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An Enriched Homogeneous Nuclear Reactor*†

Los Alamos Scientific Laboratory of the University of California, Los Alamos, New Mexico
(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.

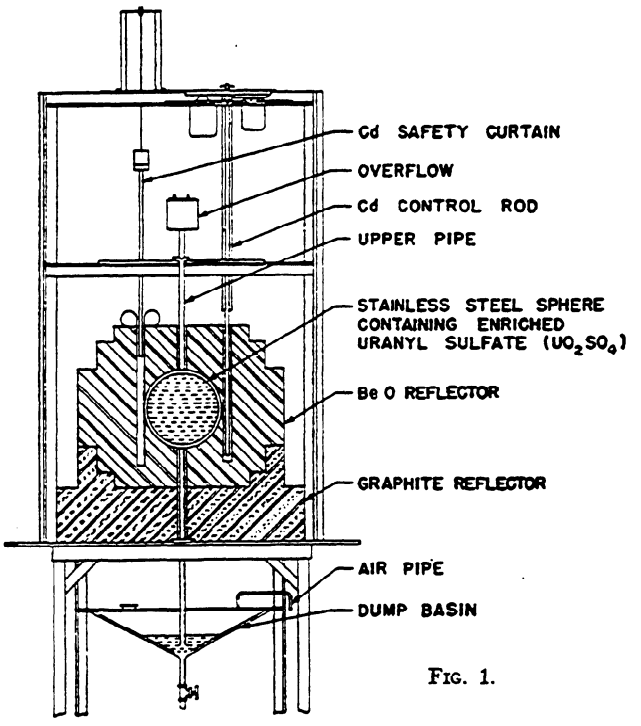

FIG. 1.

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.

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.

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.

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.

critical mass, intercepting the abscissa at the critical 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

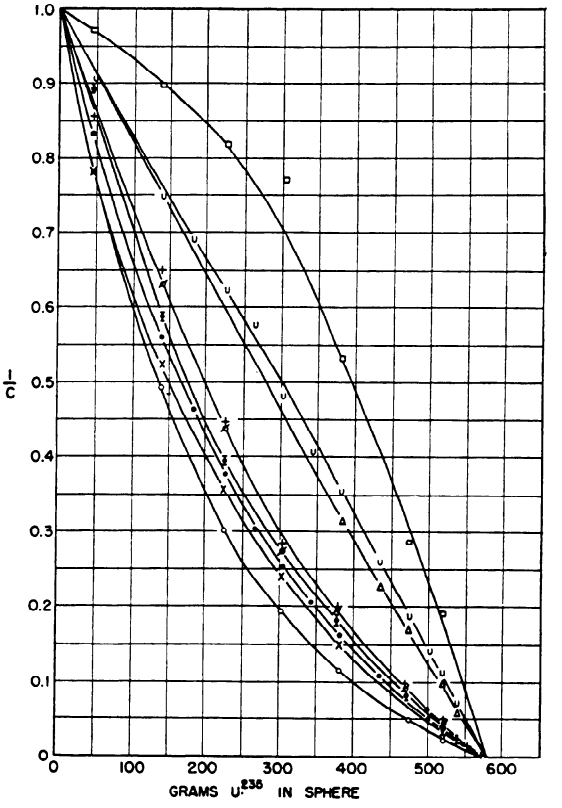

FIG. 2.

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]

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

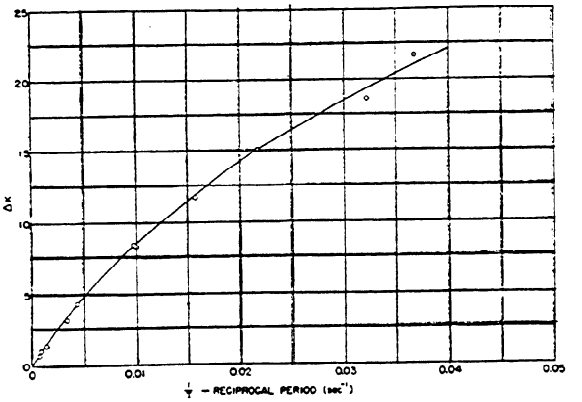

FIG. 3.

[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:

$$\tau_p = 135 \pm 20 \ \mu\text{sec, and } \gamma f = 0.0086.$$

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	—
$UO_2(NO_3)_2 \cdot 6H_2O + H_2O = 13.65$ 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 $\tau_p = 135 \times 10^{-6}$ sec, $\gamma f = 0.0087$, and Hughes' data[12] on delayed neutrons

$$\Delta K = \left(\frac{135}{T} + \frac{626}{T+0.62} + \frac{6287}{T+2.19} + \frac{16{,}538}{T+6.51} + \frac{62{,}604}{T+31.7} + \frac{24{,}421}{T+80.2} \right) \times 10^{-6}, \qquad (3)$$

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 $3.0 \times 10^{-4} (\Delta K/K)$ 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/cm^2/sec exists at the center of the reactor. A flux of thermal neutrons of the order of 10^9 n/cm^2/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/cm^2/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

