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3. Koutz, Taylor, McReynolds, Dyson, Stolne, Sleeper & Duffield, "Design of a 10-kw Reactor for Isotope Production, Research & Training Purposes," Geneva Proceedings, vol. 10 pp. 282-286, 1958.

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Design and Description of Water Boiler Reactors

By L. D. P. King,* USA

I. INTRODUCTION

It is the purpose of this paper to give a brief survey of the origin, design, and operating characteristics of water boiler type reactors. Through long usage the name "Water Boiler," in the reactor field, has become associated with small enriched homogeneous reactors. Basically the water boiler consists of a container filled with enriched uranium and water solution surrounded by a neutron reflector, a set of control rods to adjust the criticality, and usually a gas handling system.

The first need of a water boiler type assembly arose early in 1943 when it became necessary to know the critical-mass of homogeneous solutions of U^{235} in various concentrations and moderating media. The purpose of this assembly was not only to provide critical mass data but also to provide experience in the operation and control of an enriched chain reacting assembly. This unit soon became known as Lopo (low power) since it was operated at essentially zero power in order to simplify the overall design.

As a result of the successful operation and experience gained from Lopo, it seemed desirable to construct a power unit to be used as a strong neutron source for various experiments. This first power water boiler called Hypo (high power), was put into operation in December of 1944. After 14,000 kilowatt hours of operation it was decided to redesign this reactor in order to make it a more useful research tool.

The rebuilt reactor known as Supo has been used up to power levels of 45 kw with peak thermal fluxes of 3.7×10^{10} neutrons/cm^2/sec/kw. This model of the water boiler began operation in 1950 and is in use at the present time after about 200,000 kilowatt-hours of running time. This reactor has been found to be a very versatile and reliable research tool.

From the data accumulated on Supo, it appears that with some redesign this model of the water boiler can produce substantially higher flux levels. A more radical design proposal known as the Test Tube Reactor appears to have some promising features.

The Atomic Energy Research Department of North American Aviation Inc. has constructed two water boiler type reactors. A one-watt unit designated as WBNS (Water Boiler Neutron Source), went into operation in April, 1952. A 500-watt reactor was completed in November, 1953 as a neutron source for the Livermore Research Laboratory in California.

The North American Aviation group also has design proposals for two 50-kilowatt reactors; one is a general research unit which will be constructed for the Armour Research Institute at Chicago, the second is especially designed for medical research.

The North Carolina State College has had a 10-kilowatt water boiler in operation since September, 1953. This reactor is used in the university research program, especially for the training of students in reactor technology.

II. TESTED WATER BOILER DESIGNS

A. Zero Power Reactor, Lopo, Los Alamos, 1944

This reactor was really a critical assembly experiment using enriched uranyl sulphate solution in water. The zero power operating level was chosen after considering a power model in order to eliminate shielding requirements and minimize possible troubles which might arise in connection with radiation effects on the solution. These potential difficulties were concerned with holding uranium in solution, the gas evolution from decomposition products produced by the fission process, and the contamination of the solution by the fission products themselves.

The design of Lopo was based on the requirement that a minimum amount of uranium should be used. This necessitated the use of a good reflector and the use of materials throughout which had a minimum neutron absorption. It was also required that there be an accurate control of reactivity and the entire system be as simple as possible consistent with safety.

Uranyl sulphate was chosen in preference to uranyl nitrate since it has a lower neutron cross section and has a larger uranium solubility. Table I lists the components of the homogeneous mixture used in Lopo which soon became known as "soup."

Calculations indicated that beryllium oxide would make an excellent reflector and that a 1-ft diameter sphere would be the proper size to minimize the uranium requirements for a 7 per cent to 15 per cent enriched solution. Corrosion studies showed that stainless steel (type 347 18-8) would be a satisfactory material to contain the solution.

The schematic design of Lopo is shown in Fig. 1. Control of reactivity was accomplished by means of a 34-in. long cylinder of cadmium $\frac{3}{4}$ in. in diameter. The rod could be moved remotely in a vertical direc-

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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
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 per cent

tion and set to within 0.5 thousandth of an inch. An additional cadmium rod was used as a shutdown safety. In order to eliminate temperature effects the entire apparatus was enclosed in a thermostated enclosure.

The solution could be dropped into a subcritical geometry below the sphere when not in use. Numerous safety features were incorporated in the design of the solution handling system, shown in Fig. 2, so as to eliminate accidental loss of solution.

Since this was the first chain reaction with enriched material, many precautions were taken while approaching the critical condition. 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. A zero or no multiplication reading was obtained by filling the sphere with distilled water. Fig. 3 illustrates how far in advance the critical mass can be estimated by a judicious placing of the detectors and source. The abscissa are normalized reciprocal counting rates.

Reactivity was increased by first removing solution, then adding and thoroughly mixing some more concentrated solution to the conical pan. The new soup was then raised each time to a definite level in the pipe above the sphere. The critical mass with 14 per cent enriched uranium, for the geometry used, was found to be 565.5 grams of U^{235} at 39°C.

Several measurements were made to better understand the operating behavior of Lopo.

1. The control rod calibration was determined by comparing rod position with known additions of U^{235}. The entire rod was equivalent to 11.3 grams of U^{235} which was later determined to be $6.2 \times 10^{-3} \Delta k/k$.

2. The absolute criticality of the system or the relation between Δk and ΔM is of primary interest. (k is the reproduction constant and M the total mass of uranium in the system.) For very small changes these quantities can be considered proportional. This proportionality constant was determined by measuring the effect on control rod position when a liquid-filled plastic bubble was moved within the sphere. The bubble was filled with a boron solution of equivalent nuclear properties except for the absence of a fissionable material. The absolute criticality was determined as $5.48 \times 10^{-4} \Delta k/k$ per gram of U^{235}.

3. The temperature coefficient at 39°C was determined as 0.55 grams U^{235}/°C or a $\Delta k/k$ of 6.2×10^{-3} per degree centigrade, by varying the temperature of the entire reactor system and observing the effect on the control rod position.

4. The effective fraction of delayed neutrons (γf) and the mean prompt neutron lifetime (τ_p) were determined by a special experiment. A cadmium absorber connected to a crank on an electric motor was jerked in and out of the reflector at such a repetition-rate that the delayed neutron intensity had no time to decay but merely produced a steady background, while the fast neutrons were able to follow the fluctuations. From an absolute calibration of the reactivity effect of the cadmium for all crank positions and from

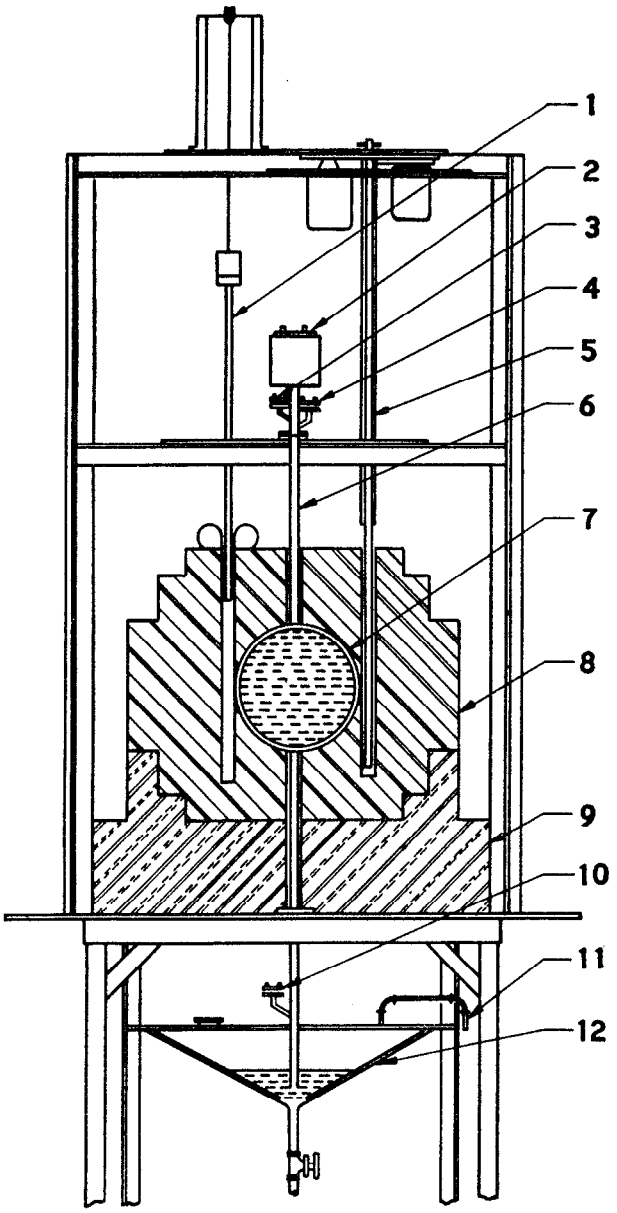


Figure 1. Cross section, LOPO: (1) Cd safety curtain; (2) overflow; (3) safety electrode; (4) level electrode; (5) Cd control rod; (6) upper pipe; (7) stainless steel sphere containing enriched uranyl sulfate (UO_2SO_4); (8) BeO reflector; (9) graphite reflector; (10) level electrode; (11) air pipe; (12) dump basin

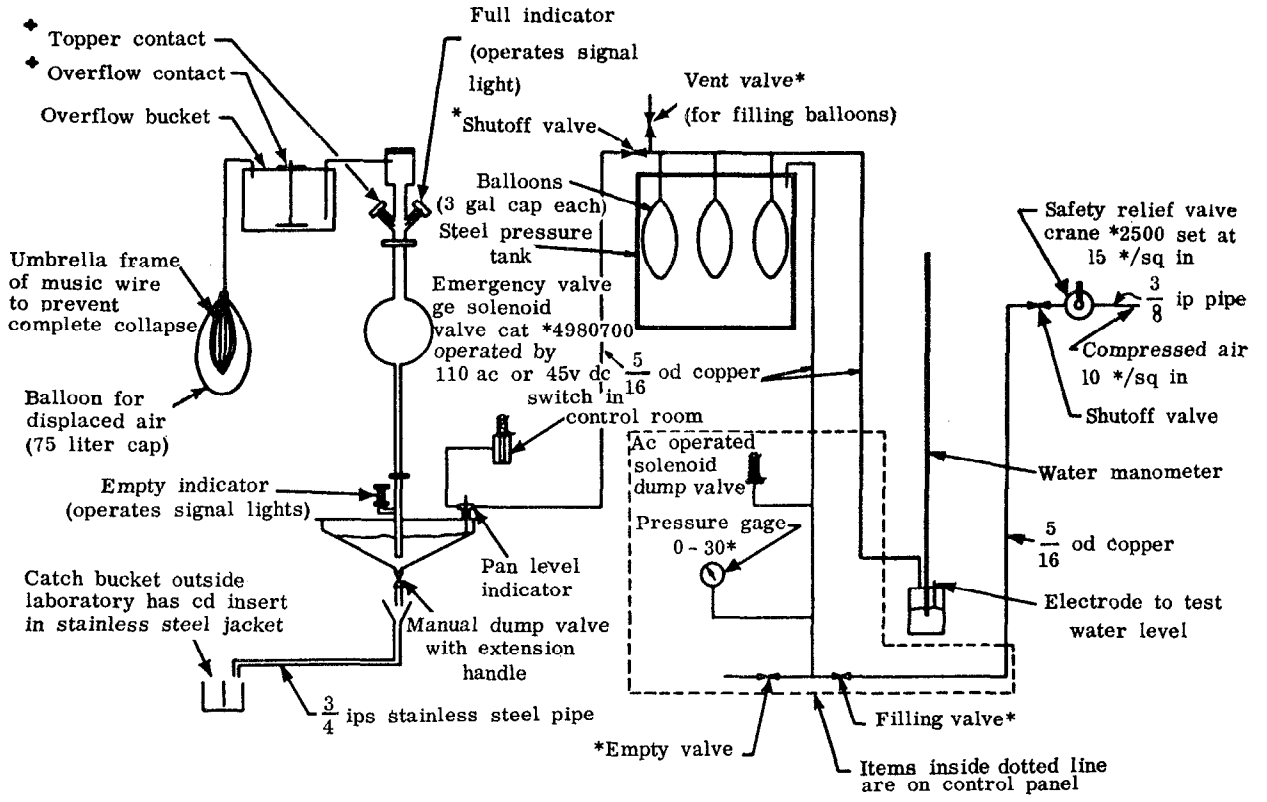


Figure 2. LOPO solution system. Fluid handling system: note, * = hoke needle valve; † = opens solenoid dump valve automatically; electrical connections not shown

the measurements of the counting rates of the gated counters at various phase angles, the value of γf was determined as 0.0086. For high crank velocities the prompt neutron lifetime can be determined by the phase lag between the counting rates and the absorber position. A value of 135 ± 20 microseconds was determined.

