 4 ft from the front of the column. This curtain is raised and lowered by a gear motor and pulley system controlled either from the control panel or hypo room.

Obviously, it is necessary that adequate physiological shielding be provided for the protection of the personnel. This shielding is accomplished by placing over all faces of tamper and thermal column 1/32-in. sheet cadmium and 4 in. of lead to absorb the slow neutrons and resulting γ rays. This surface is then covered on all sides, except the front face of the thermal column, by 5 ft of concrete. The concrete is all poured except for that above the tamper and the thermal column. To have ready access to the tamper, the concrete at the back of the tamper was poured on a cart set on rails. Because a possibility always exists that work may have to be done on the tamper or thermal column, the concrete on top of each is in the form of removable blocks. All the ports which extend through the concrete are normally plugged with wood to reduce leakage, and, in addition, the ports opposite the sphere are each shielded by 4-in. lead doors (Fig. 10b).

Figure 10a shows the front of the thermal column with its 6-in. Pb shielding, the removable concrete blocks above the thermal column, and the 5-ft concrete shielding on the sides.

Control, Shim, and Safety Rods

The reactivity of the boiler is controlled by means of four cadmium rods operated from the control room: two shim rods, a control rod, and a safety rod. The latter always remains out during operation. It is used only to stop the chain reaction in case the intensity should get too high. For additional safety, the two shim rods are designed with a release mechanism so that they can be used for safety as well as control. These safety devices are necessary in case the power is raised too rapidly. Under normal operating conditions, the boiler is self-regulating because of the temperature effect; however, if the rods are pulled out too fast, without a safety device the heat liberated might be enough to vaporize the solution before the increased temperature had time to control the reactivity. The fastest period theoretically obtainable with the boiler is approximately 0.02 sec. The rods are mounted vertically so that those used for safety may fall freely when released. This eliminates the necessity of a fast mechanical device to push them in.

The total gram equivalence of the control and shim rods is about 160 g, which is about 35 g more than that necessary to compensate for the maximum temperature effect.

The arrangement of the four rods is shown top view in Fig. 9. Cadmium is contained in the lower 30 in. of each rod. The rods extend from the top of the cement structure to 5 in. below the bottom of the sphere. They have a total motion of 2 ft, which means that when they are out, the bottom of the cadmium is about at the top of the BeO tamper.

Shim Rods. The shim and safety rods slide in metal sheaths, as shown to scale in Fig. 11. For minimum neutron absorption, the lower halves of the sheaths are made of 1/32-in.-wall aluminum. Both halves of the three sheaths can be seen in place in Fig. 6; above the iron plate the sheaths are iron.

The two shim rods are identical. They were made as light as possible so that they could be operated directly by selsyns. Each rod is 113 in. long and weighs 4 lb. It consists (Fig. 11) of two long strips of dural 2 in. apart. The lower end of the gap between the strips is filled by a sheet of Cd (30 in. long, 2 1/2 in. wide, and 0.032 in. thick) sandwiched between two similar sheets of dural. As shown in cross section in the figure, each side of the Cd sandwich fits in a slot cut in the corresponding dural strip. To minimize the total weight of the rods, this slot extends the full length of each strip.

Rack-and-pinion devices are used to move the rods. The racks are 26 in. long and are mounted at the top of each rod between the dural strips. The pinion gear is mounted directly on the selsyn shaft.

In order that the rod act fast enough for safety, it must be allowed to drop freely. Since it must also have a fairly accurate position control, a rather complicated mechanism is necessary. This is shown in Figs. 12a and b.

To allow the rod to drop freely, the pinion gear (1), Fig. 12a, must be released from the selsyn. For this reason, the pinion is coupled to the selsyn. In order to drop the rod, the coupling (2) is broken, and the pinion rotates freely on the selsyn shaft. The coupling is held closed against the force of two springs by a push a-c solenoid (8). When the current through the solenoid is cut off, the springs open the coupling, and the rod drops in. With this arrangement, the rods will automatically drop in case of power failure.

It was originally planned to use the control rod for fine adjustment between predetermined fairly large intervals of the shims. In order to make the shim rods more useful, these stationary intervals were reduced to 1/16 in. in the final design, with continuous motion between intervals possible for control purposes. The shim is held at any desired interval by means of a ratchet (4) which engages in a tooth of a ratchet gear (3) fastened to the selsyn shaft. The gear has 48 teeth (since one revolution of the pinion moves the rod 3 in., the rod moves 1/16 in. per tooth). The ratchet is engaged or disengaged by a solenoid (5). If it is disengaged, the rods can be moved by turning the knob fastened to the shaft of the selsyn in the control room (Fig. 13). In this way the operator actually feels the weight of the rod. The selsyns used are Navy No. 7G. They are rated for 3.4 in. oz per degree, linear to 30 deg of phase lag. Since the radius of the pinion is 1/2 in. and the rods weigh 4 lb each, the control-room selsyn leads the hypo selsyn by 10 deg, or 1 1/3 notches on the ratchet.

The position of the rod is indicated by a revolution counter geared to the control-room-selsyn shaft as shown in Fig. 13. Each number in the first digit represents one notch on the ratchet, or 1/16 in. of motion of the rod. When the rod is all the way out, the indicator reads 350, i.e., 7.3 turns of the selsyn.

During operation of the boiler, the shim rods rather than the control rod have been found to be the most convenient control. One shim is usually left out in some fixed position. The other can be used for either manual or automatic control.

The circuit for the shim rods is shown in Fig. 14. The rod is dropped by cutting the alternating current to the coupling solenoid. This may be done in several ways: by the safety tripping circuit which shorts the alternating current through a thyratron; by a manual switch; or by the microswitch (1) which activates the holding relay (3), thereby cutting the alternating current until the relay is reset. Microswitch (1) is used to prevent damage to the mechanism. If the rod is raised too high, for example, by the automatic control, it contacts this switch and is automatically dropped. Switch (2) is a S.P.D.T. microswitch indicating by lights (6) and (7) whether the rod is in or not.

In order to be able to reproduce positions of the rod, it is essential that the pinion coupling be reengaged in the same relative position to the ratchet every time after the rod is dropped. An asymmetric tooth in the coupling joint limits the engagement to one position in each revolution. Actually the circuit is so arranged that the coupling solenoids cannot be activated unless the position indicator in the control room reads 000. The mechanism for this is shown in detail in Fig. 13. The knobs on the two gears, (1) and (2), lift up the pivoted arm (3) at each revolution. Only at zero do both knobs pass under the arm at the same time. When this occurs, the arm is lifted enough to operate switches (4) and (5) (Figs. 13 and 14). Switch (4), Fig. 14, releases the mechanical catch of the holding relay (3), while switch (5) resets the thyratron safety circuit. The safety circuit is reset, however, only if the indicators of both rods read 000. This is accomplished by requiring that the two parallel microswitches, one from each rod, simultaneously open the plate supply of the fired thyratron (Fig. 26).

Air brakes shown in Fig. 11 are used for the shim and safety rods. Two small dural shafts (1) fastened to the top of the rods hit a piston (2) held up by a spring (3) in a cylinder (4). The brakes operate over the last 4 in. of travel.

Control Rod. A detailed description of the control rod (Fig. 15) may be found in Report LADC-819. It was adapted to the hypo from the low-power boiler by extending the screw shaft and outer case. The rod proper consists of a 34-in.-long cylinder of cadmium formed by wrapping and soldering a 0.017- by 1.5-in. strip around a brass tube 3/4 in. in diameter. Another brass tube is fitted snugly over the outside of the Cd. The rod has a vertical motion of 40.7 in. A nut soldered to the inside brass tube has a key which moves in a keyway cut in the upper aluminum and steel tubes. As shown, the motion of the rod is obtained by rotating the long steel screw (pitch 0.05 in. per thread). The screw is driven by a variable-speed d-c motor through a clutch. The position of the rod can be set within a mil, and it is indicated at the control panel by a selsyn system.

The motion is controlled by a knob from a center-tapped 220-volt variac on the control panel. The circuit is shown in Fig. 16. A reversing switch is connected to the knob in such a way that turning the knob clockwise raises the rod and turning it counterclockwise lowers it. This rod is now used mainly for changing the operating range of the boiler and seldom for control purposes.

Safety Rod. The safety rod is shown schematically in Fig. 17. It is identical in construction to the two shim rods. The circuit diagram is shown in Fig. 18.

During operation the safety rod is held "out" by an a-c solenoid, the core of the solenoid being attached to the rod. An interruption of the current in the magnet brought about manually or by any of the safety circuits allows the rod to fall freely. As shown in Figs. 18 and 26a, the solenoid coil is in series with the contacts of a N.O. d-c relay and microswitch. The relay is operated by the safety tripping circuit. The microswitch closes only when the solenoid is in contact with the safety rod, i.e., only when the solenoid core is in place. Without such a device, if the safety tripping circuit were reset after the rod had been dropped, the solenoid would burn up.

The solenoid is raised or lowered by a geared a-c motor mounted on the superstructure of the hypo. Limit switches stop the motor when the magnet reaches either its top or bottom positions. As shown in Fig. 17, they are operated by a pivoted arm which follows the thread of the cable drum. Two switches operate indicator lights on the control panel, one to show when the magnet is up, the other to show when the rod is down.

In Fig. 19 are shown the two shim selsyns (the automatic-control gear box attached to the left-hand one), the control-rod mechanism suspended from the upper iron plate, and the safety-rod mechanism on top. The level indicator with its selsyn and the water inlet are also clearly visible.

Detectors and Indicators

The devices which indicate neutron flux from the hypo are activated by two kinds of ionization chambers, BF_3 and 25.

The most important and useful detecting system is that of the galvanometers. These give a continuous reading, and are very sensitive to changes in and proportional to the neutron flux. The sensitivity to very small variations in power is increased manyfold by using a null method with a high-sensitivity galvanometer. This galvanometer, on full or 0.1 sensitivity, is kept near its zero position by a slight continual motion of the shim rods by an operator or by the automatic control.

Figure 20 shows the two galvanometers in series, supplied by a large 25-coated ionization chamber which will be described later. The chamber is in a high flux so that the ionization current is of the order of 7×10^{-6} amp/kw, and the first galvanometer, which is deflected by the total current, must be shunted to 1/1000 of its maximum sensitivity for any powers over 1 kw. This, of course, makes it insensitive to changes of even several per cent. All this ionization current goes through the differentially connected galvanometer also, but its spot is kept on scale by an equal and opposite current. This current is supplied by a continuously variable source of emf obtained from a potentiometer, applied through a resistor of the proper value.

The deflection of the differential galvanometer would be 5×10^5 mm/kw if it were physically possible; so by the null method, a change of neutron density of 1 part in 500,000 is detectable at this power and of 1 part in 50,000 is controllable. This sensitivity, however, is proportional to the power of operation and is therefore less at low powers.

A protecting relay system has been installed to short out the differential galvanometer automatically if any of the controlling rods should drop unexpectedly (Fig. 24).

A curve of the galvanometer bucking voltage vs. counts from a 25 chamber (Fig. 21, curve I) shows that the chamber saturates at high power. Curve II shows how this effect is eliminated by raising the collecting voltage from 750 to 1800 volts. Because of insulation limitations, however, normal operation is at 1200 volts.

Since the chamber is only about 45 cm from the sphere, ionization due to the gamma activity of the accumulated fission fragments was expected to produce a variable and appreciable background. This has been found to be negligible.

It was desirable to eliminate ion-producing processes which result from past history of the boiler or from the total nvt having passed through the ionization chamber. This meant using a construction material for the chamber which gave very little residual activity after a strong bombardment. It had been found at Chicago that if ordinary "black" or cold-rolled iron were used, practically the only activity present was due to Mn impurities. Therefore the chamber, Fig. 22, is built entirely of this metal.

The chamber was designed with paralleled plates connected as shown to permit a rather large surface area in a convenient volume so that the large ionization currents required for high sensitivity could be obtained.

The chamber contains a total of 184 mg of 25. All plates except those on the ends are coated on both sides. The coating is the residue left after heating an original 345 mg of 63.1 per cent enriched U_3O_8 put on in the form of nitrate with a zapon binder.

The small 25 chamber which has been used to determine the linearity of the galvanometer system is used to integrate the total power. This is accomplished by setting the discriminator of a scaler to a value which will give some predetermined number of counts for 1 kw-min of operation. This system, recorded on a modified mechanical counter through a scale of 256, is never turned off, and it is read at the control panel at the beginning and end of each run. This chamber also operates a counting-rate meter which contains a safety-rod-dropping circuit (Fig. 26b).

This 25 chamber consists of an aluminum foil in the form of a cylinder 1 in. long by 5/8 in. in diameter, coated with a thin layer of 63.1 per cent enriched U. There are 1.15 mg of U_3O_8, making 0.613 mg of 25, and a consequent cross section of roughly 0.85×10^{-3} cm^2. The chamber is connected to the preamplifier by a 3/4-in.-OD 7.5-ft dural tube. Both chamber and tube contain argon at about 20 psia. The signal lead, a 0.008 in. piano wire, connects the chamber to a Sands Model 101 preamplifier and 100 amplifier.

Another midget 25 chamber can be used for flux measurements in the thermal column or as a fixed monitor. It was made by coating 25 on a platinum foil which was then rolled into a cylinder and sealed into a glass tube. The tube was filled to a pressure of 1 atm with pure argon and sealed off. A photograph of this type chamber is shown in Fig. 23. The chamber is mounted at one end of a 7/8-in.-OD aluminum tube 8 ft long so that it can be placed in the middle of the thermal column through one of the small side ports shown in Figs. 8 and 10b.

Safety Devices

There are three independent detectors which can be adjusted to drop the safety and shim rods at any predetermined intensity (Fig. 24). Two of these are BF_3 chambers connected to d-c amplifiers (Fig. 25) similar to those used

in the low-power boiler. The other is the above-mentioned small 25 chamber and counting-rate meter which includes a safety-tripping flip-flop circuit (see Fig. 26b).

The safety circuits (Fig. 26a) are arranged with two bias batteries. When the intensity goes up to a predetermined value, the normal safety rod is released by firing a thyratron. If the intensity should still continue up to a point 50 per cent higher, another thyratron, with its grid more highly biased, is fired and causes both shim rods to drop. This system has been most satisfactory. The safety rod only, or both shim and safety rods, can also be dropped manually by switches on the control panel. These switches are shown as "safety" and "super-safety" in Fig. 26a.

The safety-rod thyratron is automatically reset by a condenser when the neutron intensity becomes sufficiently low (Fig. 26a). A delay in reenergizing the lifting solenoid has been described in the section on the control rods.

For the shim rods, the thyratron continues to conduct until the plate lead is opened simultaneously by the two switches labeled "shim-rod reset" (Fig. 26a), as mentioned above.

During the operation of the boiler, flushing air must always be flowing to prevent the formation of an explosive mixture. In addition, cooling water may or may not be flowing, depending on the power of operation. Since it is always possible either through mechanical failure or through carelessness of the operator to start a run without air or water, additional preventive safety devices have been installed to protect the equipment from possible damage.

In series with the light that indicates the flow of air is a relay in the grid circuit of a thyratron. This thyratron is in parallel with those of the safety-monitor system. When the air is left off, or is not flowing sufficiently to light the indicator, the thyratron is fixed which drops the safety rod.

The criterion in the case of the flow of water is the temperature of the soup. Current from the thermocouple in the soup is put through a galvanometer, and a phototube is placed in the path of the spot, so that when a temperature exceeding 85° is reached, the phototube "fires" another thyratron, again dropping the safety rod.

In the same category of preventive safety devices are included those to prevent unauthorized personnel from tampering with the control mechanisms or operating the boiler. The power for the operation of the rods is controlled by a locking switch, the key to which is available only to authorized personnel. To prevent the manual raising of the rods without using the control panel, the rods have been enclosed in a small removable structure normally kept locked.

Automatic Control

Since continuous manipulation of one of the shim rods is necessary to keep the neutron intensity or power level constant, it was considered desirable to use an automatic control shown schematically in Fig. 27.

The system utilizes the current from the large 25 chamber (Fig. 22), which also supplies the power-indicating galvanometers, to control the level directly. The control system is divided into four main parts: (1) a power-determining device (Fig. 27), (2) a d-c amplifier and mixer (Fig. 28), (3) an a-c amplifier (Fig. 29), and (4) a regulated power supply.

The intensity level at which the control operates is determined by the off-balance voltage applied to the d-c amplifier. The automatic control then causes the intensity to rise by pulling the shim rod out until the voltage developed across the resistor, connected to the large 25 chamber, cancels the applied voltage. Any subsequent boiler fluctuation will cause the control to move the shim rod in such a direction as to remove the unbalance.

Any voltage change occurring across the resistor is amplified by the d-c amplifier and applied to the mixer or converter. The converter is essentially a linear gate circuit which delivers a 60-cycle output whose amplitude is proportional to the amplitude of the direct current and whose phase is determined by the polarity of the direct current. The converter output is fed into an a-c amplifier, where it is built up until enough power is available to drive a small reversible two-phase motor. The motor drives a shim rod by a rack and pinion through a train of gears and a safety-release mechanism (Fig. 12b).

The unbalanced voltage is obtained from a General Radio potentiometer adjusted so that the dial reads 0 to 180 watts directly (Fig. 20). This reading is multiplied by 1, 4, 10, or 40, depending on the setting of a switch which taps the resistor in series with the 25 chamber. This enables the sensitivity of the system to be essentially constant over the entire power range. The power obtained by setting the dial is fairly accurate, except at high powers where the chamber starts to saturate slightly (Fig. 21). However, once the control is set, the power level is maintained to approximately 0.05 per cent. Precise checks on power are made by counting the number of fissions in the small 25 chamber located near the tamper.

The usual procedure for automatic control is to raise manually the intensity to the approximate level desired. During this operation the gears and motor of the control system must be disengaged. This is accomplished by a clutch normally disengaged by a spring, but engaged for automatic operation by the solenoid shown in Fig. 12b. When the desired intensity level is reached, the automatic-control switch is thrown on. This switch, by means of a relay, connects the driving motor to the a-c-amplifier output, engages the clutch of the automatic control, and releases the ratchet holding the shim before the control takes over.

Should the condition arise that the control tries to drive the rod in further than its zero position, the clutch of the control is released automatically.

OPERATION

Approach to Critical

In as much as the estimates of the critical mass for the hypo indicated that additional 25 might be required, a determination of the critical mass was undertaken as soon as the sphere and its fittings had been installed. The

chemists, under Helmholtz's direction, prepared a solution containing approximately 56 g of 25 per liter and arranged a system whereby the solution could be added to the sphere in known volumes or could be withdrawn for mixing.

The method used was to run a Saran tube to the botton of the sphere through the level-indicator tube. Then, by means of a vacuum pump, the solution could be raised into a large graduate, and known quantities of solution could be added and mixed before lowering it into the sphere. More complete mixing with the solution in the sphere was accomplished by raising and lowering 2 1/2 liters 10 times between the graduate and the sphere.

Counts were taken with the detecting chambers when approximately 3, 6, 9, 10, 11, and 12 liters of the solution were in the sphere, and the reciprocal of the counting rate in each case was plotted against the mass of 25 in the sphere. Five more smaller additions were then made as the critical condition was approached until a total of 767 g (all the material then available) had been added for a total of 13.65 liters (bubbler level). The data then indicated that the hypo was about 6 g from critical. After a slight delay, an additional 103 g of 25 was procured. This material was of somewhat lower enrichment, being 10.8 per cent as compared to the 14.6 per cent material already on hand. To avoid difficulties in calibrating the rods, it was decided to mix the two batches so that there would be no change in isotopic ratio for the further additions. The resulting enrichment was 14.0 per cent. This decrease from 14.6 per cent was estimated to increase the critical mass by about 20 g.

After mixing the 1.5 liters of new material with that already in the sphere, 25 was added by removing a small amount of the solution from the sphere and replacing it by an equal volume of more concentrated solution. It should be noted that all measurements near critical and those for the rod calibrations had to be done at constant volume in the sphere so as to have identical geometric conditions. The solution was then stirred by pumping several liters between the sphere and an auxiliary container. The final critical mass thus obtained was 806.5 g.

Rod Calibration

Measurements were made on the low-power boiler of boiler period vs. grams of 25 above critical. Calculations and an independent experiment (Report LADC-816) had shown that 20 g of 25 represented 1 per cent in K. The equation (in-hour formula)

$$\delta K = \Sigma \frac{P_i \tau_i}{\tau + \tau_i}$$

where P_i = amplitude of periods

τ_i = neutron periods

τ = pile period

relating excess reactivity δK with neutron periods is known from work on the Chicago piles. The equation for delayed neutrons is also known from work by Snell and others.

From the boiler periods and percentage in K/g of 25 the equation can be evaluated for the delayed neutrons from the boiler. This differs from that obtained by Snell, etc., because of the difference in leakage between fast and slow neutrons from the boiler. The correction for the amplitudes is 0.008, which compares well with the effective number of delayed neutrons (τf) for the water boiler calculated in LADC-816.

The resulting reactivity equation for the boiler is shown in Fig. 31

$$\delta K \times 10^6 = \frac{122}{\tau} + \frac{1000}{\tau + 0.7} + \frac{32,500}{\tau + 6.5} + \frac{50,900}{\tau + 34} + \frac{16,600}{\tau + 83} \qquad (1)$$

The 122 in the first term is the period in microseconds of fast multiplication for the boiler measured in LADC-816. The microre, suggested by Fermi, is used as a measure of reactivity. This unit is used in all calibration work, a microre meaning a change of $K \times 10^{-6}$. The quantity given in the present formulation is δK change, which is the reactivity change in microres. Independent calculations based on cross sections for the soup components and absorption by the stainless-steel container and cooling coil give an equation (Fig. 30)

$$\delta K = K - 1 = 1.219 = \frac{m}{m + 177} - 1 \qquad (2)$$

relating reactivity (δK) to total mass of 25 (m) in the sphere. The critical mass is taken as 808 g. This value of M_c differs by 1.5 g from that initially found because of the additional absorption produced by the introduction into the solution of a thermocouple in a stainless-steel thimble. This equation has an initial slope of 222 and a final slope of 196, i.e., the value of 1 g of 25 changes from 222 to 196 microres as material is added from critical to the final amount of 870 g of 25. This shows the greater meaningfulness of a reactivity unit as compared to using grams of 25 as a unit.

