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An Enriched Homogeneous Nuclear Reactor*†

(Received December 12, 1950)

A discussion is given of the design considerations, operational procedures, safety devices, and performance of a small homogeneous reactor using enriched uranium in a water solution and beryllium oxide and graphite for the neutron reflector. A high power and a low power phase of this reactor are described.

I. HISTORY

A DECISION was reached in August, 1943, to build at Los Alamos a small homogeneous reactor that would use an aqueous uranyl salt solution enriched in U^{235}. This reactor was to be used to gain experience in the operation and control of a chain-reacting assembly while using a minimum of active material. It shortly became known as the "Water Boiler," a name that has achieved status through years of usage. Basically, the water boiler consists of a container filled with the enriched solution surrounded by a neutron reflector and a set of control rods to adjust the criticality. The critical mass calculations for such an assembly were first performed by R. F. Christy.

A value of 10 kilowatts was arbitrarily chosen as a worth-while operating level, and a group under the direction of D. W. Kerst with the advice of R. F. Christy worked on preliminary plans and calculations for such a power operation, completing these in September, 1943. It then appeared more advisable to construct first a boiler of much lower power. This design is referred to as LOPO. The decision was reached because it eliminated heavy shielding requirements while minimizing possible difficulties which might arise in connection with keeping the uranium compounds in solution, gas evolution from decomposition of the water by fission fragments, and contamination of the solution by fission fragments. The plans for LOPO were completed in November, 1943. A separate building to house the water boiler was built in Los Alamos canyon, sufficiently removed from the rest of the technical area to exclude any possible hazard. Assembly[1] of LOPO under the direction of D. W. Kerst proceeded through the spring of 1944, and it went critical in May, 1944, with 565 grams of U^{235}.

As a result of the successful operation and experience gained from LOPO, it seemed desirable to construct a high power unit to be used as a strong neutron source for various experiments. A power of 1 kilowatt was chosen as a suitable value to give a neutron flux of about 5×10^{10} with a minimum of cooling requirements.

The design of this new water boiler, called HYPO, was undertaken by a group[2] under the leadership of L. D. P. King with the advice of E. Fermi. The chemical work was under the direction of L. Helmholtz. Essential design features were completed in October, 1944, and construction proceeded during November, 1944. Critical conditions were reached in December, 1944, with 808 grams of U^{235} in a 14.5 percent enriched solution.

The operation of the boiler was completely successful until a precipitate formed, and a drop in reactivity occurred on July 7, 1945, after 1000 kilowatt hours of operation. Some minor design changes were made along with maintaining the solution at a higher acid concentration, and the boiler was put into operation again.

II. LOWER POWER WATER BOILER (LOPO)

A. Design Considerations

The first experimental version of the water boiler, LOPO, was designed with the requirement in mind that a minimum of active material be used. This implied (1) a minimum of absorbing material, and (2) a neutron reflector of high reflecting power. It was also required that the design be as simple as feasible consistent with safety and that accurate control of reactivity be possible.

The schematic design of LOPO is shown in Fig. 1. Uranyl sulfate in ordinary water was chosen for the enriched solution, since the sulfate is more soluble and has less neutron absorption than the other common water soluble uranyl salt considered, i.e., uranyl nitrate.[3] Calculations of R. F. Christy[4] showed that if one wanted to operate with relatively low enrichment, somewhere between 7 percent and 15 percent U^{235}, the diameter of the sphere containing the solution should be about 1 ft for a minimum amount of U^{235}. Hence, after corrosion tests,[5] a 1-ft diameter, $\frac{1}{32}$-in. wall,

* This work was performed under the auspices of the Manhattan Project and the AEC.

† This paper does not include recent modifications and operating experience with the water boiler. It covers operation to October, 1946.

[1] The group assembling and operating the low power boiler consisted of C. P. Baker, F. L. Bentzen, J. Bridge, R. E. Carter, H. Daghlian, G. Friedlander, H. Hammel, J. Hinton, F. de Hoffmann, M. G. Holloway, D. W. Kerst, L. D. P. King, H. M. Lehr, J. H. Midney, R. E. Schreiber, J. W. Starner, and P. H. Watkins.

[2] This group consisted of H. L. Anderson, F. L. Bentzen, J. Bridge, R. E. Carter, L. Helmholtz, J. Hinton, L. D. P. King, D. Nagal, J. C. Nevenzel, R. E. Schreiber, J. W. Starner, J. Tabin, and P. H. Watkins.

[3] L. Helmholtz and G. Friedlander, "Properties of uranyl sulphate solutions," MDDC-808.

[4] For a rough indication of how such a calculation is performed see R. F. Christy, MDDC-72.

[5] G. Friedlander and P. H. Watkins, section on corrosion studies in report LADC-819.

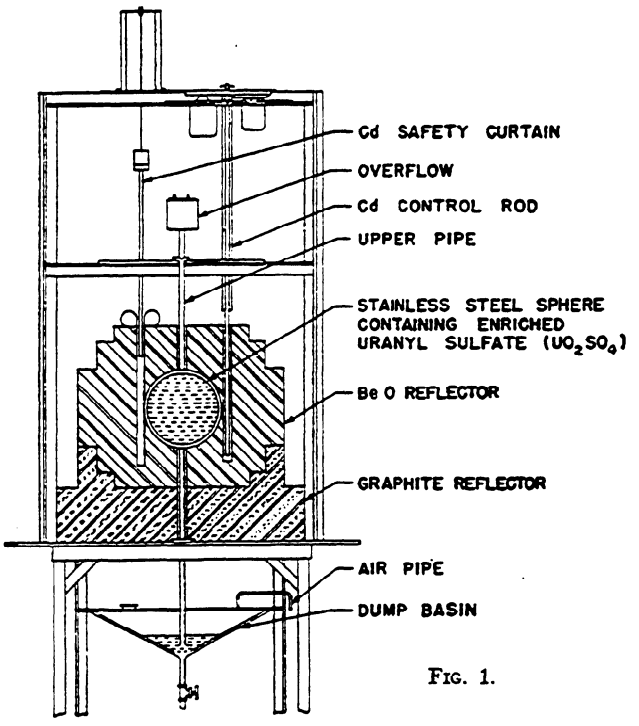

FIG. 1.

stainless steel (type 347 18–8) sphere was chosen to contain the solution. The composition of the solution as used in LOPO is given in Table I. Calculations indicated that beryllium oxide would make the best neutron reflector, and the Chemistry-Metallurgy Division of the Laboratory developed a method of producing 3-in. ×3-in.×6-in. bricks of density 2.7 which were used in LOPO.[6]

Control of reactivity was accomplished by means of a single control rod, which consisted of a 34-in. long cylinder of cadmium $\frac{3}{4}$ in. in diameter, moved in a vertical direction and operated by means of a selsyn. Calculations indicated that the negative temperature coefficient of LOPO would be about $10^{-3}(\Delta K/K)$ per degree centigrade. Since it was intended to run LOPO only at a few hundredths of a watt of power, the heat generation in the solution itself would be negligible. However, temperature fluctuations might be produced by external causes. Because it was hoped to make accurate reactivity measurements of LOPO, a thermostated enclosure was built completely surrounding the boiler. An electronic control circuit[7] maintained the temperature in the enclosure to 0.01°C.

TABLE I. LOPO solution composition.

Element	Grams	Moles	σ_a barns per atom
U^{235}	580	2.47	640
U^{238}	3378	14.19	12.1[a]
S	534	16.66	0.45
O	14,068	880.4	0.0009
H	1573	1561	0.31
Stainless steel sphere and re-entrant tube	1100	20	—

$UO_2SO_4 \cdot 2\frac{1}{2}H_2O + H_2O = 15$ liters
Density 1.348 at 39°C
U^{235} concentration 14.67 percent

[a] Corrected for high energy contribution.

[6] A detailed description of the design factors of LOPO can be found in a report from this laboratory, LADC-819.

The solution could be dropped into a flat conical storage basin below the steel sphere where it was in a noncritical configuration. Numerous safety features were included in the design to prevent unexpectedly supercritical conditions or accidental loss of solution.

B. Approach to Critical

Because this was the first chain reaction with enriched active material, many precautions were taken while approaching critical. Five independent neutron detectors placed in different positions were used to determine the multiplication of a 200-millicurie radium-beryllium source placed at the center of the sphere by means of a thimble type re-entrant tube through the upper pipe, indicated in Fig. 1. A zero reading, i.e., for no multiplication, was obtained by filling the sphere with distilled water. The empty sphere (i.e., sphere with solution dumped) and source were used to standardize all detectors before and after each change of concentration.

Active material was added in small amounts by dissolving additional enriched uranyl sulfate in one or two liters of solution which had been removed from the conical pan. This more concentrated solution was replaced, and the mixture forced into the sphere by air pressure. Great care was taken by various means to assure adequate mixing of the solution before addition of further enriched material.

The neutron detectors used to determine the multiplication were (1) Indium foils with and without cadmium around the foil in the reflector 3 in. from the sphere surface; (2) Manganese foils in the re-entrant tube placed at the center and near the edge of the sphere; (3) An external BF_3 ionization chamber bare and in a paraffin block, 9 in.×113 in., covered with cadmium; (4) A small U^{235} ionization chamber about $\frac{5}{16}$ in. o.d. placed in the re-entrant tube about 3 in. from the center; (5) A large U^{238} ionization chamber placed against the sphere in the reflector (this ionization chamber had 248 square centimeters area covered with 2 g of U^{238}).

The shape which the curves of Fig. 2 have when plotting reciprocal counting rate (normalized to unity at zero mass of U^{235}) against mass of U^{235} can be qualitatively understood.[7a] Thermal detectors placed inside the reacting region should give an approximate straight line and hence the best extrapolated estimate of the

[7] Developed by M. Sands (unpublished patent application).
[7a] See "Approach to critical," LADC-819, Section II.

mass (detectors placed at the center were too near the 200-millicurie radium-beryllium source and hence gave a concave downward curve). The best position for such a detector is probably at the node of the third harmonic of the thermal neutron distribution which has a high peak at the source. One of the manganese detectors was placed approximately in this position after the strong source effect was observed at the central position. Detectors placed outside the reactor should ideally give curves concave upward, since they count both fast and slow leakage. It is apparent from the trend of all the curves that rather accurate predictions of the critical mass could be made before actually going critical. When the last addition had been made, the control rod was pulled out slowly until a good counting rate was obtained, the driving source removed, and then the boiler ran itself, the neutron level responding to the control rod.

The U^{235} in the sphere at this time was 574.8 g. Correcting for the rod position, a missing reflector block, due to the presence of one of the recording ionization chambers, and a small re-entrant tube gave 565.5 g of U^{235} as the critical mass. This checked original calculations of R. F. Christy extremely well, probably somewhat fortuitously.

After criticality had been reached, the highest power to which LOPO was run during its entire existence was about 50 milliwatts at an average temperature of 39°C.

C. Calibration Measurements

The first measurement was to determine the position of the control rod at which the reaction would just be self-sustaining (i.e., $K=1$, where K is the reproduction factor including delayed neutrons) against varying amounts of U^{235} in solution. This measurement serves as an intermediate step in the measurement of the quantity one is really interested in, namely, the absolute criticality of the system as a function of rod position for a specified mass of U^{235} normally in the operating boiler. Thus, we wish to obtain a relation between ΔK and ΔM (here M denotes the mass of U^{235}). Let $\Delta K = c_1 \Delta M$. Then c_1 is not necessarily constant, but it can be shown that for a chain-reacting assembly of the water boiler type, it is adequate to consider it a constant provided $(\Delta K/K) \ll 1$. The constant c_1 was determined by means of a "boron bubble" experiment,[8] which involved displacing a small portion of the active solution by a solution of equivalent nuclear properties except that it did not give rise to fission, and then measuring the effect of this insertion on control rod position.[9] The factor c_1 was determined to be 5.48×10^{-4}. A

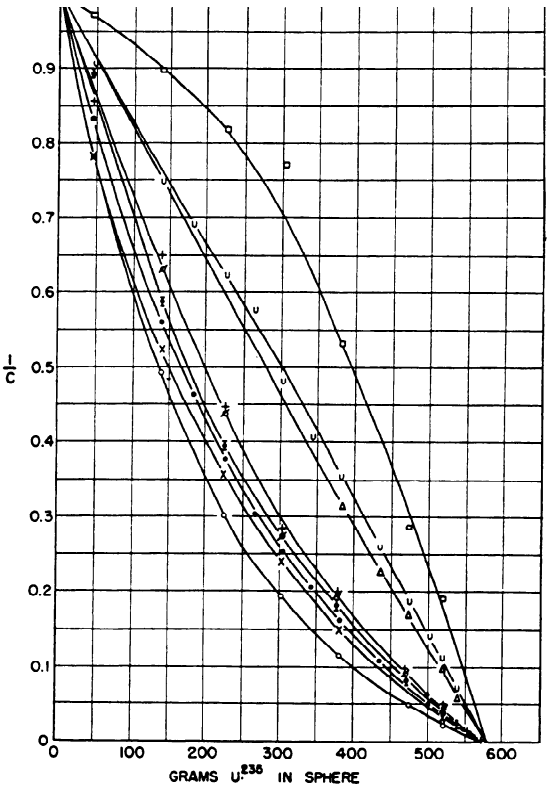

FIG. 2.

theoretical calculation[10] of this quantity was performed and the value checked exactly.

For a given K greater than unity, the neutron intensity of the water boiler rises with a definite period T. This can be measured experimentally; and the results are plotted in Fig. 3. Theoretically the relation between ΔK and T is known to be given by a relation of the form,[11]

$$\Delta K = \frac{\tau_p}{T} + \gamma f \sum_i \frac{q_i \tau_i}{T + \tau_i},$$

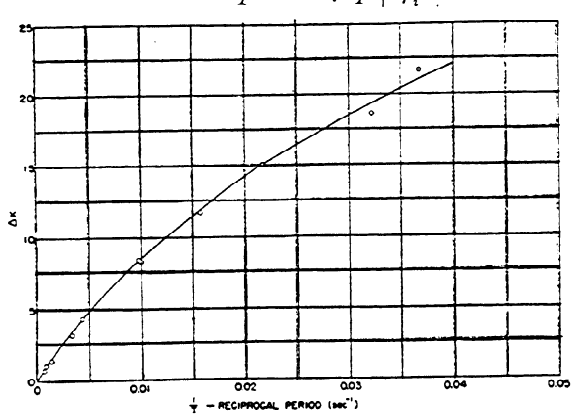

FIG. 3.

[8] The experiment was performed by F. L. Bentzen, J. Bridge, E. Fermi, R. P. Feynman, F. de Hoffmann, D. W. Kerst, L. D. P. King, and G. A. Young—see LADC-816.

[9] The theoretical considerations concerned with the measurement of K and K_p are described in some detail by F. de Hoffmann in *The Science and Engineering of Nuclear Power* (Addison Wesley Press, Cambridge, Massachusetts, 1949), Vol. II, Chapter 9. These considerations are based on reference 8.

[10] E. Fermi and J. Hinton, LADC-818.

[11] See, for instance, Chapter 5 by F. L. Friedman, in *The Science and Engineering of Nuclear Power* (Addison Wesley Press, Cambridge, Massachusetts, 1947), Vol. I.

TABLE II.

T in seconds	$(\Delta K)_{experimental}$	$(\Delta K)_{theoretical}$
25	2.21×10^{-3}	2.12×10^{-3}
40	1.64×10^{-3}	1.60×10^{-3}
100	0.855×10^{-3}	0.835×10^{-3}
400	0.274×10^{-3}	0.254×10^{-3}

where the symbols have the following meaning: τ_p is the average time from one fission to the next, due to prompt neutrons alone; T is the period of the water boiler; γf is the effective fraction of neutrons which are delayed; q_i is the fraction of delayed neutrons in a given delay period relative to the total number f; and τ_i is the particular period of the delayed neutrons under consideration. We speak here of an "effective" fraction of delayed neutrons, since the delayed neutrons are emitted with energies of several hundred kev[12] compared to the mean neutron energy from prompt fission which is higher than one Mev. Thus, the delayed neutrons have a different effectiveness in maintaining the reaction as compared to the prompt ones. Strictly speaking, γ should be different for each period, but we choose to deal with an appropriately weighted average γ. The values of q_i and τ_i are well known.[12] However, we need to establish values for τ_p and γf. An experiment[8] to establish τ_p and γf by means of rapidly oscillating an absorber in the water boiler was performed and the following values obtained:

$$\tau_p = 135\pm20\ \mu\text{sec, and } \gamma f = 0.0086.$$

Another method of estimating γf is available. This is to consider Eq. (1) with T large compared to τ_p and τ_i. Then

$$T\Delta K \approx \gamma f \sum_i q_i\tau_i = 12.7, \qquad (2)$$

where the q_i's and the τ_i's are those of Hughes *et al.*[12] The results of Fig. 3 together with the $T=400$-sec value of Table II indicate that $T\Delta K$ approaches about 0.11 or that γf is about 0.0087 which is as good a check as we may hope for with the value obtained.

TABLE III. HYPO solution composition.

Element	Grams	Moles	σ_a barns per atom
U^{235}	869.6	3.7	640
U^{238}	5341	22.44	12.1
N	731	52.2	1.75
O	13780	860	0.0009
H	1312	1302	0.31
Stainless steel sphere and cooling coil	3000	55	—

$UO_2(NO_3)_2\cdot6H_2O+H_2O=13.65$ liters
Density $=1.615$
U^{235} concentration 14.5 percent

[12] Hughes, Dabbs, Cahn, and Hall, Phys. Rev. 73, 111 (1948).

Thus, we may write Eq. (1) using $\tau_p=135\times10^{-6}$ sec, $\gamma f=0.0087$, and Hughes' data[12] on delayed neutrons

$$\Delta K=\left(\frac{135}{T}+\frac{626}{T+0.62}+\frac{6287}{T+2.19}+\frac{16{,}538}{T+6.51}+\frac{62{,}604}{T+31.7}+\frac{24{,}421}{T+80.2}\right)\times10^{-6}, \qquad (3)$$

where T is the boiler period in seconds. Table II shows a comparison of the measured ΔK for a given T (as obtained from the smoothed curve of Fig. 3) and the ΔK calculated from Eq. (3).

Because of the large expansion coefficient of the water solution, the neutron leakage, and hence the criticality of the system, is strongly dependent on temperature. The average value of the temperature coefficient was found, correcting for expansion, to be $3.0\times10^{-4}(\Delta K/K)$ per degree centigrade.

III. HIGH POWER WATER BOILER (HYPO)

A. General

The HYPO boiler is a particularly useful tool in an experimental physics laboratory since it is one of the smallest and most economical types of chain reactors so far built. Due to the small volume of the reactor, strong neutron fluxes can be produced at moderate power. The model described here has a peak power of 6 kw. At this power a neutron flux of about 3×10^{11} neutrons/cm²/sec exists at the center of the reactor. A flux of thermal neutrons of the order of 10^9 n/cm²/sec is produced in a graphite thermalizing reflector surrounding the reactor. This permits the production of well-collimated beams having a flux of the order of 10^6 n/cm²/sec from the end of a thermal column.

The HYPO differs from the LOPO in that some safety features and a mechanism for the handling of the uranium solution by remote control were added; internal cooling of the solution, neutron and gamma-ray shielding, and a system for flushing air over the solution to remove the gases generated in the reaction were incorporated; uranyl nitrate, rather than sulfate was chosen. To make the boiler a convenient research tool, a graphite thermal column was built against one face of the reflector and a number of ports were placed in the column and the reflector. The control system of the HYPO was made more elaborate than that for the LOPO, both to provide a wider range of control and to make the operation more nearly automatic and foolproof. The latter feature made it possible for a technician to operate the reactor after a rather brief training period.

Although the reactor and reflector occupy a cube about 5 ft on a side, the addition of a thermal column and shield make the completed unit quite massive.