5. The theoretical relation between excess reactivity (Δk) and reactor period (T) is given by the equation

$$\Delta k/k = \tau_p/T + \sigma_f \sum_i \frac{q_i \tau_i}{T + \tau_i}$$

where the q_i and τ_i are the respective amplitudes and periods of the delayed neutron fractions relative to the total number f. Substituting experimental values for Lopo and the known delayed neutron periods gave

$$\Delta k/k = \left[\frac{135}{T} + \frac{626}{T + 0.62} + \frac{6287}{T + 2.2} + \frac{62{,}600}{T + 31.7} + \frac{24.420}{T + 80.2}\right] \times 10^{-6}$$

This equation correctly predicted the periods of the reactor for known excess reactivity values.

6. Short time fluctuations of the neutron intensity when Lopo was run at critical, were studied by means of a fast recording counter and by a circuit which permitted adjusting counting gate widths and times between gates. These variations were found to be much larger than for an ordinary Poisson fluctuation.

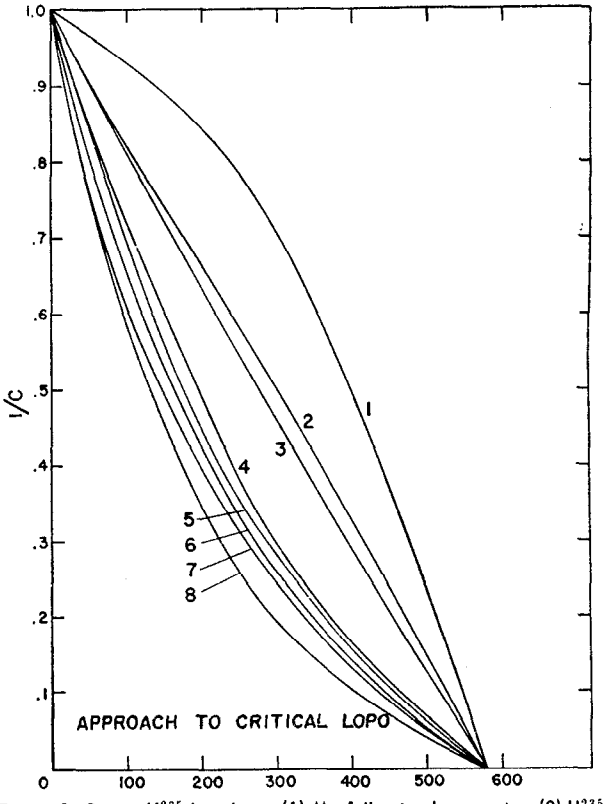


Figure 3. Grams U^{235} in sphere: (1) Mn foils at sphere center; (2) U^{235} chamber 3 in. from center; (3) Mn foils at node of 3rd harmonic; (4) BF_3 + Cd + Ch_2 outside reflector, BF_3 + Cd outside reflector; (5) U^{238} chamber against outer sphere surface; (6) BF_3 chamber outside reflector; and (7) In foils 3 in. from sphere surface; (8) In + Cd foils 3 in. from sphere surface

Table II

Material	*Size of reflector*	*Critical mass, grams U^{235}*
BeO	3 ft mock sphere	572 ± 2
BeO-graphite	2 ft BeO cube surrounded by 1½ ft of graphite shell	573 ± 2
Graphite-BeO	18-in. graphite cube surrounded by 1 ft of BeO shell	735 ± 10
Graphite-tuballoy slugs	4 ft cube of graphite and 20 slugs of tuballoy 2½ in. diameter, 2¼ in. long placed 12 cm from edge of sphere	740 ± 10
Graphite	4 ft cube graphite	760 ± 10
H_2O-tuballoy slugs	5 ft diameter cylinder, 5 ft high with 63 tuballoy discs 2¼ in. × 2½ in. spaced equally on a spherical surface 20 cm in radius	1100*
H_2O	5 ft cylinder, 5 ft high	1200*

* Extrapolation estimates.

7. Neutron distribution measurements taken in the sphere and reflector were found to check theoretical predictions.

8. Tests were made on several reflector materials to compare their relative effectiveness. The results are shown in Table II.

B. Power Water Boiler, Hypo, Los Alamos, 1944–1949

The construction of this reactor was based on the satisfactory operation of Lopo and the fact that such a reactor due to its small size can produce strong neutron fluxes at moderate power. An operating level of one kilowatt was originally chosen because: (1) the cooling requirements were simple; (2) bubbling or frothing due to gas evolution from the solution decomposition products was not expected to be serious; (3) not much additional enriched material was required and; (4) neutron fluxes of the order of 5×10^{10} were expected.

The general design was influenced by that of the low power experiment. The principle modification consisted in eliminating the hydrostatic control and poor geometry storage system, a precaution which no longer seemed necessary after the experience gained in the operation of Lopo. The new design features for increased power operation were numerous: (1) a change of solution from uranyl sulphate to uranyl nitrate since an extraction method for the removal of fission products was known only for the latter at that time; (2) installation of additional control rods for greater operational flexibility; (3) introduction of a horizontal one-in. pipe or "glory hole" through the sphere to permit access to the highest neutron flux; (4) addition of a water cooling and an air flushing system; (5) construction of a gamma ray and neutron shield; (6) the addition of a graphite thermalizing column; (7) the use of a 1/16-in. thick stainless steel sphere instead of the 1/32-in. thickness used in Lopo to provide for the possibility of a greater corrosion rate when operating at higher fluxes and temperatures.

A simplified section through Hypo is shown in Fig. 4. The numbers in this figure point out the following components: (1) one-foot diameter core sphere, (2) thin walled stainless steel safety drip pan around beryllium oxide, (3) secondary solution catcher at base of graphite, (4) heat exchanger, (5) "glory hole" irradiation port through core, (6) removable graphite sections for experimental work.

Figure 5 shows details of the sphere assembly. After initial operation it was found that the 157 inches long cooling coil shown would permit operation at 5.5 kilowatts without exceeding the normal operating temperature of 85°C. This was somewhat higher than expected and indicated that the bubbles formed during operation did not decrease the effective heat exchanger surface area. As shown in Fig. 5, the solution level was maintained several centimeters below the top of the sphere in order to provide a space for solution expansion and a larger surface area for the release of gas bubbles. Because of the explosive nature of the hydrogen and oxygen mixture released by radiolysis and the highly concentrated radioactive gases produced in the solution, a means of diluting and flushing-out these gases was required. Approximately 50 cm^3/sec of filtered air was admitted through the level indicator tube and discharged to a stack.

An adjustable contact type level indicator was required to determine the solution level. A fixed bubble tube served as a solution addition tube and an absolute level indicator. Initially only distilled water was added to replace the decomposition products; but after several hundred kilowatt hours of operation it was observed that the reactivity of the solution had increased considerably. Chemical analysis of the solution indicated a 30 per cent 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. At this time it seemed desirable to remove the large drain tube shown in Fig. 4 and replace it with a small tube running to the top of the reactor. A rapid dump tube did not seem necessary. The removal of this pipe eliminated a possible trap for precipitation products and the new ¼-in. od. tube made it possible to make additions to the solution during reactor operation. These were made about every 35 kw-hr of operation in the ratio of water to acid of 1.4:1. About 6 cm^3 of water plus acid were required per kw-hr of operation.

The reactivity was controlled by 3 vertical cadmium rods. Two of these had continuous selsyn position control and one had only an in or out position. These rods are outside and tangential to the sphere surface

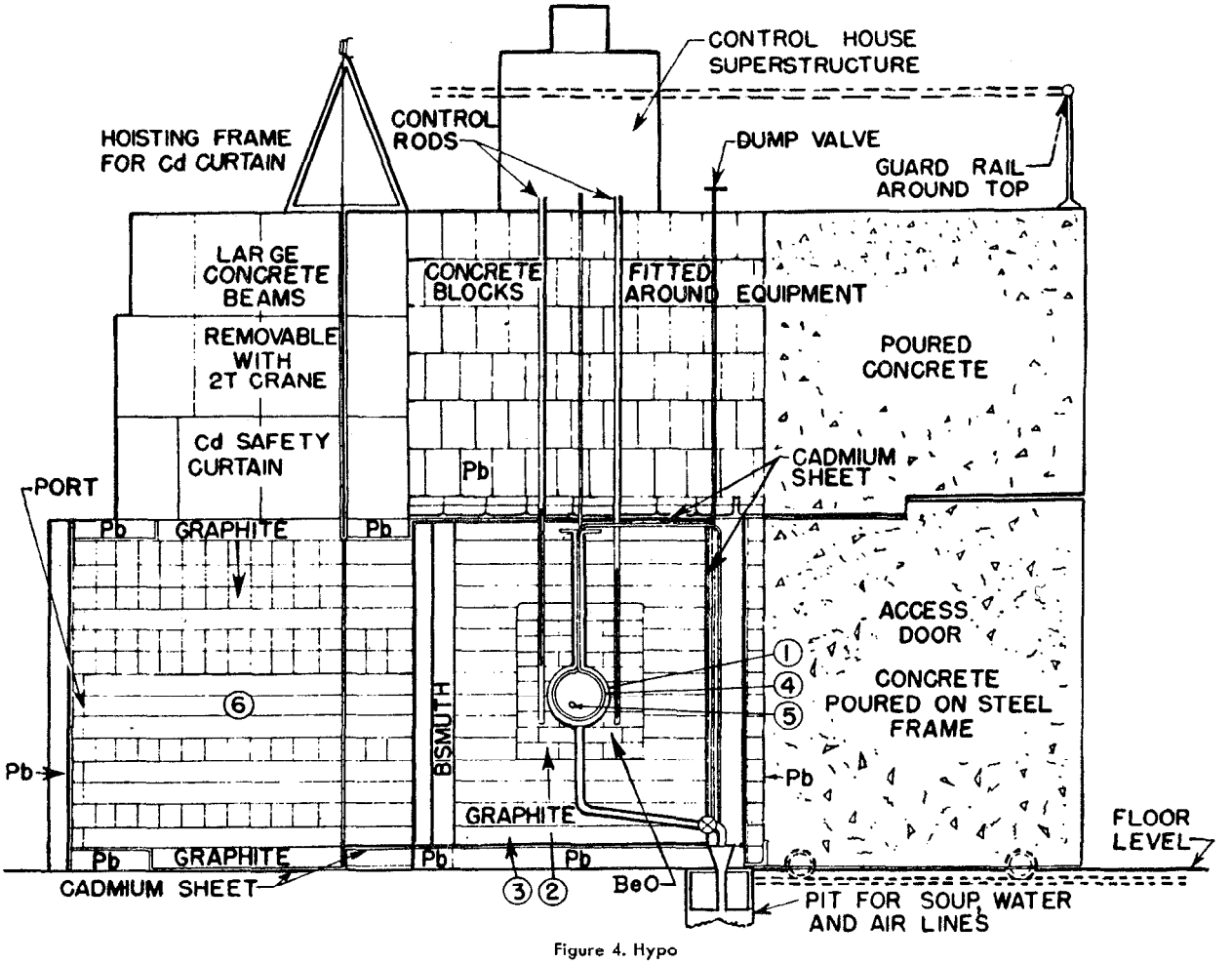


Figure 4. Hypo

as shown in Fig. 4. Cadmium sheet 3 in. wide by 30 in. long is contained in the lower portion by an aluminum frame. An automatic control unit attached to one of the rods was used to eliminate small drifts in neutron intensity due to convection and currents and bubble formation in the core.

Approach to critical was done in a manner similar to that used in Lopo. Since rather good estimates of the critical mass could be made beforehand, a considerable amount of U^{235} could be added initially. The solution composition for Hypo is shown in Table III. The critical mass was found to be 808 grams of U^{235}. The normal operating mass was 870 grams U^{235}. This additional material was required in order to have sufficient Δk to override the negative temperature coefficient of $2.6 \times 10^{-4} \Delta k/k$ per °C and have some excess k for experimental purposes. The absolute calibration of the reactor was determined to be approximately $2 \times 10^{-4} \Delta k/k$ per °C.

The thermal flux at the center of the "glory hole" was measured with small calibrated Mn foils. It was found to be 5×10^{10} neutrons/cm^2/sec/kw.

The radioactive fission-product gases produced in Hypo were blown by a stream of air through a long tube whose axis was a negatively charged wire. The various gases deposited their solid radioactive daughters upon the wire in a manner proportional to their half-lives. By cutting the wire into sections and analyzing each one for several fission products the fraction of the fission product chains swept out of the water boiler during normal operation was determined. These values are shown in Table IV.

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	13,780	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%			

C. High Flux Water Boiler, Supo, Los Alamos, 1950–1955

This model of the water boiler resulted from rather extensive changes in the Hypo model. Higher neutron fluxes were desirable as well as more research facilities.