This apparent loss of reactivity per gram of 25 with increased concentration was observed during the rod calibration, since the effect of the rods appeared to change with equal additions of 25. This difficulty was overcome in the calibration since there was a considerable region over which the calibration curve was linear. It was therefore possible to connect the early out-position section of the calibration curve to the later in-position section by a shift until the linear portions coincided. (See Fig. 32.)

The correctness of applying both Eqs. 1 and 2 to the high-power boiler was demonstrated by the excellent agreement obtained between the reactivity read from the curve (Eq. 1) for each measured boiler period and comparing it with the expected reactivity determined from Eq. 2. This close check was observed over the entire range of periods measured, extending from several minutes to about 1 sec.

After the complete calibration of one rod, the interrod calibrations were comparatively simple, since the soup concentration was no longer changed after all the 25 had been added. It was merely necessary to hold the boiler at constant power while the effect of one rod on the reactivity was compared to that of another.

Temperature Effect

A determination of the temperature coefficient of the hypo was made over a wide range. The results are shown in Fig. 33a. A negative coefficient of 262 microres = 1.33 g of 25 equivalent per degree centigrade is obtained. The temperature of the solution as a function of boiler power is shown in Fig. 33b.

Start of Power Operation

During the time that the various calibrations were being made, the shielding was completed and the thermal column was built. The monitoring equipment was installed, and the safety chambers were withdrawn into regions of lower flux. Operation at power was then started, and it became apparent that a steady power of over 5 kw was obtainable. The power calibration was made by measuring the heat carried away by the cooling water when a steady state was reached. Calibration of the monitors in terms of power and measurement of the flux at various places with Mn foils was carried on during this time.

Loss of Nitrate

After the hypo had been run for several hundred kilowatthours, it was observed that its reactivity had increased remarkably. It was found necessary to insert a piece of cadmium in one of the ports to make further operation safe. After some investigation, it was found that the increase in reactivity was due to the fact that the uranyl nitrate was gradually being converted into a basic nitrate and that the free nitrate was presumably being carried away by the flushing air. Chemical tests indicated that about 30 per cent of the nitrogen had disappeared. Other tests indicated that if this process were continued much further, a precipitate would be formed. The normal nitrate was formed again when nitric acid was added to test solutions. Because of the gain in reactivity, a 20 per cent deficit of nitrate was considered normal for operation. This permitted operating the boiler at higher powers. The procedure of adding 0.04 mole of normal nitric acid and 8 cc of distilled water per kilowatthour of operation was adopted to replace any additional evaporation and electrolysis losses. This was added in 50- or 100-cc lots when the level indicator showed a lower level than bubbler level. An automatic system for these additions is being considered.

PERFORMANCE

Control Panels and Operational Procedure

The control panel is shown in Fig. 34. The panel rack on the extreme right contains the following units from top to bottom: (1) counting-rate meter with adjustable neutron-level safety tripper, (2) power integrator scale of 256 [both (1) and (2) operate from a small 25 chamber], (3) row of trouble lights to indicate if running conditions are right, i.e., air flow, water flow, shims out from zero position, Cd curtain up, safety catcher bucket empty, (4) galvanometer shunts and cadmium-curtain motor control, and (5) Esterline-Angus recorders of neutron level, one on BF_3 safety monitor and the other on small 25 chamber.

The second rack contains (1) bubbler-level indicator, (2) main power-lock safety tripping circuit, BF_3-chamber intensity meters and safety-rod raising switch, (3) galvanometer scales, (4) shim-rod selsyns, ratchet switches, and reset mechanism, and (5) potentiometer for supplying galvanometer bucking voltage.

The third rack has (1) water- and air-flow meters with control valves, (2) light-indicating low-water flow with coolers off, (3) level-indicator selsyn control with level scale, (4) control-rod-position scale and raise-lower variac control, and (5) sphere temperature and power meters.

The fourth rack contains (1) clock, (2) scale of 256 for monitoring thermal column with midget 25 chamber, (3) automatic power-level selector, and (4) intercommunication system.

The fifth rack contains (1) 12-point thermocouple recorder for sphere, tamper, inlet- and outlet-water temperatures, and counting-rate meter (this unit not regularly used), (2) potentiometer for temperature checking, and (3) G-M counter to detect fission gas or other radioactivity in the control room.

Typical operating procedure is as follows: The 25-chamber power integrator, solution level, and sphere are recorded. Flushing air (50 cc/sec) and cooling water (0.8 gpm) are turned on. The direct-reading galvanometer is set on maximum sensitivity. The desired deflection and bucking voltage for the high-sensitivity or null galvanometer are read from the available curve for the particular power at which it is desired to run. The control and two shim rods are checked for "in position." The safety rod is raised. The shim rods are then slowing raised one at a time, and the galvanometer deflection is observed. The position of the shim rods for the boiler to start will depend on the initial temperature of the sphere. Because of variations in the background activity of the solution, the rate of rise of the neutron flux depends on the past running history of the boiler. Considerable caution is therefore necessary when first starting. When the desired reading is obtained on the direct-reading galvanometer, the bucking voltage is connected to the null galvanometer which at full sensitivity represents 50,000 cm/kw. If the automatic control is used, the bias voltage is adjusted for the desired power operation, and it will run one of the

shim rods to maintain constant power. In this running condition the row of 10 trouble lights is on. If any one of these goes out, it is possible to tell at a glance whether water, air, temperature, etc., is abnormal.

The boiler responds very rapidly to shim-rod positions, and these can be changed at almost whatever speed the operator desires to turn the knob. This means that an experienced operator can bring the boiler up to full power or go from a low to a high level in a few seconds. This rapid response is accomplished by letting the boiler rise with the rod out too far so that a considerable amount supercritical is running. As the desired power is approached, the shim can rapidly be run back. A visual observation of the neutron intensity on one of the recording meters makes it possible to have an almost vertical rise with immediate leveling off at the desired intensity level.

Flux and Power

With inlet-water temperatures around 5°C and the 870 g of 25 in the boiler, it is possible to run the boiler continuously at 5.5 kw without exceeding a temperature of 85°C in the sphere. There is still considerable excess reactivity to permit experiments with absorbing material near the sphere when running at this power. The increase in power above that originally planned was possible because of the overdesign in the cooling system and absence of very violent frothing or bubbling in the solution. The power measurements based on inlet- and outlet-water temperatures, measurements made with standardized manganese foils and a small fission chamber, gave the following flux intensities. Cadmium ratios were obtained with standard indium foils.

Position, in.	Cd ratio	Position, in.	nv/kw
		0	0.83×10^9
2	500	2	6.9×10^8
12	2,500	20	1.49×10^8
24	50,000	38	0.255×10^8
36	90,000		

All distances are measured from the Cd curtain in the thermal column which is 4 ft. from the end of the column.

The above data give a diffusion length of 29.4 cm in the solid graphite column. The equation for the flux in the column is

$$nv/kw = 0.83 \times 10^9 e^{-z/29.4}$$

where z is the distance in centimeters from the cadmium curtain. The flux at the center of the sphere in the glory hole is about 5×10^{10} per kilowatt.

Steadiness during Operation

The boiler is not so steady in operation as the large graphite piles. This is probably because of the bubbling and large convection currents in the solution when operating at high power. The intensity level can be maintained, however, to 0.01 per cent at 1 kw when the full sensitivity of the null galvanometer is used (50,000 cm/kw). The shim rod must be moved continually to maintain this accuracy. If the boiler runs itself after reaching temperature equilibrium, it will maintain a constancy of about 0.2 per cent when running at 1 kw. The automatic control has about the same accuracy as the best hand control.

Applications

The boiler has been used for numerous activations in the high flux in the center of the sphere (3×10^{11}). The thermal column is ideal for irradiations of high intensities with excellent cadmium ratios.

Numerous experiments have been performed by making a large cavity in the column and using a beam of neutrons out of the front of the column. A strong fission-spectrum source (2×10^{7} neutrons/sec) was obtained in such a beam by bombarding a 25 target. Several transmission and scattering experiments have also been performed.

An experiment is in progress for measuring 49 and 25 activities for short times after irradiation by shooting the samples at high velocity through the glory hole.

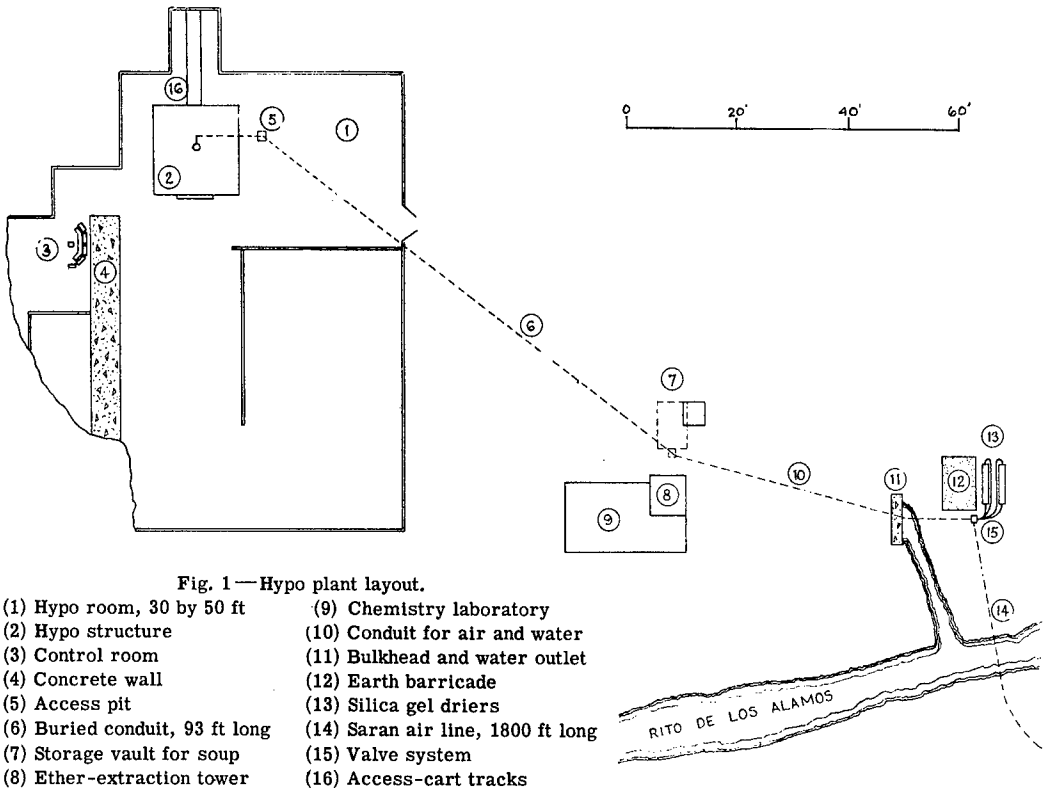


Fig. 1—Hypo plant layout.

(1) Hypo room, 30 by 50 ft
(2) Hypo structure
(3) Control room
(4) Concrete wall
(5) Access pit
(6) Buried conduit, 93 ft long
(7) Storage vault for soup
(8) Ether-extraction tower
(9) Chemistry laboratory
(10) Conduit for air and water
(11) Bulkhead and water outlet
(12) Earth barricade
(13) Silica gel driers
(14) Saran air line, 1800 ft long
(15) Valve system
(16) Access-cart tracks

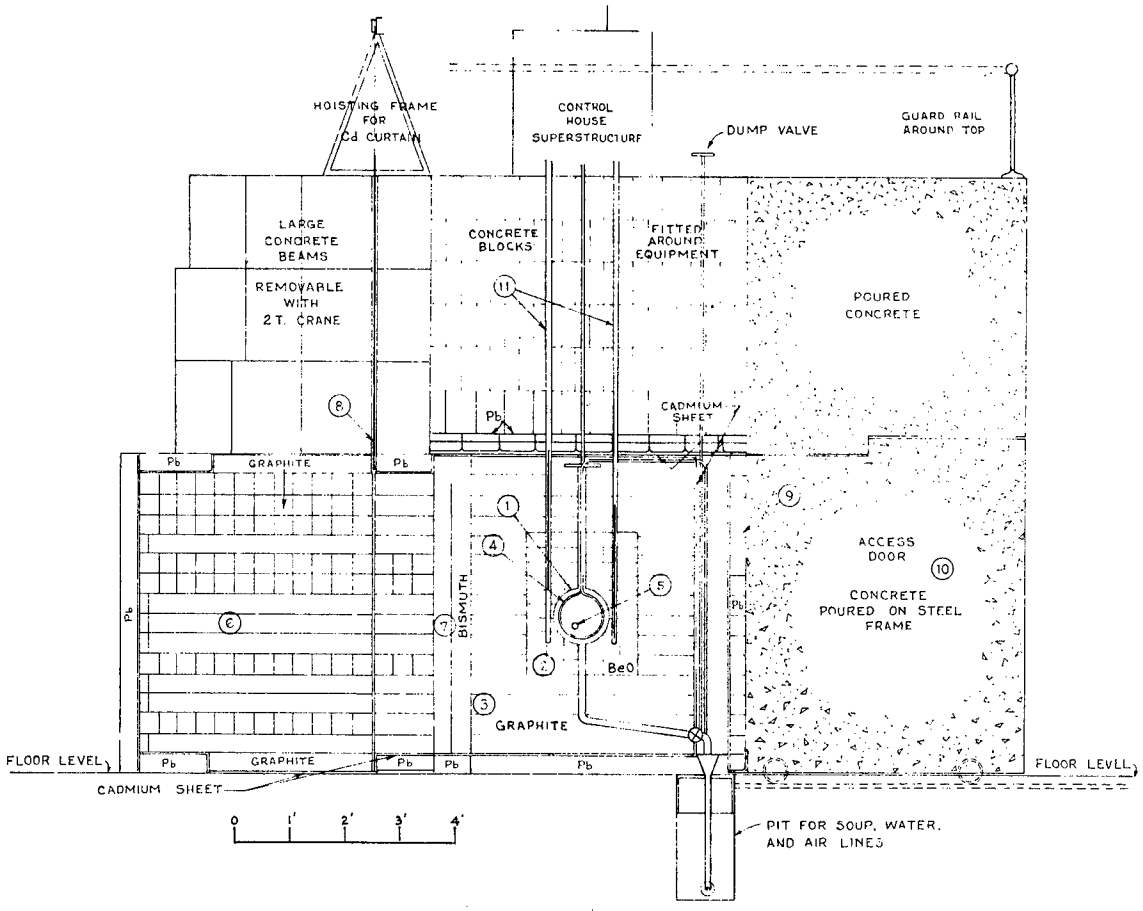


Fig. 2—Section through hypo (simplified).

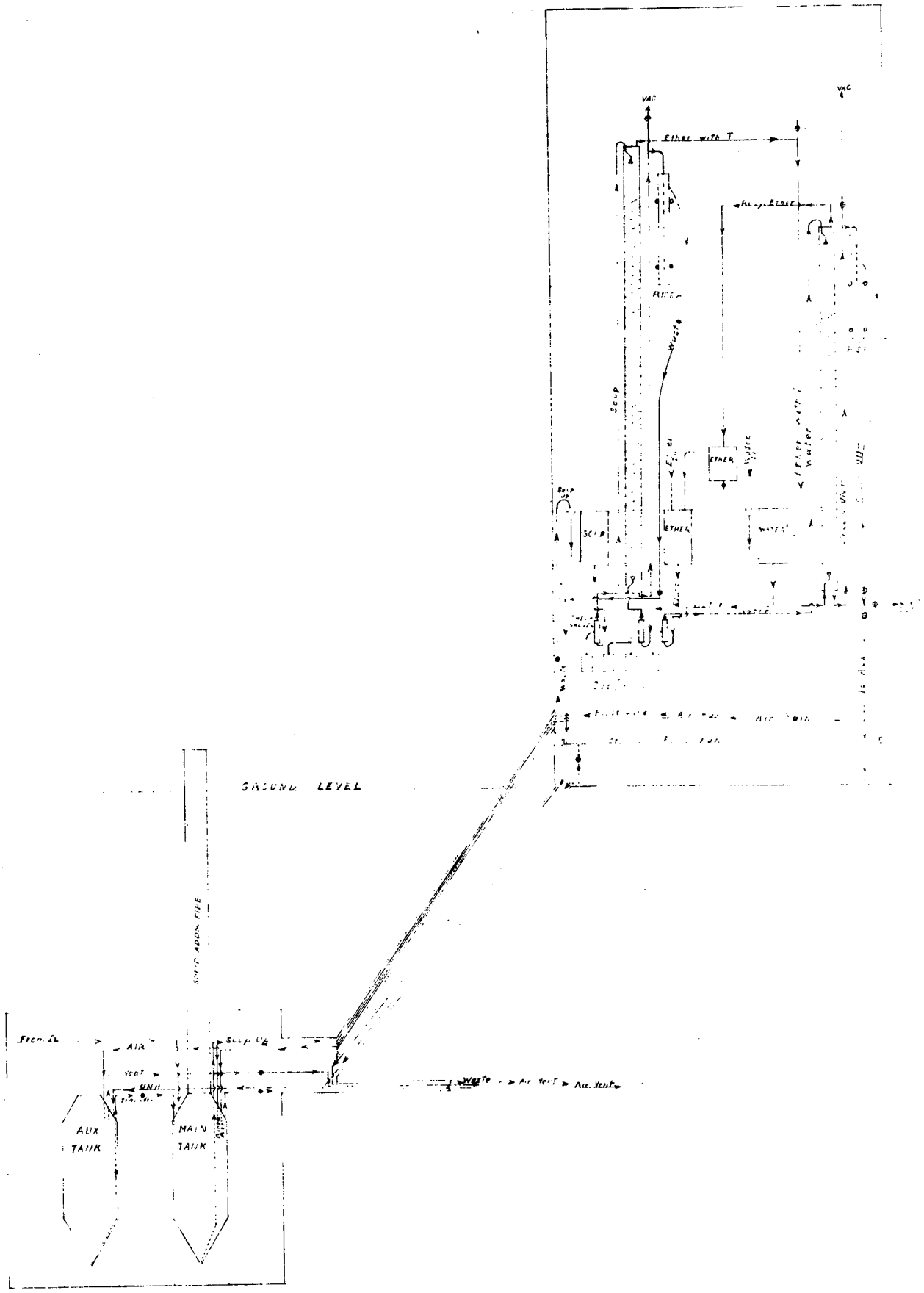


Fig. 3 — Qualitative flow sheet for Omega ether-extraction system.

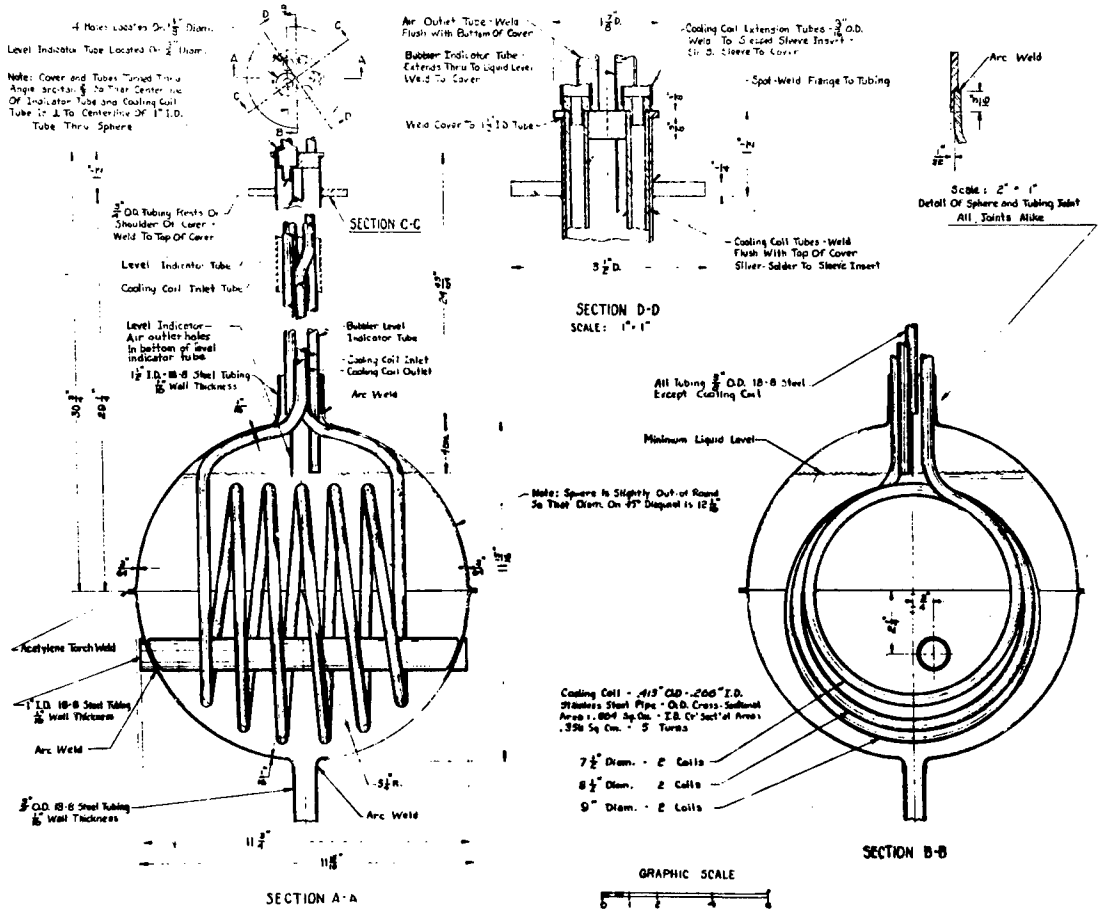


Fig. 4a—Details of sphere assembly. Total volume of sphere, 14,700 cc; volume of 3/4-in. pipe, 200 cc; total, 14,900 cc. Unused volume of sphere, 700 cc; coil displacement volume, 343 cc; 1-in. tube displacement volume, 180 cc; total, 1223 cc. Minimum volume of solution required, 13,780. (Unused volume of sphere is at 4 cm liquid level.) All welds are to be made with argon or helium in sphere. The material used is type 347 stainless steel throughout.