As already reported the LOPO required 565 g of U^{235}. The design changes in converting to HYPO were

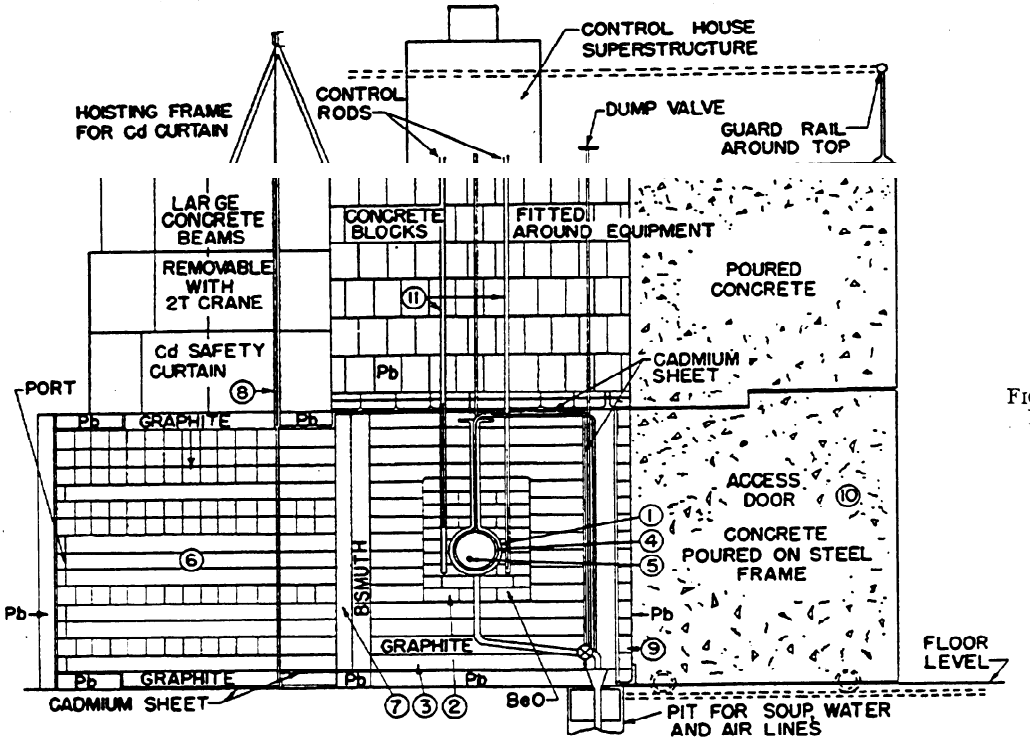

FIG. 4. Section through HYPO (simplified).

estimated to necessitate an additional 205 g of U^{235}. The 205 g were required for the following reasons: thicker sphere: 20 g; cooling coil: 80 g; "glory hole" (a 1-in.-diameter hole through the reactor sphere): 30 g; a change from uranyl sulfate to uranyl nitrate: 75 g. This made the predicted critical mass 770 g. Actually, measurements made as material was added indicated a critical mass of 773 g. There were only 767 g of the 14.6 percent material available. New material of lower isotopic concentration was obtained and added to the old solution. This gave a resulting concentration of 14.0 percent and a final critical mass of 808 g.

In order to accommodate absorbers and to take care of the loss of reactivity due to temperature rise, more than the critical amount is actually used in the HYPO boiler, the excess being controlled by the cadmium control, shim, and safety rods. The solution (October, 1946) contained 870 g of 14.5 percent material of a composition as given in Table III.

B. Constructional Details

The major components of the HYPO, which will be described in the following sections, are the following:[13]

As indicated in Fig. 4, the reactor (1) is a 12-in. diameter, $\frac{1}{16}$-in. wall 18–8 stainless steel sphere containing the active solution. It is surrounded by a reflector 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. 4). The sphere is pierced by a horizontal pipe ("glory hole") (5) to enable one to have access to the highest possible neutron flux. Between the reflector and the thermal column (6) is a bismuth wall (7) which provides gamma-ray protection for the thermal column. A removable cadmium curtain (8) can be used as a shutter for thermal neutrons in the column. The shield around the entire assembly consists of 4 in. of lead (9), $\frac{1}{32}$ in. of cadmium, and 5 ft of concrete (10).

1. *Sphere Assembly*

A six-turn cooling coil $\frac{1}{2}$-in. i.d. and with an effective length of 157 in. is wound in the form of a helix inside

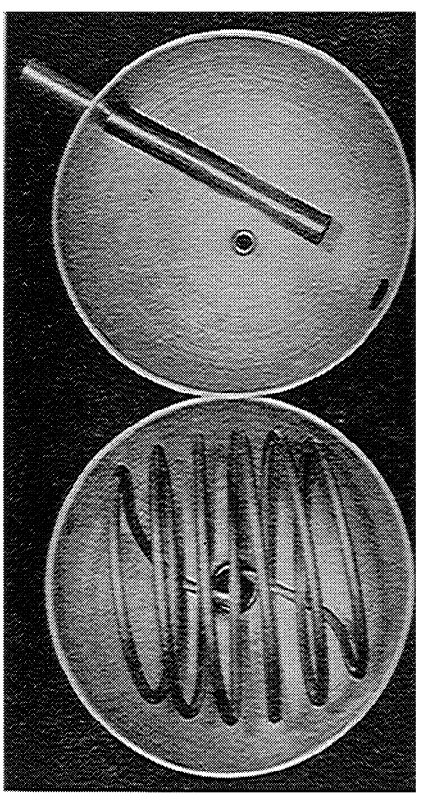

FIG. 5.

[13] A detailed description may be found in LADC-822.

FIG. 6.

the sphere. Figure 5 shows 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 cooling water. Electrolysis of the water in the solution was expected to produce 2 cc/sec of hydrogen and oxygen due to the heavy ionizing currents 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 overdesigned to take care of this possibility. The inlet-outlet water pipes are arranged so that the coil will not drain by gravity. A water bucket in the outlet 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 5°C and permit 6-kw operation the year around. The water outlet 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 outlet which is about 200 ft from the building.

Because of the explosive nature of the hydrogen-oxygen mixture released by electrolysis and the highly concentrated radioactive 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 $\frac{3}{8}$-in. i.d. tube which is pointed at the end and serves as a solution level indicator as well as an air inlet. The tube is 11 ft long and is held concentric to a $\frac{3}{4}$-in. tube by means of a single lavite insulator 7 ft from the sphere. The tube can be raised or lowered by a selsyn controlled gear; a sylphon forms the flexible gas seal. The level can be read to 0.01 in. The concentric tubes have been used for a rapid analysis of the boiler gas by making the outer tube the air inlet and the central one the gas outlet leading directly to the test equipment.

A $\frac{3}{8}$-in. tube extends 4 cm down into the sphere and acts as a minimum solution level indicator. If the tube is in the solution, the "burping" produced by a small air flow through the tube is picked up by a microphone and can be made audible or visible at the control panel by means of a loud speaker or neon light.

To permit an easy escape for the bubbles and to prevent possible frothing from electrolysis as well as to allow adequate space for the expansion of the liquid, the sphere is not completely filled with the uranyl nitrate solution. A maximum solution level of 3 cm and a minimum of 4 cm from the top of the sphere are used.

A copper-constantin thermocouple in a $\frac{3}{16}$-in. tube extends through the bubbler tube into the center of the sphere. Thermocouples are connected also to inlet and outlet water. These temperatures are read directly on a panel meter. Thermocouples were installed at various tamper points; unimportant temperature rises were observed at the power used.

A $\frac{3}{8}$-in. air outlet tube is welded into the top of the $1\frac{1}{2}$-in. upper sphere tube. This is connected to a small chamber outside the boiler shield which acts as a safety solution catcher. 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 cause a detonation. Beyond the safety catcher the air goes 200 ft under ground to large silica gel drying tanks which can be reactivated by remote control. From the drier, a 200-ft copper tube extends under ground, and then an 1800-ft Saran tube takes the highly active gases a sufficient distance from the building.

A considerable portion of the fission activity ($\sim$30 percent) is carried out by the flushing air (about 15 R/hr a few feet from the line while operating at full power).

Difficulty was experienced after 1000 kw-hr of operation because of the formation of a precipitate which clogged the drainpipe of the sphere. It was removed and replaced by a $\frac{1}{8}$-in. pipe which threads through the shield and finally emerges on top. The precipitate was found to be due to loss of nitrate and is now prevented by periodic additions of dilute nitric acid. The $\frac{1}{8}$-in. pipe is used for these additions. Air bubbled through this pipe can also be used to help stir the solution when the boiler is not running.

2. Reflector, Thermal Column, and Radiation Shield

The reflector consists of a 24-in.×24-in.×27-in. BeO core next to the sphere surrounded by graphite to form the 60-in.×48-in.×60-in. rectangular parallelopiped (Fig. 6). The BeO blocks are part of those used for LOPO; the graphite consists of 4-, 2-, and 1-ft stringers $4\frac{1}{4}$ in. square. The BeO and graphite have experimentally determined densities of 2.69 and 1.614, and neutron diffusion lengths of 29.4 cm and 48.45 cm, respectively.

Two safety drip pans were installed in the reflector to prevent loss of solution in case a leak should develop. Both drip pans drain into a funnel leading to an external vault.

The reflector is designed to permit the removal of various blocks of graphite in order to obtain neutron beams, irradiate samples, insert monitors, etc. Two of the 5 horizontal ports extend up to the sphere from opposite sides and are drilled with a 1-in.-diameter hole coaxial with the "glory hole" through the sphere. Vertical ports are primarily used for monitors.

Adjacent to one side of the reflector is a 5-ft cube of graphite to thermalize the neutrons. Numerous experimental ports have been provided here as in the reflector. The transverse ports can be made to extend completely through the column. The longitudinal ports can be varied almost at will but normally extend to the cadmium curtain. The largest port obtainable without complete remodeling of the thermal column is 34 in. ×34 in. extending into the thermal column 4 ft.

The cadmium curtain acts as a shutter for thermal neutrons and can be used for timing purposes or to reduce the neutron intensity during changes in experimental equipment.

The concrete shield at the back of the reflector was poured on a cart set on rails to permit easy access to the reflector. The shield on top of the thermal column is in the form of large cement blocks supported by the column. Above the reflector the shield is supported by beams resting on a ledge provided by the concrete side walls.

To give additional gamma-ray protection in front of the thermal column (where there is only graphite if work is being done on the column), an 8-in. thick pier of bismuth is placed between the reflector and the thermal column. This results in a substantial decrease in the direct gamma-radiation from the sphere itself, without a serious neutron loss. To make up for the lack of concrete in front of the thermal column, the neutron and gamma-ray leakage is further reduced by adding a 1-in. layer of polythene and a $\frac{3}{4}$-in. layer of boron-containing plastic inside the cadmium and by increasing the thickness of the lead to 8 in. The G-M counter background in front of the column when operating at full power is only a few times that due to cosmic rays.

All of the ports which extend through the concrete are normally plugged with wood capped by cadmium and 2 in. of lead. The ports opposite the sphere are shielded by an additional 4-in.-thick lead door to permit easy access to the "glory hole."

3. Control, Shim, and Safety Rods

The reactivity of the boiler is controlled by means of four cadmium rods operated from the control room: a shim rod, two control rods, 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 control 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 due to 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 45 g more than that necessary to compensate for the maximum temperature effect.

The arrangement of the four rods is shown top view in Fig. 7. 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 reflector.

The two control rods and the safety rod are of identical construction and slide in metal sheaths, the lower halves of which are made of 1/32-in. aluminum for minimum neutron absorption.

In order for the rods to act fast enough for safety, they must be allowed to drop freely. Since the control rods must also have a fairly accurate position control, a fairly complicated mechanism is necessary. (For details refer to reference 13.) The position of a control

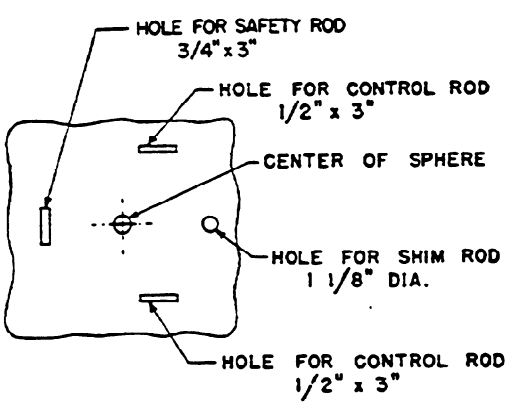

FIG. 7.

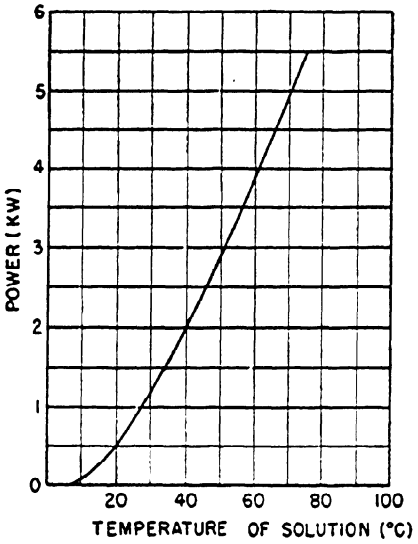

FIG. 8. Equilibrium running conditions for 50 cc/sec inlet water at 8°C.

rod is indicated by a revolution counter geared to the control room selsyn shaft.

During operation of the boiler, one control rod is usually left out in some fixed position. The other can be used for either manual or automatic control. The safety rod is held "out" by an ac 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.

The shim rod and its mechanism consist of a hollow cylinder of cadmium about $\frac{3}{4}$ in. in diameter and 34 in. long which is held in concentric brass tubes. A reversible motor raises and lowers the rod by means of a screw mechanism. A selsyn indicator gives the position of the rod to about 0.001 in.

4. *Detectors and Indicators*

The most important and useful detecting system is that of the galvanometers, supplied by a large U^{235}-coated ionization chamber. These give a continuous reading which is 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 control rods by an operator or the automatic control.

A small U^{235} 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 a kilowatt-minute of operation. This system, recorded on a modified mechanical counter through a scale of 256, is never turned off and 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.

Another midget U^{235} chamber can be used for flux measurements in the thermal column or as a fixed monitor.

5. *Safety Devices*

There are three independent detectors (two large and one small U^{235} chambers) which can be adjusted to drop the safety and shim rods at any predetermined intensity.

The safety circuits 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 percent higher, another thyratron with its grid more highly biased is fired and causes both control rods to drop. This system has been most satisfactory. The safety rod only, or both control and safety rods, can also be dropped manually by two switches on the control panel.

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. Additional safety devices to drop the rods are installed in connection with air and water.

6. *Automatic Pilot*

For very accurate control of the neutron level, almost continuous slight motion of the controlling rod is necessary. An automatic control has been made to relieve the operator from this rather fatiguing job. The system uses the current from the large U^{235} chamber which also supplies the current for the control galvanometers and consists of (1) a power determining device, (2) a dc amplifier and mixer, (3) an ac amplifier, and (4) a regulated power supply.

The intensity level at which the control operates is determined by the off-balance voltage applied to the dc amplifier. The pilot then causes the intensity to rise by pulling the control rod out until the voltage developed across the input resistor cancels the applied voltage. Any subsequent fluctuations of the boiler will cause the control to move the rod in such a direction as to remove the unbalance.

Any voltage change occurring across the input resistor is amplified by the dc amplifier and applied to the mixer or converter. The mixer is essentially a linear gate circuit which delivers a 60-cycle output whose amplitude is proportional to the amplitude of the dc and whose phase is determined by the polarity of the dc. The converter output is fed to the ac amplifier where it is built up until enough power is available to drive a small reversible two-phase motor. The motor drives the controlling rod rack and pinion through a train of gears with a safety release mechanism.

The unbalanced voltage is obtained by a standard potentiometer. The dial of the potentiometer reads power directly to a few watts. The accuracy of the dial calibration is assured by checking with the standard cell. Once the control is set, the power level can be maintained to about 0.01 percent with only an occasional slight drift.

C. Operation

1. Approach to Critical

A solution containing approximately 56 g of U^{235} per liter was prepared, and a system arranged so that the solution could be added to the sphere in known volumes or portions withdrawn for mixing. The method was used to run a "Saran" tube to the bottom of the sphere through the level indicator tube. Then, by means of a vacuum pump, part of the solution could be raised into a large graduate and known quantities of solution added and mixed before lowering it into the sphere. More complete mixing with the solution already in the sphere was accomplished by raising and lowering $2\frac{1}{2}$ liters ten 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 solution were in the sphere. A plot of the reciprocal of the counting rate *versus* the mass of U^{235} in the sphere gave an indication of the expected critical mass. Six more smaller additions brought the boiler to critical with 808 g of 14 percent enriched uranium. It should be noted that all these smaller additions, as well as those for the rod calibration mentioned below, had to be done at constant volume in the sphere in order to have identical geometrical conditions.

2. Rod Calibration

Calculations were carried out based on cross sections for the active solution components and absorption by the stainless steel container and cooling coil giving an equation,

$$\Delta K = K - 1 = 1.219[M/(M+177)] - 1, \qquad (4)$$

relating the excess reactivity ΔK to the total mass (M) of U^{235} in the sphere. This equation has an initial slope of 222 and a final slope of 196; i.e., the effectiveness of one gram of U^{235} becomes less as material is added from critical to the final amount of 870 g of U^{235}.

The apparent loss of reactivity per gram of U^{235} with increased concentration was observed during the rod calibration, since the effect of the rods appeared to change with equal additions of U^{235}. 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 in the later "in" position section by a shift until the linear portions coincided; i.e., the intercalibration of the rods was done by comparing one rod operating on the curved characteristic with the other working on the linear portion.

3. Temperature Effect

A determination of the temperature coefficient for the water boiler was made over a range from 20°C to 50°C. A negative coefficient of 1.33 g of U^{235} equivalent per degree centigrade was obtained.

The temperature of the solution as a function of boiler power is shown in Fig. 8.

4. Loss of Nitrate and Water

After the boiler had run for several hundred kilowatt hours, it was observed that its reactivity had increased considerably. Chemical analysis of the solution indicated a 30 percent deficit in the original nitrogen content. The uranyl nitrate was apparently gradually being converted into basic nitrate and the free nitrate carried off in the flushing air. Laboratory tests indicated that the solution would precipitate if the loss of nitrogen exceeded 35 percent. When nitric acid was added to the test solutions the normal nitrate was again formed.

At this time it seemed advisable to add some acid but to maintain the nitrogen concentration about 20 percent lower than the original value since this permitted operation at higher power with the available material. Previous additions to the solution had consisted of distilled water to make up for that lost by electrolysis. The loss of nitrate necessitated additions of concentrated nitric acid as well as water in the ratio of water to acid of about 2.8:1.

After 1000 kw-hr of operation, as mentioned before, a precipitate was formed. The laboratory tests of a precipitate forming only at 35 percent deficit in nitrogen were apparently not borne out when the material was under intense irradiation and imperfect mixing existed immediately after additions were made.

The nitrogen concentration was then brought back to that for normal uranyl nitrate, and no further precipitation has occurred with an additional 3500 kw-hr of operation.

Additions now are made in the ratio of water to acid of 1.4:1 to maintain the normal concentration of nitrogen. About 6 cc of water and acid are required per kw-hr of operation.

5. Controls and Operational Procedure

All operations necessary to starting, running, and stopping the boiler are done from the control desk located behind a 5-ft concrete wall in another room. Indicator lights and various warning signals aid the operator in locating difficulties.

The typical operating procedure is as follows: The U^{235} chamber power integrator reading solution level and sphere temperature are recorded. Flushing air (50 cc/sec) and cooling water (0.8 gal/min) 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 which correspond to the desired operating power are read from a calibration curve. The two control rods are checked for "in position." The safety rod is raised. The control rods are then slowly raised one at a time and

the galvanometer deflection observed. The position of the rods necessary for the boiler to start will depend on the initial temperature of the sphere. Because of the 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; this is especially true until the multiplication rate is actually known from the galvanometer or counter. 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 control rods to maintain constant power. In this running condition a row of 10 trouble lights is on. If any one of these goes out, one can tell at a glance whether water, air temperature, etc., are abnormal.

The boiler responds very rapidly to control rod positions, and these can be changed at almost whatever speed the operator desires to turn the control rod 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 so far that one is running a considerable amount supercritical. As the desired power is approached, the control rod can be run back rapidly. A visual observation of the neutron intensity on one of the recording meters enables one to produce an almost vertical rise with immediate leveling off at the desired intensity level.

D. Performance

1. Flux and Power

With an inlet water temperature of about 8°C and the 870 g of U^{235} in the boiler, it is possible to run continuously at 5.5 kw without exceeding a solution temperature of 85°C. There is still some excess reactivity left to permit experiments with absorbing materials 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 the absence of violent frothing or bubbling in the solution.

The power measurements were based on inlet and outlet water temperatures. Measurements made with standardized manganese foils and a small fission chamber gave the following flux intensities in the thermal column. (Cadmium ratios were obtained with standard indium foils):

Position in inches	Cd ratio	Flux/kw (neutrons/cm²-sec-kw)
0	—	0.83×10^9
2	500	6.9×10^8
12	2500	1.5×10^8
24	50,000	0.26×10^8
36	90,000	

All distances are measured from the cadmium curtain toward the outer end of the column. The equation for the flux per kw in the column from the foregoing data is $0.89\times10^9 \exp-(Z/29.4)$, where Z is the distance from the cadmium curtain, and the relaxation length is 29.4 cm.

For numerous experiments where a strong thermal neutron beam was desired, a cavity was made in the thermal column: $24\frac{3}{4}$ in.$\times24\frac{3}{4}$ in., starting 1 ft from the outer end. This gave a flux of 7×10^5 kw on a target 1 ft in front of the thermal column; the cadmium ratio using the cavity is about 1500.

Experiments with fast neutron beams can be done by removing the reflector stringer which surrounds the one-inch transverse hole to the boiler. This exposes the end of the "glory hole" and a 3 in.$\times$3 in. area of the sphere itself. The following flux measurements were made just beyond the concrete shield with various detectors to get some idea of the neutron energy distribution.