The modifications were made in two parts. The first phase, begun in April, 1949 and completed in February, 1950, improved the experimental facilities

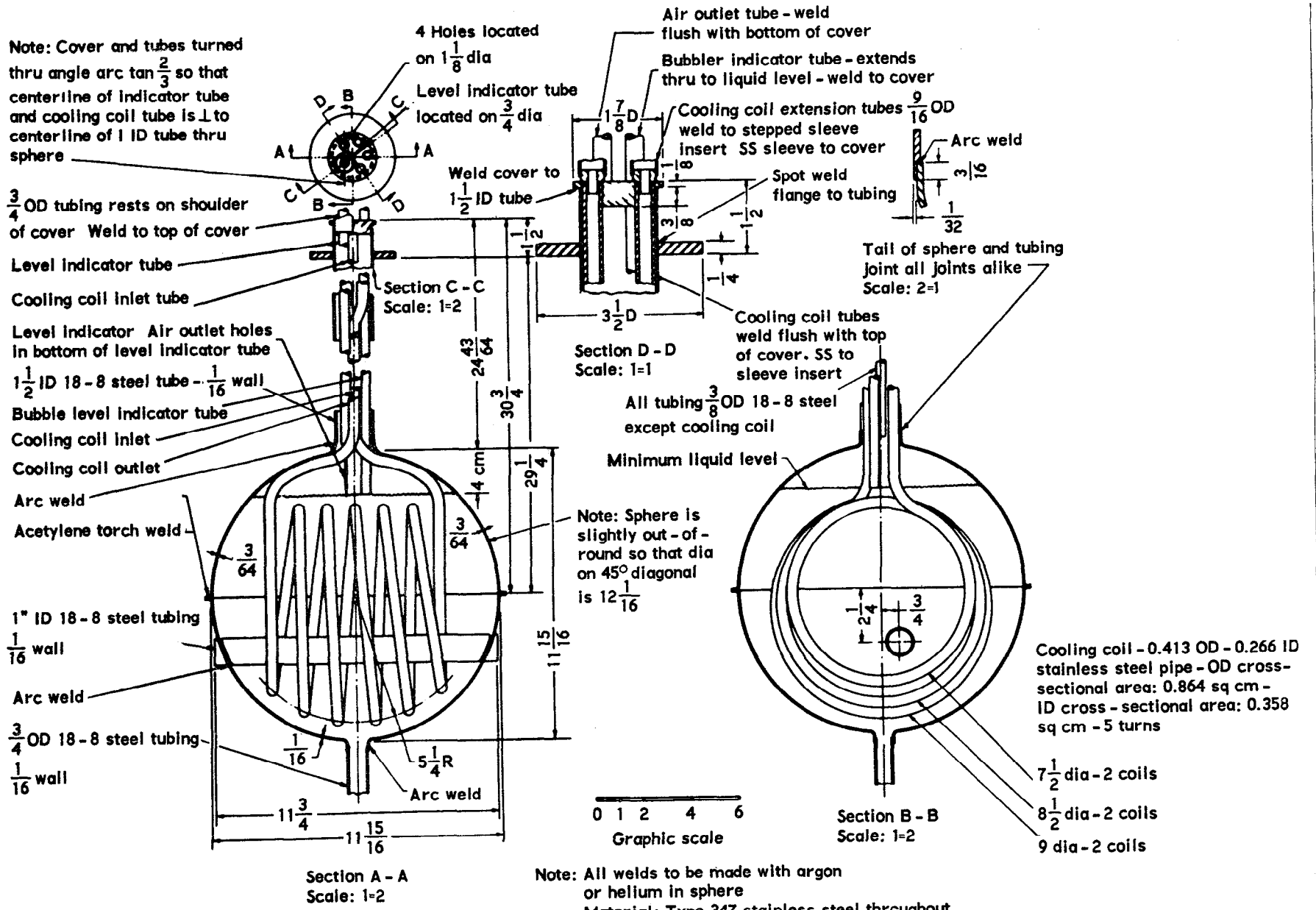


Figure 5. Hypo sphere assembly

Table IV. Estimated Fractions of Fission-Product Chains Swept Out of Water Boiler During Normal Operation

Mass no.	Fission gas	Important solid members of chain	Per cent swept out: >75 %	50–75 %	25–50 %	10–25 %	1–10 %	<1 %	<1 %
83	1.9 hr Kr		x						
85	4.6 hr Kr		x						
	~10 yr Kr		x						
87	75 min Kr	6.3×10^{10} yr Rb	x						
88	3 hr Kr	17.5 min Rb	x						
89	2.6 min Kr	15 min Rb							
		55 d Sr		x	x				
90	33 sec Kr	30 yr Sr							
		60 hr Y					x	x	
91	9 sec Kr	9.7 hr Sr							
		57 d Y						x	
(92)	3 sec Kr	2.7 hr Sr							
		3.5 hr Y							x
(94)	1.4 sec Kr	20 min Y							x
95	2 sec Kr	11 hr Y 35 d Cb							
		65 d Zr							x
97	Kr	17 hr Zr							
		75 min Cb							x
133	5.3 d Xe		x						
135	9.2 hr Xe	2×10^4 yr Cs	x						
	10 min Xe	2×10^4 yr Cs	x	x					
137	3.4 min Xe	35 yr Cs		x	x				
138	17 min Xe	33 min Cs	x						
139	41 sec Xe	85 min Ba					x		
140	16 sec Xe	12.8d Ba							
		40 hr La				x	x		
141	1.7 sec Xe	18 min Ba 28d Ce							
		3.5 hr La							x
143	1.3 sec Xe	33 hr Ce							
		13.8 d Pr							x
(144)	Xe	275d Ce							
		17 min Pr							x
(145)	1 sec Xe	1.8 hr Ce							
		4.5 hr Pr							x

and increased the neutron flux. The second phase, begun in October, 1950 and completed in March, 1951, increased the thermal neutron irradiation facilities, improved the reactor operation, and removed the explosive hazard in the exhaust gases.

The first group of alterations consisted of the following:

(1) The space around the reactor was increased by enlarging the building so that experiments could be carried out on all four sides instead of on only two.

(2) The construction of a second thermal column was made possible by eliminating a removable portion of the reactor shield. This made available a neutron beam and irradiation facilities on a previously unused face of the reactor.

(3) The entire spherical core assembly was replaced:

(*a*) Three 20-foot long, ¼-in. O.D., 0.035-in. wall stainless steel tubes replaced the former single cooling coil. This increased the operating power level from 5.5 kw to a maximum of 45 kw. A factor of three higher heat transfer coefficient than predicted by theory is believed to be primarily due to fluid agitation from radiolytic-gas-bubble evolution.

(*b*) A new removable level indicator and exit gas unit was installed in the sphere stack tube. The stack tube itself was made more accessible for future modifications.

(*c*) External joints were not welded, but unions or flare fittings were used to simplify the removal of the sphere or permit pipe replacements.

(*d*) An additional experimental hole was run completely through the reactor tangent to the sphere. This $1\frac{7}{16}$-in. id tube supplements the 1-in. id "glory hole" running through the sphere.

(4) The beryllium portion of the reflector was replaced by graphite. The all-graphite reflector gives a more rapid and complete shutdown of the reactor and eliminates the variable starting source produced by the (γ,n) reaction on beryllium. A 200 millicurie RaBe source placed in the reflector is used as a start-up neutron source.

(5) Two additional vertical control rods were added which move into the sphere volume in re-entrant thimbles. These consist of about 120 grams of sintered B^{10} in the form of $\frac{9}{16}$-in. rods about 18 inches long. These rods gave the additional control required by the change to an all-graphite reflector. Previously observed shadow effects were eliminated by the internal position of the rods and by the location of the control chambers under the reactor.

Table V. Effectiveness of Control Rod Materials*

Material	*Comments*	*Grams U^{235} equiv.*	*Est. % Δk/k*
Cadmium	0.015-in. cadmium 18 in. long wrapped on 0.595 od brass tube with 1/16-in. wall. Inside length tube 17¾ in. Weight cadmium 71.7 gm; weight brass tube 183.3 gm.	~39	1.3
Cadmium	0.015-in. cadmium wrapped on ½-in. polystyrene rod.	~39	1.3
Cd + paraffin	Above brass tube filled with 46.5 grams of paraffin.	~26	.87
B_4C	Density of B_4C 1.33 weight B_4C hand tamped 73.3 grams.	~53.5	1.8
B_4C + Cd	Same cadmium sleeve as above.	~58	1.9
B^{10}	95.5% B^{10} material in above brass holder 68 grams B^{10}.	~68.5	2.3
B^{10}	Same as above.	~73.5	2.4
B^{10}	92.5 grams B^{10} tamped into brass holder as above but 18⅛ in. long inside.	~78.5	2.6
B^{10}	Sintered 95.5% B^{10} plugs 0.555 in. diameter overall length 17.9 in. B^{10} density 1.73; actual weight B^{10} 116.5 grams.	~80.2	2.67
B^{10} + Cd	Above stainless tube plated with about 0.003 mil cadmium*	~82.2	2.74

* These are actual rods in use.

(6) The reactor solution was changed from 15% U^{235} enriched uranyl nitrate to one of 88.7% enrichment. This makes possible the continued use of a low uranium concentration in the solution with the poorer all-graphite reflector. The gas evolution produced by nitric acid decomposition is greatly reduced, due to the lower total nitrogen content.

(7) The entire inner reactor shield was improved to permit higher power operation with a low neutron leakage and also to increase the neutron-to-gamma-ray intensity in the thermal columns. Cadmium was replaced by B_4C + paraffin and additional steel shielding was added.

Table V lists the observed effectiveness of various control rod materials which were tested in order to determine which material would be used for the internal rods of Supo.

After operating the reactor with the above modifications for about 10,000 kw-hr at a power of 30 kw the following (second group) alterations were made:

(1) The original south thermal column was completely rebuilt with improved shielding to provide many more irradiation facilities.

(2) A recombination system was constructed to handle the "off" gases from the reactor. The use of a closed circulating gas system with a catalyst chamber of platinized alumina removed any explosive hazard in the exhaust gases due to the presence of hydrogen and oxygen. The operating characteristics of the reactor have been greatly improved by returning directly back to the reactor as water all but a very small fraction of the gases produced.

(3) A shielded solution-handling system was constructed to simplify the handling of routine solution analysis and for the removal or change of the entire reactor solution.

Figures 6 and 7 are vertical cuts through the north-south central plane of the reactor. The reflector, two thermal columns and general type of shielding are shown. The two special transverse experimental holes can be seen. The location of the recombination system in the reactor shield is indicated.

Figure 8 is a schematic layout of the recombiner system. Gas produced in the reactor, primarily hydrogen and oxygen, is carried by the circulating air in the system first through a vertical condenser in the sphere stack. This condenser, which occupies the space previously used for the level indicator, removes most of the water and acid vapor, as well as solution spray. From here the air passes through a stainless steel wool trap to capture fission fragments and entrained uranium before entering the blower. The blower feeds the gas into one of two interchangeable catalyst chambers containing platinized alumina pellets. Here all the hydrogen and oxygen are recombined and the gas leaving the catalyst chamber contains the water vapor formed. A second condenser reduces the temperature of the gas leaving the catalyst chamber to about the same temperature as that of the gas leaving the first condenser. Any excess pressure produced in the circulating system can be bled into a 150-ft exhaust stack. The circulation rate (100 liters/minute) is such that the hydrogen concentration is kept below the detonation limit at all points of the system.

Figure 9 is a bottom and side view of the sphere, showing the internal parts. The three nesting cooling coils are arranged so that turns are separated by about 1 inch through the volume, except in the uppermost 5 cm where there is no solution. The re-entrant thimbles for the B^{10} control rods can be seen. The location of the "glory hole" in the final assembly is indicated.

Figure 10 shows the sphere assembly in position with the reflector partially constructed. The small tube out of the bottom is used for solution addition or removal and for routine sampling. This view is from the new thermal column cavity looking south.