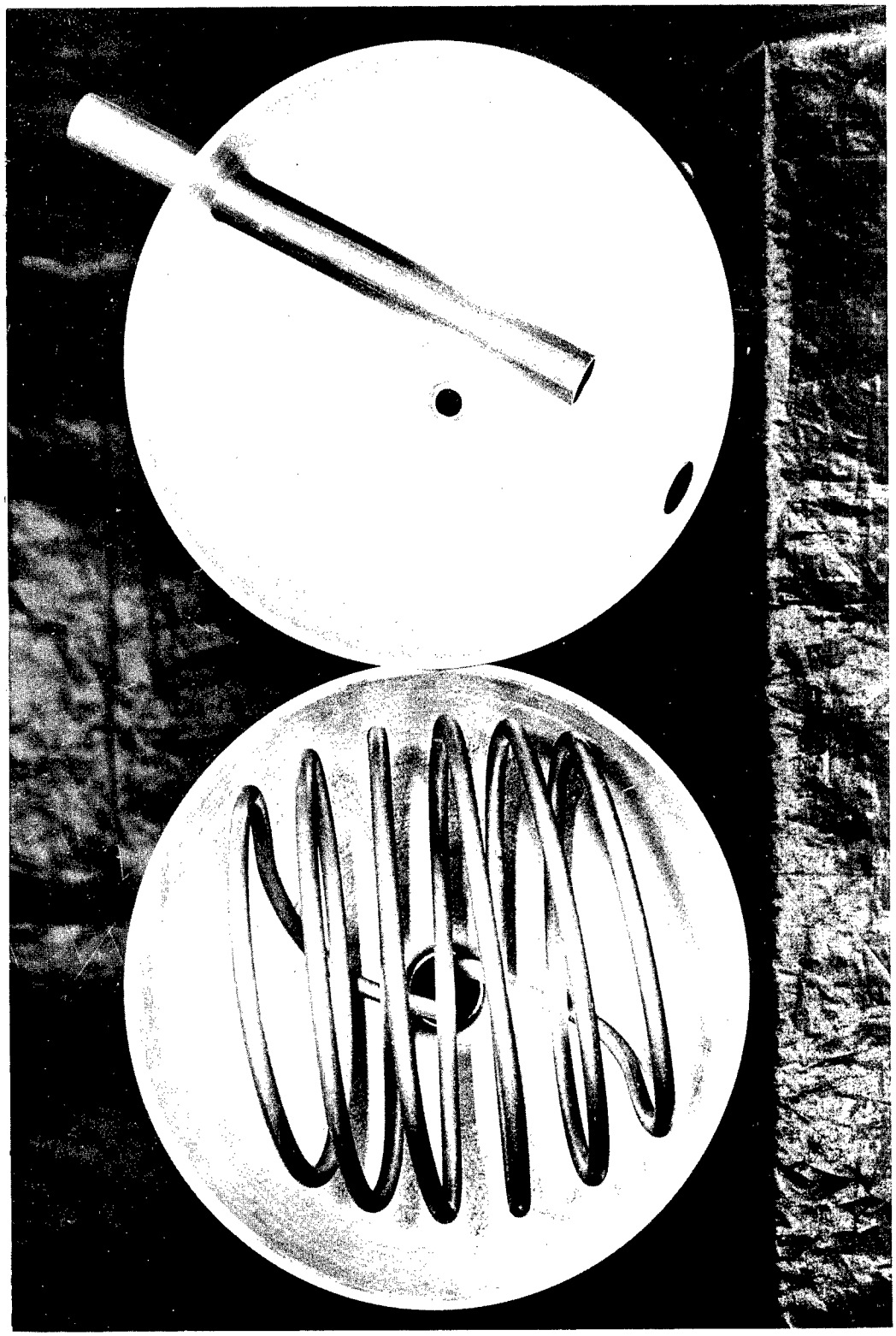


Fig. 4b—Cooling coil.

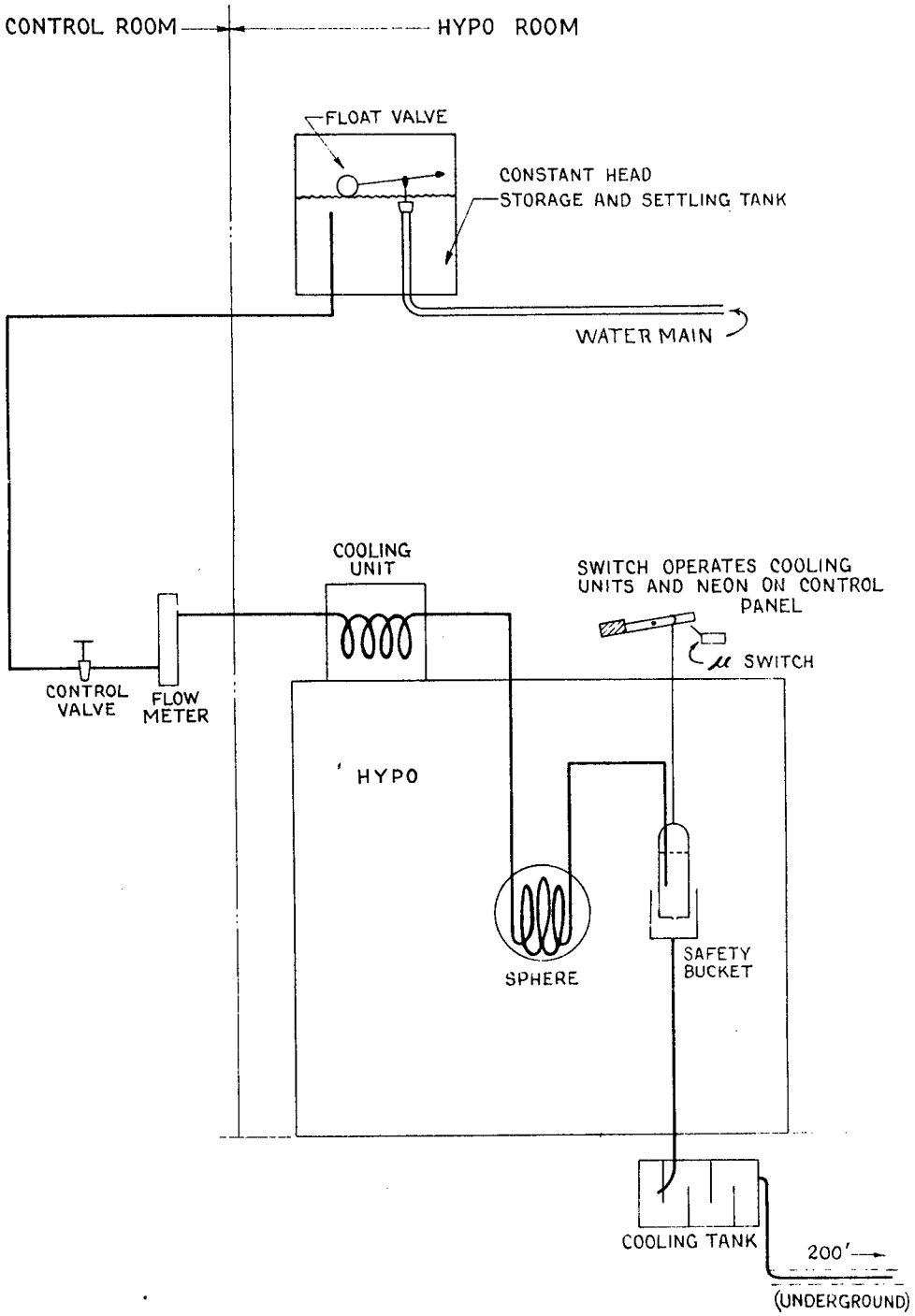


Fig. 4c — Water-cooling system.

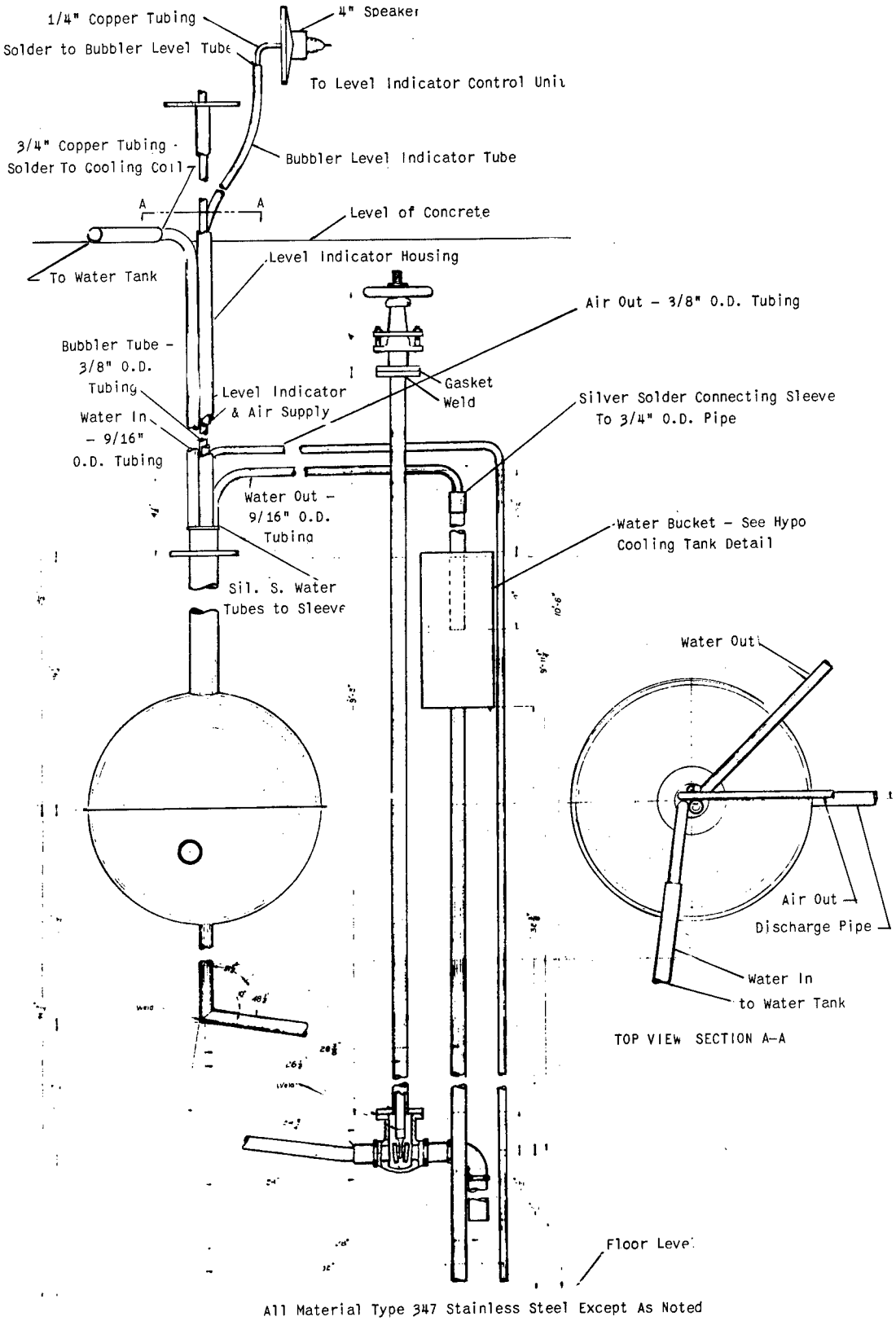


Fig. 5—Outlet of cooling coil. All material is type 347 stainless steel except as noted.

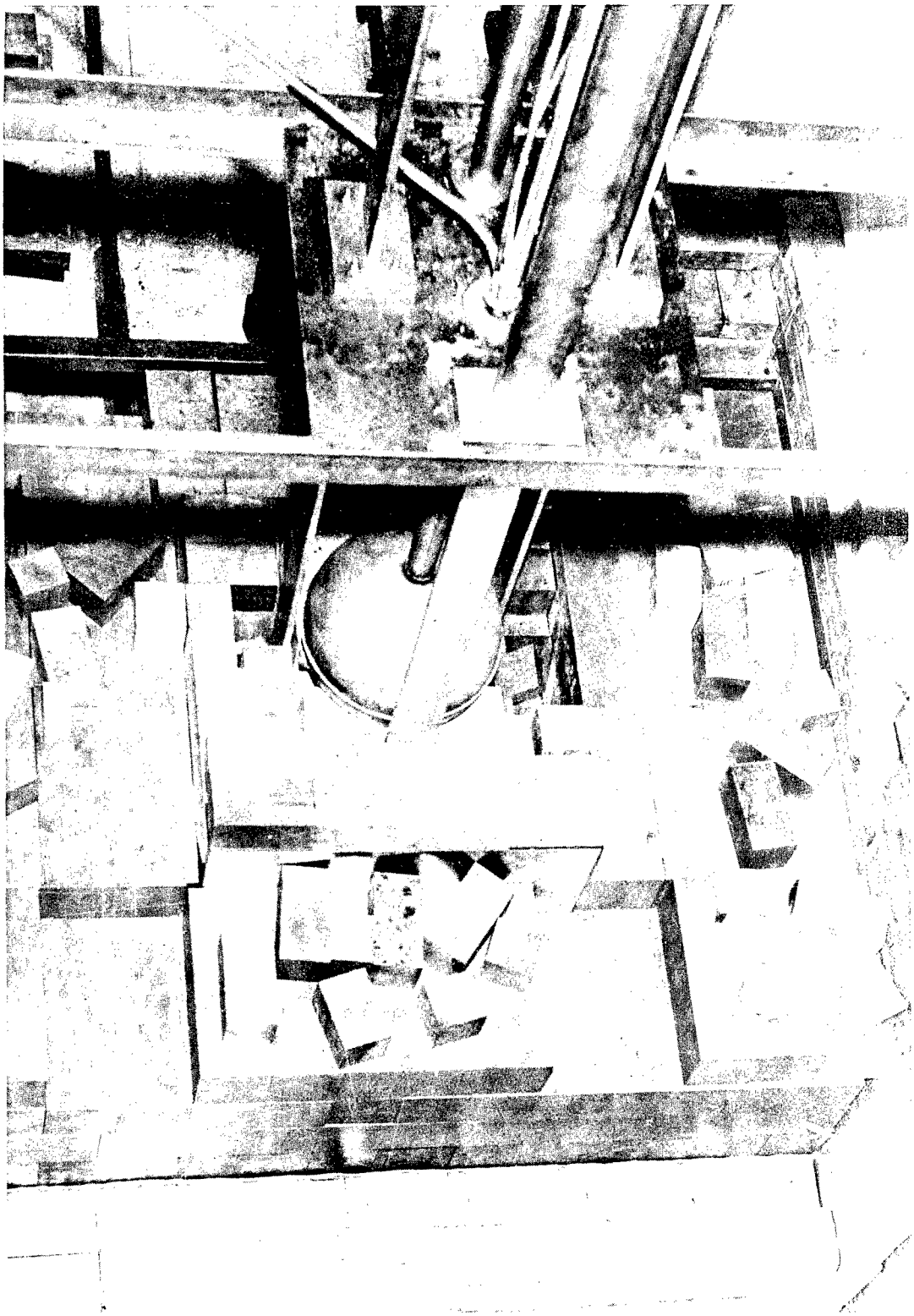


Fig. 6—Tamper.

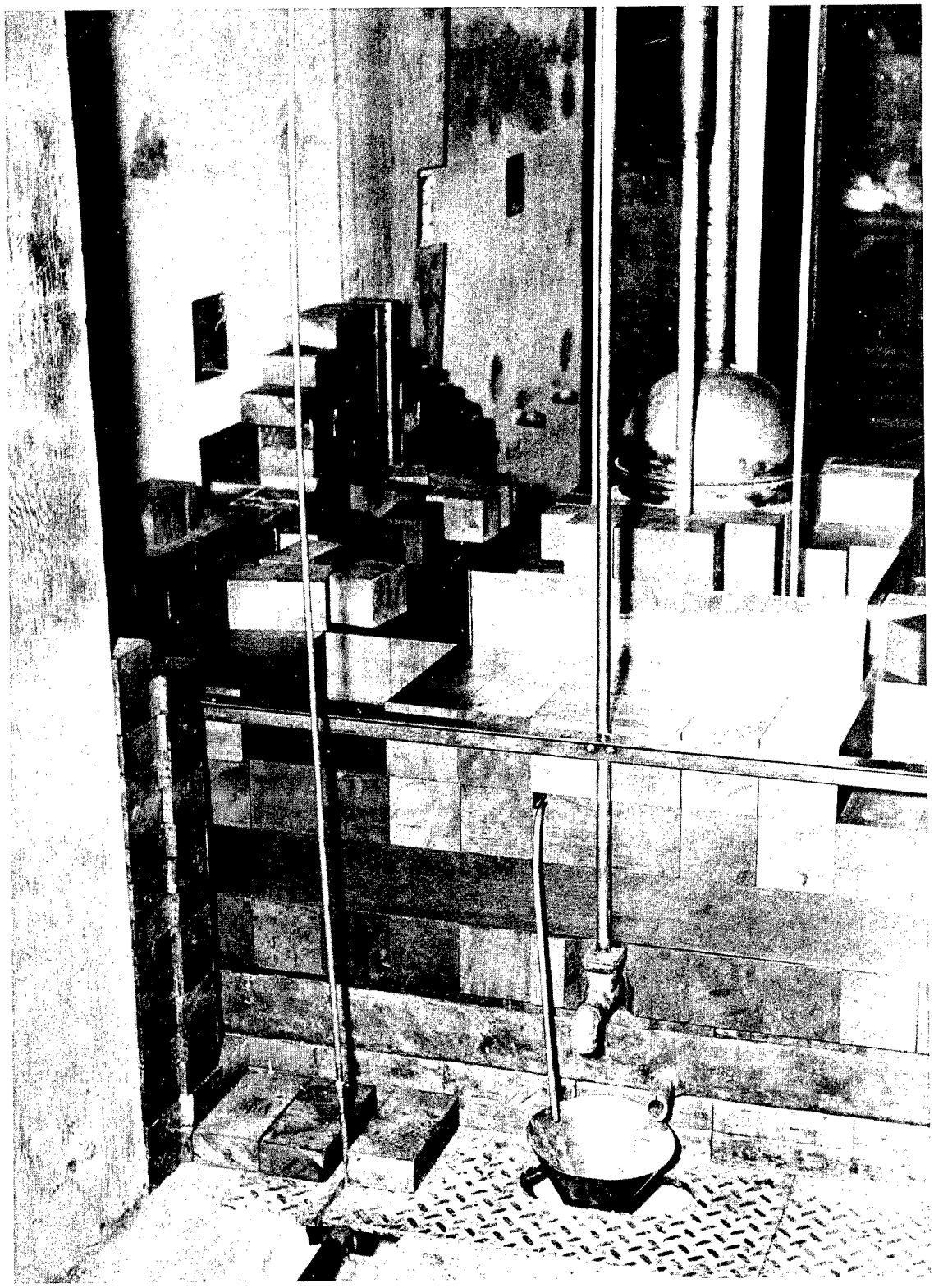


Fig. 7 —View of tamper showing drip pan.

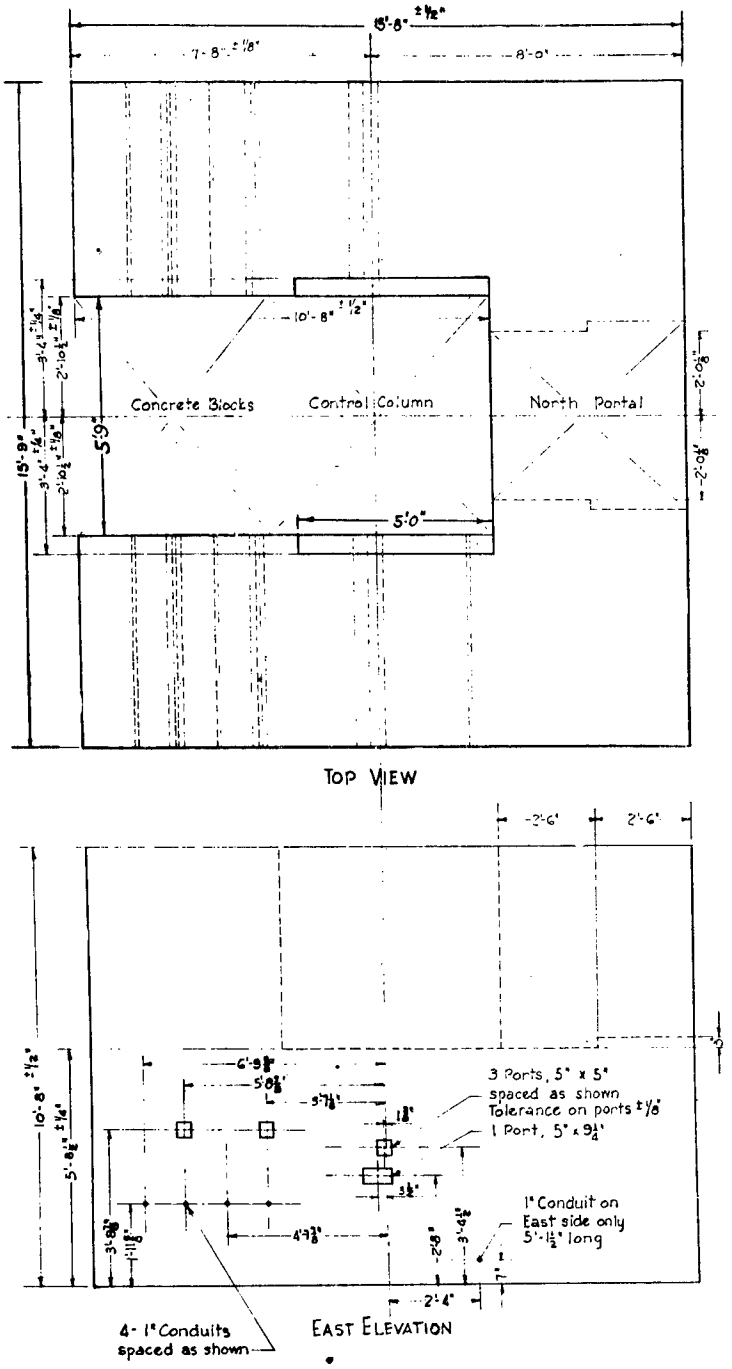


Fig. 8 — Tamper diagram.