Detector	Flux/kw (neutrons/cm²-sec-kw)
U^{235} chamber	5×10^5 (thermal)
U^{238} chamber	4×10^6
Np^{237} chamber	5×10^6

Cd ratios with indium foils: 4.5.

Measurements made 8 ft from the concrete showed a well-collimated beam the same width as the aperture in the concrete.

Gamma-ray measurements made with the 3 in.$\times$3 in. area of the sphere exposed indicated an effective source of about 2000 curies from the $4\frac{1}{4}$-in.$\times4\frac{1}{2}$-in. opening in the concrete shield. These measurements were made a short time after the boiler was shut off after a run of several hours at high power.

Distribution measurements were taken through the reflector and "glory hole" with manganese and gold wires. The following fluxes relative to that at the center of the sphere were obtained.

	Au	Mn
Center sphere	1.0	1.0
Edge sphere	0.8	0.8
Max in BeO	0.85	0.85
Edge in BeO	0.66	0.68
Outer edge graphite	0.045	0.036

The flux at the center of the sphere in the "glory hole" was measured with small calibrated Mn foils. It was found to be about 5×10^{10}/neutrons/cm²-sec-kw.

2. Steadiness of Operation

The water boiler is inherently not as steady in operation as the large graphite piles. This is probably due to the large convection currents and to bubble formation taking place, especially when operating at high power. If the boiler runs after reaching temperature equilibrium, it will maintain a constancy of about 0.2 percent when operating at 1 kw. The intensity level can, however, be maintained to 0.01 percent or better when operating at 1 kw or over when the full sensitivity of

the bucking galvanometer is used. This required almost continuous motion of the control rod; the automatic control gives about the same accuracy as the best hand control.

Measurements have been made to determine the shutting-off factor for the boiler after various running conditions. If three rods are dropped simultaneously, the neutron intensity drops a factor of 6 within the first second and then there is a gradual decrease due to the delayed neutrons and gammas from fragment decay. Only a very small difference in the background activity was observed, however, between runs when the boiler had been operating for 50 kw-hr immediately before and in another case when the boiler had not been in in operation for 48 hr.

E. Concluding Remarks

The following remarks are applicable as of October, 1946, at which time HYPO had run for 4500 kw-hr.

Corrosion of the stainless steel after the initial pickling in a uranyl nitrate solution has not been detectable in a spectroscopic analysis for Cr, Fe, and Ni; neither is the production of fission fragment contamination detectable.

The only features which have given trouble were (1) handling of the exhaust gases, (2) precipitation of the solution when run with too low a nitrogen concentration.

The exhaust gases are highly radioactive and corrosive. They carry away varying amounts of gaseous fission fragments, the fractions depending on their half-lives. An analysis of the gases indicates that those with half-lives of less than 1.5 sec are not removed due to the slow rate of sweep in the solution itself. For example, Kr^{89} with a half-life of 2.6 min was swept out to the extent of 30 percent. Some of the longer-lived gases are removed nearly 100 percent. These experiments seem to indicate that roughly 30 percent of the total fission fragment activity is carried out by the flushing air.

Nitric acid fumes, the high moisture content, and loss of nitrate from the solution require the use of strainless steel for the entire length of the exhaust pipe unless there exists a suitable moisture trap. Difficulties have been encountered from using silver solder and copper tubing for parts of the exhaust line even though removed some 25 ft from the boiler with a safety bucket between to catch any solution.

As a result of the high radioactivity of the gases, it may be somewhat difficult to dispose of them. In isolated sections of the country, such as Los Alamos, these can be released into the atmosphere if the distance is sufficient so as to cause no G-M counter disturbances at the Laboratory; this may require 2000–5000 feet of line, or possibly a high stack if the air currents are suitable. In congested communities the gas disposal problem becomes more serious, but other solutions of the problem seem feasible.[14]

Because of the low corrosion and contamination rate of the boiler solution, a slight simplification in the original design may be advisable. It has been found that all additions and removals of solution can be done quite satisfactorily from the top with the aid of a small vacuum pump. The average activity of the solution 48 hr after operation is about 10–20 cm/cc. This permits removal of the "hot" solution from the top in small batches without the need of elaborate shielding. Since all operations have been done in this way, the need of a lower pipe and dump valve becomes unnecessary; the lower hemisphere could then be spun without an outlet hole.

Further modifications are useful if active material in the boiler is increased. The reflector can be made entirely of graphite. This requires approximately 35 percent more material. The use of graphite would simplify the fabrication of the inner reflector and make the boiler more useful for critical measurements.

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[14] Other possible solutions are: (1) recombination of hydrogen and oxygen which would permit one to dispense with the gas flushing system and to retain all the fission activity in the boiler or (2) appropriate storage and/or delay traps for the radioactive gases.

REFERENCE 18b

L. D. P. KING, "WATER BOILERS," LOS ALAMOS SCIENTIFIC LABORATORY REPORT LA-1034, CHAPTER 4 (DECEMBER 1947).

VOLUME V

CRITICAL ASSEMBLIES

Editor: O. Frisch

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VOLUME V

CRITICAL ASSEMBLIES

Part II

Chapter 4

Written By:

L. D. P. King

CHAPTER 4

WATER BOILERS

L. D. P. King

4.1 WATER BOILER HISTORY

Estimates for the critical mass and dimensions of homogenous mixtures of both 49 and 25 in various moderating media were required early in 1943. This necessity arose from the production of appreciable amounts of active material in solution at separation plants. Early estimates of these quantities were made by several people.(1) (2)

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(1) J. R. Oppenheimer and R. Serber, Unpublished.

(2) R. F. Christy and John A. Wheeler, CP-400.

In August 1943 it was decided to build the so called "water boiler" at site Y. The "water boiler" is a homogeneous chain reacting pile using an enriched uranyl solution in water. The purpose of this instrument was to gain experience in the operation and control of a chain reacting source and to prepare personnel and equipment for critical experiments as soon as kilograms of active material were available. The lack of large amounts of material necessitated the use of a slow neutron reaction, and the use of the best possible tamper or reflector.

A value of 10 kilowatts was arbitrarily chosen as a worth while operating level and preliminary plans and calculations made for such a power operation were completed September 1943.

It then appeared more advisable to first construct a boiler of much lower power. This would eliminate:

(1) the shielding requirements

(2) possible difficulties of keeping the uranium compounds in solution

(3) decontamination of the solution by separating out fission fragments

(4) uncertainty of gas evolution in appreciable quantities from fission fragments and decomposition of the water.

Plans for a low power boiler or lopo were completed in November 1943. A new building, Omega, in Los Alamos canyon was to house the water boiler. Its remote location eliminated any possible hazard to the rest of the technical area. Assembly of sphere and tamper were begun in March and the boiler went critical as soon as sufficient material was available, namely in May 1944 with 565 grams of U^{235}.

Due to the successful operation and experience gained from lopo it seemed desirable to construct a high power unit to be used as a strong neutron source for various experiments. A power of 1 kilowatt was chosen as a suitable value to give a flux of about 5×10^{10} with a minimum of cooling requirements. The original 10 kilowatt high power design was modified considerably. Essential design features were completed in October and concrete foundations and shield begun. Critical conditions were reached in December 1944 with 808 grams of U^{235}.

The operation of the boiler was completely successful until a precipitate formed and a drop in reactivity occurred on July 7, 1945 after 1100 kilowatt hours of operation. Some minor design changes were made along with maintaining the solution at a higher acid concentration, and the boiler was put in operation again. It has now (July 1946) run an additional 2600 kilowatt hours without further trouble.

4.2 LOW POWER BOILER (LOPO)[3]

(3) C. P. Baker, F. L. Bentzen, J. Bridge, R. E. Carter, H. Daghlian, H. Hammel J. Hinton, F. de Hoffman, M. G. Holloway, D. W. Kerst, L. D. P. King, H. M. Lehr, J. H. Midney, R. E. Schreiber, J. W. Starner, LA-134. "Water Boiler"

4.2-1 Design Considerations

The primary purpose of the low power boiler was to obtain a chain reaction with a minimum of material as soon as enriched uranium became available.

The design features were therefore made accordingly: (1) A minimum of absorbing material. (2) The best possible tamper. (3) Accurate control of reactivity. (4) General simplicity consistent with safety.

(1) Corrosion tests[4][5] made by the chemists to determine the most suitable material for holding the active material showed that 18-8 stainless steel was the best available. Type 347 was especially good where welding was necessary. Welding in an inert atmosphere to prevent oxidation and pickling before use were found to be advantageous. The extremely low corrosion rate found permitted using a thin walled container.

Uranyl sulphate in water was chosen for the enriched solution since the sulphate is more soluble and has less neutron absorption than the nitrate.[6][7] The final solution composition is shown in

(4) G. Friedlander, P. H. Watkins, Water Boiler, LA 134 (Section on corrosion studies.)

(5) L. Helmholtz, J. Nevenzel, P. H. Watkins, Water Boiler Chemistry, Los Alamos Technical Series, Volume VIII, Chapter 7.

(6) L. Helmholtz, J. Nevenzel, P. H. Watkins, Water Boiler Chemistry, Los Alamos Technical Series, Volume VIII, Chapter 7.

(7) L. Helmholtz, G. Friedlander, Properties of Uranyl-Sulphate Solutions LAMS-30

Table 4.2-1A.

(2) Calculations[8] indicated that beryllium oxide would make the

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(8) L. Helmholtz, J. Nevenzel, P. H. Watkins, Water Boiler Chemistry, Los Alamos Technical Series, Volume VIII, Chapter 7.

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best neutron reflector or tamper. The metallurgy division, under the direction of Mr. Balke, developed a method of producing 3 x 3 x 6 inch bricks of density 2.7. These dimensions were chosen for convenience in constructing a pseudo sphere tamper 3 feet in diameter. The method used involves five steps:

(a) Pressing BeO powder for two hours in a steel die at 50,000 pounds per square inch;

(b) Sintering at 1250°C;

(c) Shaping by scraping, sawing, chipping, or grinding;

(d) Hot pressing in a graphite mold at 700°C and 2,000 pounds per square inch for two hours;

(e) Final shaping and finishing to tolerance by surface grinding. The special shaped bricks were made at Los Alamos while most of the rectangular bricks were made by the Fansteel Co., using the same method.

(3) In order to maintain criticality accurately it is necessary (a) to construct a control rod which could be adjusted to very close limits and (b) the temperature of the boiler had to be maintained accurately constant.

(a) The control rod consisted of a 34 inch long cylinder of cadmium formed by wrapping a thin strip around a brass tube 3/4 inch in diameter. Another brass tube is fitted snugly over the outside of the cadmium to eliminate any motion of the cadmium. The rod moved in a vertical direction with its end going from 12 inches

TABLE 4.2-1 A

Solution Composition

(A) Low Power Boiler $UO_2SO_4 \cdot 2\frac{1}{2}H_2O + H_2O$ = 15 liters

Element	Grams	Moles	σ_a Barns per atom	σ cubic centimeter	σ per gram U^{235}
U^{235}	580	2.47	640	955	1.6462
U^{228}	3378	14.19	12.1*	103	.1774
S	534	16.66	.45	4.74	.0082
O	14068	880.4	.0016	.85	1.832 total
H	1573	1561	.31	282.3	------
Stainless steel sphere and reentrant tube	1100	20	----	~ 36	

Density 1.348 cd 39°C

U^{235} concentration 14.67%

* From E. Fermi

TABLE 4.2-1 B

(B) Mock Solution for Boron Bubble Experiment 388gms/liter $U^*O_2SO_4 \cdot 2\frac{1}{2}H_2O$ + 10 gms/l H_3BO

Element	Grams per cubic centimeter	Barns per atom	σ Scatter	σ_a per cubic centimeter	σ_s per cubic centimeter
U^{235}	.000927	640	----	.000151	-----
U^{228}	.2247	12.1	8.2	.006818	.00466
B	.001749	721**	----	.070192	-----
S	.0303	.45	1.5	.000271	.00085
H	.1059	.31	41	.019001	2.59941
O	.9404	.0016	4.2	.000006	.14894

* Depleted

** Effective as compared with U^{235} for boiler neutrons

TABLE 4.2-1 C

(C) High Power Boiler $UO_2(NO_3)_2\ 6H_2O - H_2O - 13.65$ liters

Element	Grams	Moles	σ_a Barns per atom	σ square centimeters	σ per gram U^{235}
U^{235}	869.6	3.7	640	1428	1.642
U^{228}	5341	22.44	12.1	163.5	0.188
N	731	52.2	1.75	55.1	0.063
O	13780	860	.0016	.8	0.00
H	1312	1302	.31	243	0.27
Stainless steel sphere and cooling coil	3000	55	---	~ 100	

Density - 1.615

U^{235} concentration 14.5%

below the sphere center to a somewhat higher position above the center. The motion of the rod was obtained by rotating a long steel screw (pitch .05 inches per thread) with a variable speed electric motor thru a clutch. A nut soldered to the inside brass tube has a key which prevents rotation of the rod itself. A ball bearing at the end reduces end play to 0.2 mil. The position of the rod is indicated by a Selsyn which is coupled by a 2:1 gear. This gives 0.100 inch per revolution of the Selsyn. The Selsyn on the control rack had a dial with 100 divisions each of which represented 1 mil vertical motion of the rod. Tests indicated that settings of the rod repeated to less than .5 mils. (See Figure 39).

(b) The reproduction factor K is very sensitive to the temperature θ of the solution. Calculations indicated that a change in reactivity of $10^{-3}/C^{o}$ was to be expected. At low power of a few milliwatts which would give adequate counting rates the temperature generation is negligible. However, fairly rapid fluctuations could be produced by external causes. A thermostated house was therefore built completely enclosing the boiler. The electronic control circuit[9] maintained the

(9) Developed by M. Sands, Unpublished.

temperature in the house to .01°C or K within 10^{-5}.

(4) From the estimates of the amount of material that would be required it seemed probable that a 1 foot diameter sphere would contain sufficient material and moderator without going to very high concentrations. (See Figures 1A and 1B). These curves are based on some unpublished calculations of Christy made in 1944.[10]

(10) R. F. Christy, Unpublished

Figure 1 A

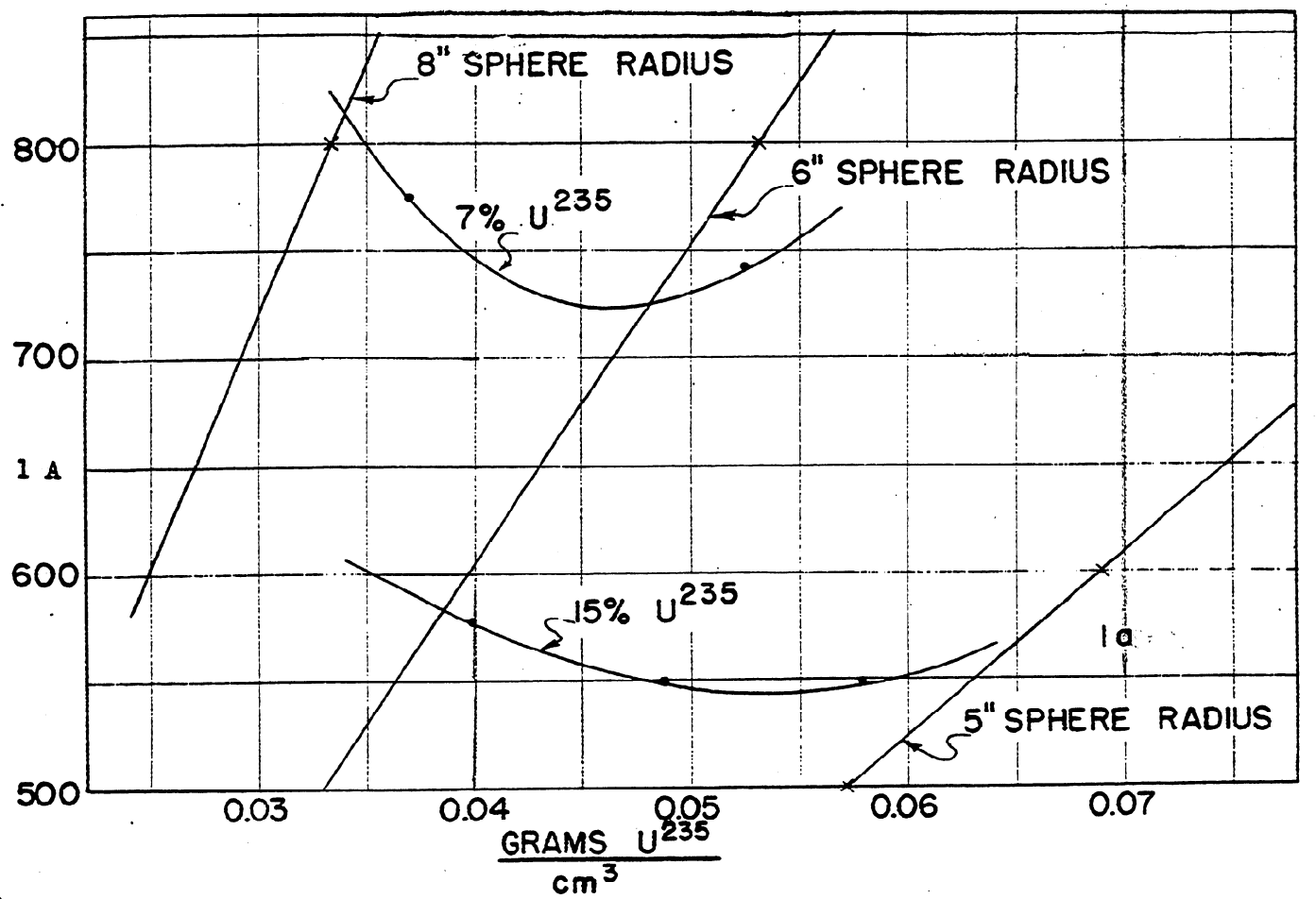
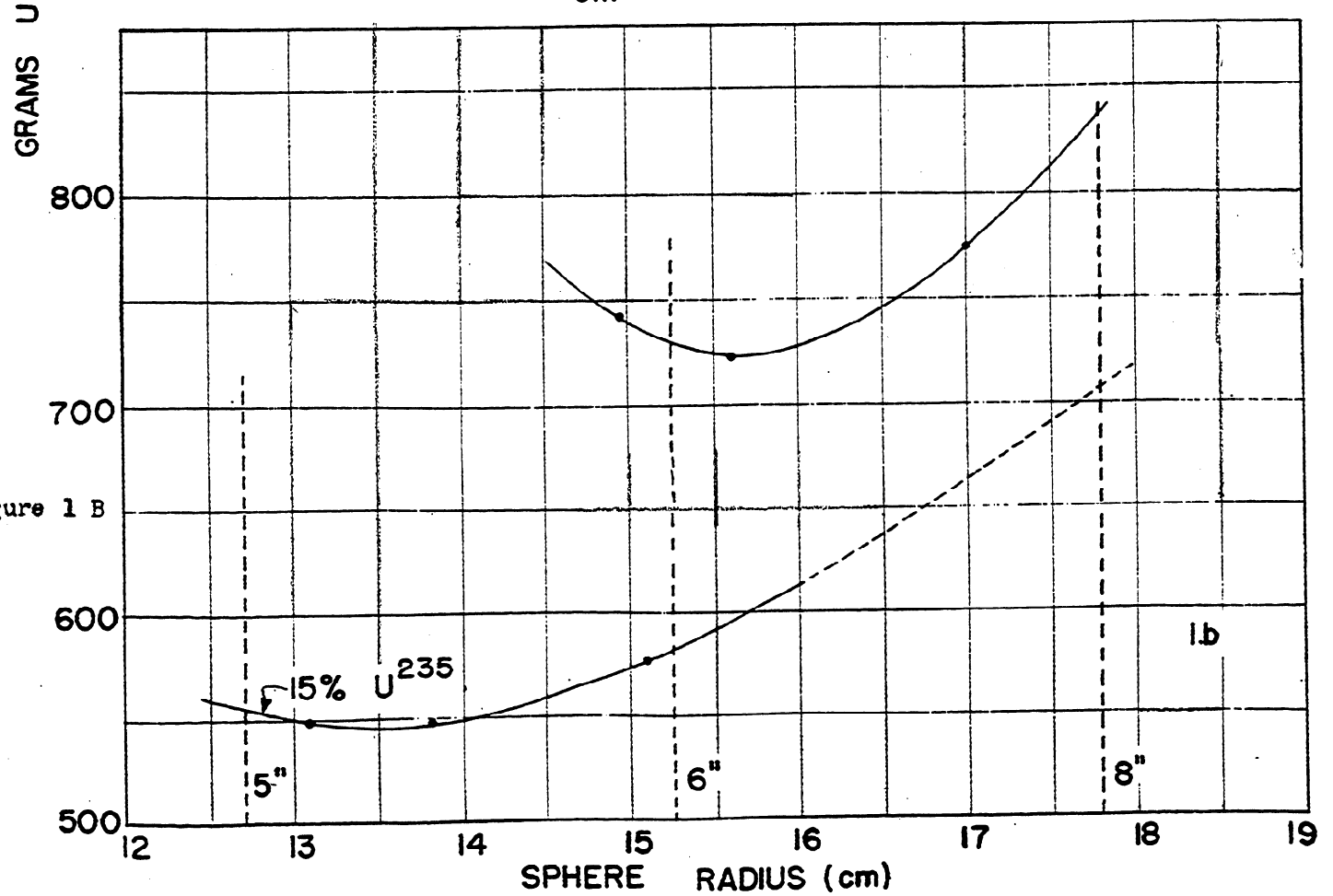


Figure 1 B



The constants used were σ_{U235} = 600 barns; ν = 2.15; τ (age) = 30 square centimeters.