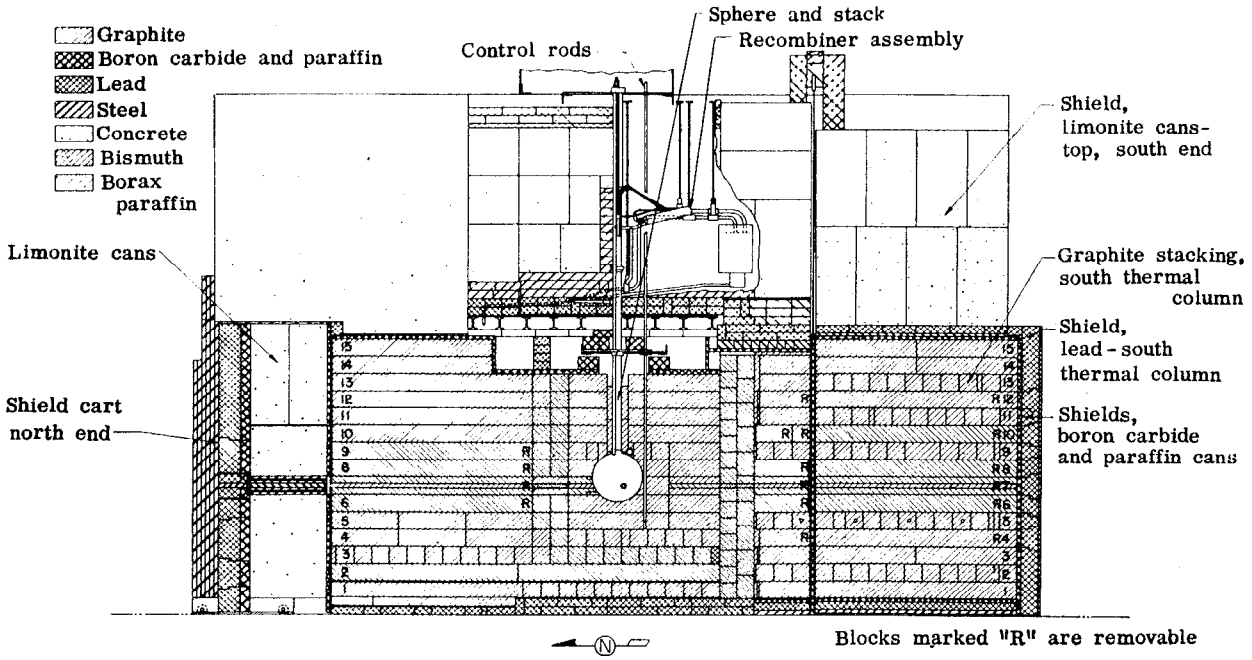


Figure 6. North-south vertical section of water boiler (Supo model)

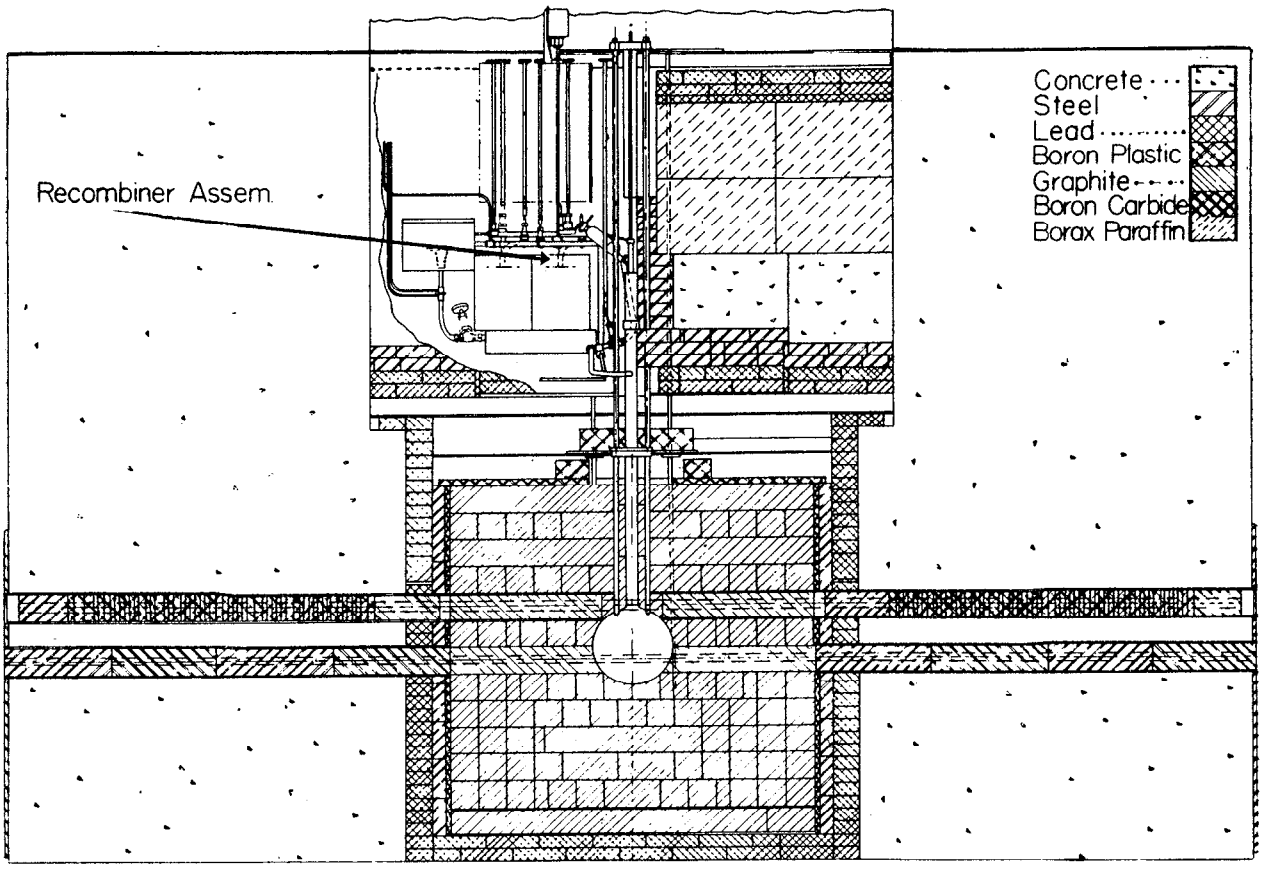
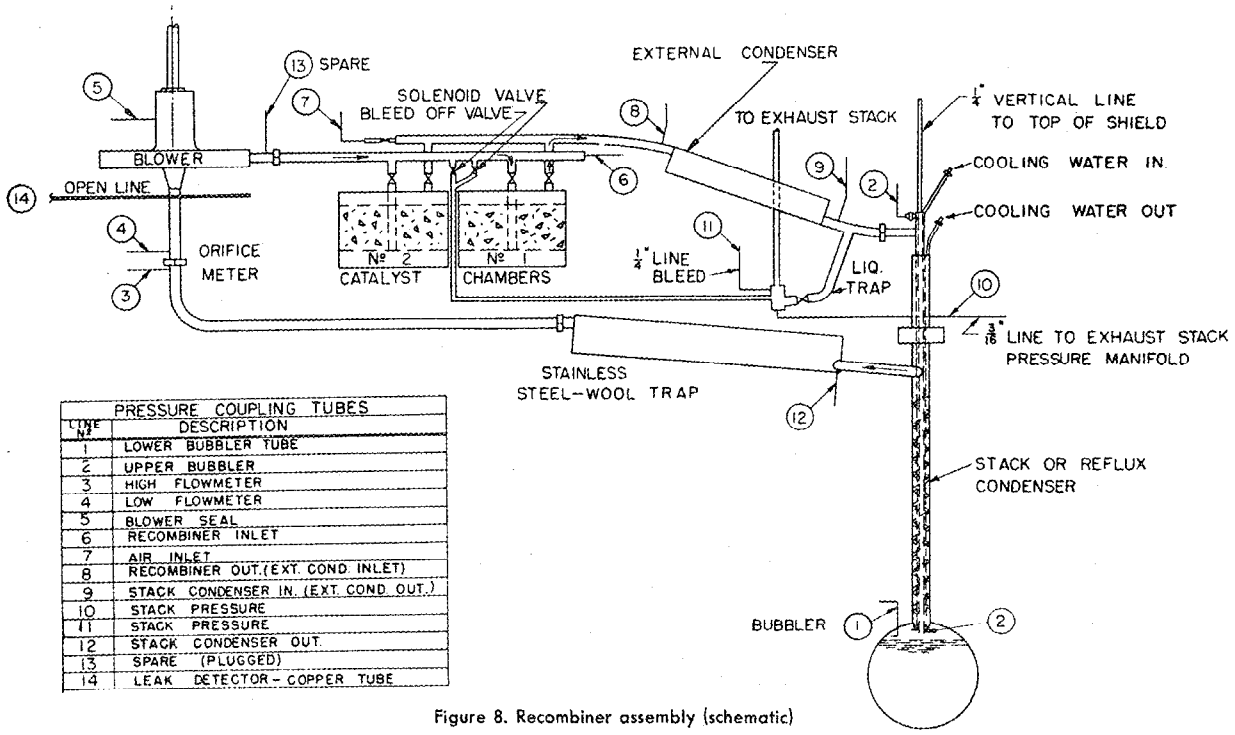


Figure 7. East-west vertical section of water boiler (Supo model)



LINE №	PRESSURE COUPLING TUBES DESCRIPTION
1	LOWER BUBBLER TUBE
2	UPPER BUBBLER
3	HIGH FLOWMETER
4	LOW FLOWMETER
5	BLOWER SEAL
6	RECOMBINER INLET
7	AIR INLET
8	RECOMBINER OUT.(EXT. COND. INLET)
9	STACK CONDENSER IN. (EXT. COND. OUT.)
10	STACK PRESSURE
11	STACK PRESSURE
12	STACK CONDENSER OUT.
13	SPARE (PLUGGED)
14	LEAK DETECTOR - COPPER TUBE

Figure 8. Recombiner assembly (schematic)

The bismuth pier across the south thermal column is in the background, and a portion of the shield for the north column can be seen under construction in the foreground.

An exterior view of the reactor is shown in Fig. 11. This photograph is a general view of the south face showing the multiple irradiation ports into the south thermal column. The entire control mechanism is in the small rectangular structure shown on top of the reactor.

The peak thermal flux available in the "glory hole" is 3.7×10^{10} n/cm^2/sec/kw. Figure 12 illustrates Hypo and Supo neutron distributions through the "glory hole." The curves in Fig. 13 compares the neutron fluxes and cadmium ratios existing in the

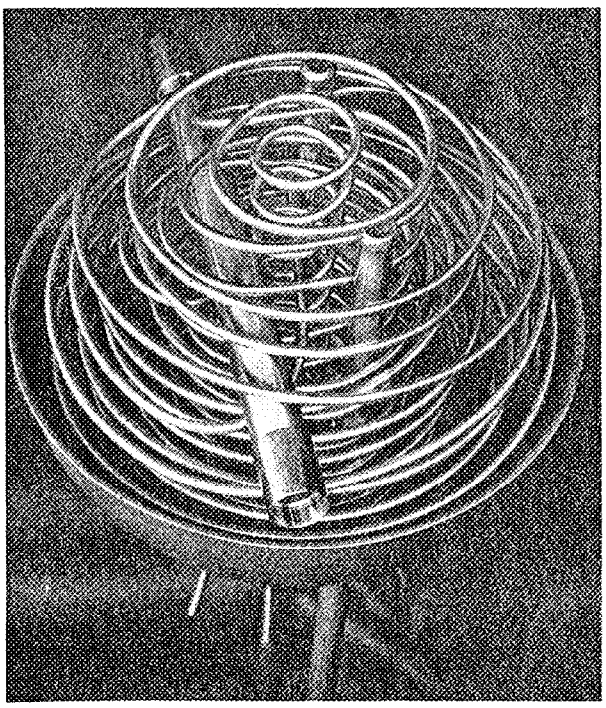


Figure 9. Supo sphere details

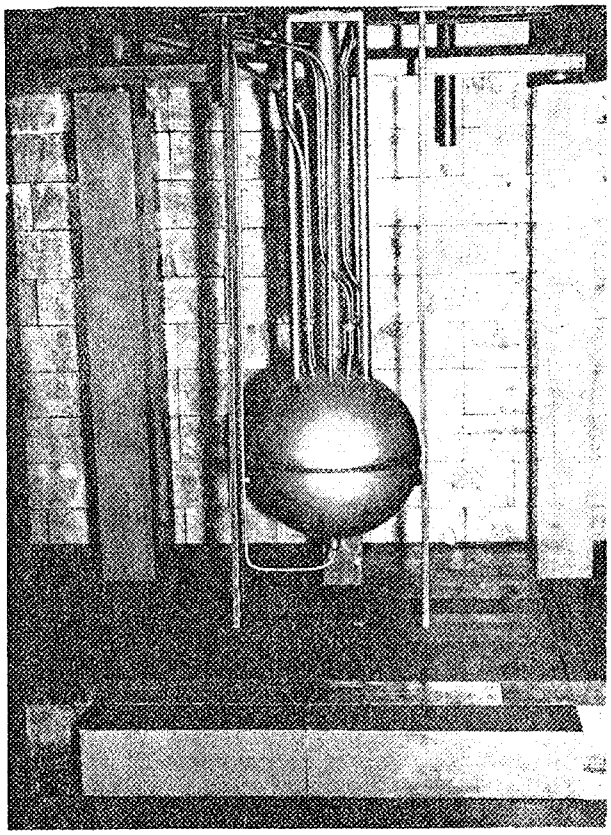


Figure 10. Supo core assembly

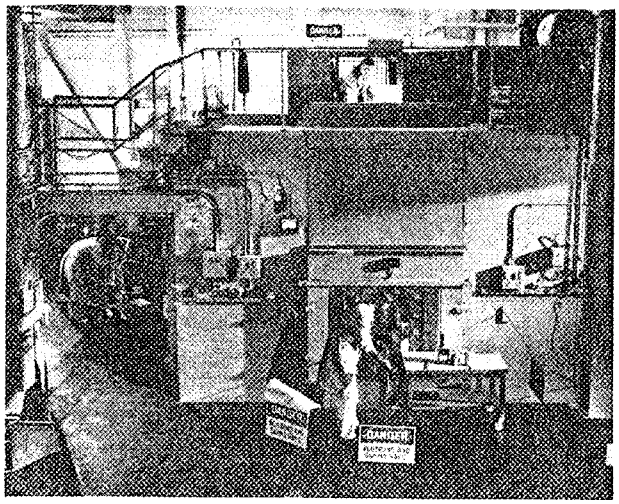


Figure 11. South face—Supo

"glory hole" and tangent hole. The curves in Fig. 14 shows the thermal fluxes and cadmium ratios existing in the north thermal column from the sphere face to the outer shield.