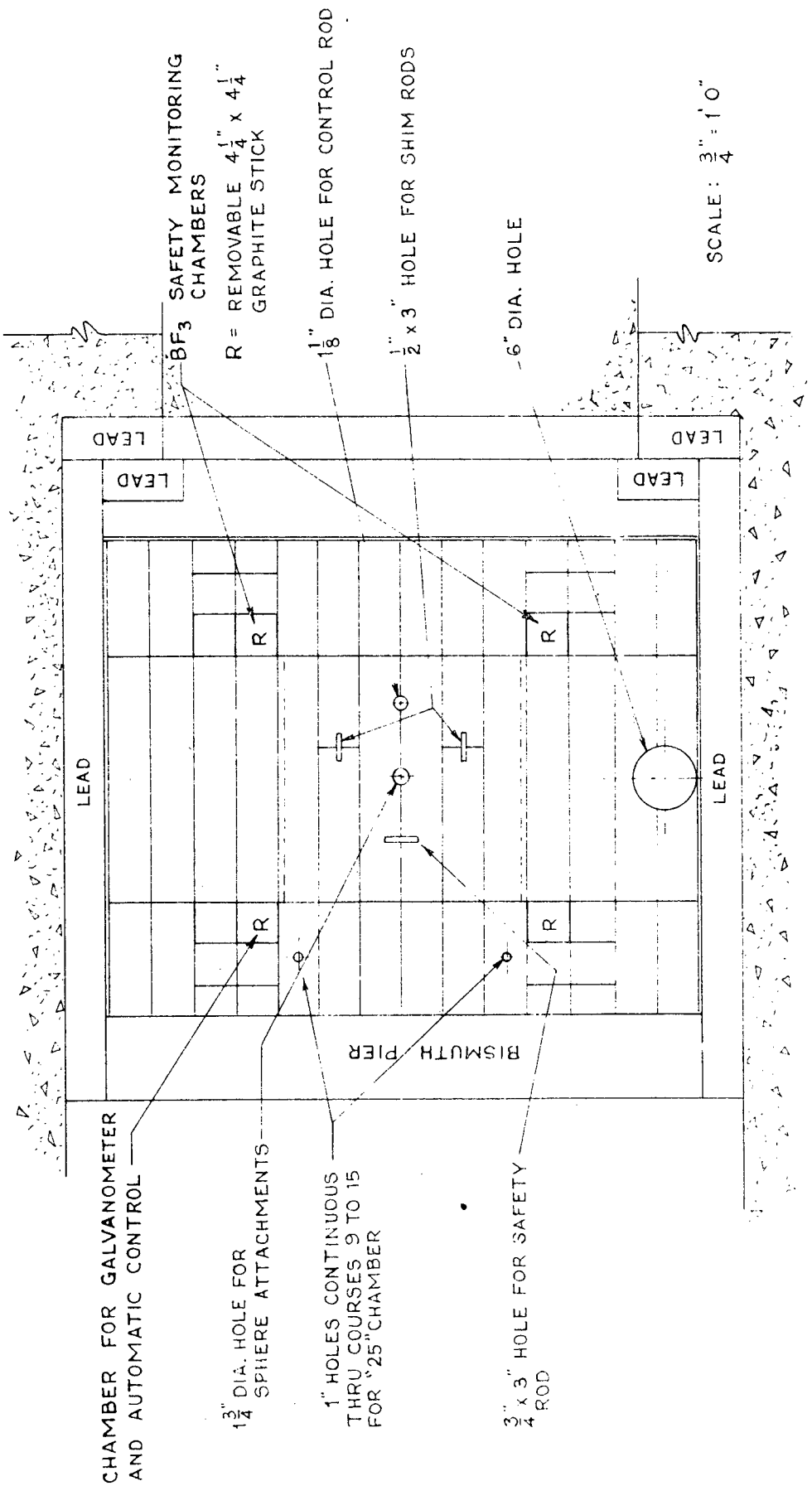


Fig. 9—Top view of tamper.

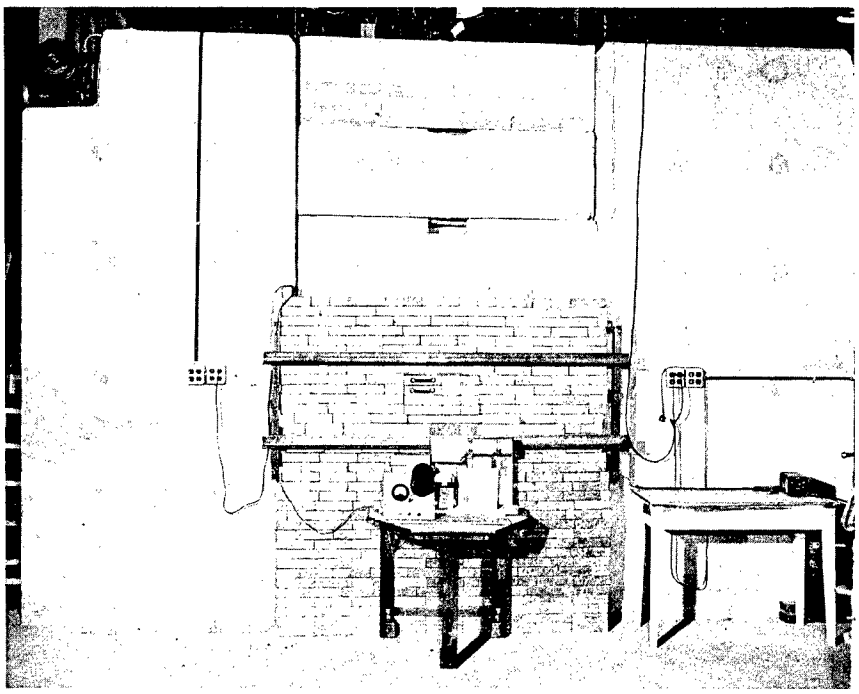


Fig. 10a—Thermal column.

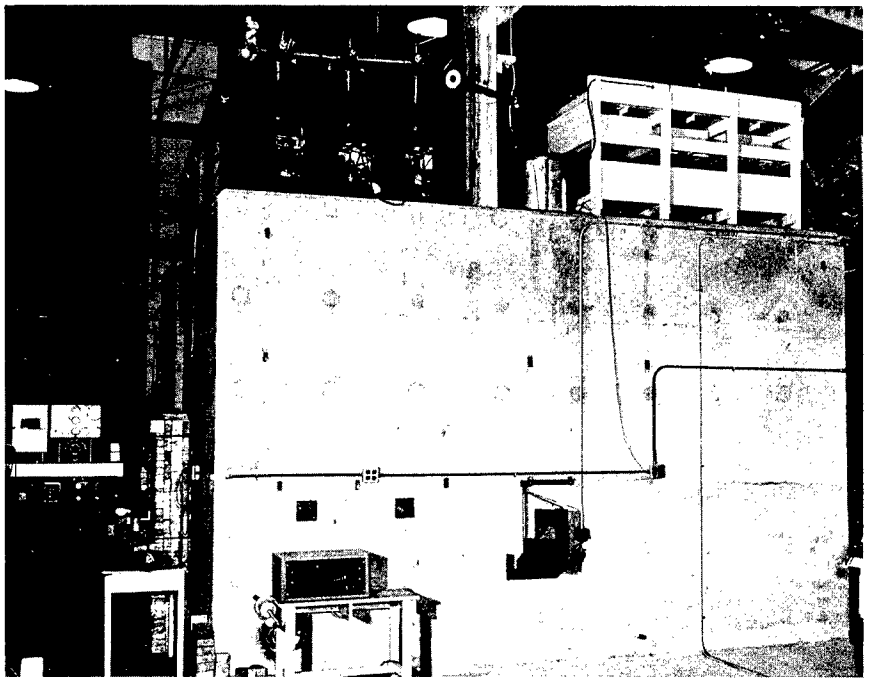


Fig. 10b—Thermal column showing ports opposite the sphere.

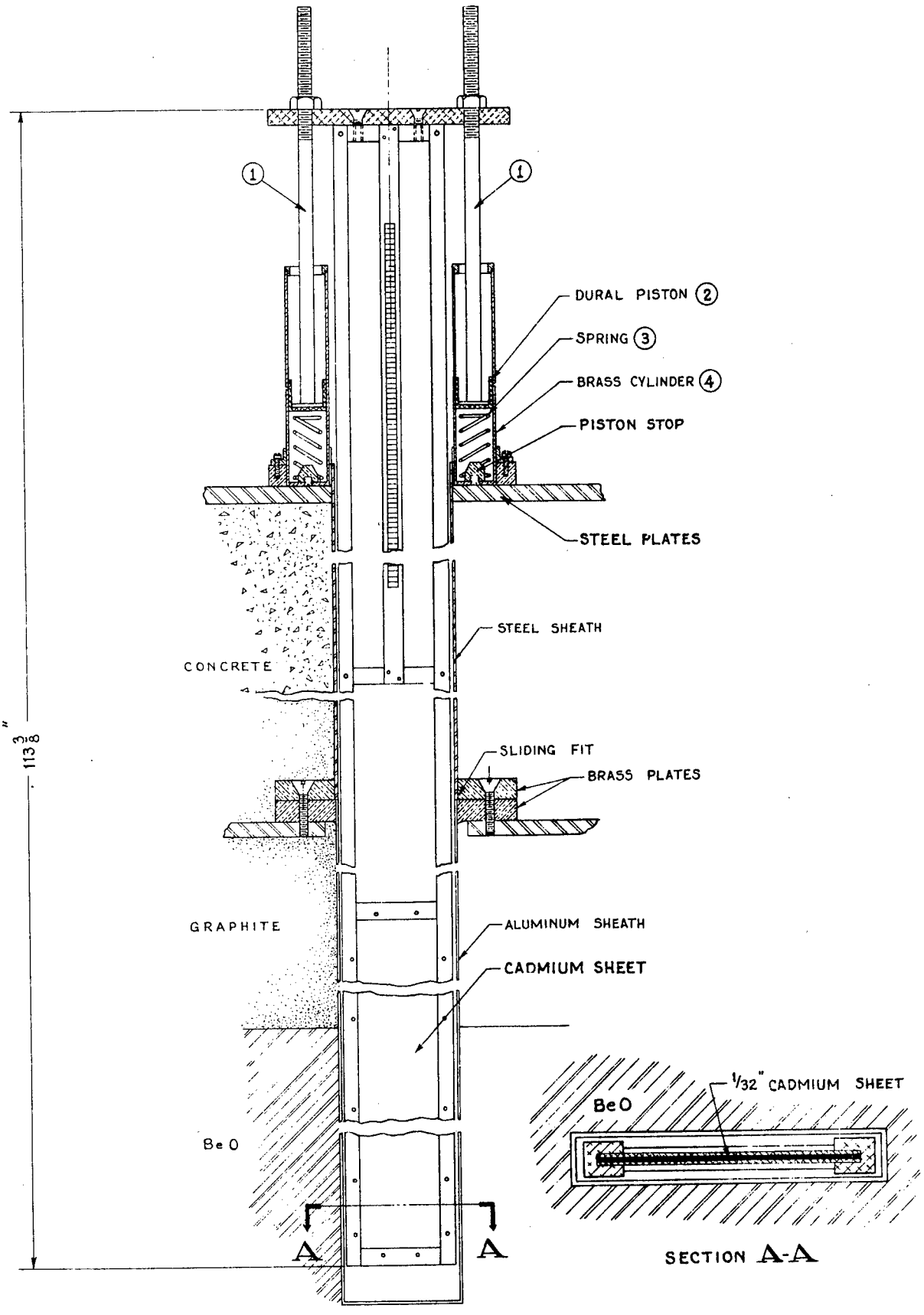
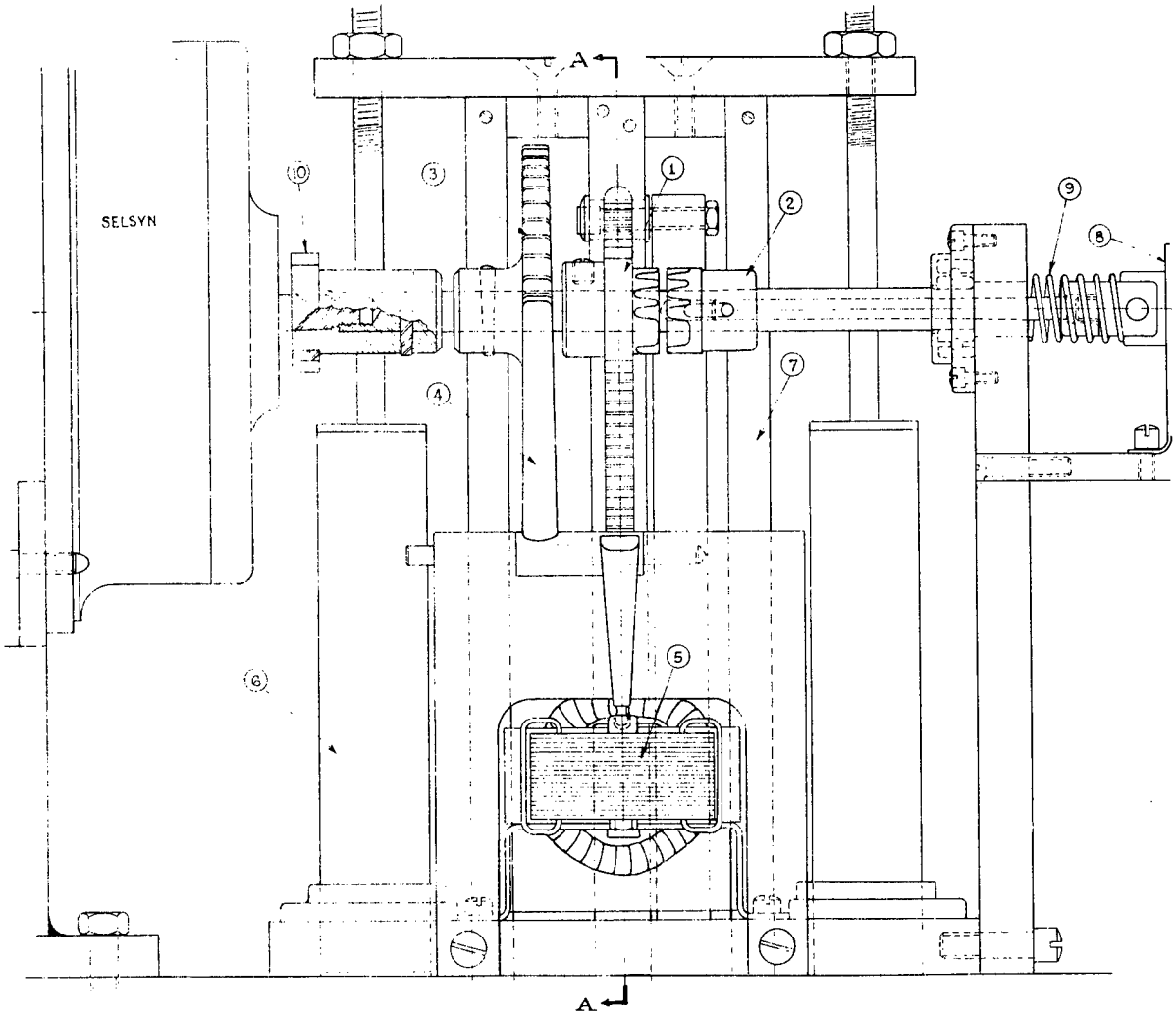


Fig. 11 — Shim-rod assembly.



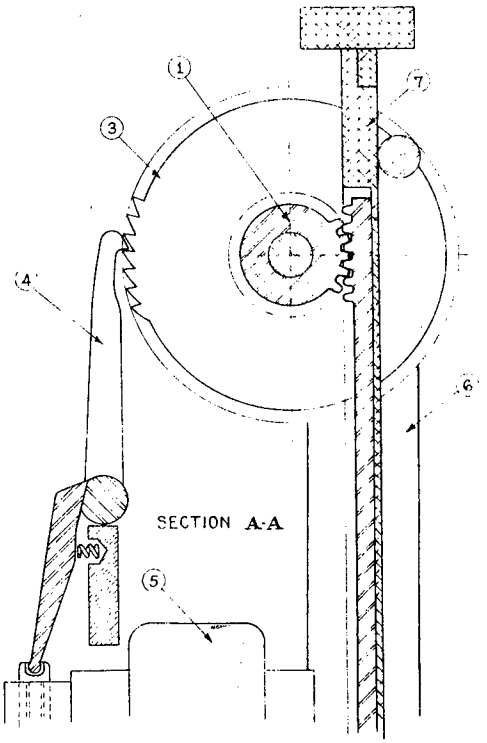


Fig. 12a—Shim-rod driving mechanism.

(1) Pinion gear	(6) Piston brakes
(2) Coupling	(7) Shim rod
(3) Ratchet gear	(8) Coupling solenoid
(4) Ratchet	(9) Decoupling spring
(5) Ratchet solenoid	(10) Automatic control gear

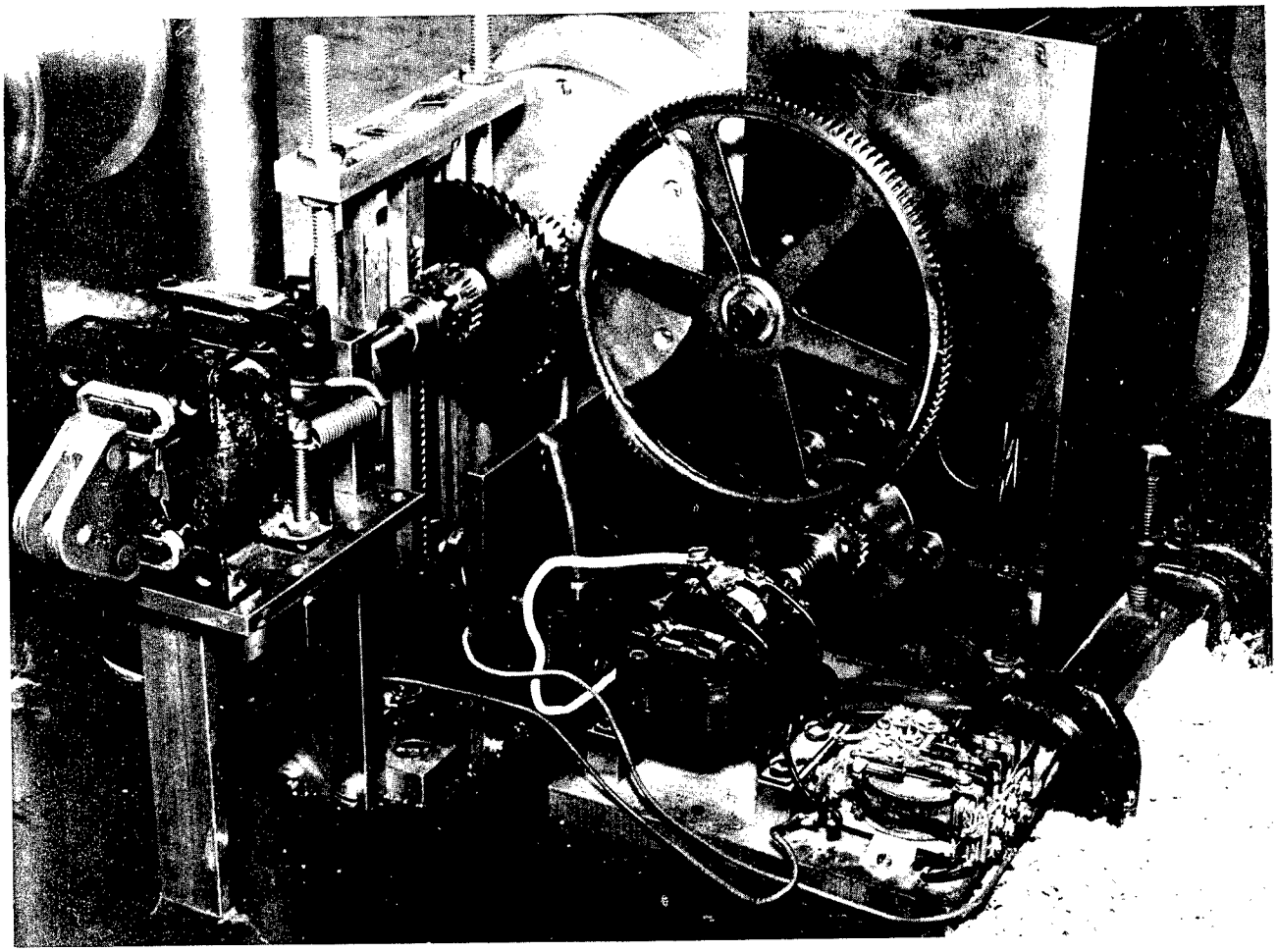


Fig. 12b—Shim-rod driving mechanism.