It was therefore decided to use a 1/32 inch wall stainless steel sphere. The volume of the sphere was 14.95 liters. Due to lack of experience with chain reactions it seemed advisable not to leave the solution in a critical geometry at all times. For this reason the solution could be kept in a flat conical pan of poor geometry completely outside of the tamper when experiments were not in progress. This necessitated a pipe coming out of the lower hemisphere for raising and lowering the solution, a tube coming out of the upper hemisphere to insure complete filling of the sphere and a closed compressed air system to raise the solution from the lower pan. To prevent water vapor from leaving the solution and thereby changing the concentration, thick walled rubber balloons contained in a pressure tank supplied the inlet air, light rubber balloons took up the air displaced by the solution as it filled the sphere. Electrical contacts served to indicate the height of the solution in the upper tube. A monometer was used to observe the rate of rise of the solution into the sphere and detect any air leaks in the closed system. (See Figures 2 and 3).

(5) Numerous safety features were included in the design to prevent accidental loss of solution or unexpectedly reaching super-critical conditions (see Figure 4).

The safety rod was automatically dropped if the neutron level rose too high or the power failed. The active material was dumped into the lower pan if:

(a) The solution rose too high in the upper pipe

(b) A leak developed anywhere in the sphere (by shorting nylon covered wires wrapped around the sphere).

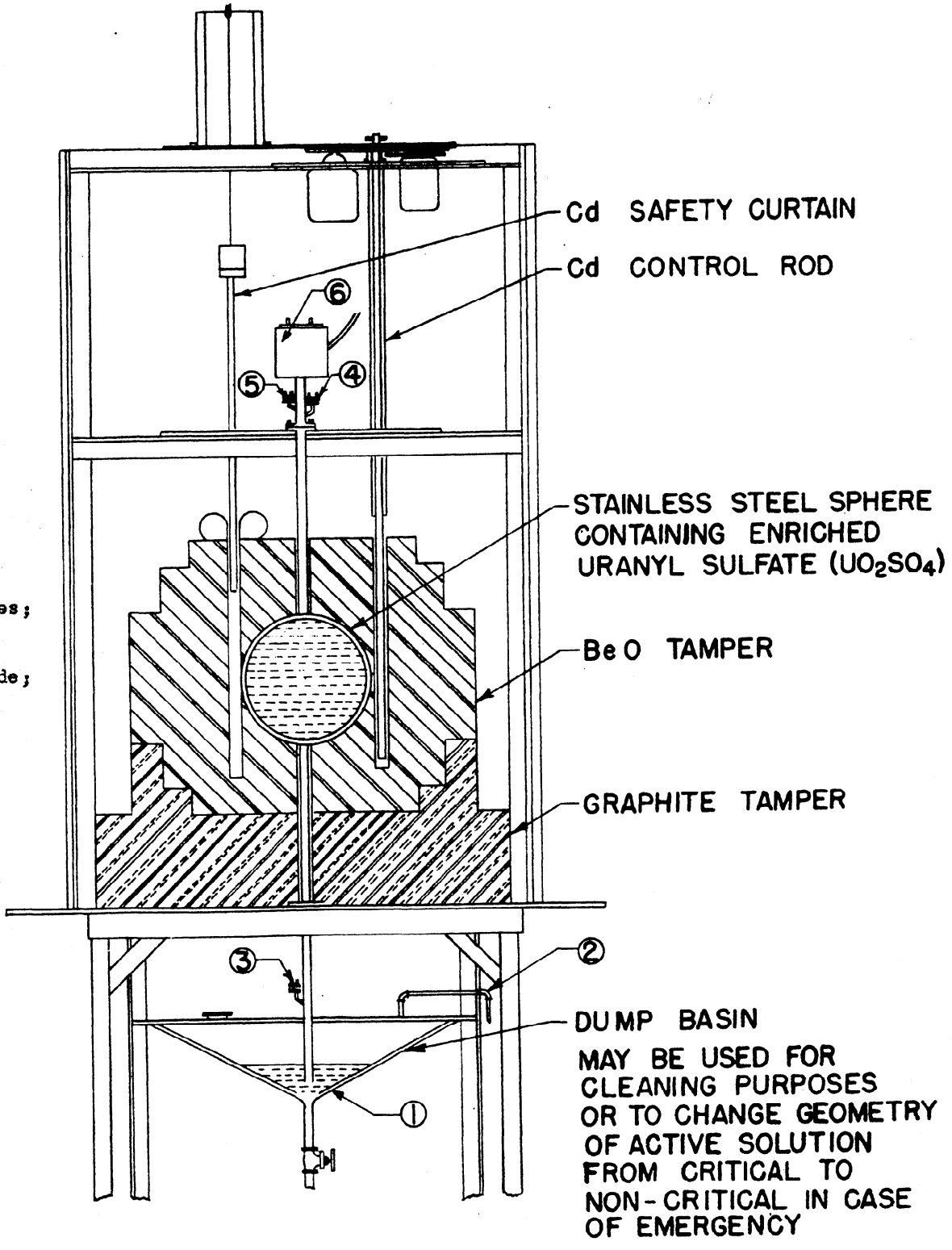


Figure 2

(1) Conical pan;

(2) Air pipe;

(3), (4) Level electrodes;

(5) Safety electrode;

(6) Overflow.

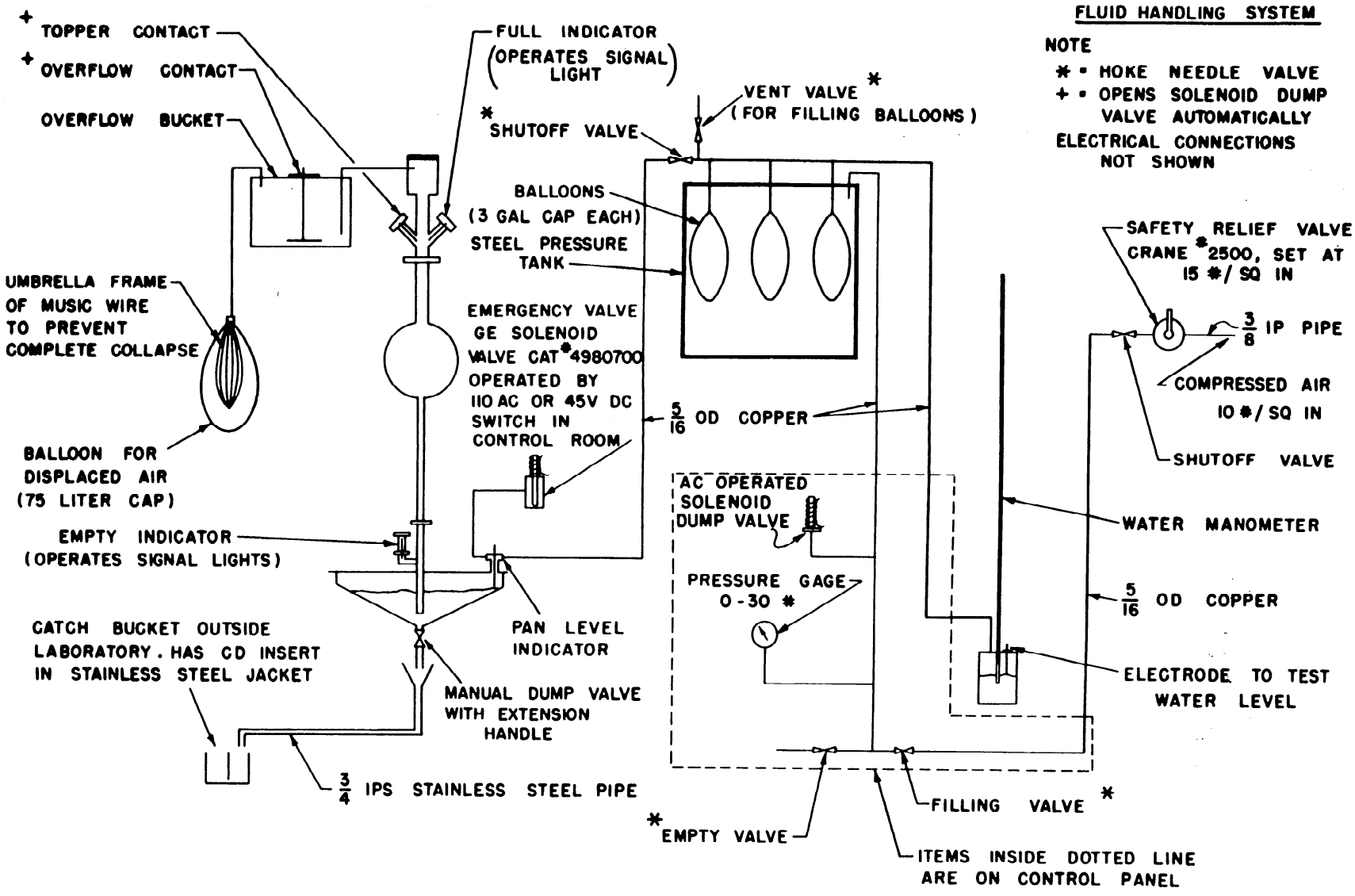


Figure 3

Fluid Handling system.

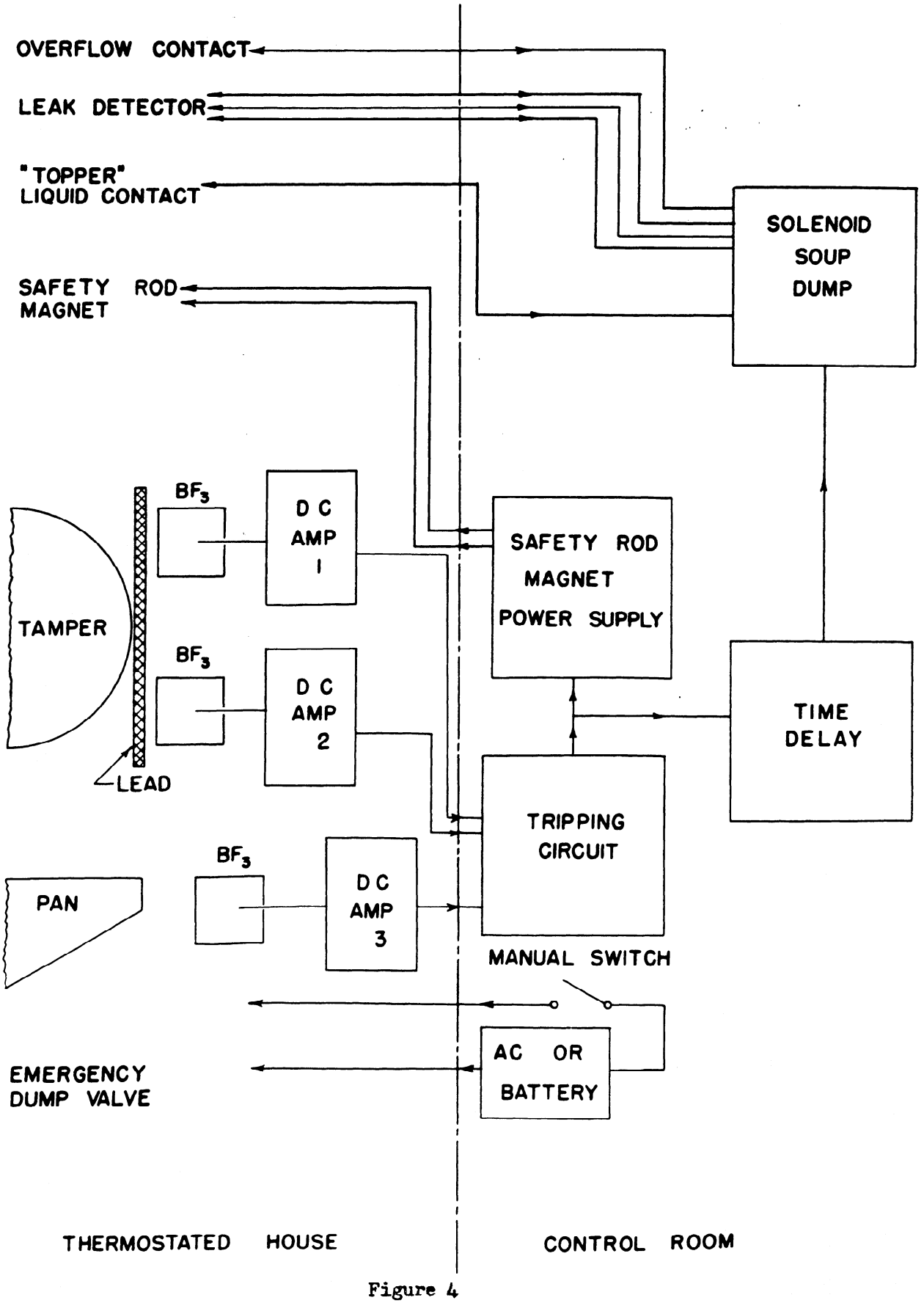


Figure 4

Safety Circuits.

Arrows in lines indicate direction of controlling impulses.

(c) If after a short time the neutron level continued to rise above a predetermined level (the delay permits the safety rod to operate first).

A safety catcher pan was placed underneath the tamper and sphere to prevent the loss of material due to leak or overflow. All safety devices operated in case of power failure. As a final precaution the conical pan was provided with a remote manually controlled dump valve which drained the solution through an underground pipe into a stainless steel bucket with cadmium inserts to discourage any further chain reaction. This provided a possible way of removing the solution from the building which seemed advisable in the case the solution became too radioactive.

4.2-2 Approach to Critical

Since this was the first chain reaction with an enriched material, considerable precautions were taken before approaching critical.

The general procedure was as follows. Five independent detectors placed in different positions were used to determine the multiplication of a 200 mc Ra Be source placed at the center of the sphere by means of a thimble type reentrant tube thru the upper pipe. A zero reading, i. e. for no multiplication, was obtained by filling the sphere with distilled water. The empty sphere and source were used to standardize all detectors before and after each change of concentration.

The chemists then proceeded to add uranyl sulphate by removing one or two liters of the solution in the conical pan and dissolving an additional amount of material. An electric stirrer was run for 15 minutes to make sure of adequate mixing before the solution was run up into the sphere. Further mixing was obtained by raising and lowering the solution between pan and sphere until

no further change in counting was detectable. This usually required three to five fillings of the sphere. The first 11 additions contained about 40 grams each of U^{235}, the next 4 about 20 grams each of U^{235} and the last 3 about 5 grams U^{235} each.

The detectors used to determine the multiplication were (1) Indium foils with and without cadmium in the tamper three inches from the sphere surface; (2) Manganese foils in the reentrant tube placed at the center and near the edge of the sphere; (3) An external BF_3 chamber bare and in a paraffin block 9 inches x 113 inches covered with cadmium; (4) A small U^{235} chamber about 5/16 inches O. D. placed in a reentrant tube about 3 inches from the center; (5) A large U^{238} chamber placed against the sphere in the north part of the tamper (this chamber had 248 square centimeters area covered with 2 grams of U^{238}).

Table 4.2-2 shows the results obtained with these detectors. The shape which the curves of Figure 5 have when plotting reciprocal count against mass can be qualitatively understood fairly easily. Thermal detectors placed inside the reacting region should give an approximate straight line and hence the best extrapolated estimate of the critical mass, intercepting the abscissa at the critical mass, (detectors placed at the center were too near the 200 mc Ra Be source and hence gave a concave downward curve). The best position for such a detector is probably at the node of the third harmonic of the thermal neutron distribution which has a high peak at the source. One of the manganese detectors was placed approximately in this position after the strong source effect was observed at the central position. Detectors placed outside the reactor should ideally give curves concave upward since they count both fast and slow leakage. It is apparent from the trend of all the curves that rather accurate predictions of the critical mass could be made before actually going critical. When the

TABLE 4.2-2

Mass (gms) "25" In Sphere	Foils In + Cd 1/c	Foils In 1/c	Foils Mn* 1/c	Foils Mn** 1/c	BF_3 Baro 1/c	BF_3+Cd+CH_2 1/c	BF +CD 1/c	"25" 1/c	"28" 1/c	
0 (dist.H_2O)	1	1	1	1	1	1	1	1	1	0
46.8	.783	.783	-	.973	.835	.857	-	.909	.889	1
140.1	.495	.524	-	.900	.560	.650	.626	.752	.589	2
183.4	-	-	-	-	.465	-	-	.693	-	3
225.7	.303	.359	-	.820	.379	.449	.440	.625	.395	4
266.5	-	-	-	-	.316	-	-	.580	-	5
303.3	.195	.241	-	.774	.257	.307	.295	.483	.284	6
343.0	-	-	-	-	.208	-	-	.411	-	7
380.2	.118	.151	.318	.534	.164	.198	.196	.359	.178	8
435.3	-	-	.230	-	.109	-	-	.267	-	9
474.9	.052	.072	.175	.290	.070	.092	.088	.191	.081	10
501.35	-	-	-	-	.055	-	-	.145	.065	11
518.47	.029	.038	.101	.195	.042	.052	.050	.117	.046	12
540.10	-	-	.063	.128	.026	-	-	.073	.027	13
555.17	-	-	-	-	-	.016	-	-	-	14
564.10	-	-	-	-	-	.008	-	-	-	15
570.879	-	-	-	-	-	.0025	-	-	.0022	16
574.829	Critical with Control Rod at 16.5" Above its Bottom Position									17

(572.8 gm) Critical mass with rod out
(565.5 gm) " " " " ", reentrant tube and 28 chamber removed
* Mn foils which were put approximately at node of third harmonic
** Mn foils in center of sphere

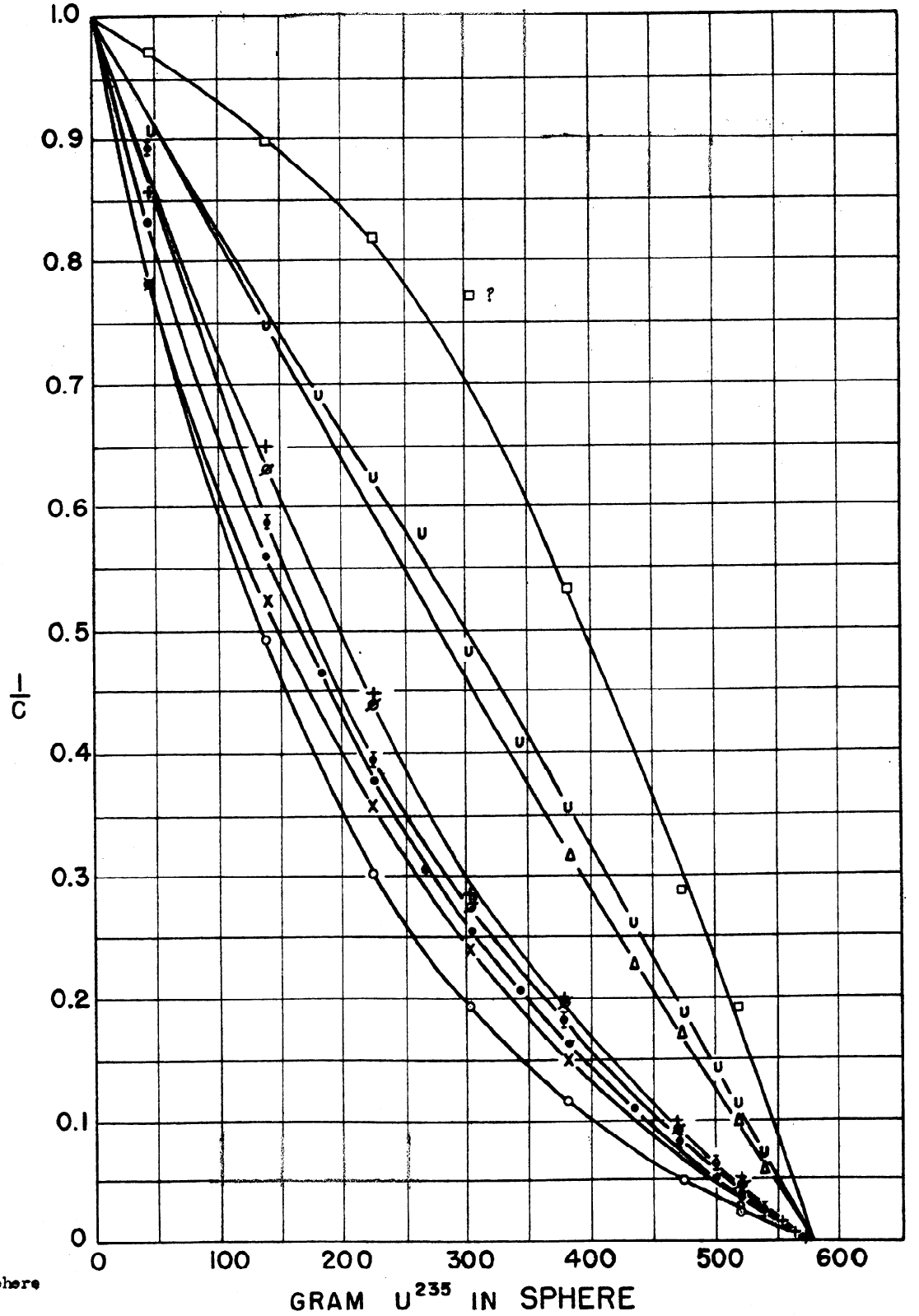


Figure 5

○ - In + Cd Foils 3" from Sphere

X - In Foils 3" from Sphere

△ - Mn Foils at Node 3rd Harmonic

□ - Mn Foils at Center of Sphere

• - BF_3 Bare Outside Tamper

+ - BF_3 + Cd + CH_2 Outside Tamper

Ø - BF_3 + Cd Outside Tamper

U - U^{235} Chamber 3" from Center

I - U^{238} Chamber Against Outside of Sphere

last addition had been made, the control rod was pulled out slowly until a good counting rate was obtained, the driving source removed and the boiler ran itself, the neutron level responding to the control rod.