Nuclear plates have been used to measure the neutron spectra emerging from the sphere with

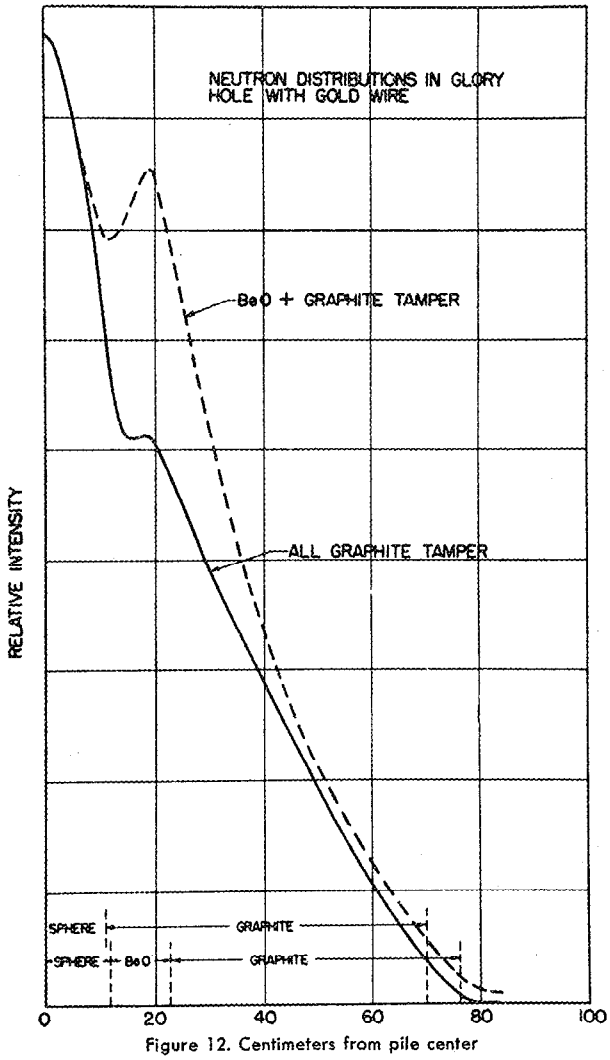


Figure 12. Centimeters from pile center

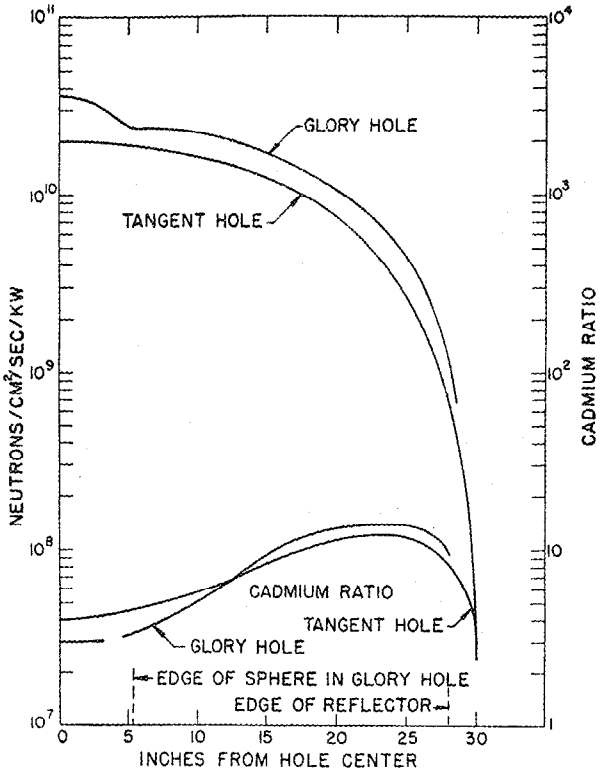


Figure 13. Supo distributions

energies over 1 Mev. These can be roughly approximated by a fission spectrum. Calculations made from fast beams emerging from the north thermal column give the following fast flux values above 1 Mev in units of n/cm²/sec/kw: (1) at the sphere surface 6.5×10^{10}, (2) at the bismuth column 1.5×10^{9} and

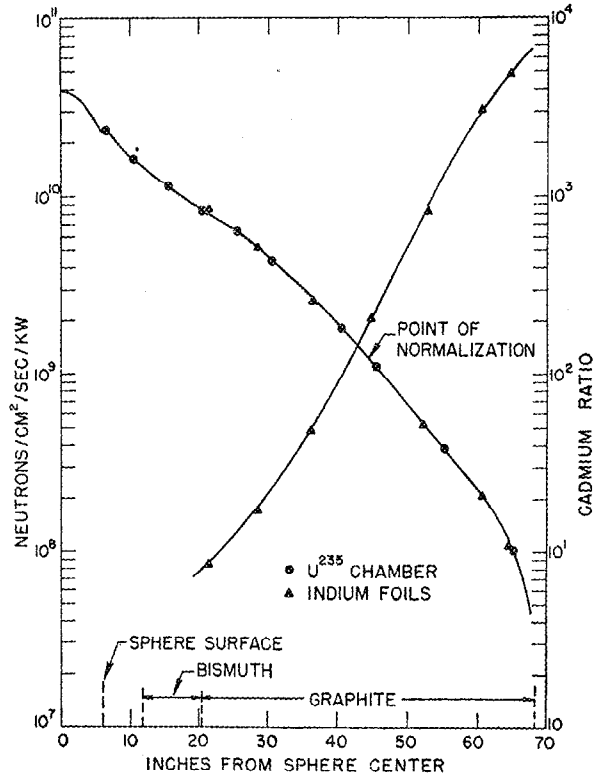


Figure 14. Supo north thermal column

(3) at a graphite face 1 ft in front of the bismuth column 4.4×10^7. A multiple U^{235} disc neutron converter when placed in the "glory hole" produces almost pure fission spectrum neutrons. With a 5-ft long, 1-in. id collimator, fast external beams of 6×10^5 n/cm²/sec/kw have been obtained with such a source.

The reactor can readily be started and stopped for short time intervals. Power levels ranging from a fraction of a watt to 45 kw have been used. An automatic level control operating from a neutron sensitive ionization chamber is used almost exclusively due to its convenience and ability to remove small fluctuations.

For high stability operation of 0.1% or better, which has been required for a few precision experiments, the power level is limited to about 30 kw. This limitation appears to be imposed by the gas circulation rate in the recombination system and the capacity of the catalyst chamber, rather than by the rate of bubble formation in the solution or the cooling capacity of the main reactor heat exchanger.

Power levels in excess of 35 kw increase the hydrogen concentration to more than 10% in the circulating gas and may increase the catalyst bed temperature above 500°C. The combination of these factors is believed to ignite the hydrogen and oxygen gas mixture in the catalyst chamber and produce small pressure fluctuations. These fluctuations produce power variations which cannot be completely compensated for by the automatic level control.

Figure 15 illustrates the effect of temperature, and bubbles from solution decomposition, on the liquid level. Estimates of bubble depth are also shown. These measurements were made during initial operation with a pointer-type level indicator.

The large net negative operating coefficient of this reactor is illustrated in Fig. 16 for various powers. It is seen that as the power level is increased, the coefficient increases substantially up to the boiling point where it loses meaning. The true temperature coefficient has been masked by an additional bubble or power coefficient. The effective decrease in solution density due to this coefficient still further increases the inherent stability and safety of this type of reactor core.

The response of Supo to sudden reactivity changes has been studied to obtain information on the power coefficient of reactivity and to separate the effects of core temperature rise and decomposition gas formation upon the reactor behavior. Reactivity was added to the reactor by ejecting a neutron absorber out of the core region, the effectiveness of the absorber being known as a function of time. A reactivity change of about 0.4% Δk was added in about 0.1 sec. The average life time of the prompt neutrons was determined as about 1.7×10^{-4} sec, assuming an effective fraction of delayed neutrons equal to 0.0085. Initially following a reactivity addition, reactivity decrease was due primarily to decomposition gas formation, at least 10% of the potential gases appearing as such within 0.2 sec. The decrease in reactivity corresponding to gas formation was initially always about 5 times the decrease attributable to core temperature rise. It therefore appears that gas formation has a very influential effect upon the safety aspects of water boiler type reactors. As the gas bubbles left the core region, reactivity decrease due to core temperature rise increased in relative importance.

Table VI. Constants and Properties of Supo

Max. power: 45 kw heat Max. power density: 2.8 kw/liter
Max. thermal flux: 1.7×10^{12} n/cm²/sec
Est. max. intermediate: 2.8×10^{12} n/cm²/se
Est. max. fast: 1.9×10^{12} n/cm²/sec
Uranium: 88.7% U^{235}
Critical mass: 777 gm U^{235}
Operating mass: 870 gm U^{235}
Solution density: 1.10; pH <2
Solution volume: 12,700 cm³
Pile dimensions:
- External size: 15 × 15 × 11 feet high
- Core: 12-in. diameter stainless steel sphere
- Moderator: Water 12 liters
- Reflector: Graphite 55-in. cube
- Thermal columns: (1) 42 inches wide, 64 inches high, 68 inches to sphere center. (2) 60 inches wide, 64 inches high, 95 inches to sphere center.

Shielding:
- 8½-in. bismuth pier in thermal columns.
- ½ in. of B_4C + paraffin; 2 inches steel, 4 inches lead, 5 feet normal concrete.

Typical running conditions, 25 kw power level:

Gas circulation rate	100 l/min
Catalyst chamber drop	2.2 in. H_2O
Reflux condenser drop	4.5 in. H_2O
Max. system pressure	3.1 in. H_2O
Exhaust line pressure	3.2 in. H_2O
Catalyst bed temperatures:	
Inlet region	467°C
Middle region	438°C
Outlet region	369°C
Reactor solution temperature	75°C
Reflux condenser water:	
Flow	0.17 gal/min
Temperature in	3.5°C
Temperature out	20°C
After condenser water:	
Temperature in	20°C
Temperature out	28°C
Air temperatures:	
Out of reflux condenser	15°C
Into catalyst chamber	45°C
Into after condenser	211°C
Into reactor sphere	33°C

Radiolytic gas production:
- Hydrogen plus oxygen: 0.44 liters/min/kw
- Nitrogen decomposition: 2.5 cm³/min/kw

The compilation in Table VI summarizes some of the constants and properties of Supo:

D. One-Watt Solution Type Reactor, North American Aviation 1952–1955

This water boiler type reactor has been constructed by North American Aviation Inc. It is designated as WBNS (Water Boiler Neutron Source) and operates at a one-watt power level with a maximum thermal flux of 4×10^7 neutrons/cm²/sec. It uses an enriched uranyl nitrate solution encased in a cylinder of graphite 5 ft in diameter and 5 ft high.

E. A 500-Watt Solution Type Reactor, North American Aviation 1953–1955

This reactor has been built by N.A.A. for Livermore Research Laboratory in California. The general design is similar to the one-watt unit except that it uses an enriched uranyl sulphate solution and has a completely closed cycle sweep gas and recombination system. The maximum thermal flux is 2×10^{10} neutrons/cm^2/sec.

The above two reactors have been described in detail in a report entitled Solution Type Research Reactors, which is a part of the Information Package for the International Conference at Geneva, and will therefore not be described any further.

F. A 10-Kilowatt Research Water Boiler, North Carolina State College 1953–1955

This reactor is notable in being the first such device not to be owned and operated by a national government. The purpose of the reactor was not to make many original contributions to reactor technology. Rather, the construction was aimed at providing as simply and quickly as possible a safe flexible nuclear reactor with the maximum adaptability to instructional and research purposes. Although the general designs of numerous components have been borrowed from the successful Los Alamos Supo model water boiler, this reactor has some different features.