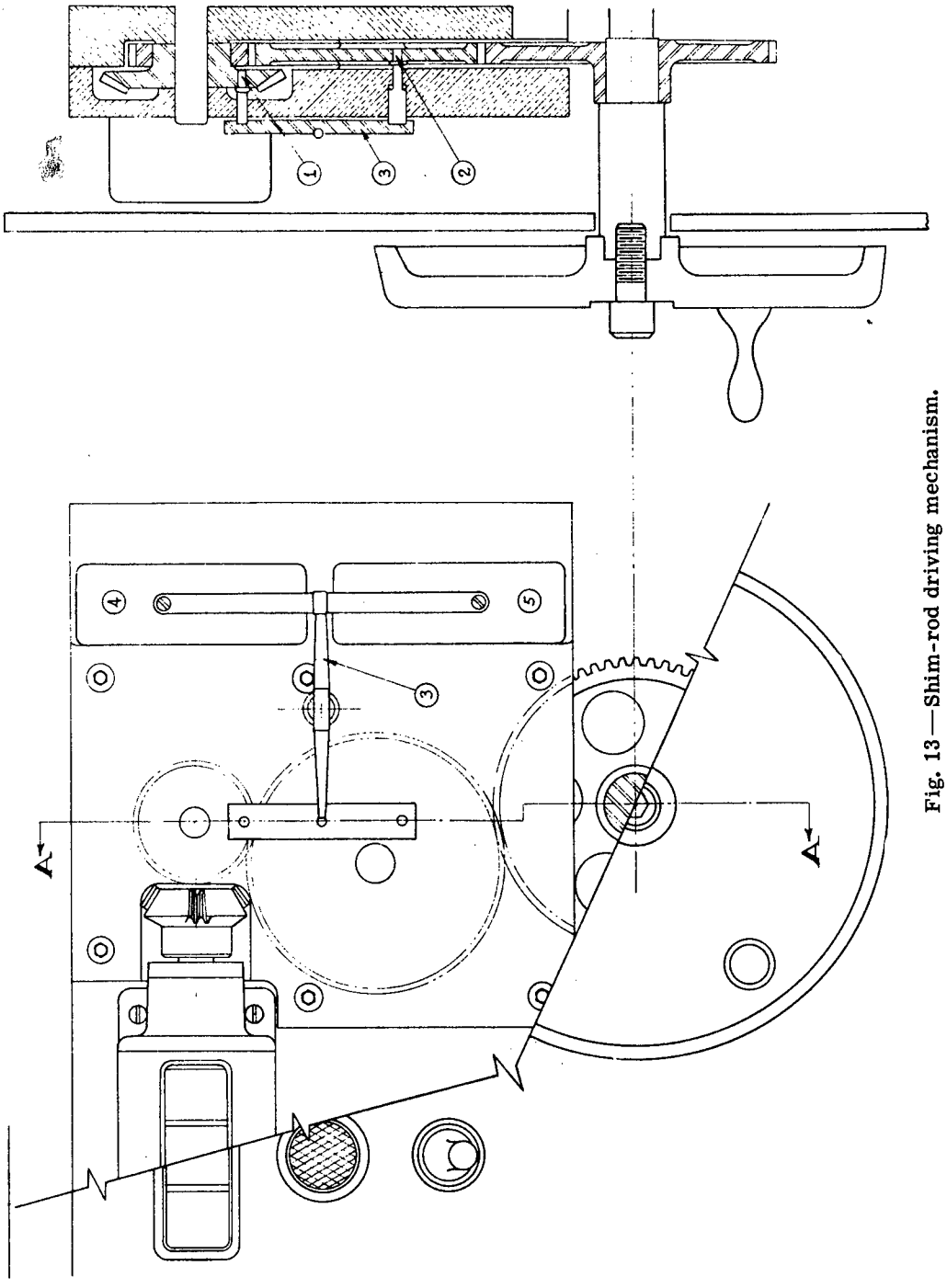


Fig. 13—Shim-rod driving mechanism.

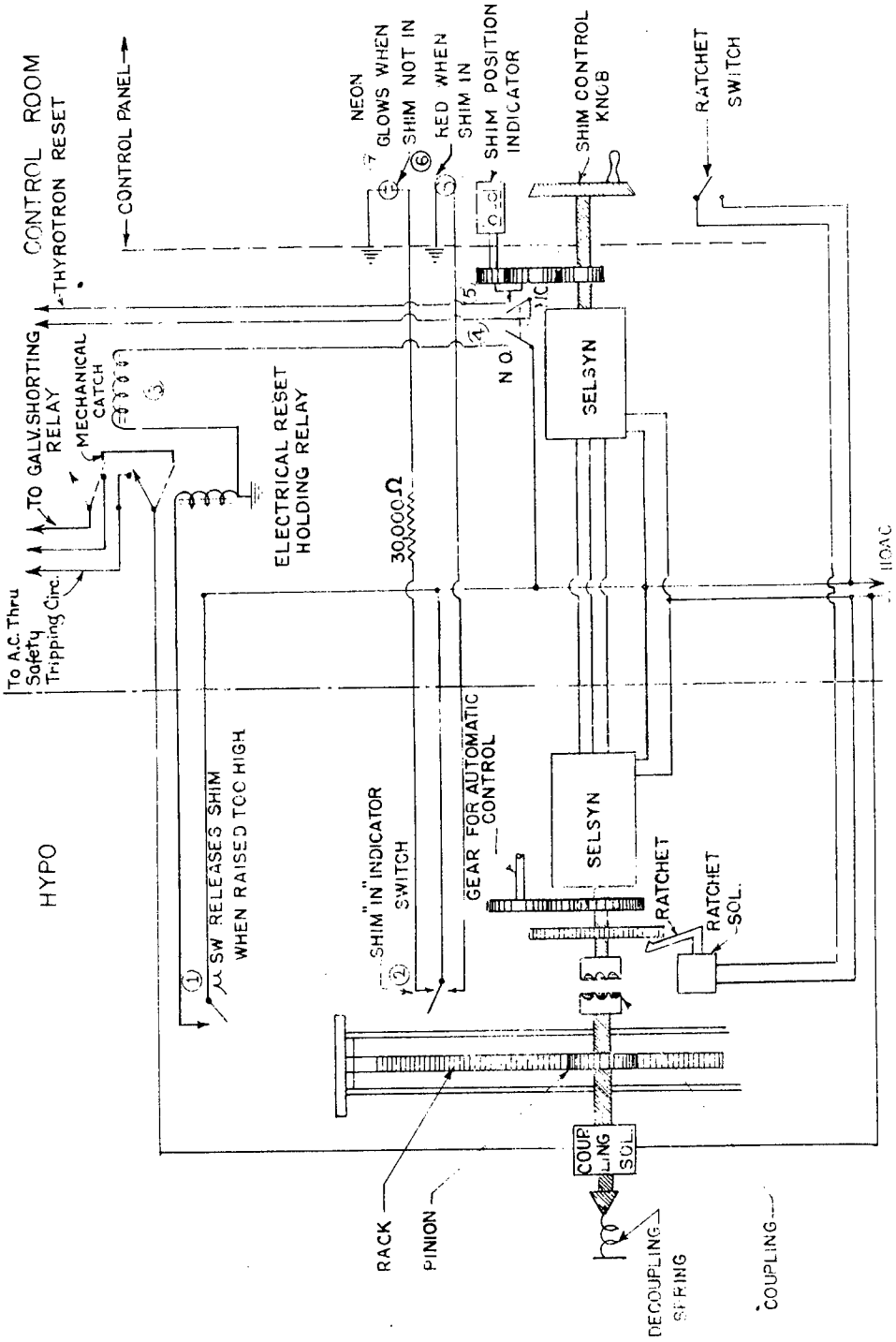


Fig. 14—Shim-rod control panel.

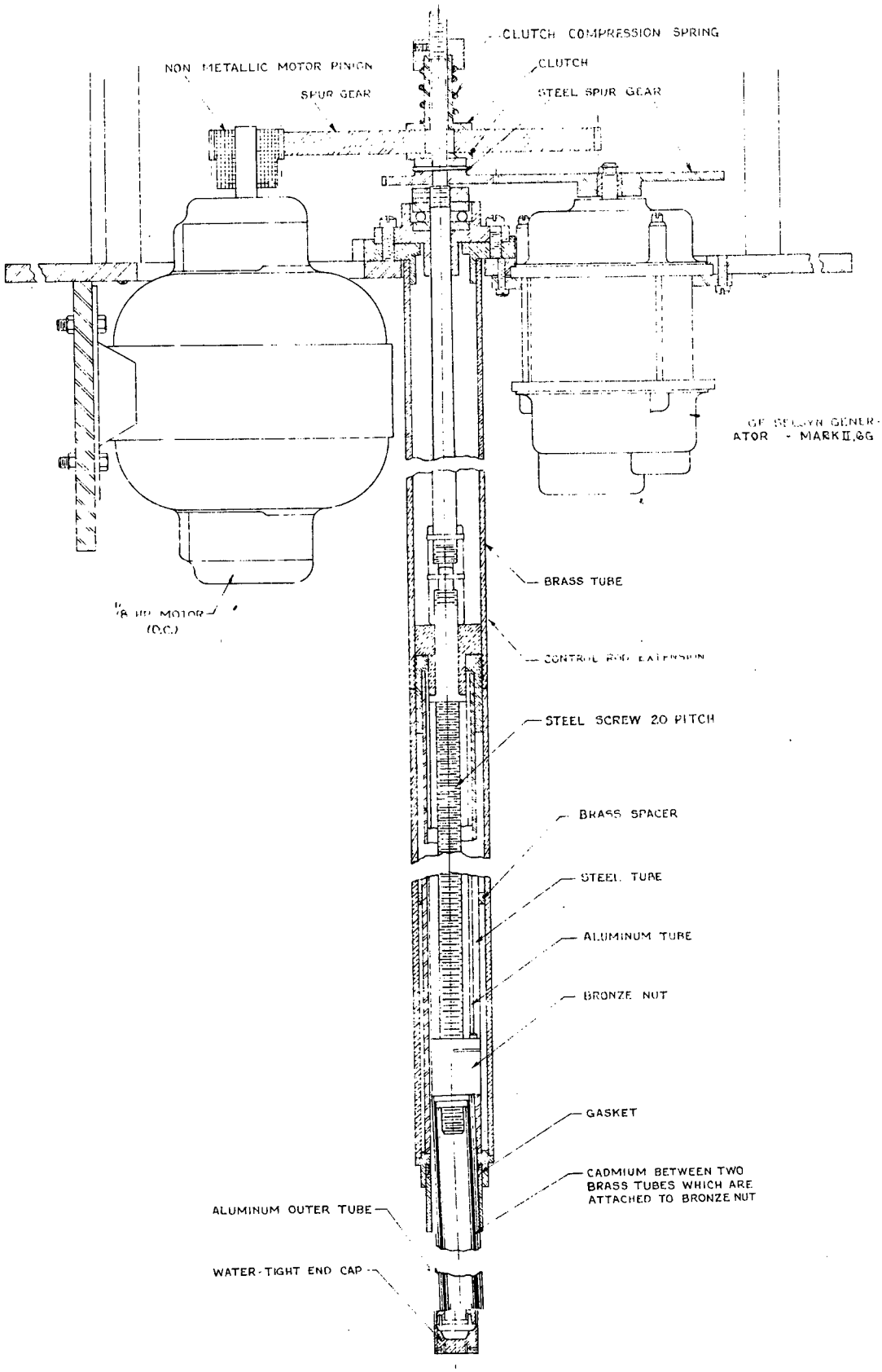


Fig. 15—Control rod.

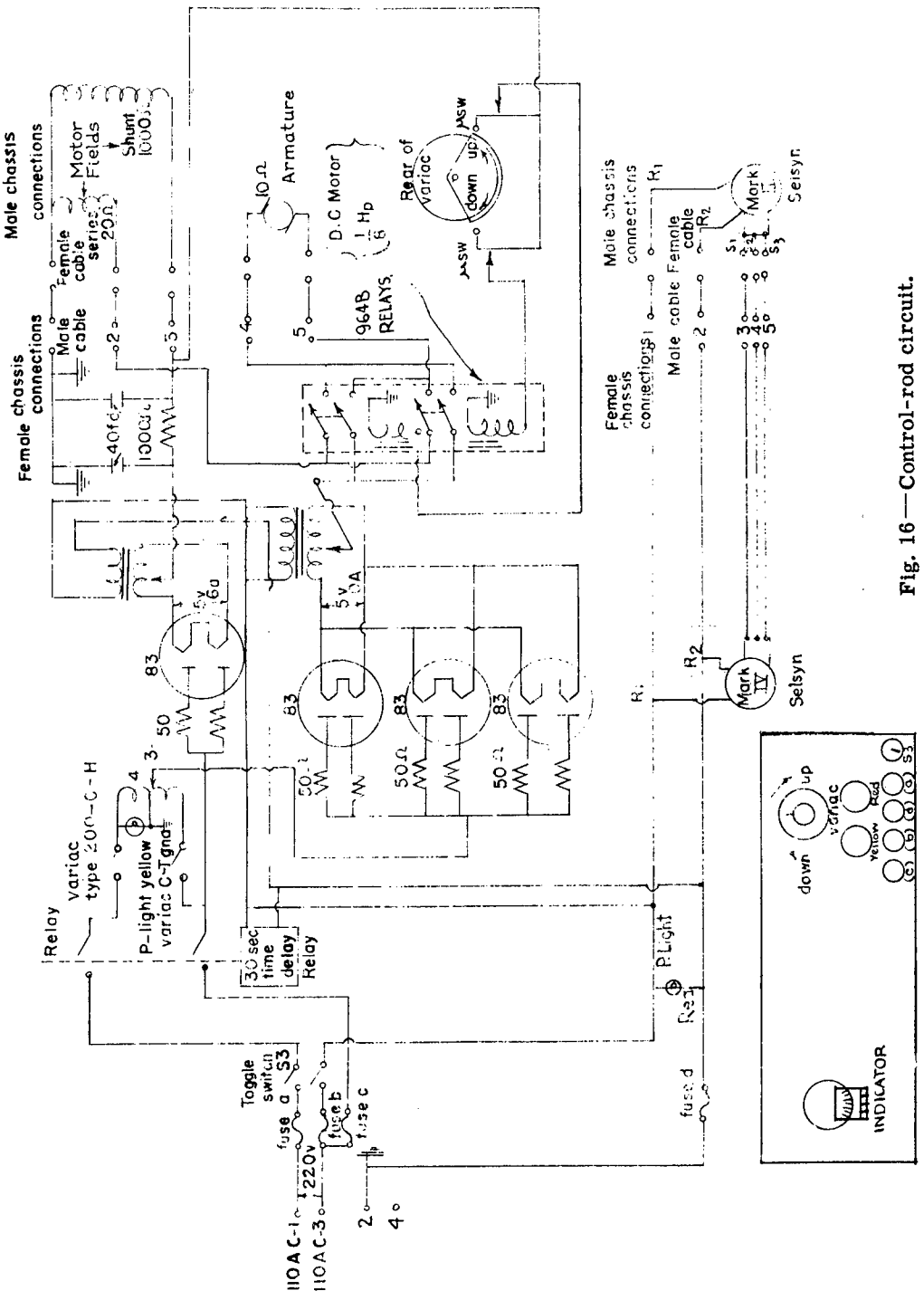


Fig. 16—Control-rod circuit.

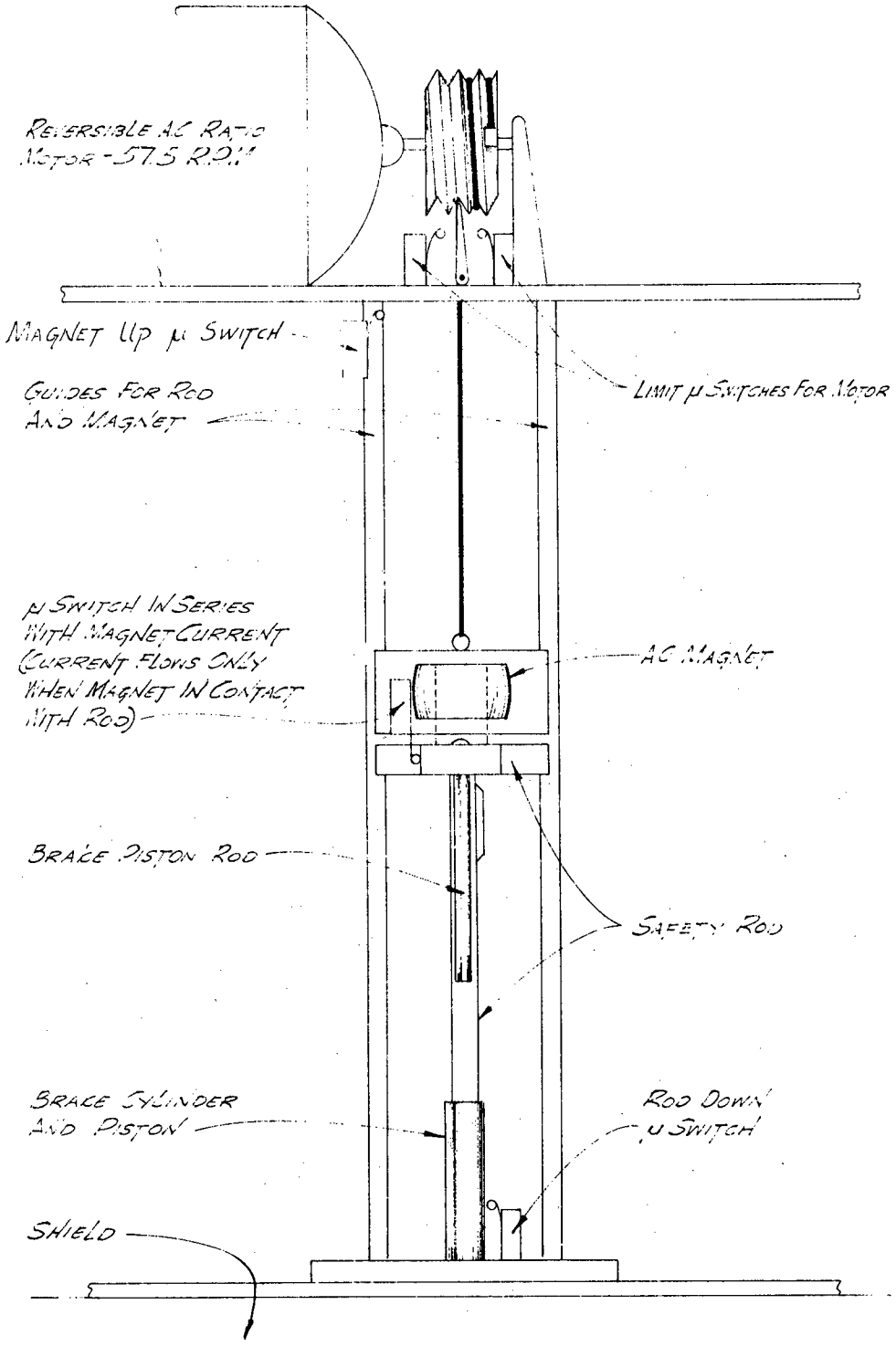


Fig. 17 — Schematic diagram of safety rod.

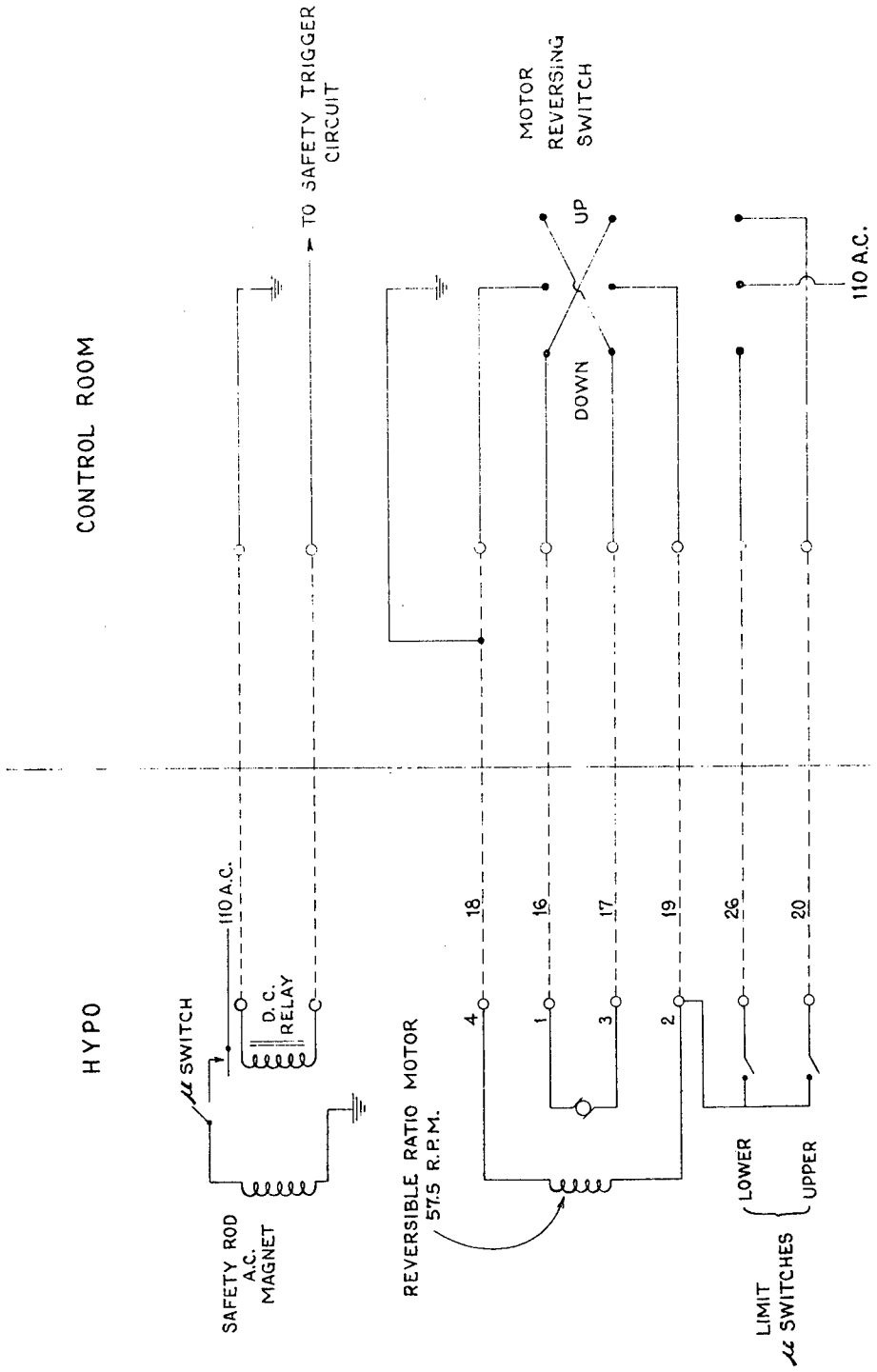


Fig. 18 --- Safety-rod circuit.