The U^{235} in the sphere at this time was 574.8 grams. Correcting for the rod position, a missing tamper block due to the presence of one of the recording chambers, and a small reentrant tube gave 565.5 grams of U^{235} as the critical mass. This checked original calculations(11) extremely well, probably somewhat

(11) R. F. Christy, Unpublished.

fortuitously.

The highest power at which Lopo was run was about 50 millwatts.

4.2-3 Experiments with Lopo

(1) Control rod calibration(12)

(12) C.P. Baker, F.L. Bentzen, J. Bridge, R.E. Carter, H. Daghlian, H. Hammel, J. Hinton, F. de Hoffman, M.G. Holloway, D.W. Kerst, L.D.P. King, H.M. Lehr, J.H. Midway, R.E. Schreiber, J.W. Starner, "Water Boiler", LA-134.

When the critical conditions were initially reached, the control rod was part way in. Active material was then removed from the sphere by dilution until the control rod was just out with the boiler still critical. Eight small additions of approximately 2 grams each of material were then made and in each case the rod position for criticality determined. Figure 6 shows the curve of the equivalent mass of U^{235} as a function of control rod position. The control rod is all the way in at zero inches. In all measurements the solution is raised to the same position in the upper pipe, about 90 centimeters above sphere level. This was approximately to the top of the tamper. Criticality was found to be insensitive to the solution level in this upper tube except for the first few centimeters. If the level above the sphere is measured in centimeters, and the total effect expressed

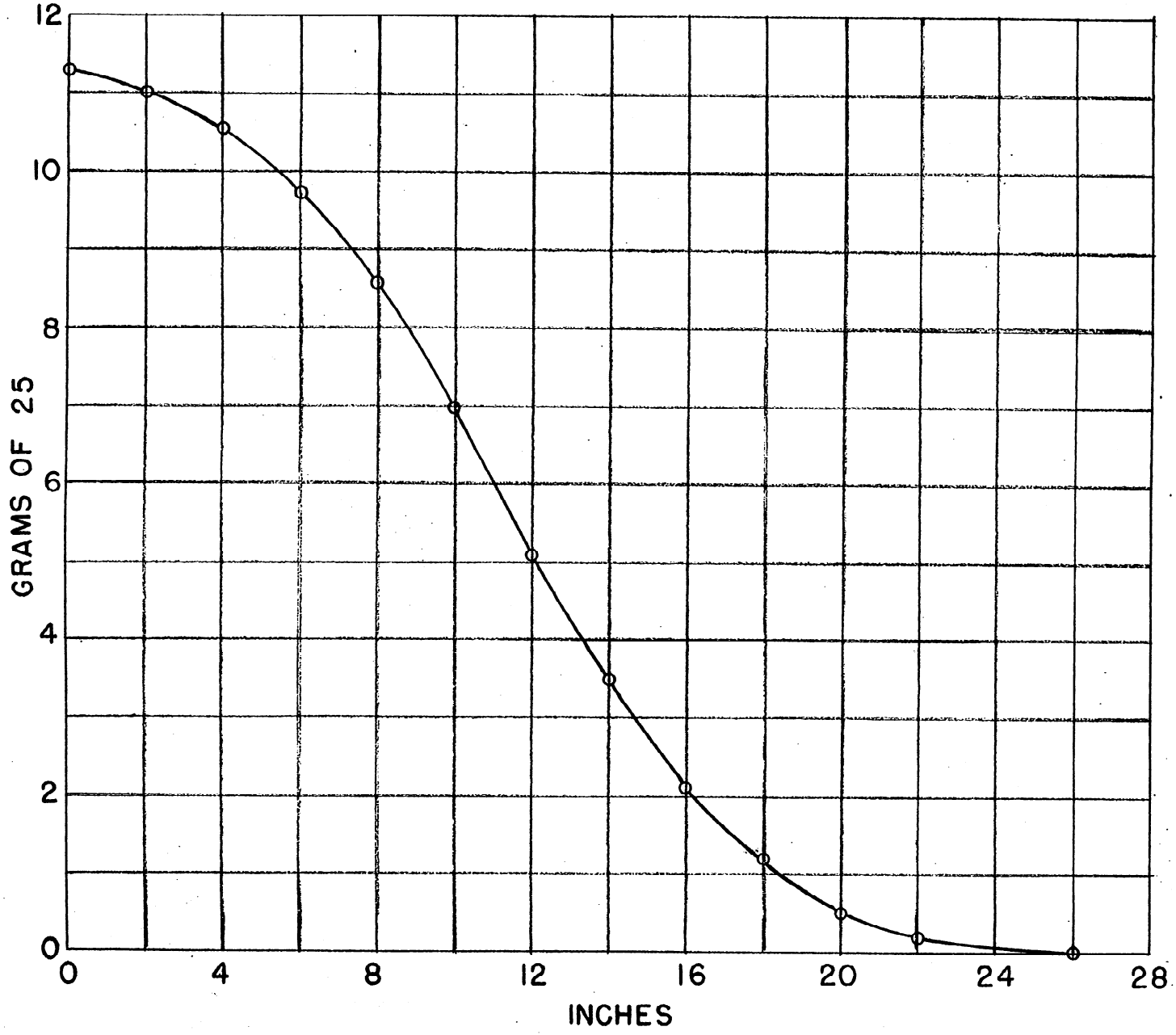


Figure 6

in grams of U^{235} equivalent, the measured values are 1 gram at 2.5 centimeters, 2 grams at 7 centimeters, 3 grams at 19 centimeters, 4.5 grams at 90 centimeters.

(2) Temperature effect.[13]

---

(13) C. P. Baker, F. L. Bentzen, J. Bridge, R. E. Carter, H. Daghlian, H. Hammel, J. Hinton, F. de Hoffman, M. G. Holloway, D. W. Kerst, L. D. P. King, H.M. Lehr, J. H. Midway, R. E. Schreiber, J. W. Starner, Water Boiler LA-134.

Due to the large expansion coefficient of the water solution the neutron leakage is strongly dependent on temperatures since both neutron age and thermal diffusion length vary with temperature. This produced quite a change in the critical position of the control rod. The effect is measured by accurately determining the critical rod positions for various temperatures of the solution. The average value found was .75 grams per degree C at 39 degree C. This is partly due to the loss of solution from the sphere due to the thermal expansion. Correcting for expansion gives .55 grams per degree C.

(3) Absolute calibration of the water boiler in terms of K[14][15]

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(14) F. L. Bentzen, J. Bridge, F. de Hoffman, D. W. Kerst, L. D. P. King, G. Friedlander: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183.

(15) F. de Hoffman, L. D. P. King, G. A. Young: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183 A.

In order to determine the relation between grams and the actual reproduction factor K of the boiler a so called "boron bubble" experiment was performed. The equivalence of K and grams of U235 was obtained by observing the critical control rod setting under normal conditions and then the setting after the introduction of a small volume or bubble (15.27 cubic centimeters) containing a

mock solution. The mock solution consisted of an appropriate mixture U^{238} and H_3BO_3 in water. The absorption and scattering cross-section of the mock solution matched that of the boiler solution closely, see Tables 4.2-1A and 4.2-1B, (except of course, that no fissions occurred in the mock solution). No change in criticality could be detected by the insertion or radial motion of the small volume when filled with the boiler solution. The bubble consisted of a thin walled lucite sphere supported on a lucite rod. The experimental results when the bubble with the mock solution is moved radially, is shown in Figure 7. The conversion from control rod setting to grams is read from Figure 6. If ΔM is the effective grams of U^{235} for any radial position then

$$\overline{\Delta M} = \frac{\int_0^r 4\pi r^2 \ \Delta M dr}{\int_0^r 4\pi r^2 dr}$$

is the equivalent of distributing the mock solution in the bubble uniformly throughout the sphere. The final value for ΔM was 1.843 grams of U235. A 7.5 per cent correction for slight differences in absorption between the mock solution and the actual solution was applied to get this result. For the mock solution

$$\sigma_{s/cc} = 2.749 \text{ cm}^2 \quad \text{and} \quad \sigma_{a/cc} = .0965 \text{ cm}^2$$

for the normal solution

$$\sigma_{s/cc} = 2.734 \text{ cm}^2 \quad \text{and} \quad \sigma_{a/cc} = .0897 \text{ cm}^2$$

Thermal cross sections were used throughout, except for boron. For this case and effective cross section of boron compared to that of U^{235} was determined assuming the higher energy spectrum to be that of pure hydrogen. This assumption is reasonable due

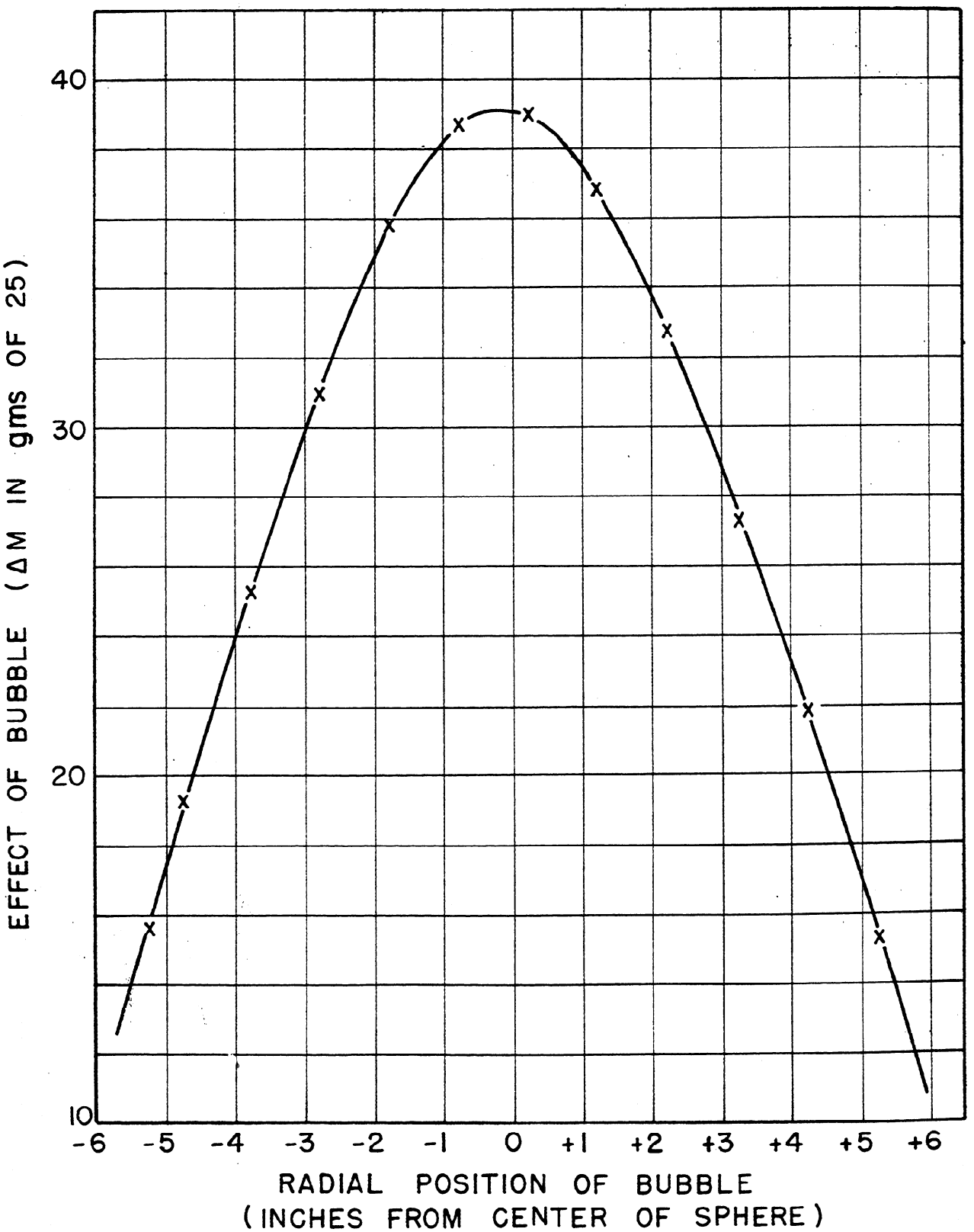


Figure 7

A Boron-bubble experiment.

△M vs Radial Position

to the large hydrogen content in the boiler solution. The effective boron cross section was found to be 2.5 per cent higher than the thermal value.

If ΔM were distributed uniformly throughout the sphere ΔK would be very nearly proportional to ΔM. Since the actual localized volume ΔM used was quite small, it is reasonable to assume that this proportionality is true.

$$\text{Then } \frac{K\ (\text{mock})}{K\ (\text{original } (=1))} = \frac{V - \Delta V}{V} = 1 - \frac{\Delta V}{V}$$

$$\text{and } \Delta K = 1 - K = \frac{\Delta V}{V} = \frac{V\ \text{bubble}}{V\ \text{sphere}} = \frac{15.17}{15 \times 10^3} = 1.01 \times 10^{-3}$$

Since $\overline{\Delta M} = 1.843$ grams of U^{235} and $\Delta K = 1.01 \times 10^{-3}$ for this $\overline{\Delta M}$ one obtains as the equivalence between reactivity and grams of U^{235}

$$5.48 \times 10^{-4}\ \Delta K/\text{gm} \quad \text{or } 548\mu\ \text{Re/gm} \quad (\text{a microres} = K \times 10^6)$$

This value checks, no doubt fortuitously, within a percent the theoretical value[16] made prior to the above result. (An error

(16) F. de Hoffman, L. D. P. King, G. A. Young: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183 A.

in the original determination[17] has been corrected in[18] after

(17) F. L. Bentzen, J. Bridge, F. de Hoffman, D. W. Kerst, L. D.P. King, G. Friedlander: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183.

(18) F. de Hoffman, L. D. P. King, G. A. Young: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183 A.

the calculation[19] was made.)

(19) E. Fermi, J. Hinton: Dependence of Reactivity of Water Boiler in the Mass of U^{235} in the Sphere, LA-470.

The calculations were made by determining the negative source (using the diffusion equations for sphere and tamper) necessary to keep the boiler running at a constant value when x grams of U^{235} are added. The fission distribution was assumed the same as the experimentally measured thermal neutron distribution. The effectiveness of a fission source at different points in the sphere was approximated by using a Ra Be source curve.

The equivalence of grams of U^{235} and reactivity can be estimated quite well from the cross sections of the solution components and any absorbing materials such as the stainless steel sphere or control rod. From Table 4.2-1 A

$$\bar{\nu} \text{ of } 14.67\% \text{ Uranyl sulphate solution} = \frac{2.1 \times 954.9}{954.9 \times 102.9 + 4.74} = 1.8873$$

$$K^{\infty} = \frac{\sigma_a(U^{235}) \times \bar{\nu}(U^{235}) \times Mc(U^{235})}{\sigma(U^{235} + H_2O + \text{Steel})} = \frac{1.832 \times 572 \times 1.8873}{1.832 \times 572 + (282 + 36+6)} = 1.4416$$

where 572 is critical mass (U^{235} in sphere)

$$L = \text{leakage} = \frac{1}{1.4416}$$

$$K = \frac{M(U^{235}) \times \sigma/gm U^{235} \times L}{M(U^{235}) \times \sigma/gm(U^{235}) + (\sigma H_2O + \sigma \text{ steel} + \sigma \text{ reentrant tube})} = \frac{M \times 2.39842}{1.832 \times M + 324}$$

and

$$\Delta K = 406 \mu R/gm\ U^{235}$$

For the boron bubble experiment the reentrant tube was out (6.2 grams U^{235} equivalent) and the control rod set at 7.15 inches (9 grams U^{235} equivalent). The estimated absorption for the rod is 195 square centimeters, (the effective surface area of the cadmium cylinder is used to get this value), that for the reentrant tube 6 square centimeters, or total square centimeters

equal 318 + 195-6 = 507

Term $K = \frac{M \times 2.706137}{1.832M + 507}$ where 580 grams is critical mass (U^{235} in sphere)

and $\Delta K = 556 \mu R/gm\ U^{235}$

This value checks the boron bubble experiment and independent calculation[20] mentioned above. See also general discussion

(20) E. Fermi, J. Hinton: Dependence of Reactivity of the Water Boiler on the Mass of U^{235} in the Sphere, LA-470.

for the measurement of K in Chapter 2 of this volume.

(4) Supercritical Behavior of the Water Boiler.[21]

(21) C.P. Baker, F.L. Bentzen, J. Bridge, R.E. Carter, H. Daghlian, H. Hammel, J. Hinton, F. de Hoffman, M.G. Holloway, D. W. Kerst, L.D. P. King, H. M. Lehr, J.H. Midway, R.E. Schreiber, J.W. Starner:"Water Boiler", LA-134.

In order to determine the supercritical behavior of lopo, periods of the boiler where measured for various supercritical control rod positions. In each measurement the intensity was allowed to rise for at least one period and then the increase in counting rate followed for one or more order of magnitude. This procedure gave straight line semi-log plots except for the longest periods. Here the long lived delayed neutrons had not yet reached an equilibrium condition and the final slope of the plots was used for the period determination. Figure 8 shows the degree of criticality in terms of grams of U^{235} as determined from the control rod calibration.