The reactor core is placed below ground level in the center of a 57-ft diameter room. This room, in turn, is in the center of the building. On three sides are laboratories for instruction and research. On the fourth is an observation room and the control room. A cylindrical core using a uranyl sulfate solution enriched to about 90% with U^{235} is used. The cylinder is made of stainless steel (347 type 18-8) with an inner diameter of 10¾ in. and 11 in. height; the wall thickness is 1/16 in. Four internal hairpin type cooling coils, shown in Fig. 18, are used to dissipate the heat developed in the core. Fourteen liters of solution fill the core to a height of 9.9 in. A volume of 0.9 liters is left above the solution to allow for frothing and solution expansion. About 848 grams of U^{235} are required for normal operation. The core is surrounded by a graphite reflector in the form of a five-ft cube.

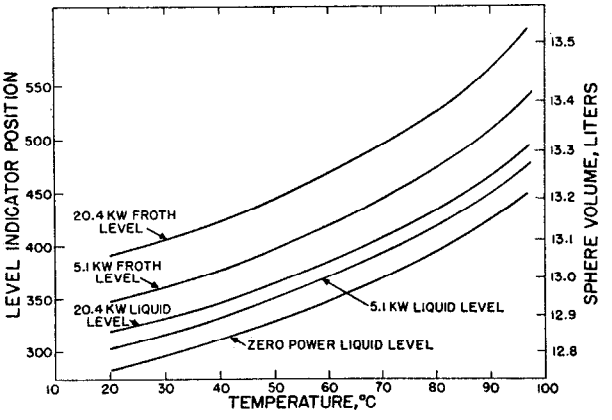


Figure 15. Supo levels

The shield consists of four to six inches of lead around the graphite followed by heavy barite type concrete. The outer shield is in the form of an octagon about 17 ft in diameter and 12 ft high. Numerous exposure facilities exist, including a thermal column, a central vertical re-entrant thimble extending into the core, and access ports from all eight faces of the octagonal shield (see Fig. 17).

A recombination unit similar to that in Supo is used. No decomposition products other than hydrogen, oxygen and fission product gases are produced. Since some air is bled into the system, however, a small amount of gas is discharged after a time delay to the atmosphere by means of a stack. Control of reactivity is maintained by four vertical rods. Two of these are internal and made of boron. Two are tangential cadmium strips.

Figure 19 shows Dr. Beck explaining the operation of the control console to two students.

During the first ten months of operation the reactor was operated at 100 watts or less. Effort during this period was devoted to the determination of the reactor characteristics, calibration of instruments and auxiliary apparatus, and the development of satisfactory operating and experimental procedures.

When the reactor was first run at about 400 watts for one hour with widely varying core temperatures, a decrease in reactivity was observed. This loss first appeared when the temperature of the fuel had been lowered to 11°C. The total loss of reactivity amounted to 40 grams U^{235} equivalent.

The loss of reactivity was established to be due to a partial precipitation of uranium, the pH of the solute having changed from the normal 2.3 to 1.3.

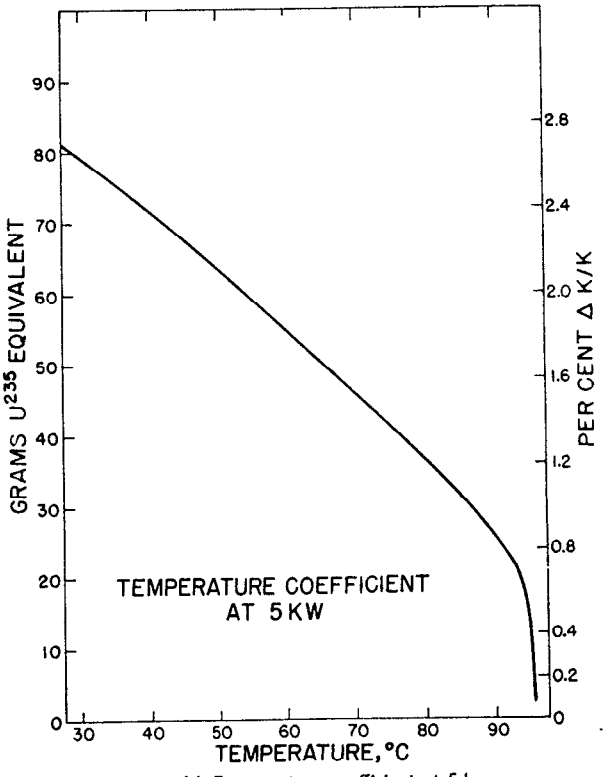


Figure 16. Temperature coefficient at 5 kw

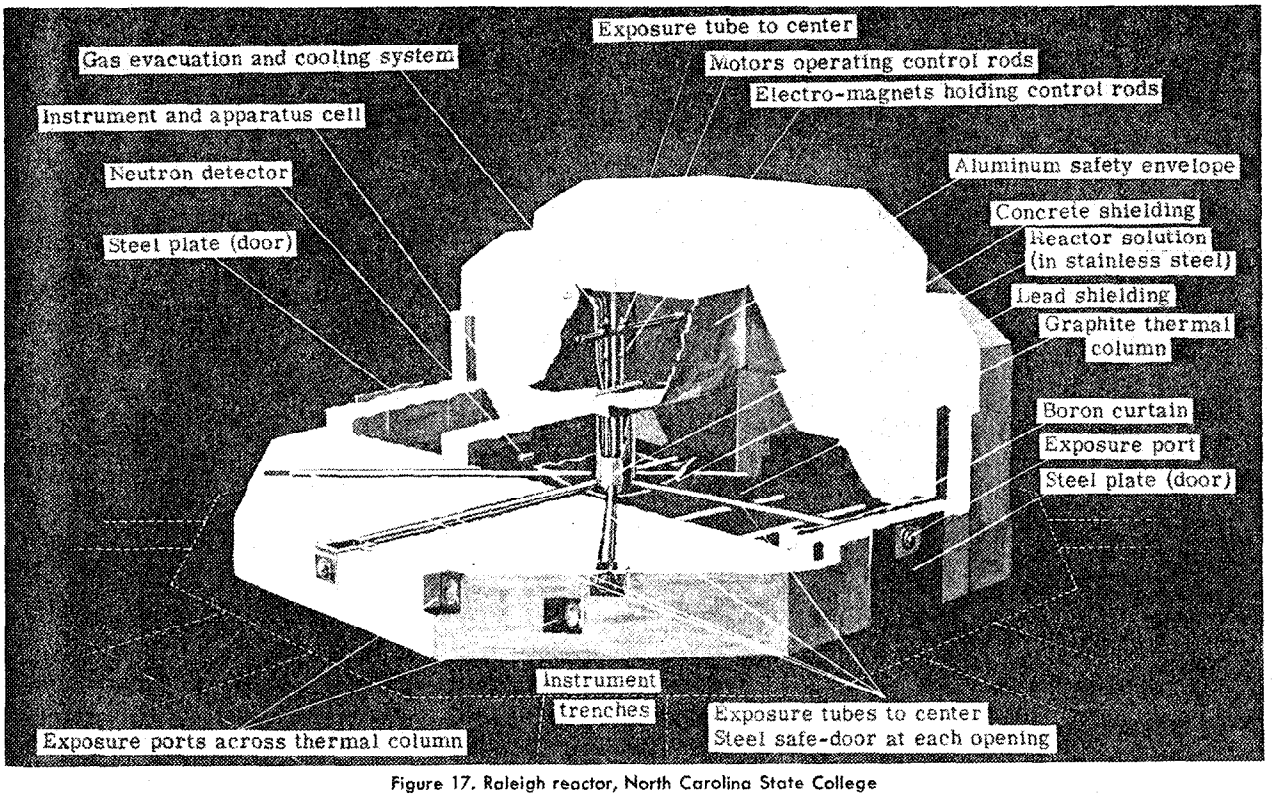


Figure 17. Raleigh reactor, North Carolina State College

The precipitate was dissolved in 7 days by the addition of cupric sulfate and ferrous sulfate to the solution along with temperature cycling and bubbling to assist stirring.

The equilibrium operating conditions at temperature are normally such that the hydrogen peroxide concentration reaches an equilibrium value due to the presence of the fission product radiations and does not continue to build up. When, however, the reactor is shut off and the temperature is dropped, one can get an excess of hydrogen peroxide which reacts with the uranyl ion producing UO_4 as a precipitate. After operating at 10 kilowatts and 80°C for example one cannot cool the solution much below 40°C without having a precipitate form. The addition of $CuSO_4$ and $FeSO_4$ catalyzes the decomposition of hydrogen peroxide.

III. WATER BOILER DESIGN PROPOSALS

A. 50 Kilowatt Medical Reactor, North American Aviation Inc.

A homogeneous, water solution type nuclear reactor has been designed to provide radiations for medical research and experimental therapy.

The enriched uranyl sulphate fuel-moderator solution is contained in a spherical core tank, surrounded by a graphite reflector and a dense-concrete shield. The reactor is cooled by recirculated chilled water. Stainless steel is used to fabricate all reactor components which come in contact with the fuel solution or reactor atmosphere. Radiolytic and fission gases produced during reactor operation are handled in a closed-cycle system. No discharge of radioactive effluents are required during operation.

Section views of the proposed reactor are shown in Figs. 20 and 21. Neutron and gamma radiation tubes, isotope production tubes, a fission-gas gamma radiation source, and two thermal columns comprise the experimental facilities. The columns contain flexible arrangements for providing large cross-section, intense beams of gamma rays, thermal neutrons, and fast neutrons, either singly or together. Tables VII and VIII give the calculated radiation intensities expected.

Figure 22 is a schematic diagram of the proposed gas circulation and recombination system. It differs from the Supo design in that the main gas stream does not sweep the reactor core region and the gas is pumped by means of water injection.

A similar core design proposal for a general type research reactor with different radiation facilities will be constructed by North American Aviation Inc. for the Armour Research Institute of Chicago, in the fall of 1955.

B. Supo Model II, Los Alamos

A study of the operating characteristics of Supo Model I has indicated that with some design modifications substantially higher fluxes could be made available.

Only such changes have been considered in this design which are known to improve the performance either due to direct experimentation or from extrapolation of known data.

The gas disposal by means of a tall exhaust stack as used in Supo offers some difficulties in highly

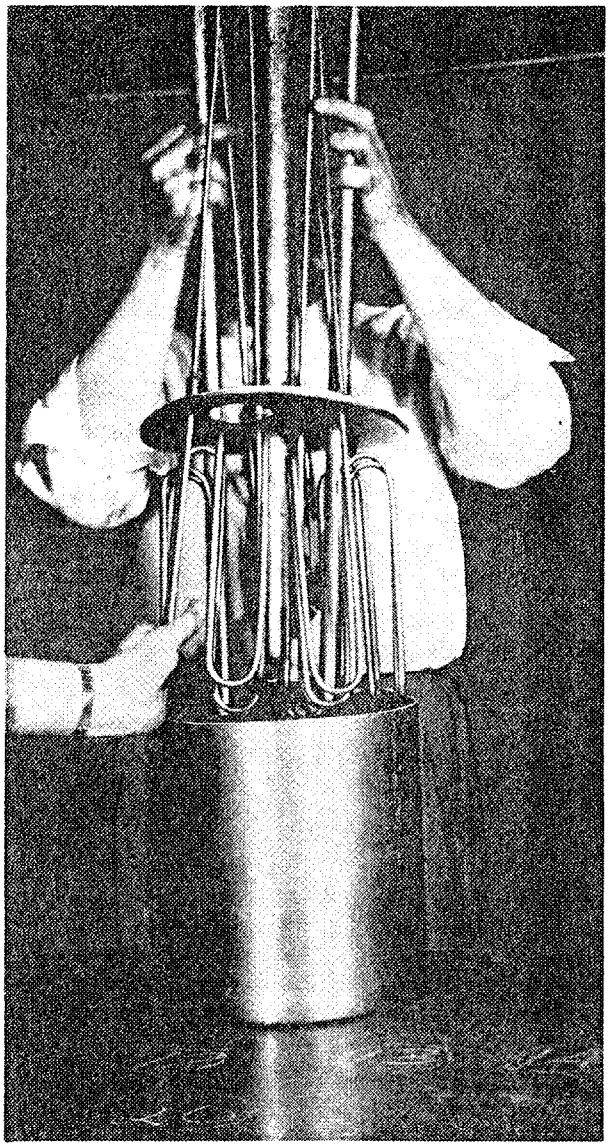


Figure 18. NCSC reactor core

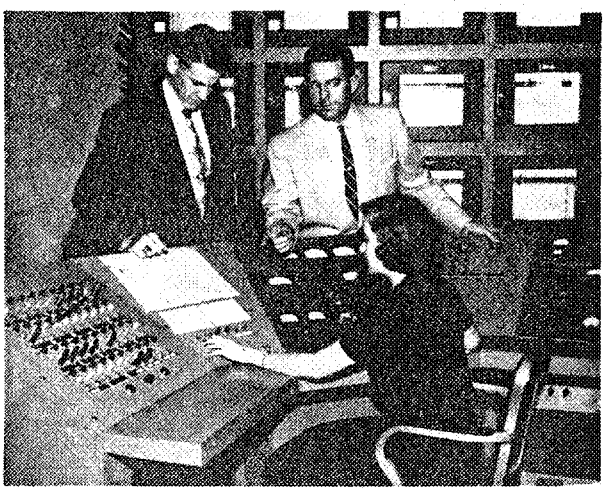


Figure 19. NCSC reactor console

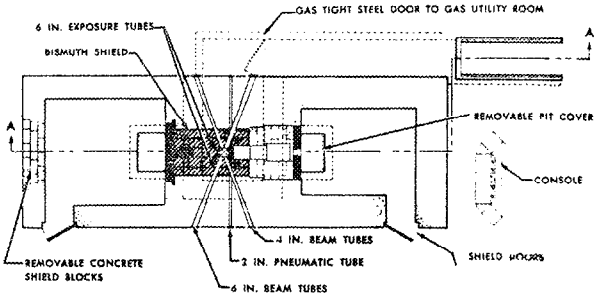


Figure 20. NAA medical reactor, top view

populated locations. This problem can be eliminated either by the recombination of the nitrogen by well known nitrogen fixation methods or using a uranyl sulphate solution as is in use at North Carolina State.