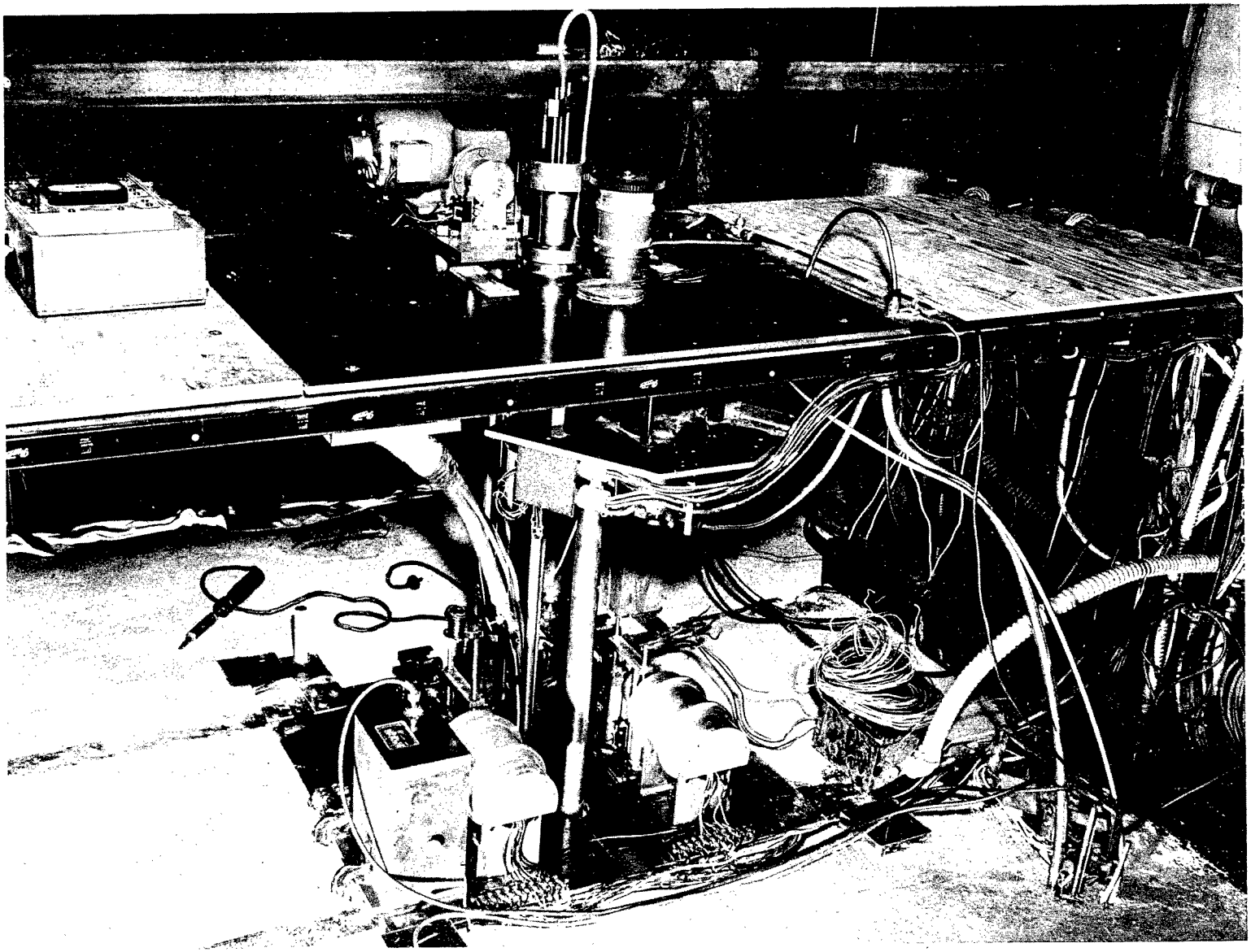


Fig. 19—Two shim selsyns (the automatic-control gear box attached to the left-hand one), the control-rod mechanism suspended from the upper iron plate, the safety-rod mechanism on top, the level indicator with its selsyn, and the water inlet.

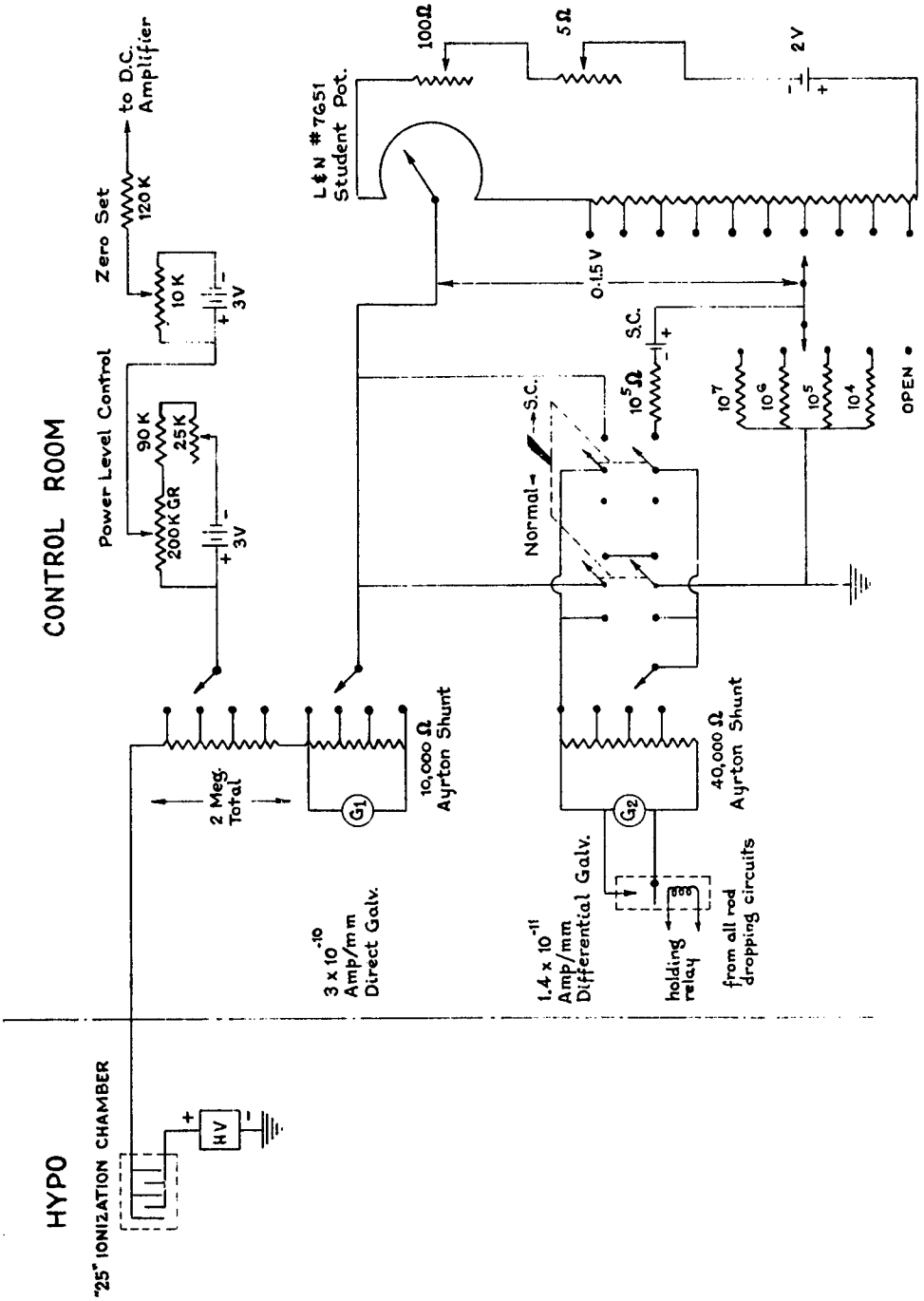


Fig. 20-- Galvanometer and automatic-control input circuit.

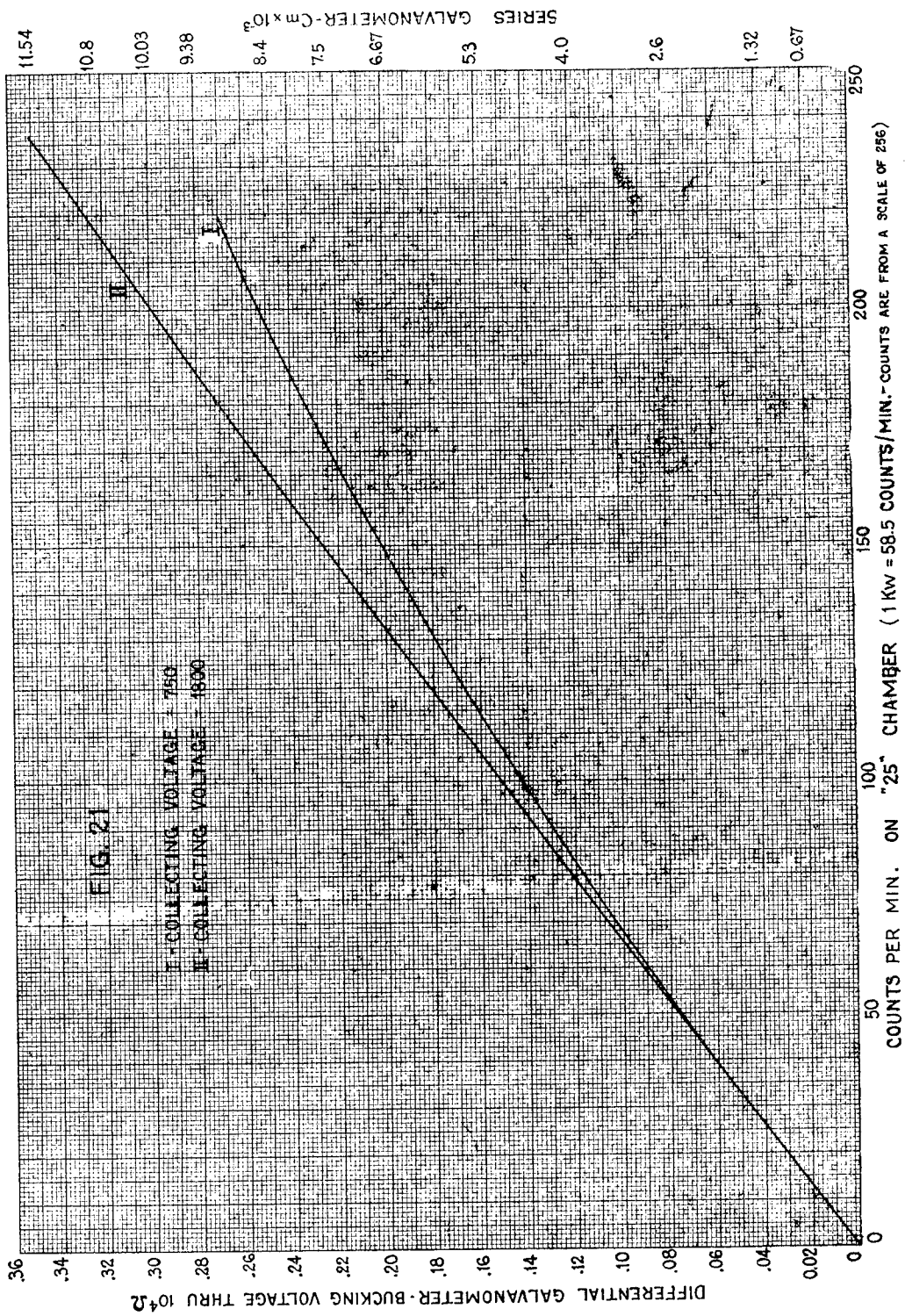


Fig. 21—Curve of galvanometer bucking voltage vs. counts from a 25 counter. I, collecting voltage, 750; II, collecting voltage, 1800.

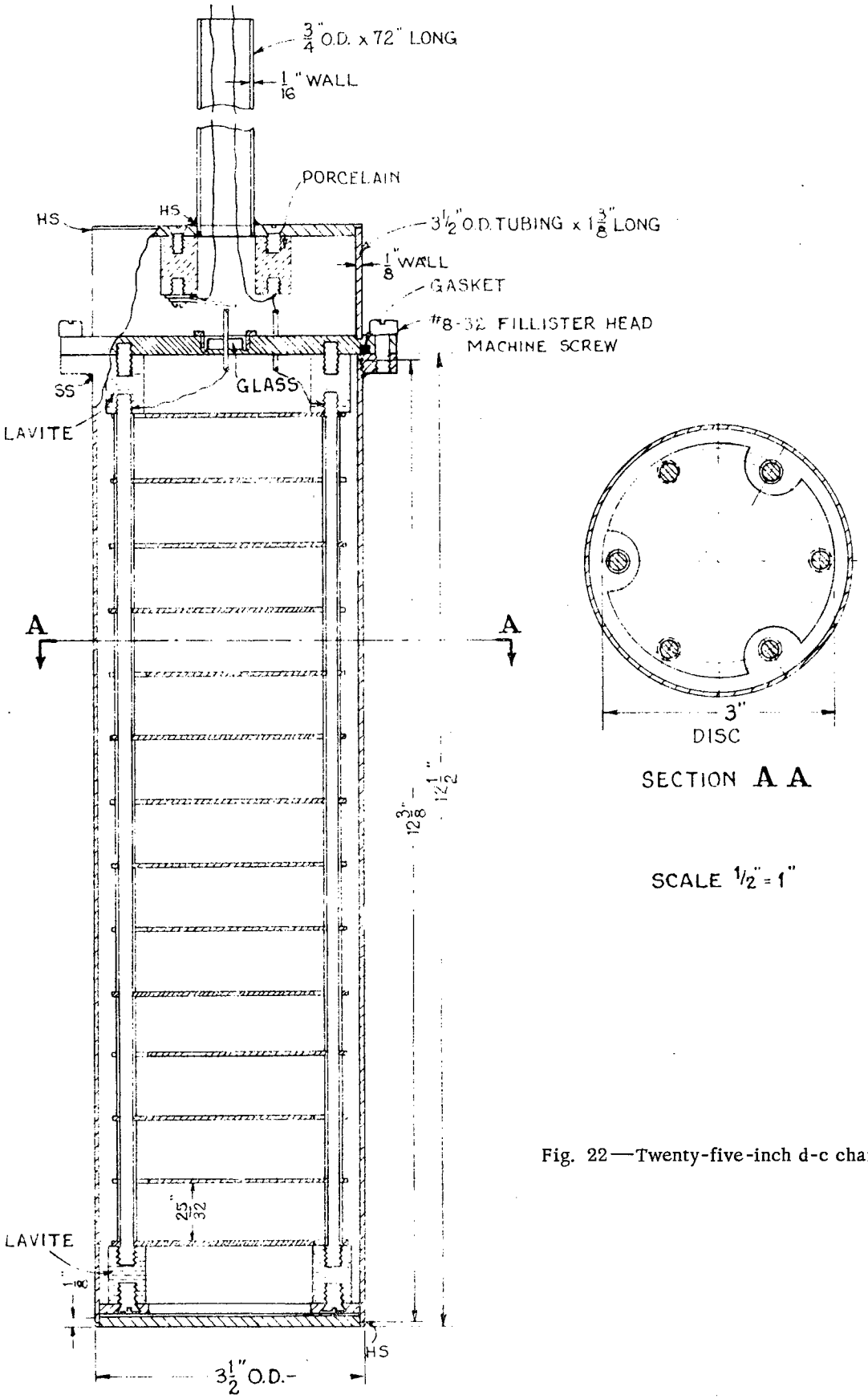


Fig. 22—Twenty-five-inch d-c chamber.

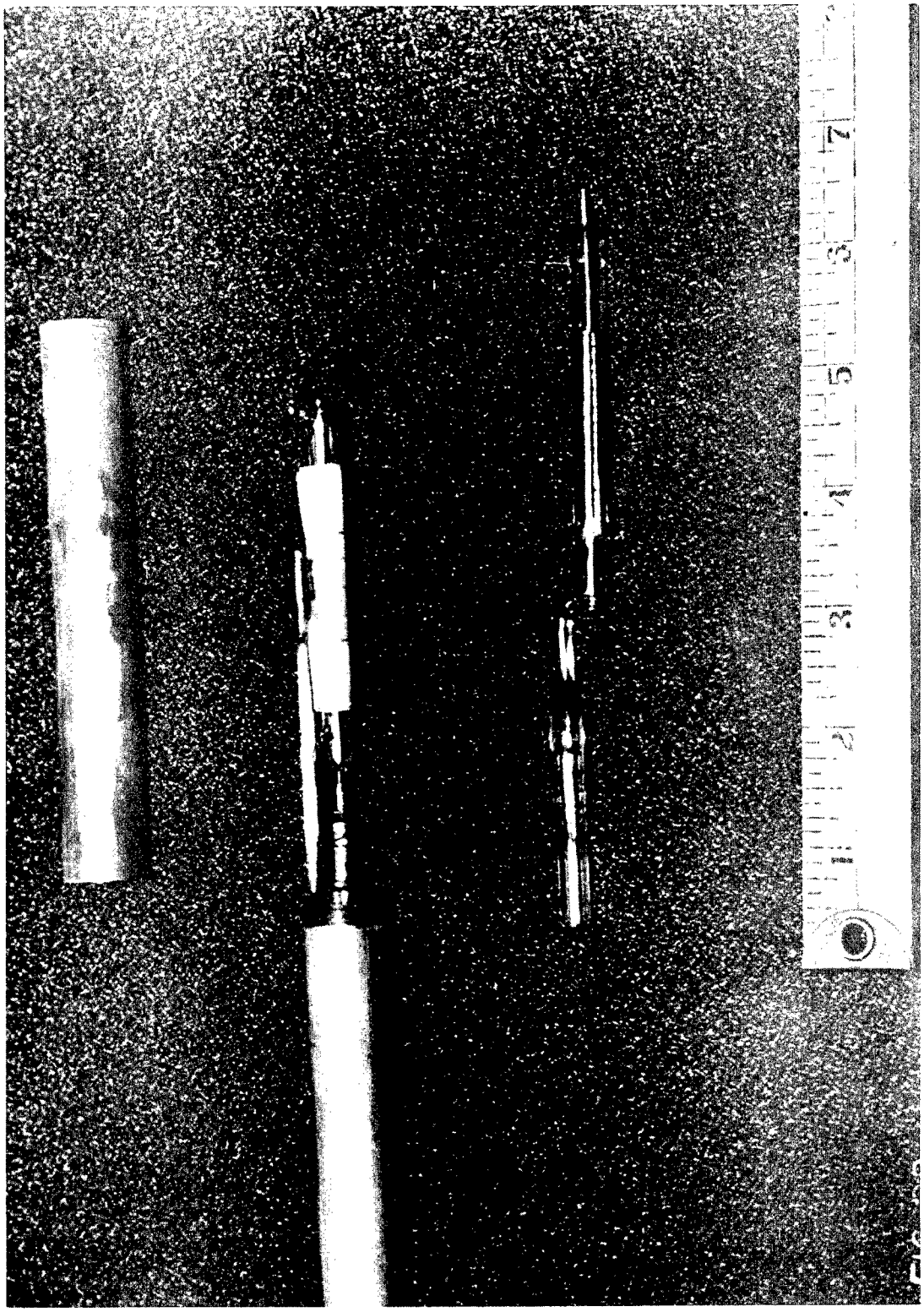


Fig. 23—Midget 25 ionization chamber.

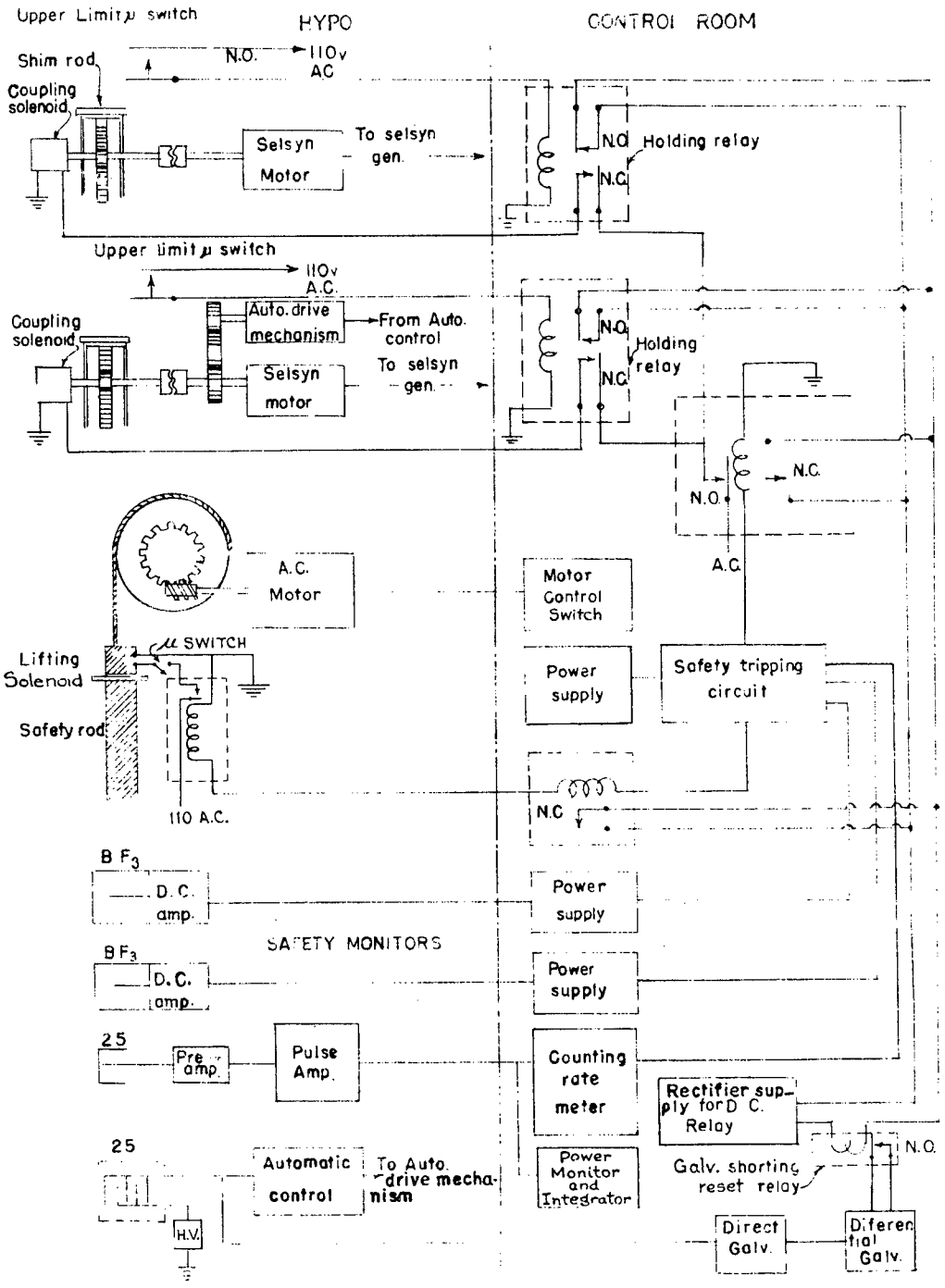


Fig. 24 — Safety circuit.