It was thought useful to determine a relation between reactivity and period for the water boiler which might be useful for a higher power boiler. This was done by determining the constants

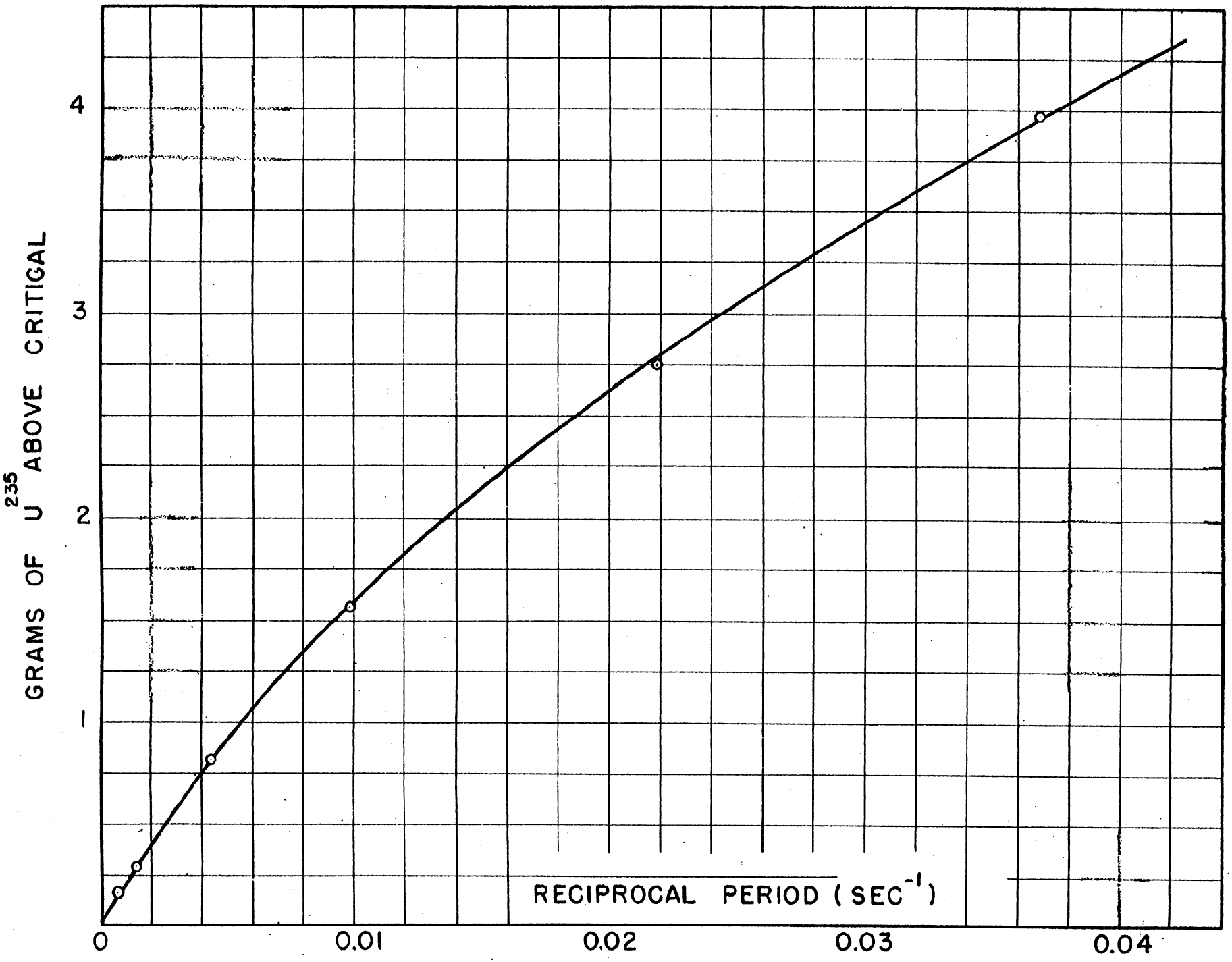

GRAMS OF U^{235} ABOVE CRITICAL
4
3
2
1
0
0.01
0.02
0.03
0.04
RECIPROCAL PERIOD (SEC^{-1})

Figure 8

in equation (9) below with the data available from the measured supercritical periods, the results of the boron bubble experiment (18.25 = 1 per cent in K) and the known delay periods. (This is equation 9 of Chapter 2 of this volume. A complete derivation of this reactivity equation is given there.)

$$\Delta K = \frac{\tau_o}{T} + \gamma f \sum \frac{q_i \tau_i}{T + \tau_i} \qquad (9)$$

in the limit

$$T \rightarrow \infty \Delta K = \gamma f \sum \frac{q_i \tau_i}{T} \quad \text{since } \tau_o \sim 10^{-4} \text{ second}$$

or

$$T \Delta K = \gamma f \sum q_i \tau_i = \text{const}$$

Taking the boron bubble result that 548 μRe = 1 gram U^{235} and the supercritical period measurements of Figure 8 we have

T(period)	Grams U^{235} equiv	ΔK in μ Re	$T\Delta K$
29.2 seconds	3.97	2176	.064
46.3 "	2.72	1491	.069
101 "	1.52	833	.084
232 "	.78	427	.099
774 "	.24	131	.101
1352 "	.13	71	.096

The last column appears to approach 0.1. The low value for the longest period can easily be accounted for by the uncertainty in the determination of ΔK for such a small change. If one neglects any difference in energy with period for the delayed neutrons $\sum q_i \tau_i$ can be obtained from the known delay periods.

$$\text{delays} = .116e^{-\tau/.61} + .330e^{-\tau/2.2} + .292e^{-\tau/6.5} + .228e^{-\tau/31.7} + .034e^{-\tau/80.3}$$

$$\gamma f = \frac{\Delta K T \infty}{\sum q_i \tau_i} = \frac{0.1}{12.66} = .0079$$

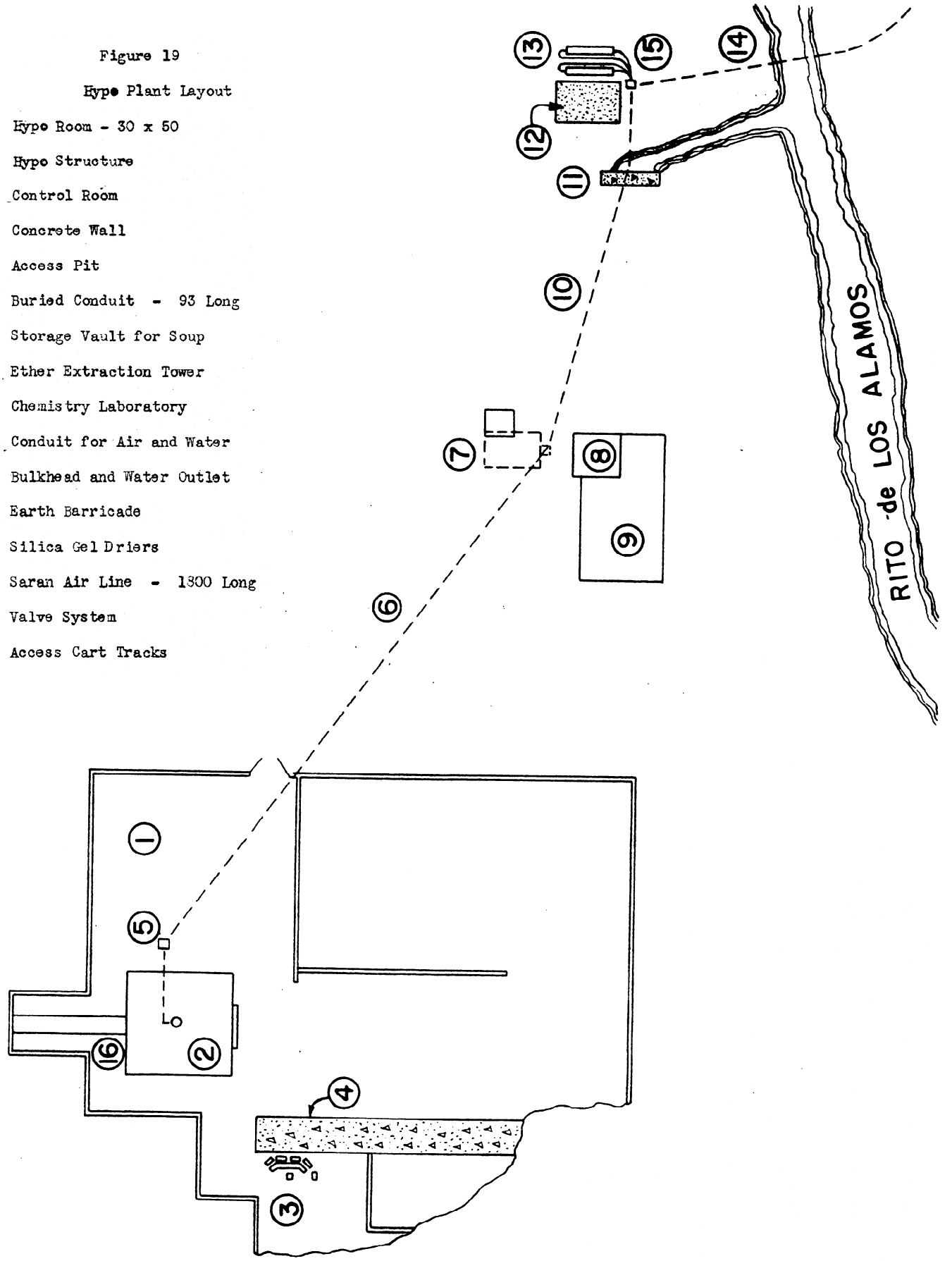
boiler solution which might have several thousand curies of activity.

The ether extraction method was chosen for decontamination since the method was well known for purification of uranyl nitrate. The flow sheet for the equipment is shown in Figure 20. The details

Figure 19

Hypo Plant Layout

1. Hypo Room - 30 x 50
2. Hypo Structure
3. Control Room
4. Concrete Wall
5. Access Pit
6. Buried Conduit - 93 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 - 1300 Long
15. Valve System
16. Access Cart Tracks



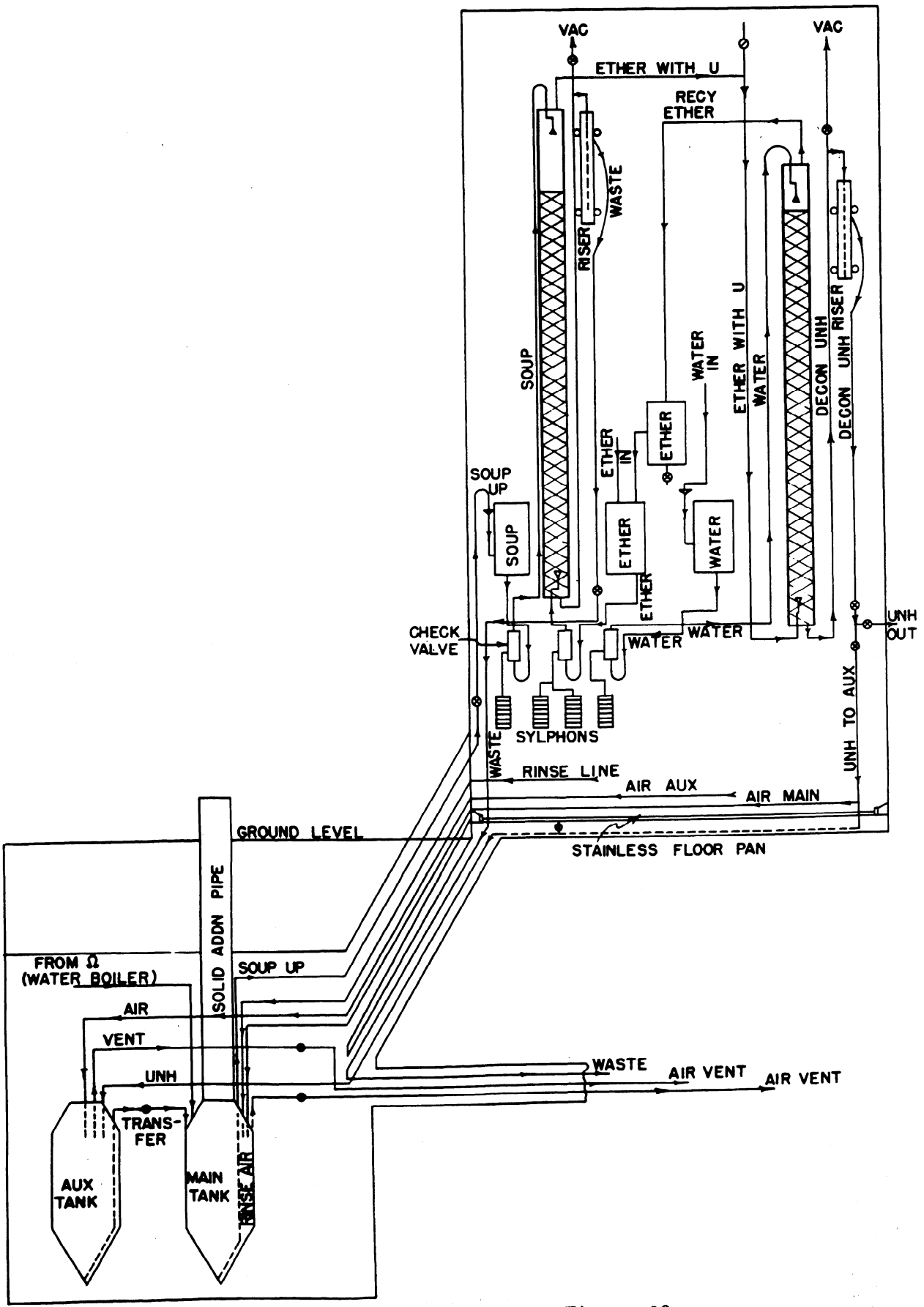


Figure 20

Ether extraction system - Omega - Qualitative flow sheet.

of the equipment and method are given in reference[36] and

(36) L. Helmholtz, J. C. Nevenzel, P. H. Watkins: High Power Water Boiler (sections on decontamination) LA-394.

Volume VIII, Chapter 7 of the Los Alamos Technical Series. It now seems that such elaborate equipment may not be needed for a water boiler since there has been no need for decontamination of the solution in over 2500 kilowatt hours of operation. This is due to the extremely low corrosion rate of the stainless steel container and the large fraction of fission activity (an estimated 30 per cent) carried out by the flushing air.[37]

(37) A. Goldstein, S. Katcoff: Sweeping of Gases from Homogenous Pile, LA-548.

(2) Critical mass estimate from lopo measurements

It was possible to get a rather good estimate of the amount of U^{235} which would be required for the high power boiler from simple calculations based on measurements made on lopo. Various tamper measurements have been described (Section 4.2-3, (8b).) These showed that the most effective tampers were BeO or a composite BeO core graphite shell. It was pointed out there, that beryllium is not an ideal tamper material for certain types of experiments due to its large γ - n cross section. The need of BeO bricks for other high priority experiments going on in the laboratory, and the amount of enriched material available lead to the choice of the composite tamper irrespective of other considerations.

Numerous other critical measurements were made to assist in estimating the critical mass required for hypo. The effect

of a 1/32 inch thicker sphere wall was measured by fitting a spare hemispherical spinning around the lopo sphere; the effect of the cooling pipe was estimated by placing a short section of the pipe at various positions inside the sphere; a similar experiment using reentrant tubes determined the effect of the "glory hole".

In all these measurements the change in control rod necessary to hold the boiler just critical gave a measure of the equivalent grams of U^{235} for each sample tested. The net result of these additional absorbers was determined as 130 grams U^{235}. (Thicker sphere 20 gram, cooling pipe 80 gram, glory hole 30 gram).

In making these estimates it was assumed that the effect of these absorbers was additive and that one could extrapolate the effect of a small absorber to one many times larger as was the case for the cooling coil. These assumptions are not necessarily true, but the results proved to be quite accurate.

The conversion from uranyl sulphate to uranyl nitrate should decrease the reactivity by about 3.4 per cent due to the larger nitrogen cross section (1.75 barnes instead of .5 barnes for sulphur). The absolute calibration of lopo (section 4.2-3c) established that 1 per cent in K was equivalent to 18.2 grams of U^{235}. This meant that a change from sulphate to nitrate was equivalent to about 70 grams.

The temperature coefficient should be about proportional to the amount of uranium in solution so was estimated to be 9 grams per degree C instead of .55 grams per degree C measured for lopo (Section 4.2-3(2).)

The total estimated critical mass, from the solution and structural changes, amount to 205 grams more than for lopo, or a total of 770 grams. This increase consisted of (1) 70 grams for the change from sulphate to nitrate, (2) 130 grams for changes in the sphere structure and (3) 5 grams for the tamper change and the four chamber monitor holes to be used in the new set up.

The actual critical mass would have been 773 grams had there been enough material with 14.6 per cent enrichment. The estimates above are seen to be quite accurate and indicate that the separate measurements were additive.

The original prediction was not this close due to the uncertainty existing at that time in the absolute calibration of lopo. This lead to an underestimate by a factor of two in the effect of the change from sulphate to nitrate.

The available 14.6 per cent material amounted to 767 grams, or, not quite enough to go critical. An additional 102 grams of U^{235} then procured had a 10.8 per cent enrichment so that after mixing a concentration of 14 per cent resulted which went critical with 806 grams. Recently, due to the loss of some of the original material and the need for more reactivity 44 grams of 42 per cent material was added. The present concentration is 885 grams of 14.5 per cent U^{235}.

4.3-2 Constructural Details

The major components of the high power water boiler, which will be described in the following sections are the following:

The reactor (1) (see Figure 25) is a 12 inch diameter stainless steel sphere containing the active solution. It is surrounded by a tamper or reflector 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 Figure 19 . The sphere is pierced by a horizontal pipe ("glory hole") (5) to enable one to have access to the highest possible neutron flux. Between the tamper and the thermal column (6) is a bismuth wall (7) which provided gamma ray protection for the thermal column. A removable cadmium curtain (8) can be used as a shutter for thermal neutrons in the column. The shield around the entire assembly consists of 4 inches of lead (9), 1/32 inch of cadmium and 5 feet of concrete (10).

(1) Sphere assembly (1/16 inch wall 18-8 type 347 stainless steel throughout all joints exposed to solution or vapor have stainless steel welds)

(a) Sphere - A one foot diameter stainless steel sphere contains the active solution. The wall thickness varies from 1/16 inch at the poles to 3/64 inch at the equator. The sphere consists of two spun hemispheres with a 1½ inch ID tube welded into the top and a 3/4 inch tube into the lower hemisphere. A 1 inch pipe is welded horizontally thru the sphere to permit irradiation at the highest possible flux. The pipe 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 on the two hemispheres together with an acetylene torch. A helium atmosphere was maintained inside the sphere to prevent oxidation (4) Figure 21 shows details of the sphere assembly.

(b) Cooling coil - A six turn cooling coil ½ inch ID and an effective length of 157 inches is wound in the form of a helix. Figures 21, 22 show the appearance of the coil. Calculations for natural convective cooling indicated that 50 cubic centimeters per second

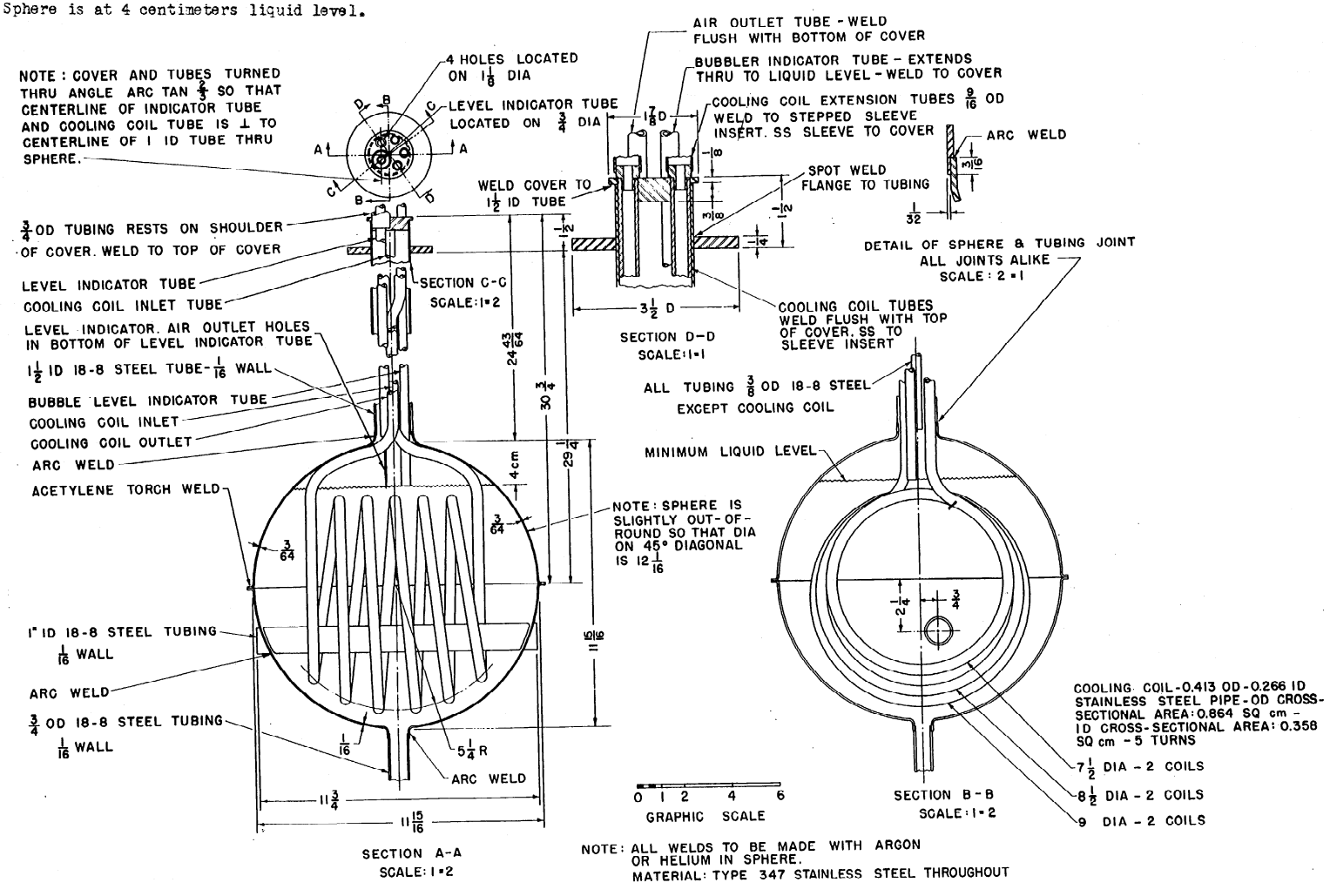
Figure 21

Hypo Sphere Assembly

Total Volume of Sphere	14700	cubic	centimeters
Volume of 3/4 pipe	200	"	"
Total	14900	"	"
Unused Volume of Sphere	700	"	"
Coil Displacement Volume	343	"	"
1 inch Tube Displacement Volume	180	"	"
Total	1223	"	"

Minimum Volume Solution Required 13780 cubic centimeters

Note: Unused Volume of Sphere is at 4 centimeters liquid level.