The present flux limitations of Supo are due to (1) the gas circulation rate in the recombination system, (2) the capacity of the catalyst chamber, (3) the capacity of the heat exchanger, and (4) the effectiveness of the shielding. These restrictions can

Table VII. Calculated Radiation Intensities Available at the Shield Face of the Thermal Neutron Facility

Use	*Thermal neutron intensity rep/min/kw*	*Thermal neutron flux n/cm²/sec/kw*	*Fast neutron intensity rep/min/kw*	*Fast neutron flux n/cm²/sec/kw*	*Gamma ray intensity rep/min/kw*
Patient therapy					
Direct beam	3.2	3.8×10^7	0.6	1.3×10^5	0.1
Penumbra	—		0.03	6.5×10^3	3×10^{-3}
Shadow	—		7×10^{-4}	1.5×10^2	3×10^{-4}
Animal research	1.2	1.4×10^7	0.009	2×10^3	0.005

Table VIII. Calculated Radiation Intensities Available from the Gamma and Fast Neutron Facility at a Distance Eight Feet from the Reactor Core Center

Use	*Description of facility*	*Gamma ray intensity rep/min kw*	*Fast neutron intensity rep/min kw*	*Fast neutron flux n/cm²/sec/kw*
Patient therapy	21 inches water no lead	1.3	0.086	1.9×10^4
Animal research	33 inches water no lead	0.50	0.0036	8×10^2
Animal research	8 inches lead	0.002	10	2.2×10^6

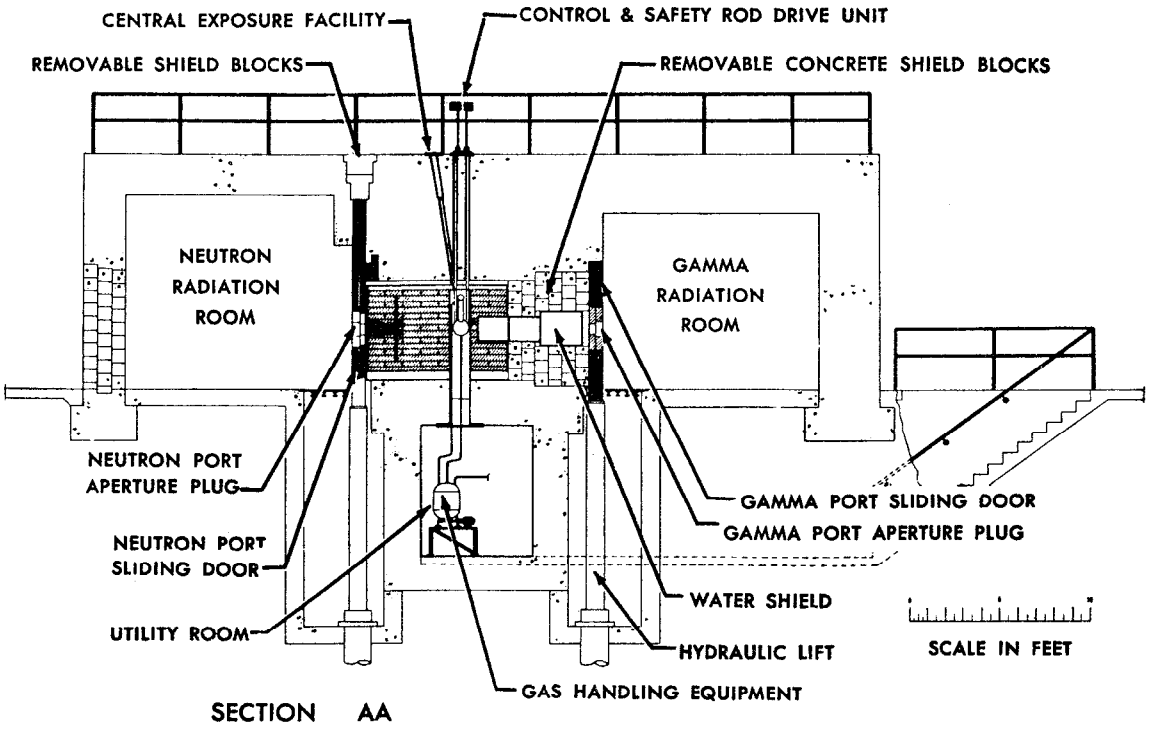


Figure 21. NAA medical reactor, side view

easily be removed by increasing the size and capacity of the necessary components.

Instabilities and reactivity loss due to bubble formation probably present the real flux limitations. Extreme bubble formation was produced in Supo by permitting the solution to boil with no water flow through the main heat exchanger. With the reactor producing 5 kw of steam in the reflux condenser of the recombination system (Fig. 8) the inherent reactor power fluctuations were found to be $\pm 5\%$. These operating conditions correspond to a release of 290 liters of vapor per minute as compared to 13 liters per minute of radiolytic gas at a normal 30-kilowatt operating level.

Figure 23 compares power coefficients for normal operation with appreciable radiolytic gas production to the 5-kilowatt boiling condition when most of the gas is water vapor. An extrapolation of the radiolytic gas production curve makes it appear feasible to run water boiler type reactors at substantially higher power densities.

Figure 24 is a schematic sketch of a proposed Supo type research reactor which incorporates improvements in the overall shield geometry and port facilities.

The spherical geometry used on Los Alamos Water Boilers was originally based on the desire to minimize the active material required for critical experiments. When power operation was begun, the upper half of the sphere was no longer completely filled with solution in order to provide appreciable surface area for the escape of gas bubbles. A cylindrical rather than a spherical shape has numerous advantages for the upper portion of the reactor vessel. (1) The free solution surface can be increased, which provides a more favorable geometry for the escaped bubbles. (2) The circulating gas can be vented more efficiently at lower velocities, which reduces entrained liquid in the gas stream. (3) Excess volume for emergency

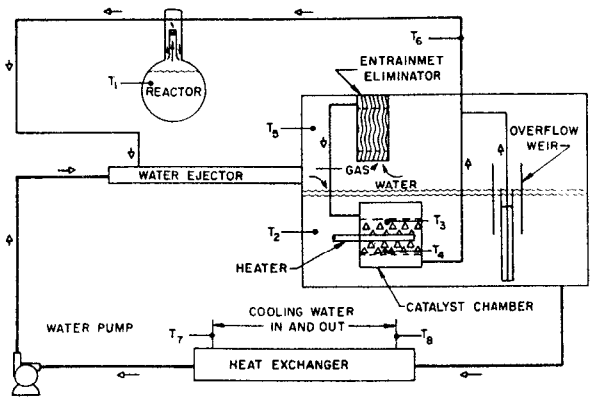


Figure 22. NAA wet gas handling system

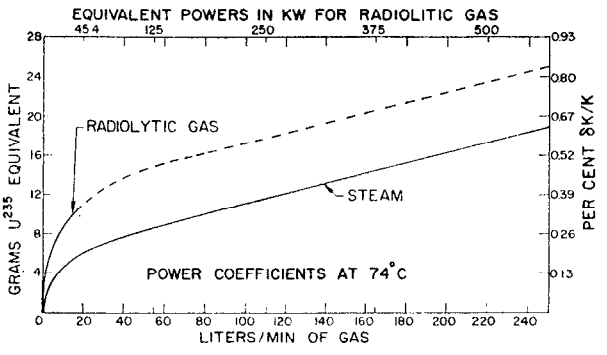


Figure 23. Power coefficients at 74°C

expansion can be easily supplied above the solution. (4) Neutron shielding and vertical access facilities can be more easily provided. Figure 25 shows a Supo type reactor design which incorporates these features.

Both the reflux and after condenser of the recombination system are included in the reactor vessel shell. The solution-gas interface of Supo I is 410 cm^2 when at full operating temperature of 88°C; this area has decreased to 245 cm^2 when operating at 30 kw. The cylindrical geometry of Supo II has three times this area which does not decrease for an increase in power.

The total heat exchanger surface area has been increased by about a factor of seven over that in Supo I. Cooling the wall of the reactor vessel contributes about 25% to this area increase and prevents the heating of the reflector by conduction now observed.

Effort has been made to prevent entrainment of solution spray into the gas circulating system. Early experience on Supo, before the recombination system was installed, has shown that adequate washback features are essential or uranium can be lost by caking onto available surfaces. The present design of Supo I where continuous washdown by condensation occurs in the reflux condenser has been found entirely satisfactory for the gas flows used. The design of Fig. 25 is believed to offer a better geometry even with the factor of 20 increase in the gas circulation rate. The neutron shielding above the reactor is supplied by part of the cooling water system and the entire reactor assembly can be easily removed from the top.

Since the recombination system shown in Fig. 8 was the first use of a catalyst chamber for recombining gases from a homogeneous reactor, numerous features were provided to determine the operation behavior and causes of failure if failure should occur. With the experience gained from the operation of this system, one can now make some simplifications with confidence.

Figure 26 is a schematic layout of a simplified recombination system which has more than ten times the capacity of the old system. The changes and essential features are: (1) the spare catalyst chamber is not necessary and actually has been removed from Supo I; (2) pressure coupling tubes 5 through 14 (Fig. 8) are not essential; (3) the external condenser can be included in the reactor; (4) the liquid trap can be removed or combined with a sampling tube if the nitrogen is recombined or a solution such as uranyl sulfate is used which produces no excess gas; (5) a single bubble tube for occasional level checking or gas sampling is desirable; (6) some means for measuring the flow rate of the circulating gas is advantageous in order to be able to shut the reactor off before high hydrogen concentrations have accumulated in case of stoppage in the gas circulation; (7) a blower with an all-welded case using a canned-rotor motor is known to give completely trouble-free service for the life of the bearings used. High grade ball bearings should last for several years of continuous operation and it is quite simple to design the bearings for easy replacement.

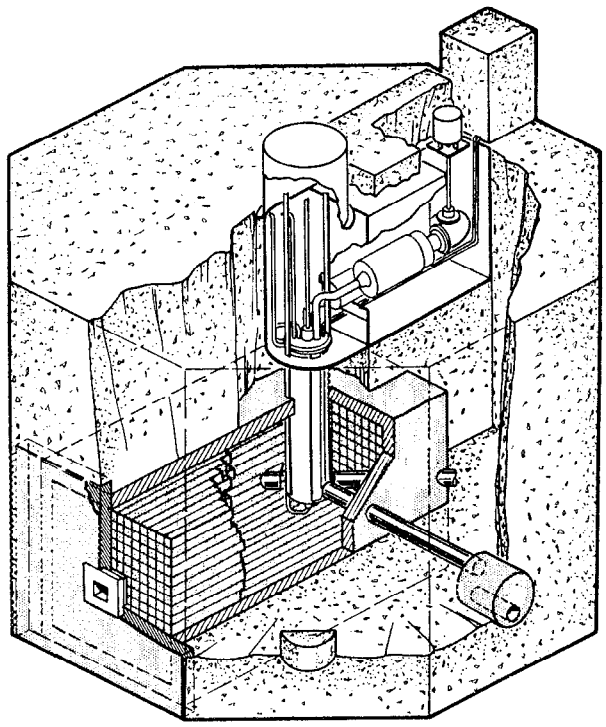


Figure 24. Schematic, Supo II

Operation of Supo I has shown that the following features are desirable in a catalyst chamber; (1) the chamber should be designed to prevent the catalyst bed temperature from exceeding 500°C during full power operation to prevent possible ignition of the gas; (2) an explosion trap on the inlet side of the unit is desirable to prevent flashback or burning at any point outside of the catalyst bed if the hydrogen concentration increased due to an accident; (3) cooling facilities on the chamber surface should be provided to avoid heating the surrounding shield.