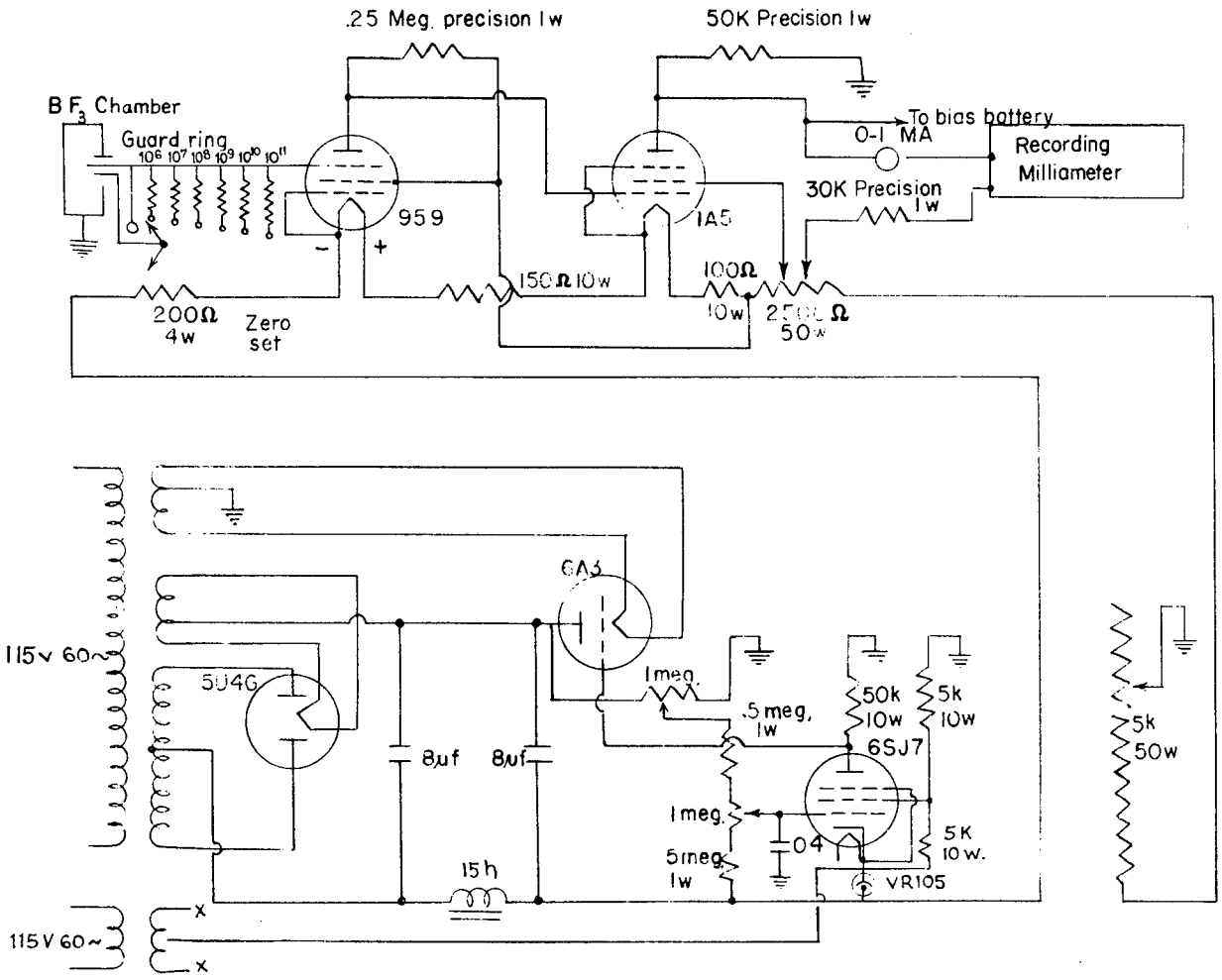


Fig. 25—Direct-current amplifier of the safety monitor.

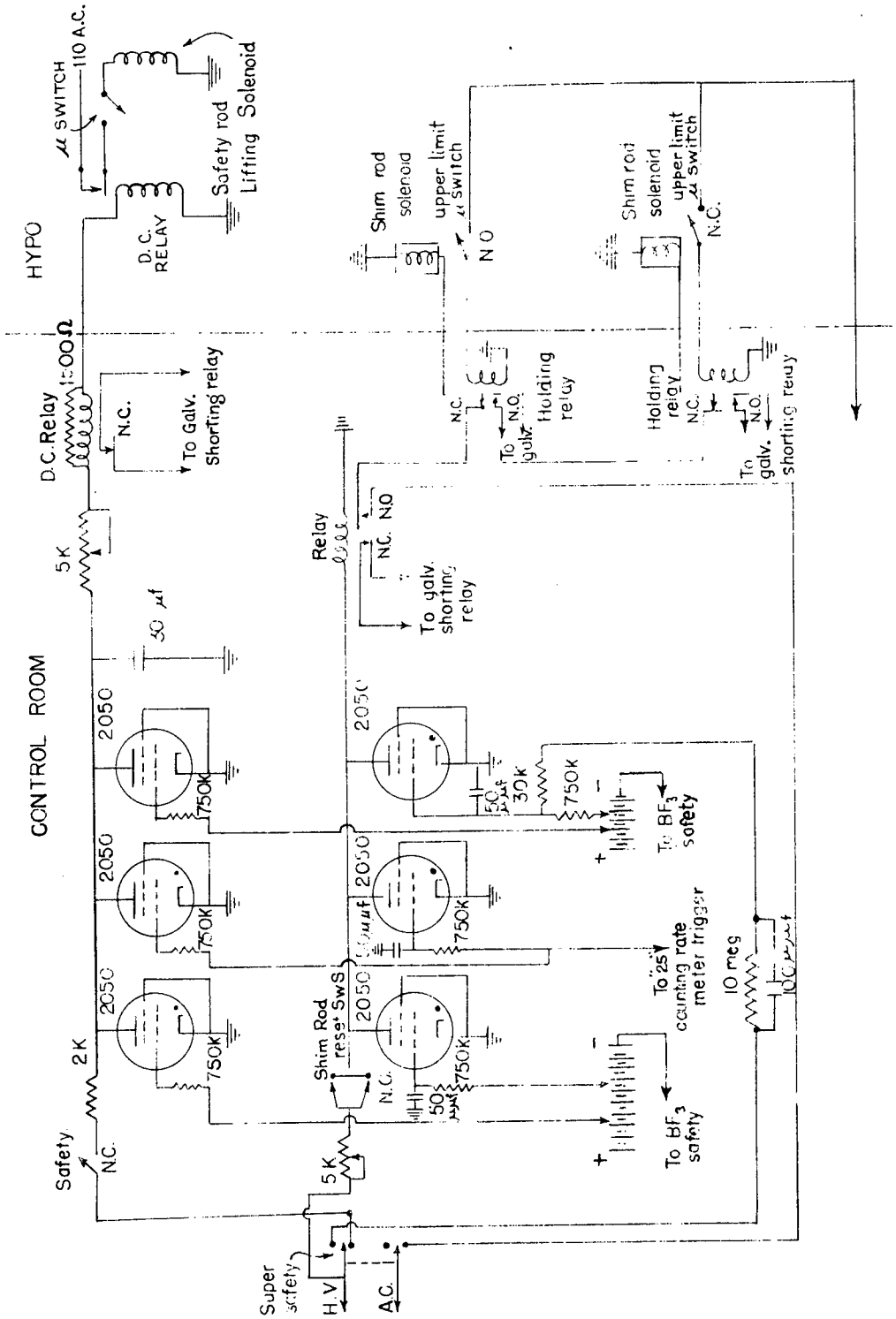
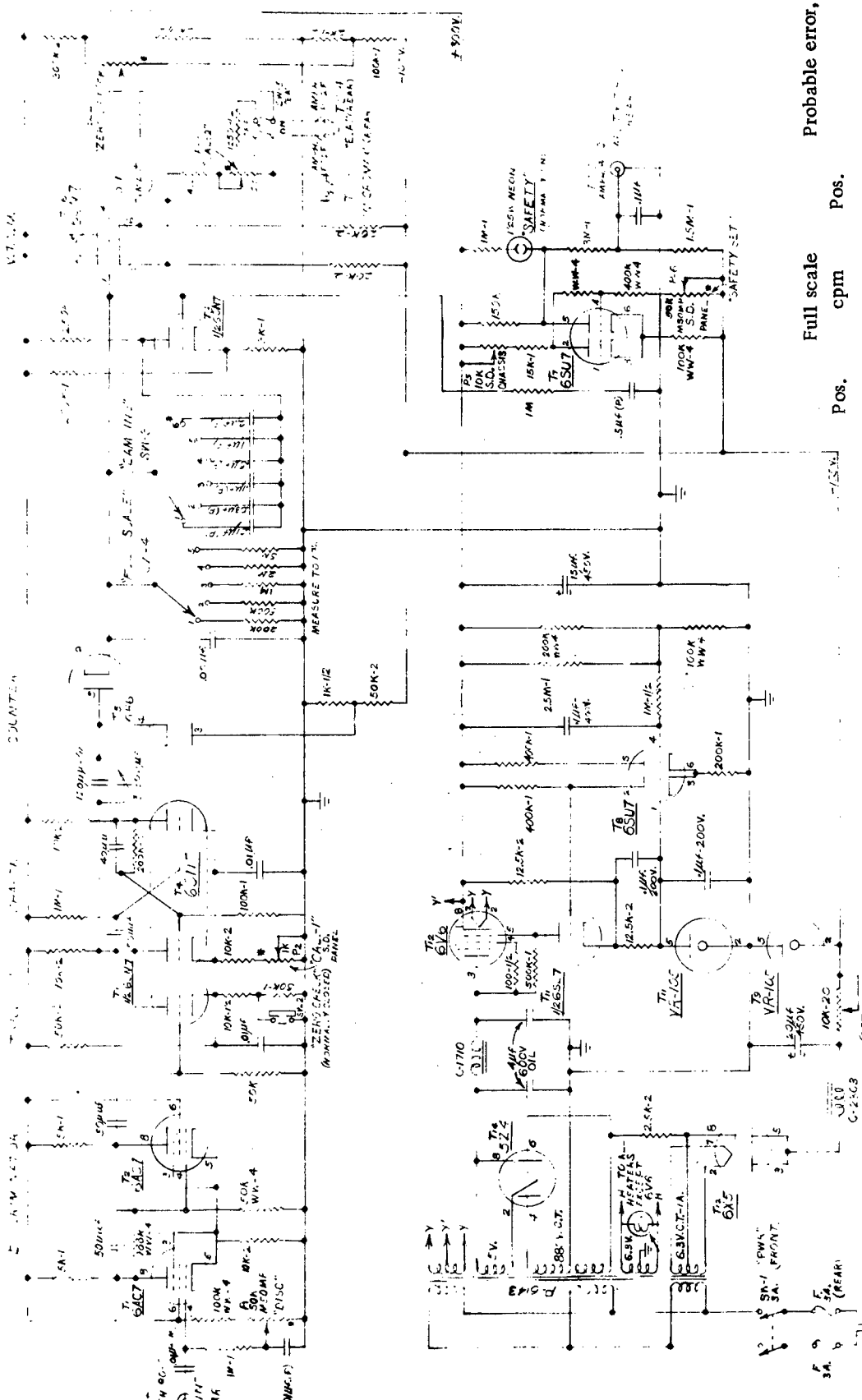


Fig. 26a—Safety tripping circuit.



Pos.	Full scale cpm	Pos.	Probable error,
1	2,000	1	20
2	5,000	2	10
3	10,000	3	6
4	20,000	4	3
5	50,000	5	2
		6	1.5

Fig. 26b—Counting-rate meter, Model 100.

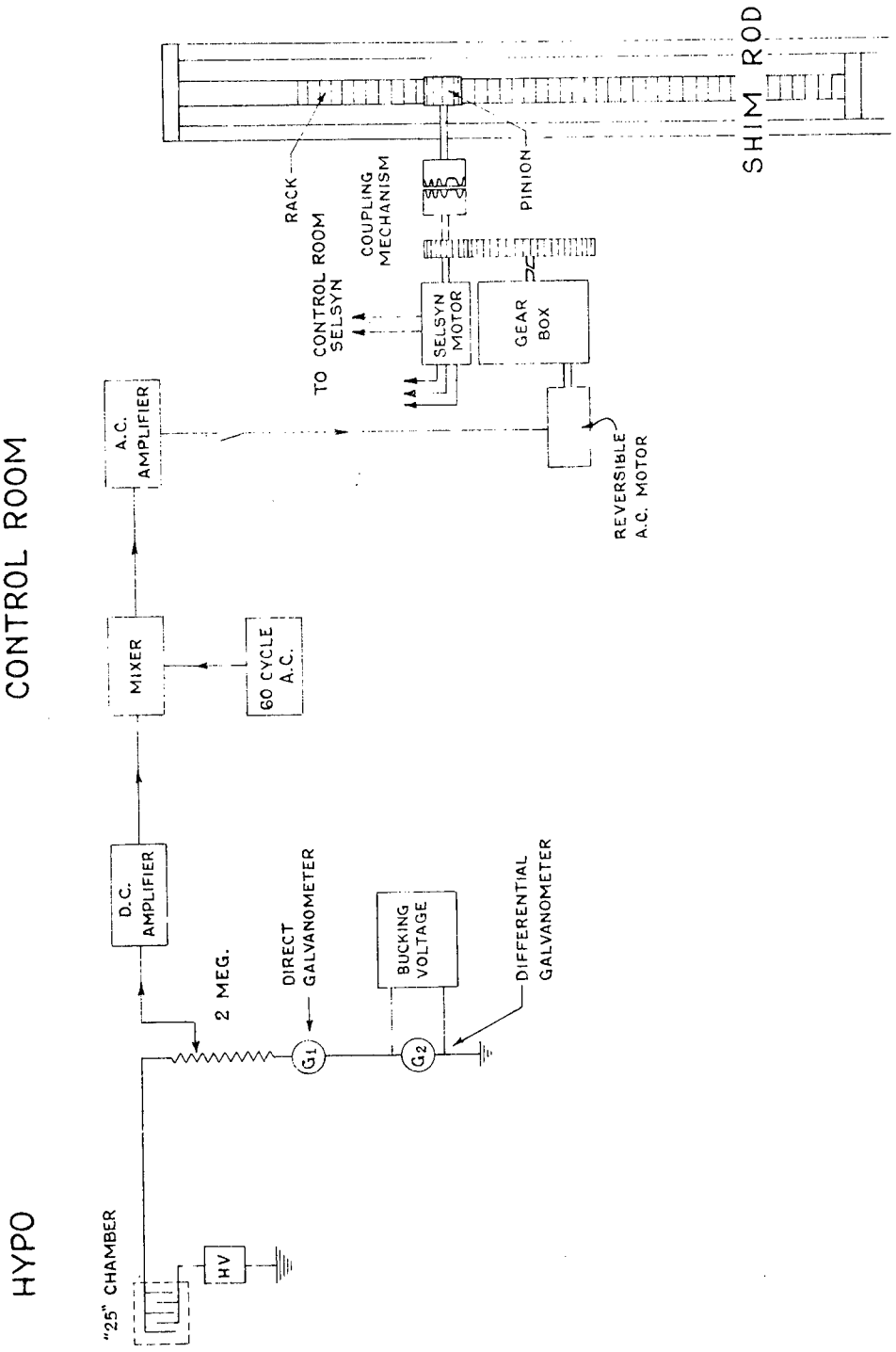


Fig. 27-- Automatic-control diagram.

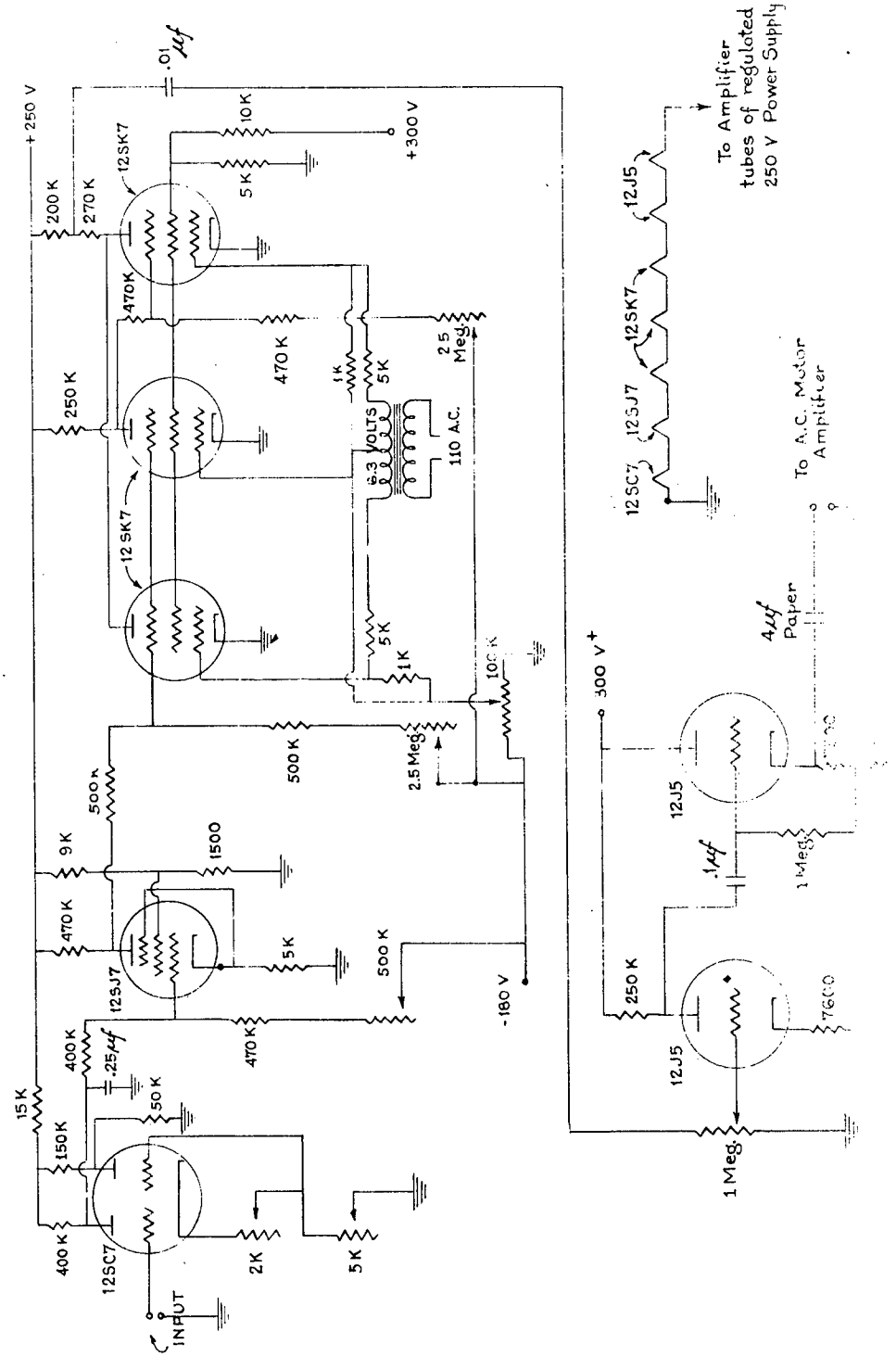


Fig. 28--Direct-current amplifier and mixer for automatic control.

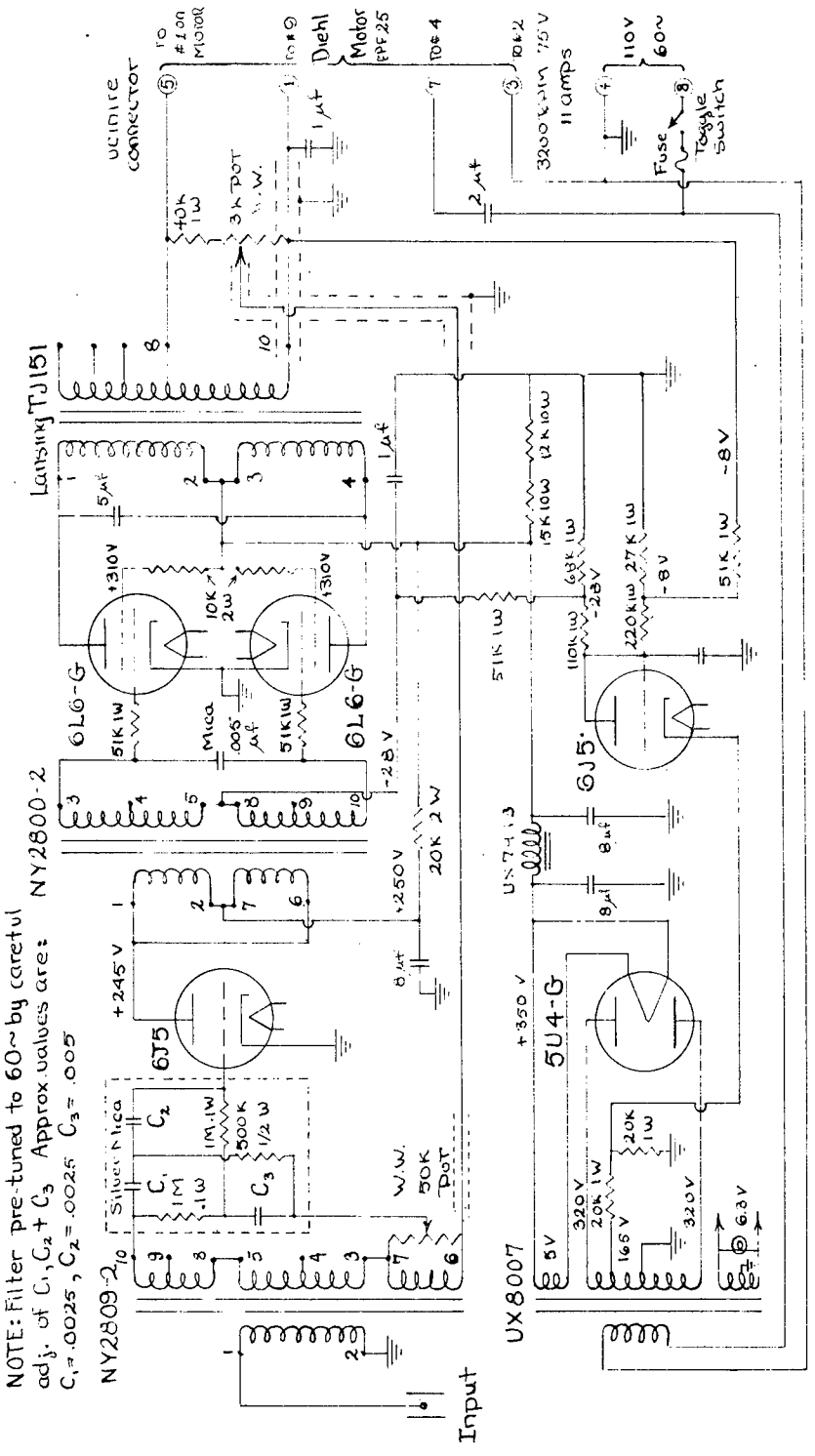


Fig. 29—Alternating-current amplifier for automatic control (modified parallel T servo amplifier from Radiation Laboratory, M.I.T.).