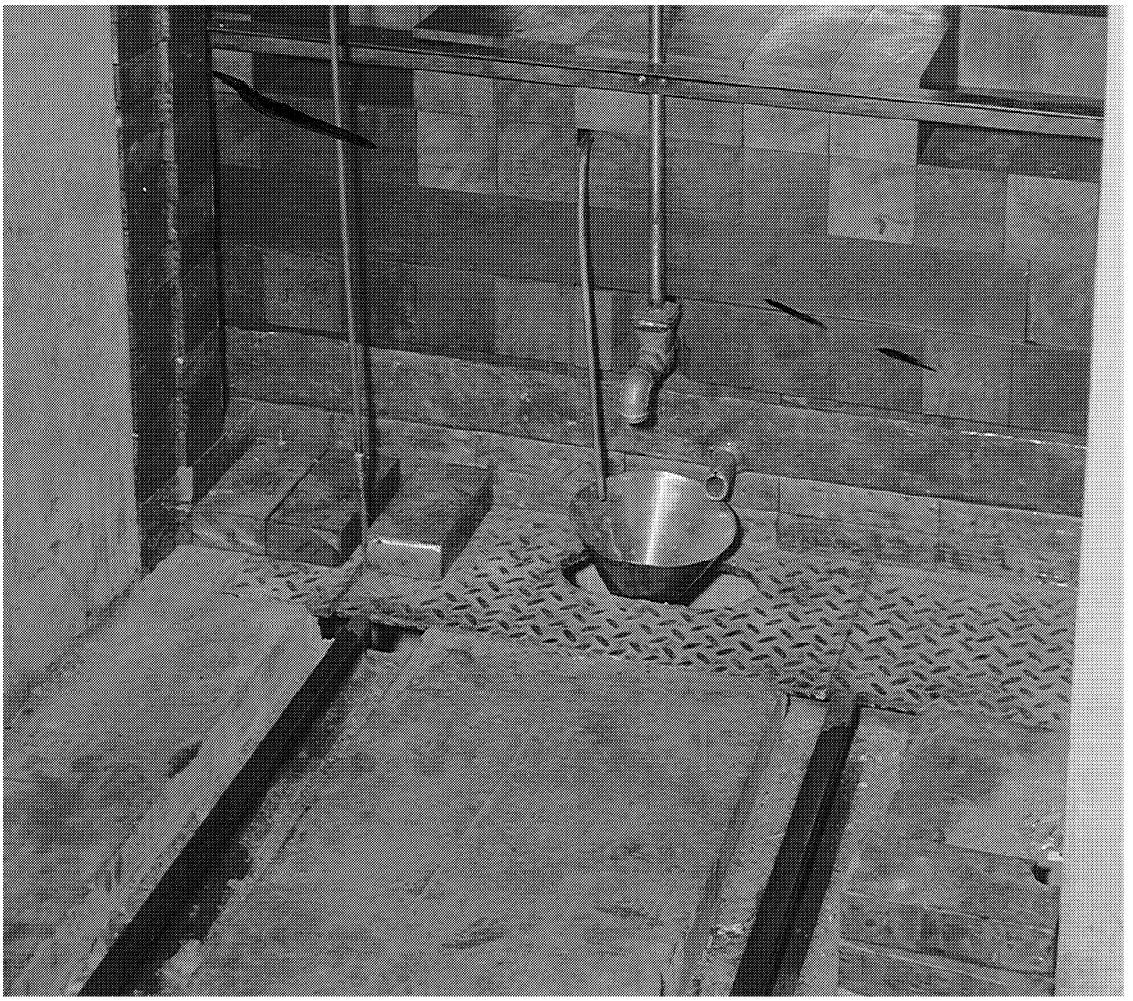
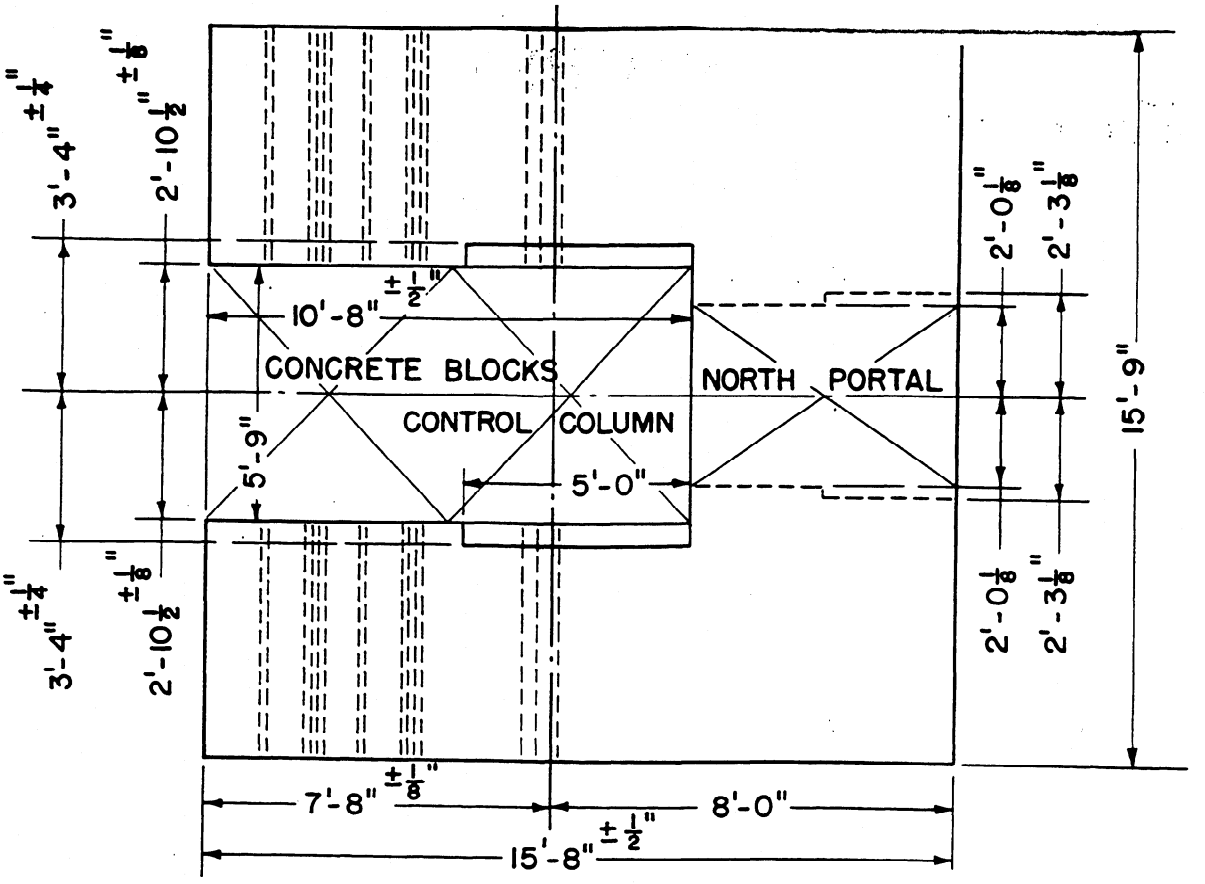
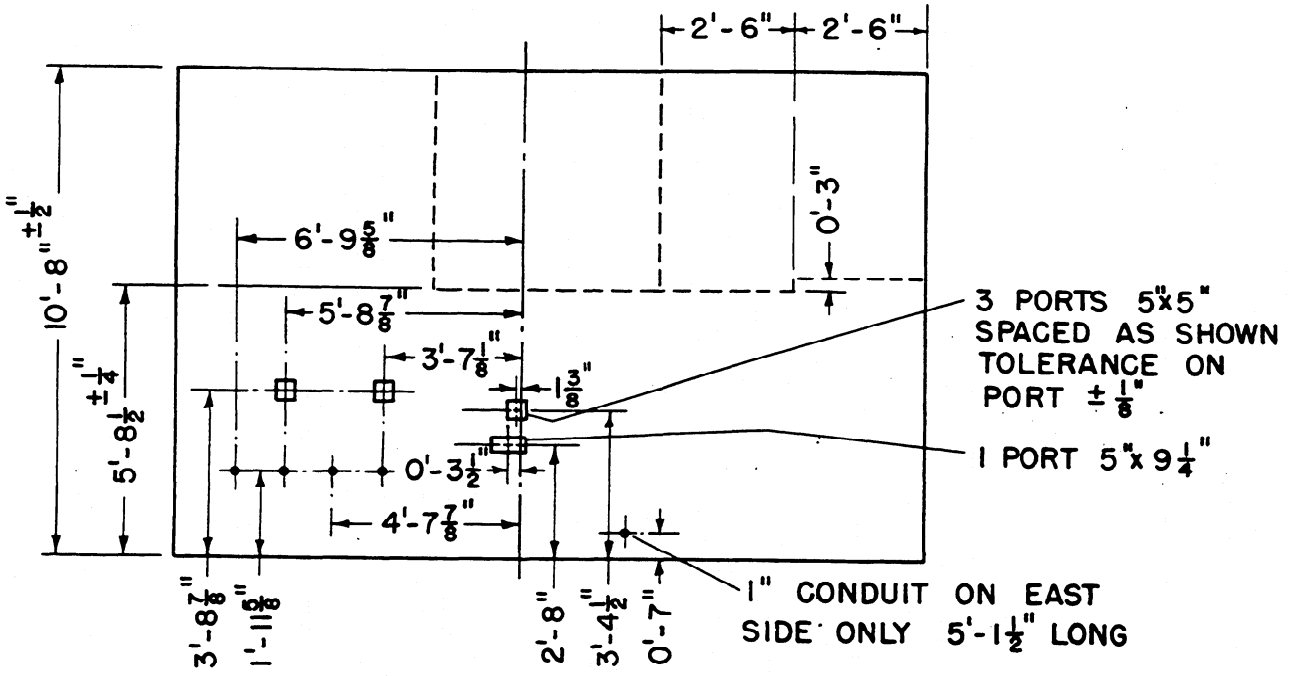


Figure 27



TOP VIEW



EAST ELEVATION

Figure 28

Ports in Shield

Figure 29. These have been primarily used for monitors.

(b) Thermal column - Adjacent to one side of the tamper is a 5 foot cube of graphite to thermalize the neutrons. Numerous experimental ports have been provided here as in the tamper (Figure 28). The transverse ports can be made to extend completely through the column. The longitudinal ports can be varied almost at will but normally extend to the cadmium curtain. The largest port obtainable without complete remodeling of the thermal column is 34 inch x 34 inch extending into the thermal column 4 feet.
A cadmium curtain extends across the thermal column 4 feet from the front of the column. This curtain can be raised or lowered by an electric motor with gear reduction and pully system controlled either from the control room or from the end of the column. The curtain acts as a shutter for thermal neutrons and can be used for timing purposes or to reduce the neutron intensity during changes in experimental equipment.

(c) Radiation shield - In order to provide adequate physiological protection and to reduce the neutron and γ-ray backgrounds to sufficiently low levels for experimental purposes an effective radiation shield is essential. This is accomplished by a combination of cadmium, lead, concrete, and bismuth.
All surfaces of the tamper and thermal column are covered with 1/32 inch of cadmium to stop the thermal neutrons. The cadmium is backed by at least 4 inches of lead to reduce the resulting γ rays. The entire unit is then enclosed by 5 feet of concrete (except at the end of the thermal column) to reduce the remaining γ rays and fast neutron leakage. The concrete is all poured except for that above the tamper and thermal column (Figure 28).

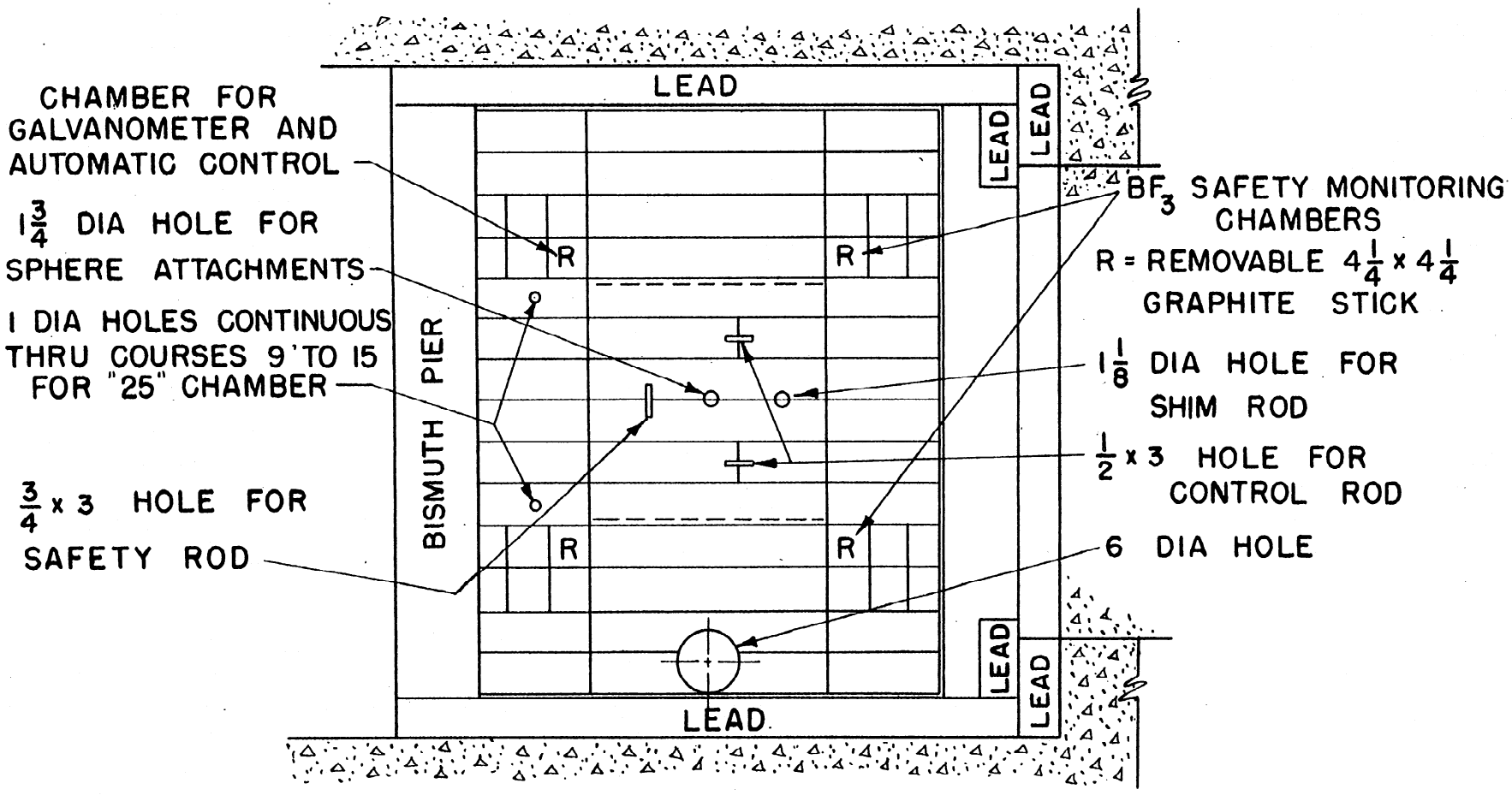


Figure 29

Top-view of Tamper.

The concrete at the back of the tamper was poured on a cart set on rails to permit easy access to the tamper. The shield on top of the thermal column is in the form of large cement blocks supported by the column. Above the tamper the shield is supported by beams resting on a ledge provided by the concrete side walls. This portion of the shield was originally made with a very low strength cement mix and small concrete blocks. Later, this was replaced by building bricks and sand. Both types of construction have been satisfactory and can be removed without much difficulty if access to the sphere is necessary from above.

To give additional γ ray protection in front of the thermal column (where there is only graphite if work is being done on the column) an 8 inch thick pier of bismuth is placed between the tamper and the thermal column. This results in a substantial decrease in the direct γ radiation from the sphere itself, without a serious neutron loss. To make up for the lack of concrete in front of the thermal column the neutron and γ ray leakage is further reduced by adding a 1 inch layer of polythene and a 3/4 inch layer of boron plastic inside the cadmium and increasing the thickness of the lead to 8 inches. The G. M. counter background in front of the column when operating at full power is only twice that due to cosmic rays.

All of the parts which extend through the concrete are normally plugged with wood capped by cadmium and 2 inches of lead. The parts opposite the sphere are shielded by wooden plugs and 4 inch lead doors to permit easy access to the "glory hole". Figures 30 and 31 are side and front views of the shield.