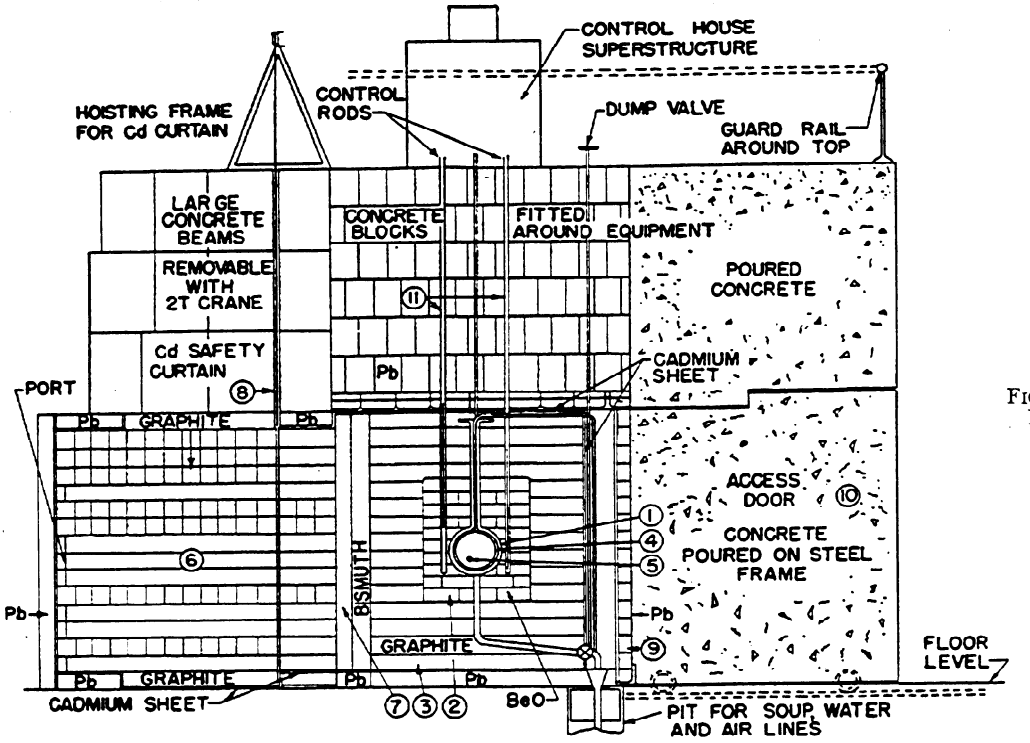

FIG. 4. Section through HYPO (simplified).

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

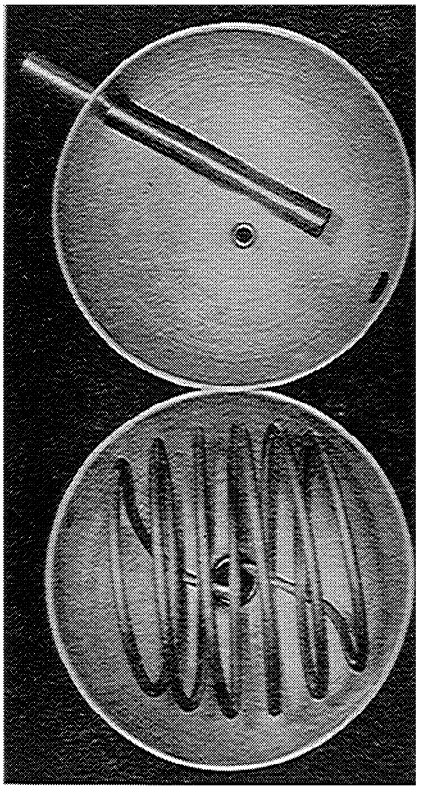

FIG. 5.

[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 (~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

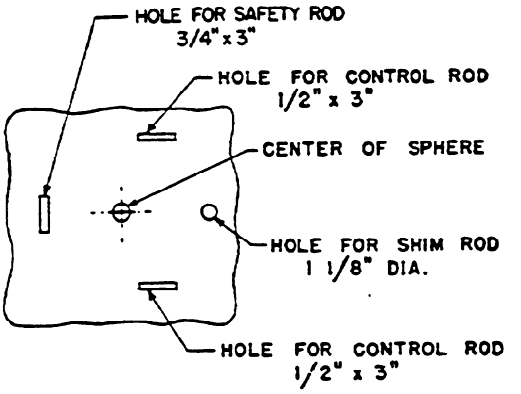

FIG. 7.

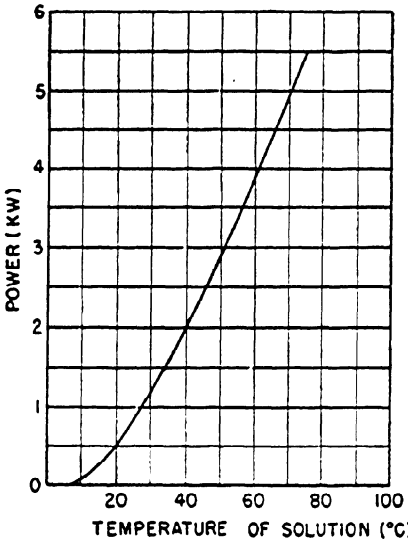

FIG. 8. Equilibrium running conditions for 50 cc/sec inlet water at 8°C.

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.