Figure 27 illustrates a possible design for a catalyst chamber which incorporates these features. This unit has a gas handling capacity 20 times greater than that used on Supo I. The re-entrant thimbles shown are thermocouple wells. A shift in the hot zone from the outside towards the center gives an indication of a loss in catalytic activity. No such shift has yet been observed in the Supo I system.

The entire recombination system becomes a very strong gamma ray source due to fission deposition on the walls of the components and from the circulating gas itself. The gas circulating in Supo I for example, had a gamma activity of 2000 curies/liter. A very high gamma ray to neutron ratio can be made available for irradiation purposes by supplying irradiation facilities which "see" a portion of the recombination system.

C. Test Tube Reactor, Los Alamos

This reactor design is a more radical modification of the water boiler type reactor than that given above. A schematic drawing of the reactor proposal is shown

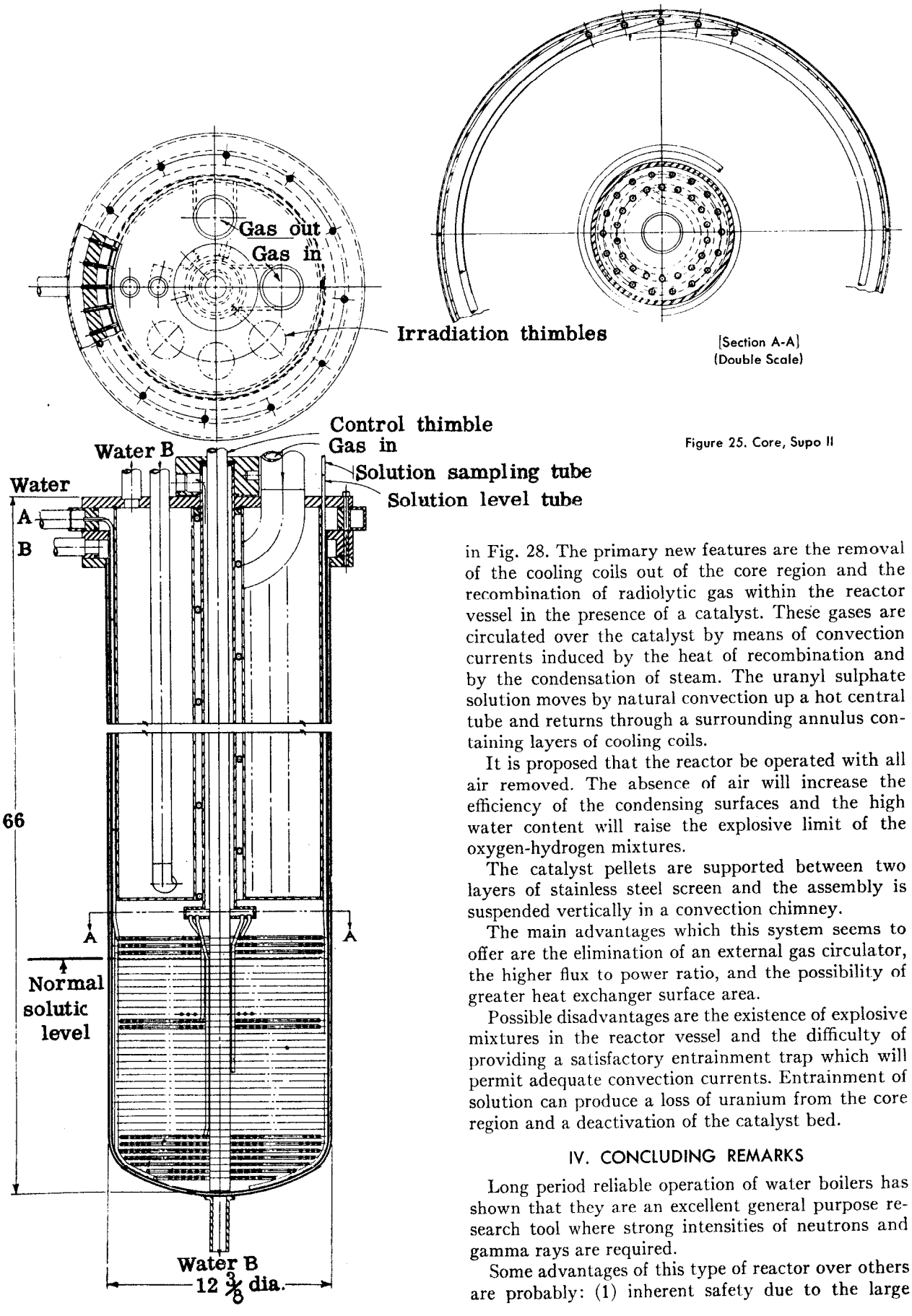


Figure 25. Core, Supo II

in Fig. 28. The primary new features are the removal of the cooling coils out of the core region and the recombination of radiolytic gas within the reactor vessel in the presence of a catalyst. These gases are circulated over the catalyst by means of convection currents induced by the heat of recombination and by the condensation of steam. The uranyl sulphate solution moves by natural convection up a hot central tube and returns through a surrounding annulus containing layers of cooling coils.

It is proposed that the reactor be operated with all air removed. The absence of air will increase the efficiency of the condensing surfaces and the high water content will raise the explosive limit of the oxygen-hydrogen mixtures.

The catalyst pellets are supported between two layers of stainless steel screen and the assembly is suspended vertically in a convection chimney.

The main advantages which this system seems to offer are the elimination of an external gas circulator, the higher flux to power ratio, and the possibility of greater heat exchanger surface area.

Possible disadvantages are the existence of explosive mixtures in the reactor vessel and the difficulty of providing a satisfactory entrainment trap which will permit adequate convection currents. Entrainment of solution can produce a loss of uranium from the core region and a deactivation of the catalyst bed.

IV. CONCLUDING REMARKS

Long period reliable operation of water boilers has shown that they are an excellent general purpose research tool where strong intensities of neutrons and gamma rays are required.

Some advantages of this type of reactor over others are probably: (1) inherent safety due to the large

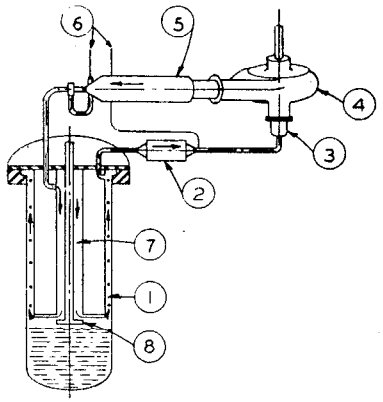


Figure 26. Schematic gas system: (1) spray condenser; (2) steel wool entrainment trap; (3) flow meter; (4) centrifugal pump; (5) catalyst chamber; (6) sampling tubes; (7) reflux condenser; and (8) solution baffle

negative temperature and power reactivity coefficients; (2) small size along with low power and uranium requirements for comparable fluxes; (3) no replacement of burned out fuel elements; (4) low cost and simplicity of design core; (5) ease of rapid shut downs and start ups; and (6) automatic removal of fission gases from core.

The chief disadvantage is the flux limitation. Even with the new designs mentioned above, stable operation with fluxes much in excess of 10^{13} neutrons/cm^2/sec are not likely. Most types of experiments can, however, be adequately carried out with such fluxes.

The main difference in the new water boiler designs described is the method of handling the radiolytic gas. The Supo system of Fig. 8 has been proven to be satisfactory, whether the wet gas system shown in Fig. 22 or the internal recombiner of Fig. 28 are satisfactory can only be demonstrated by actual test. These tests must be made under high flux reactor operation since the problems to be answered are: (1) whether with high density bubble formation there is any effect on the catalyst or any loss of uranium from entrainment and (2) whether the explosive gas mixture in the reactor core affects the operation or safety of the reactor.

Water boiler designs for pressurized high temperature operation have not been considered here. These may offer some advantages by reducing the bubble formation and permitting internal recombinations by the back reaction between hydrogen and oxygen. The use of heavy water as a moderator also has some advantages but no such unit has yet been constructed.

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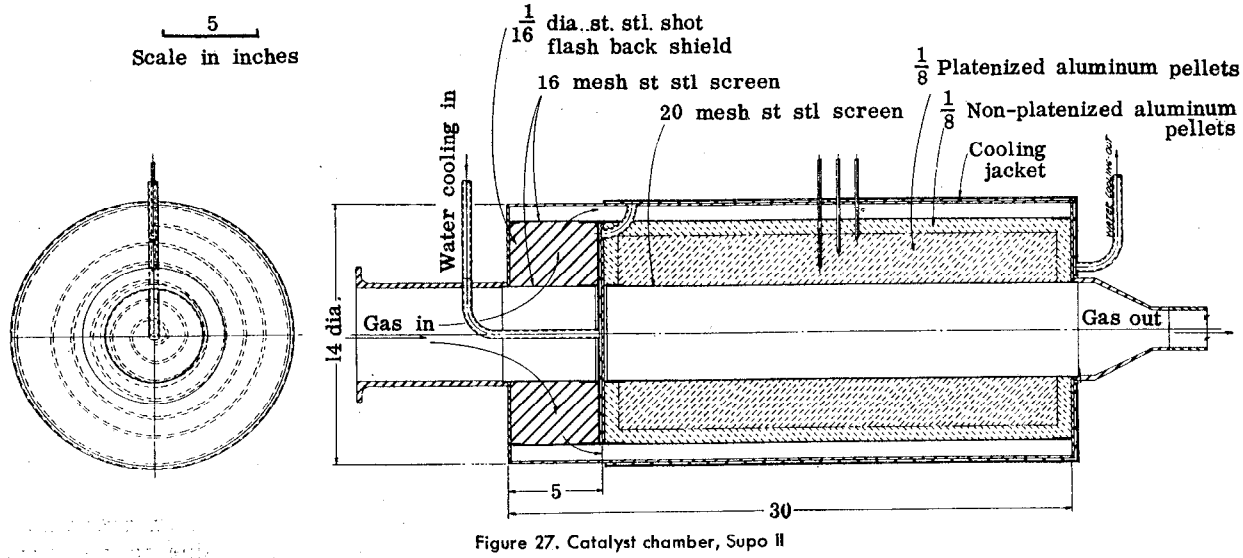
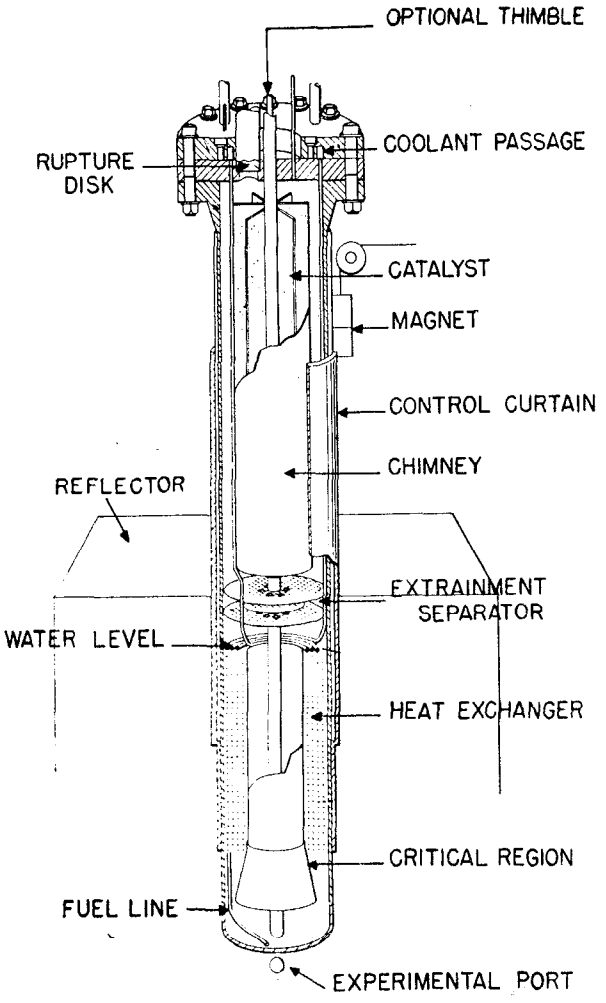


Figure 27. Catalyst chamber, Supo II



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Abbreviations

LASL Los Alamos Scientific Laboratory operated for US Atomic Energy Commission by University of California, Los Alamos, New Mexico.

NAA North American Aviation, Inc., Atomic Energy Research Department, Downey, California.

LRL Livermore Research Laboratory of the US Atomic Energy Commission operated by California Research and Development Company, Livermore, California.