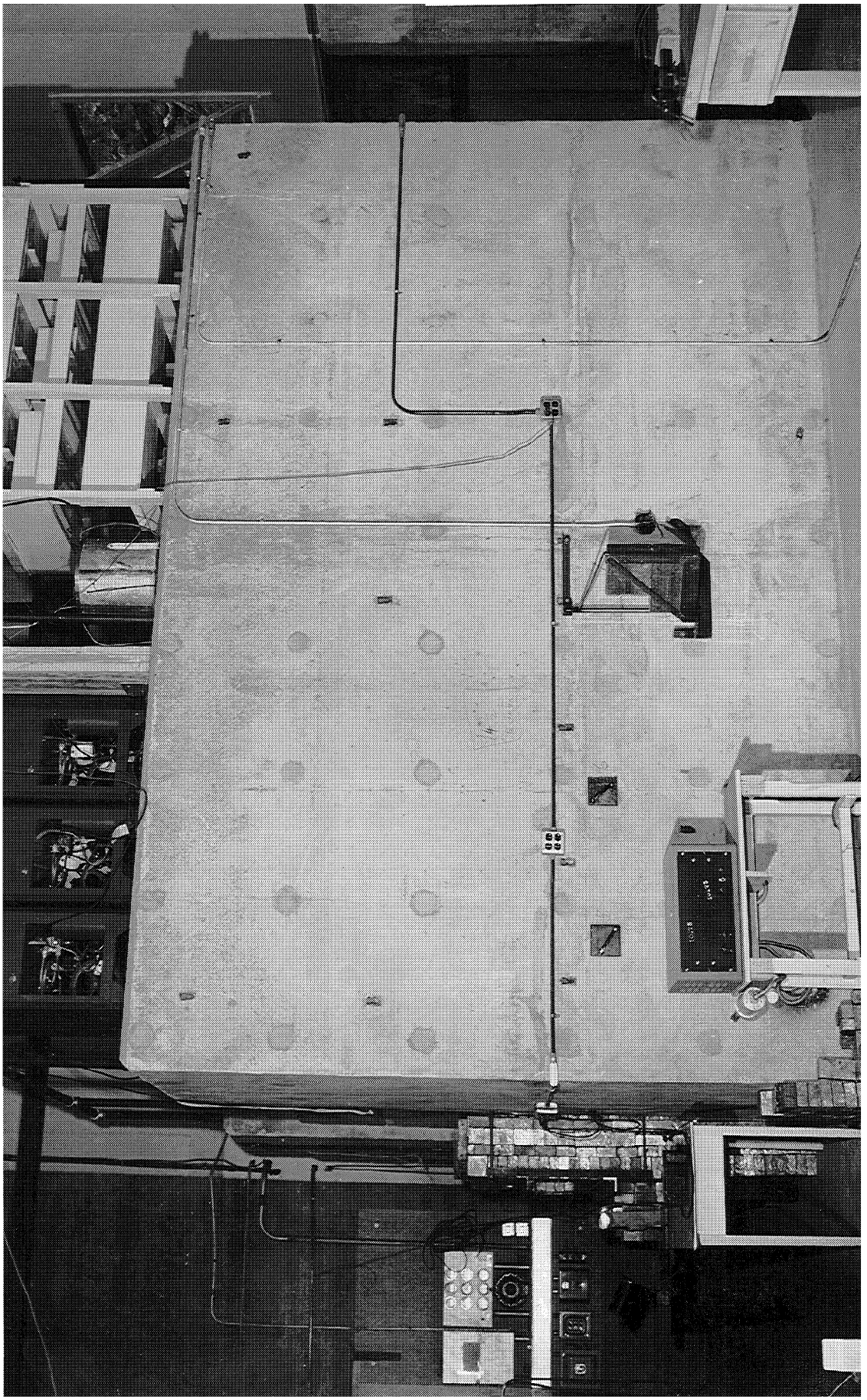


Figure 30

View of Shield

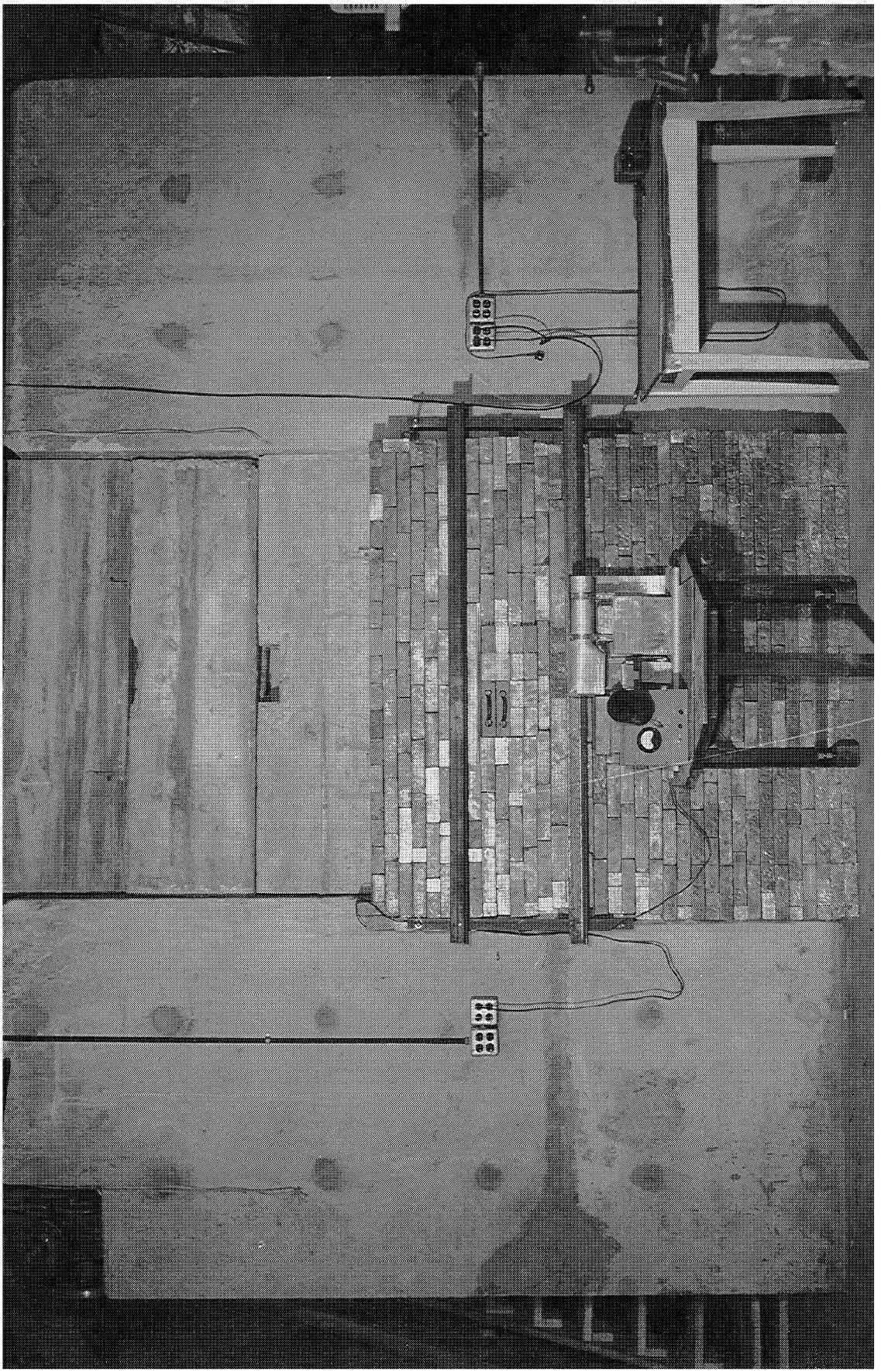


Figure 31

View of Shield

(3) Control, shim and safety rods.

The reactivity of the boiler is controlled by means of four cadmium rods operated from the control room; two control rods, a shim 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 control 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 due to 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 .02 seconds. 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 equivalence in grams of U^{235} of the control and shim rods is about 160 grams which is about 35 grams more than that necessary to compensate for the maximum temperature effect. The arrangement of the four rods in shown top view in Figure 29. Cadmium is contained in the lower 30 inches of the rod. The rods extend from the top of the cement structure to 5 inches below the bottom of the sphere. They have a total motion of 2 feet, which means that when they are out, the bottom of the cadmium is about at the top of the BeO tamper.

Control rods: The control and safety rods slide in metal sheath:

as shown to scale in Figure 32. For minimum neutron absorption the lower halves of the sheaths are made of 1/32 inch wall aluminum. Both halves of the three sheaths can be seen in place in Figure 21; above the iron plate the sheaths are iron.

The two control rods are identical. They were made as light as possible so that they could be operated directly by selsyns. Each rod is 113 inches long and weighs 4 pounds. It consists (Figure 32) of two long strips of dural 2 inches apart. The lower end of the gap between the strips is filled by a sheet of Cadmium (30 inches long, 2½ inches wide and .032 inch thick) sandwiched between two similar sheets of dural. As shown in cross-section in the figure, each side of the cadmium 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 inches long 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 Figures 33 and 34.

To allow the rod to drop freely the pinion gear (1), Figure 33, 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

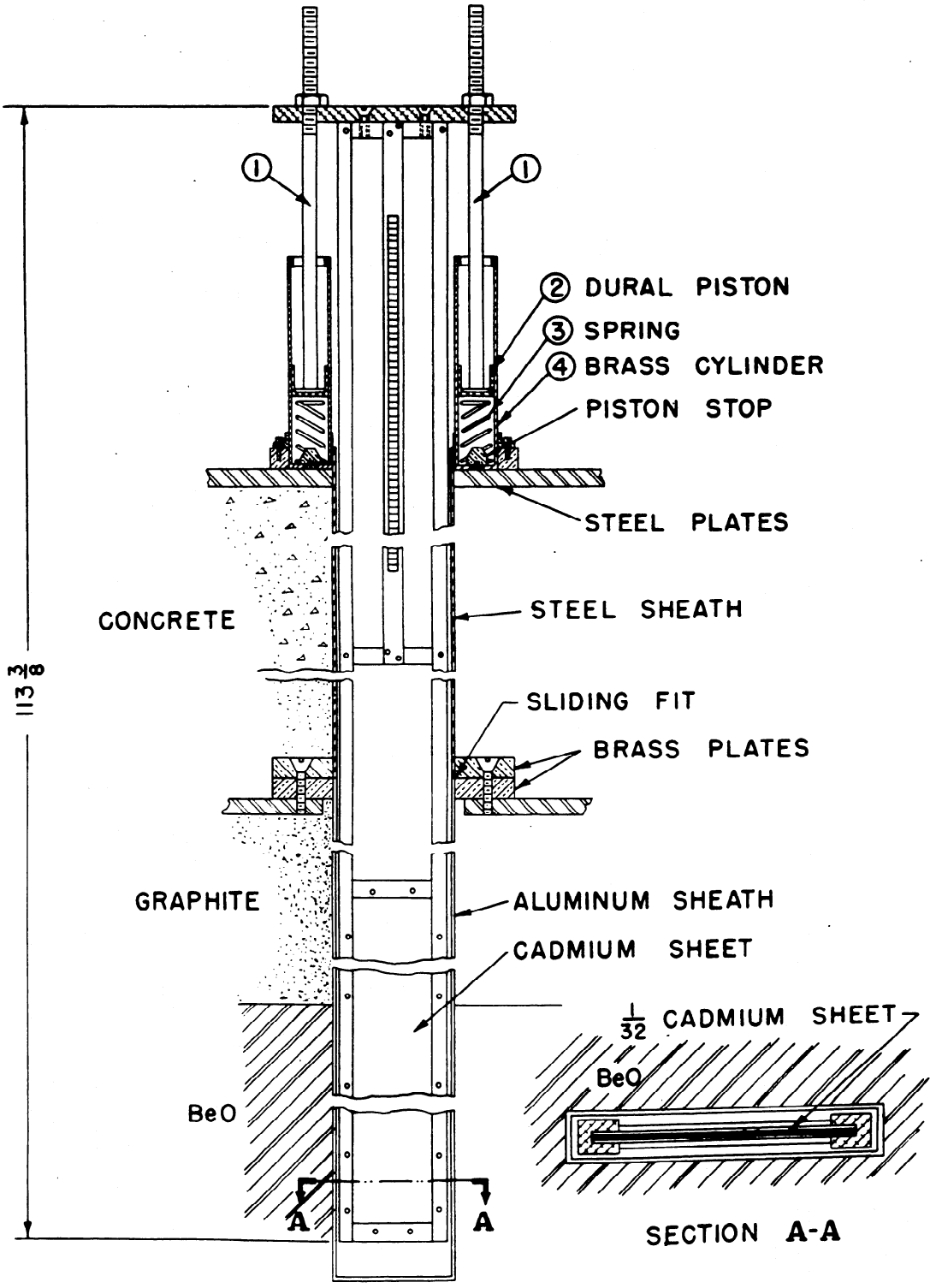


Figure 32

Control rod Assembly

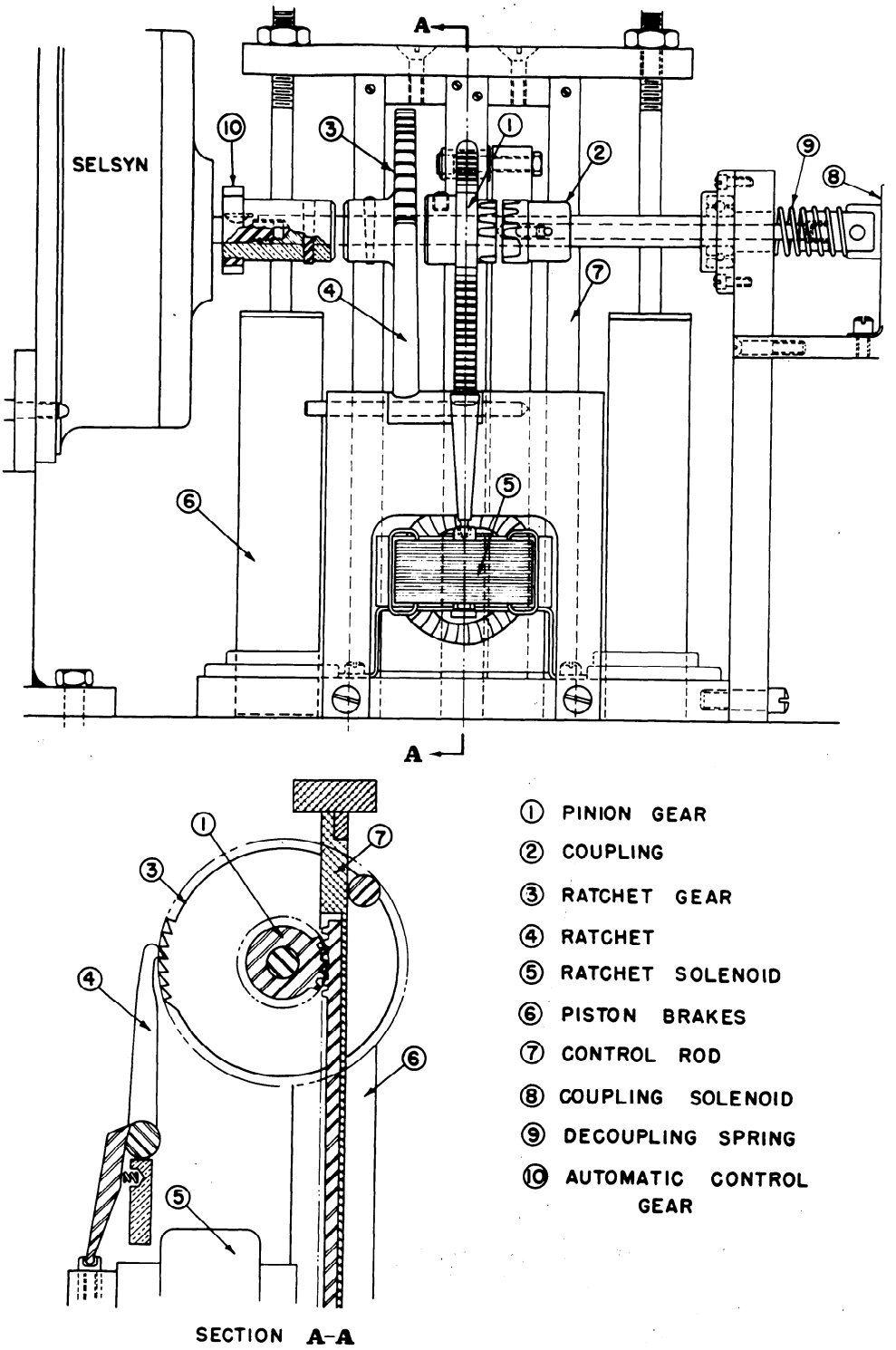


Figure 33

Control rod driving mechanism

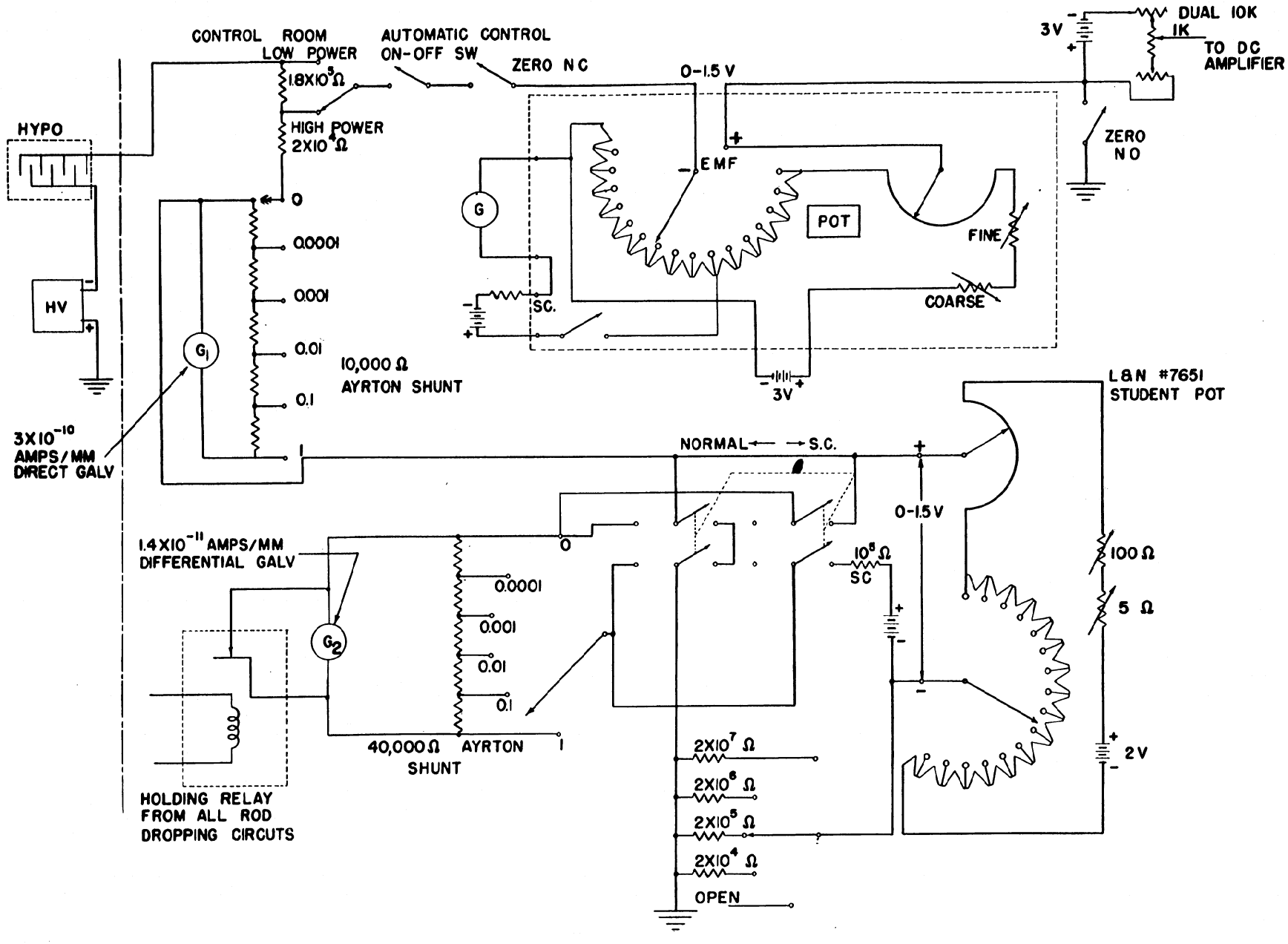


Figure 44

Galvanometer and automatic control input circuit

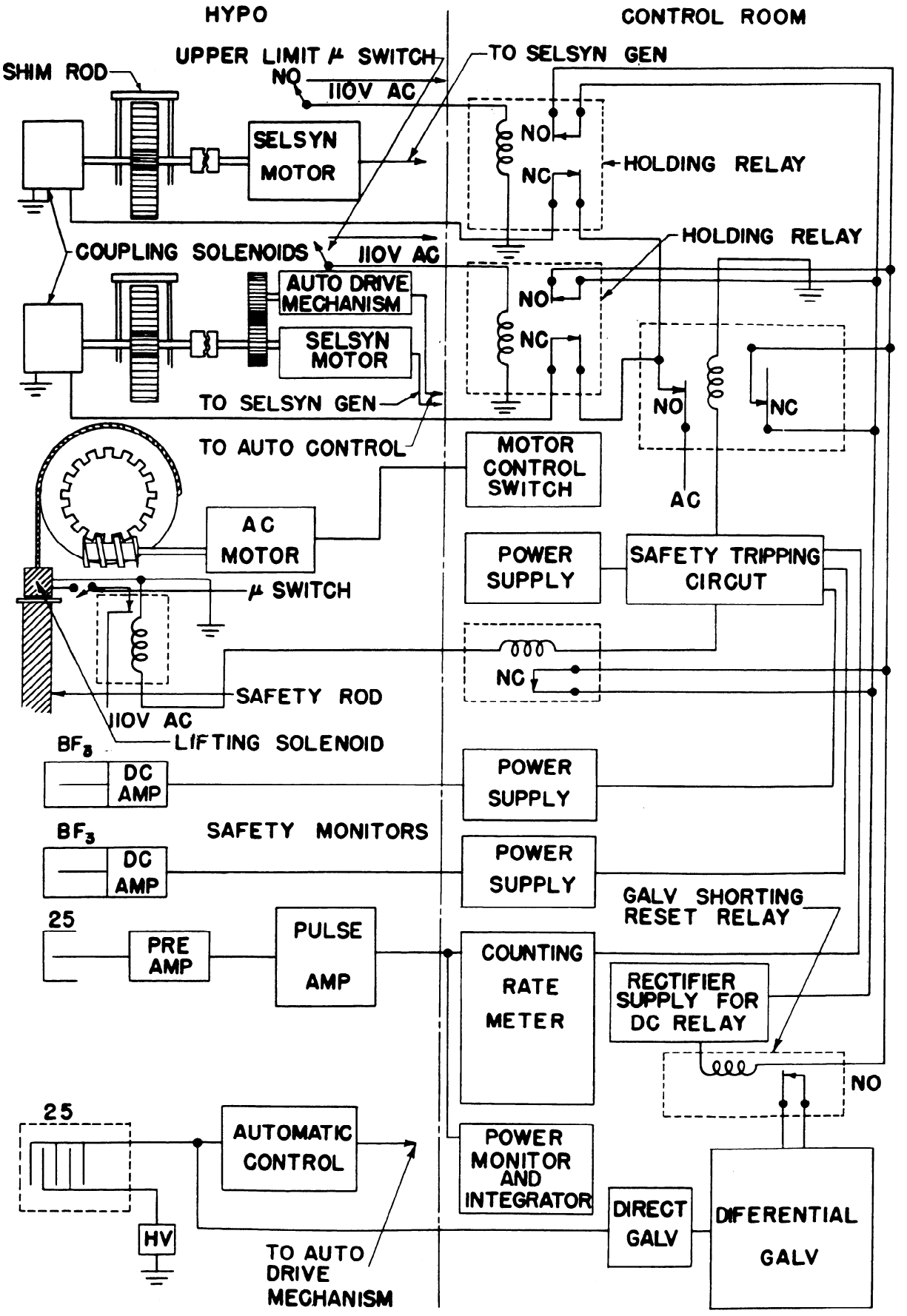


Figure 45

Safety circuit

It was desirable to eliminate ion-producing processes which result from past history of the boiler, or from the total (nv)t 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. So the chamber Figure 46, is built entirely of this material.

The chamber was designed with paralleled plates connected as shown to permit rather large surface area in a convenient volume so that the large ionization currents required for high sensitivity could be obtained. Another type chamber recently used to replace the BF_3 chambers is shown in Figure 47.

The chamber, Figure 46, contains a total of 184 milligrams of U^{235}. All plates except those on the ends are coated on both sides. The coating is the residue left after heating the original 353 milligrams of 63.1 per cent enriched U_3O_8 put on in the form of nitrate with a zapon binder.

The small U^{235} chamber which has been used to determine the linearity of the galvanomater 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 a kilowatt-minute of operation. This system, recorded on a modified mechanical counter through a scale of 256, is never turned off, and is read at the control panel at the beginning and end of each run. This chamber also operates a counting rate meter model 100 which contains a