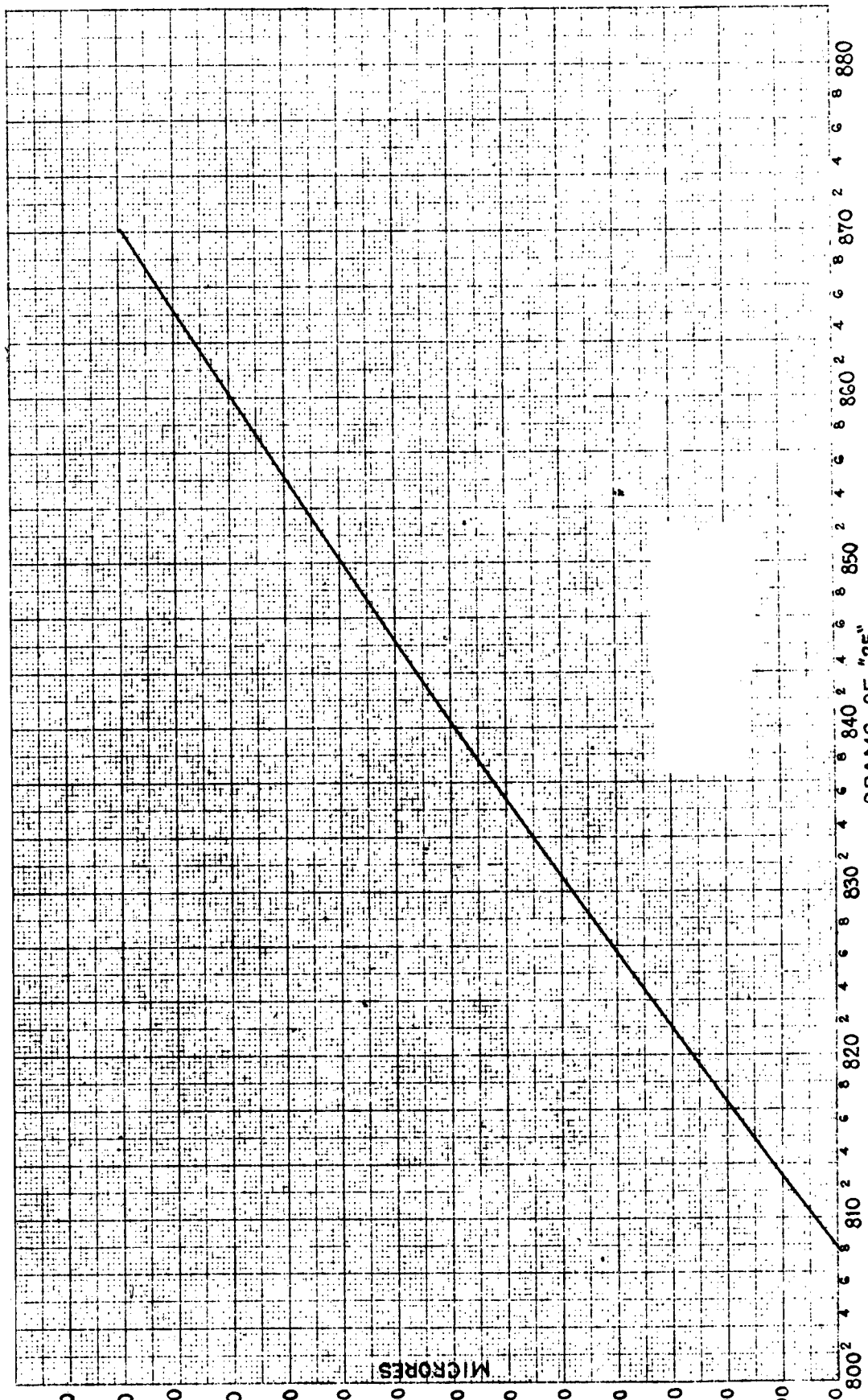


Fig. 30 —Curve relating reactivity (δK) to total mass of 25 (m)

$$K = 1.219 \frac{M_{25}}{M_{25} + 177} - 1$$

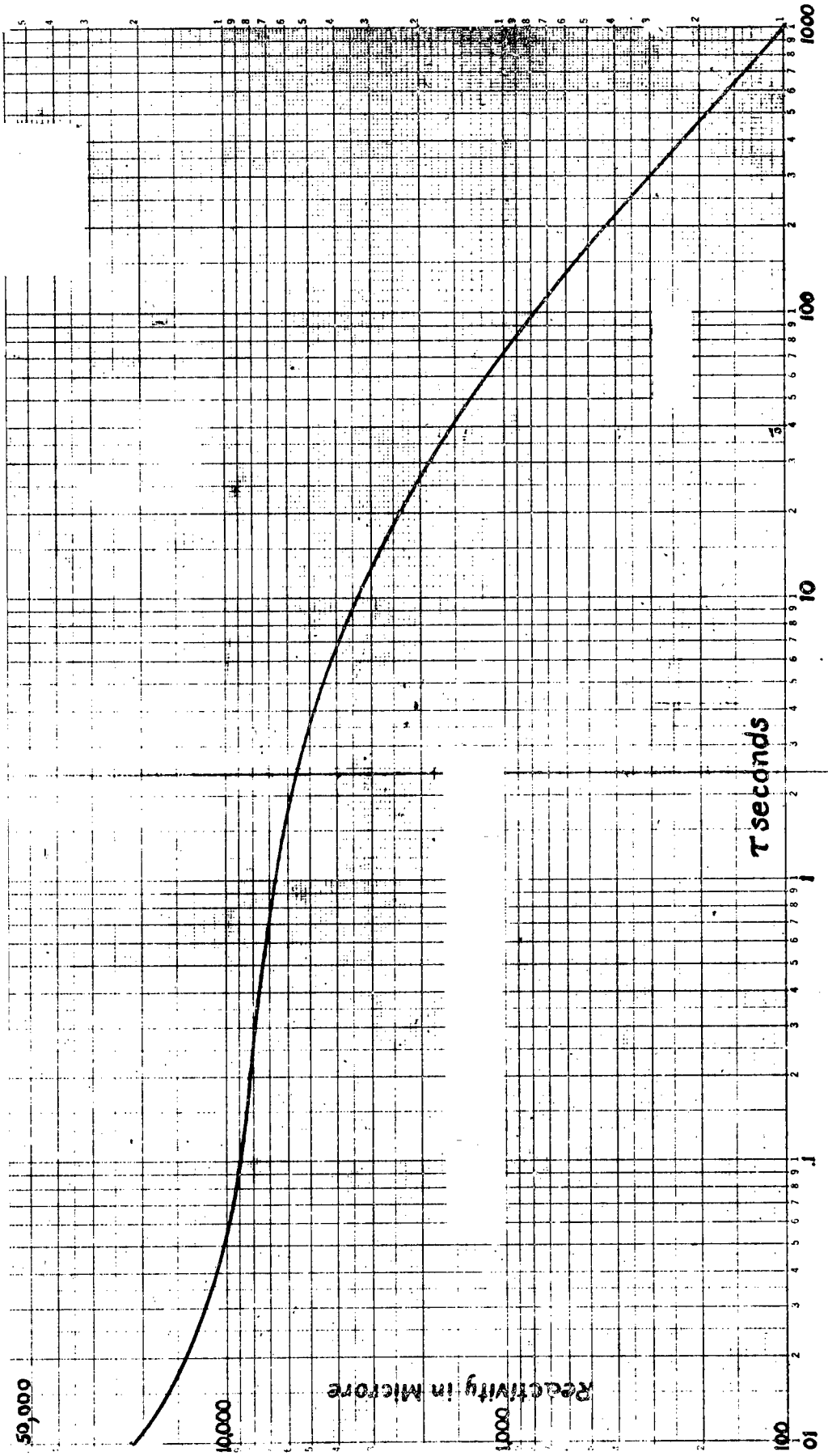


Fig. 31—Graph of reactivity equation

$$\delta K \times 10^6 = \frac{120}{\tau} \frac{1000}{\tau + 0.7} \frac{32,500}{\tau + 6.5} \frac{50,900}{\tau + 34} \frac{16,600}{\tau + 83}$$

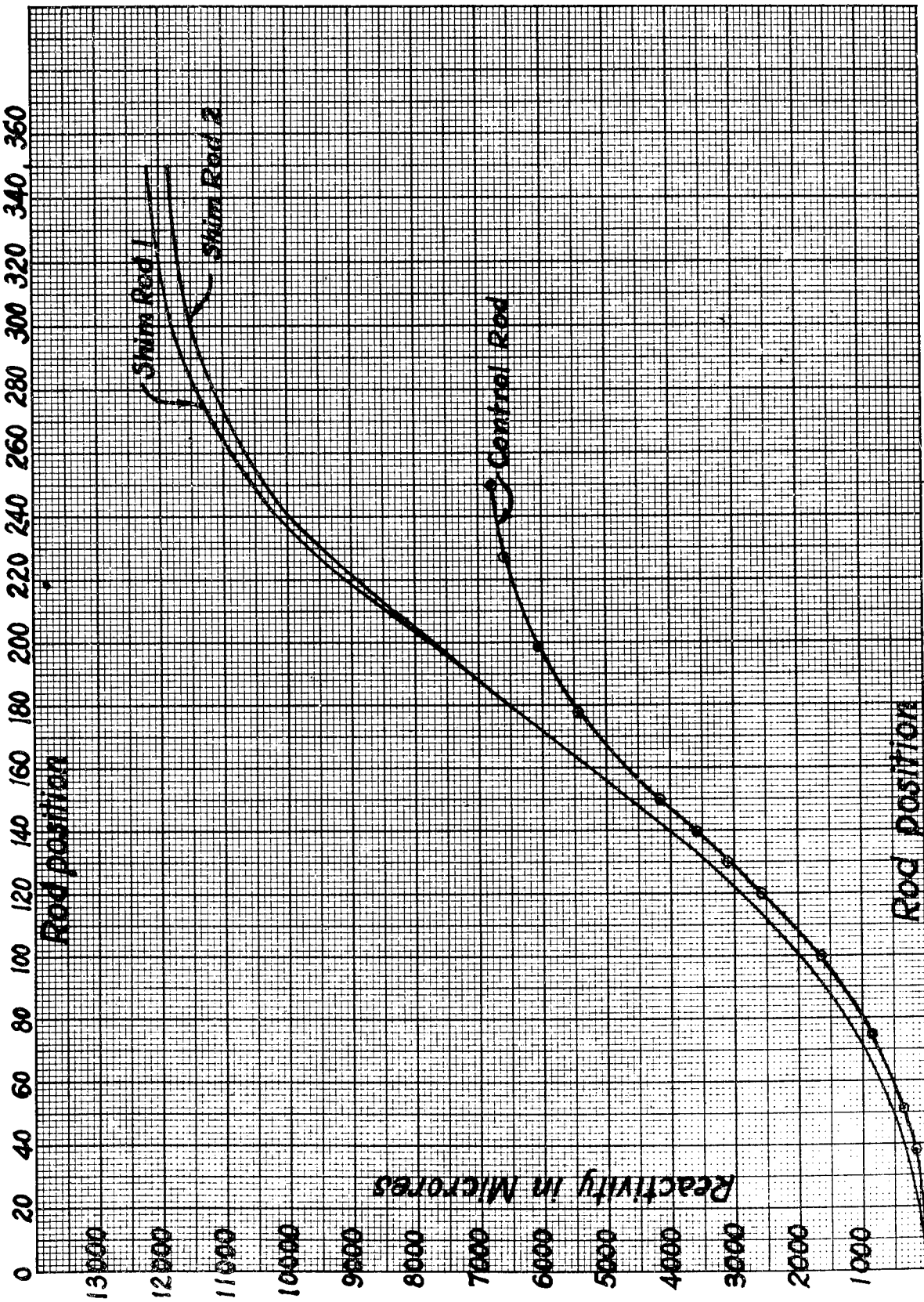


Fig. 32—Reactivity in microres vs. rod position.

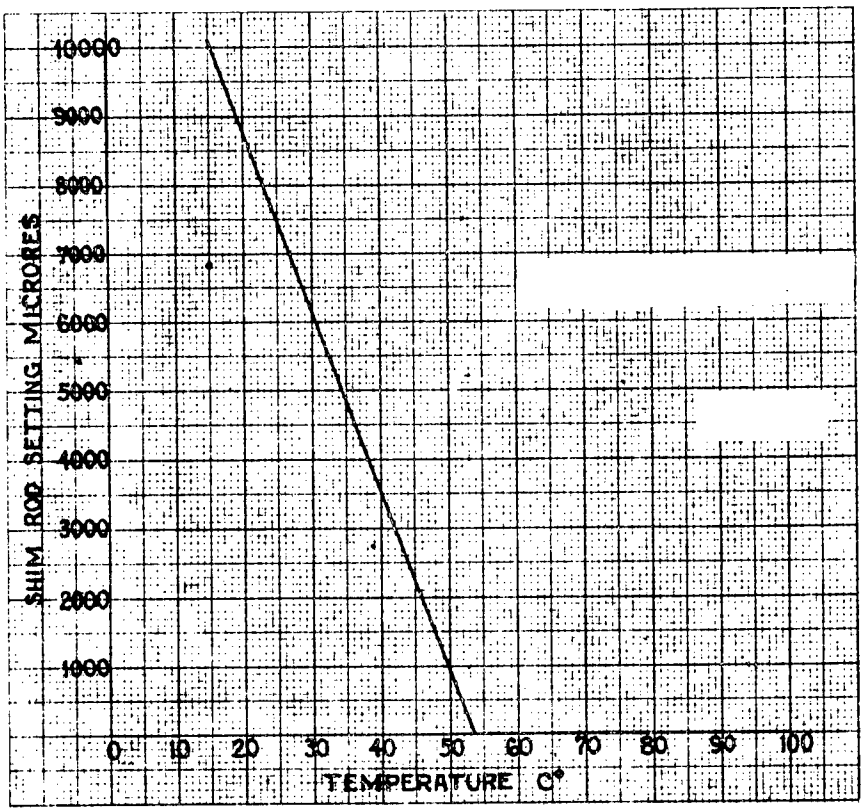


Fig. 33a —Determination of the temperature coefficient of the hypo made over a wide range. 262 microres = 1°C = 1.33 g of 25 equivalent

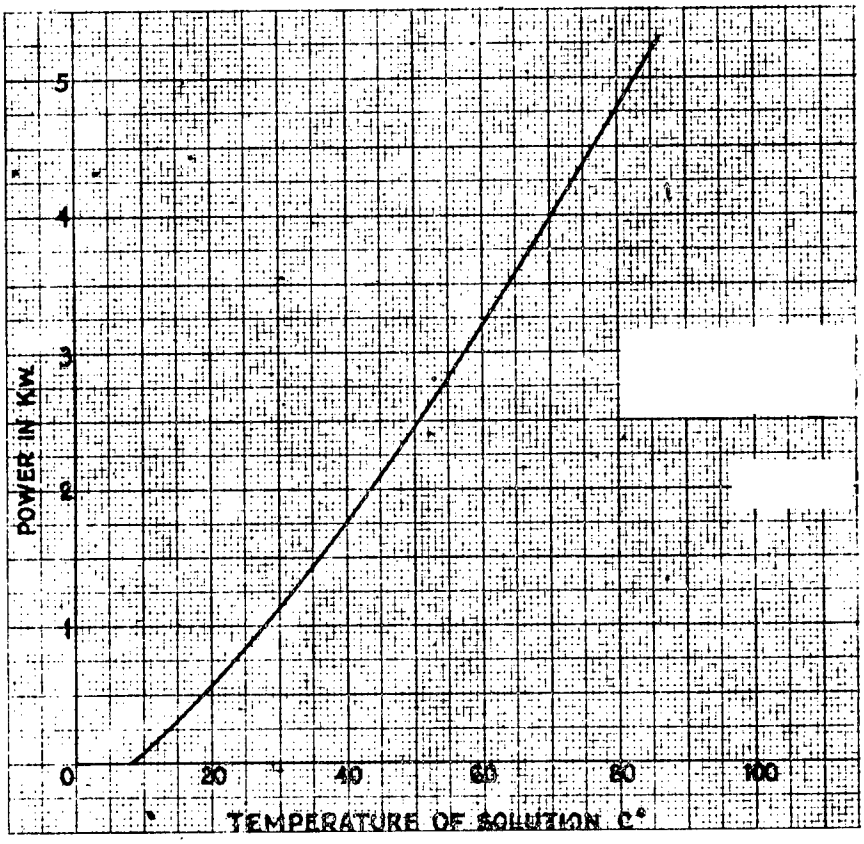


Fig. 33b —Equilibrium running conditions for 50-cc sec inlet water at 8°C.

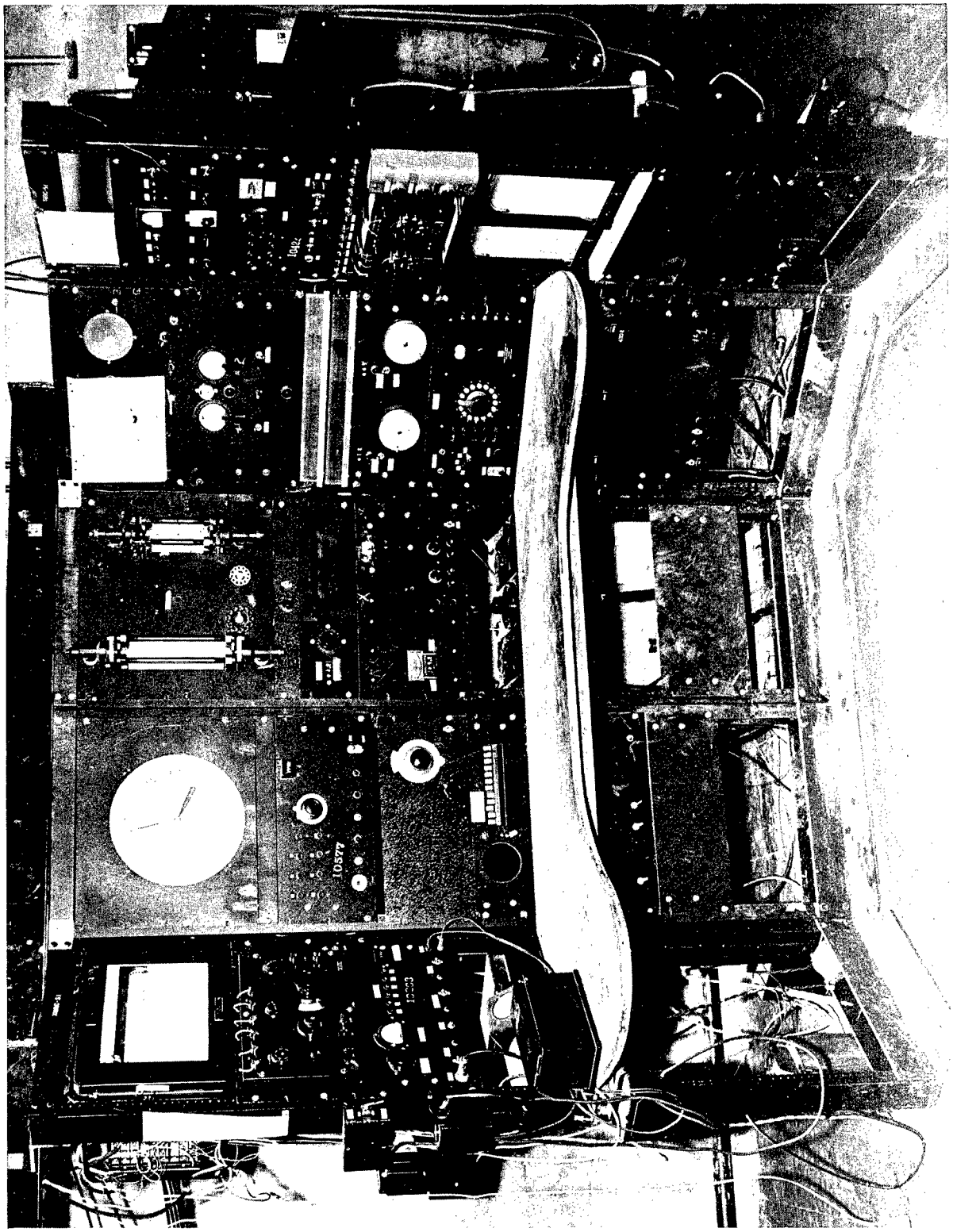


Fig. 34—Control panel.

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