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POWER CALIBRATION OF THE WATER
BOILER NUCLEAR REACTOR

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ABSTRACT

The power of the CR&D water boiler reactor has been calibrated by three independent methods to 500 watts $\pm$ 6 per cent for 95 per cent confidence limits. The three techniques were: activation of standardized gold foils, radiochemical analyses of activated uranium foils to determine the fission product yields of Ba-139 and Zr-97, and calorimetry. These methods gave answers in agreement to within 13 per cent. The thermal neutron flux at 500 watts is 2.11×10^{10} neutrons/cm²/sec in the center of the spherical core. The report includes a brief description of the reactor, discussion of the three methods used to calibrate the power, and presentation of the results.

POWER CALIBRATION OF THE WATER BOILER NUCLEAR REACTOR

INTRODUCTION

The California Research & Development reactor is of the water boiler type similar to Lopo, Hypo and Supo at Los Alamos and the NAA WBNS at Downey, California.

The reactor consists of a one foot diameter by 0.080-inch wall spherical core containing a critical mass of 687.3 grams of U-235 in approximately 14.5 liters of uranyl sulfate solution. The core is surrounded by a five foot high, five foot diameter right circular cylinder of graphite, which acts as the reflector. The sphere is penetrated on a diameter by a 1.1-inch inner diameter by 1/16 inch wall tube allowing access to the center of the sphere for measurements and high flux irradiations. The sphere contains 160 inches of coolant tubing 5/16 in. OD with 1/32 in. wall formed into a six turn helix whose diameter averages 8 inches. Distilled water is the coolant, and it is pumped through an external heat exchanger at rates up to 1.25 gpm. A flow gauge and thermocouple wells were installed in the coolant lines.

The spherical core, central tube and coolant tubing are constructed to type 316 stainless steel.

All of the foils used in the nuclear power measurements were irradiated in the central tube. Access to this region was facilitated by a continuation of this tube through the reflector and shielding.

Four boron loaded rods pass in rectangular slots tangential to the sphere for control and safety purposes. Two of the rods are used as safety rods. A third is used for coarse control, and a fourth for fine regulation. The reactor is loaded with an excess reactivity of about 0.3 per cent at room temperature.

The power detecting and recording instruments are three gamma compensated ionization chambers located in channels in the base of the reactor. One of these feeds a Beckman micro-micro-ammeter whose output is recorded continuously. Another is connected to a Log N recorder for an additional continuous power record. The output of the third is fed to a servo amplifier which maintains criticality at any pre-set power level by regulating the position of the fine control rod automatically and continuously.

For the measurements, the power level used was that indicated by the servo unit.

The power was set at approximately 500 watts for the U-235 fission product and calorimetric tests. Due to their high cross section and the need for reasonable counting rates, the gold foils were irradiated at approximately one watt and detector readings were extrapolated to 500 watts.

The above brief description of the CR&D reactor may be supplemented by consulting references (1) and (2) which describe the reactor and its components in greater detail.

EXPERIMENTAL PROCEDURES

Gold Foil Activation

Prior to the power tests a quantity of sheet gold 0.0025 inches thick was procured. A number of one-half inch diameter foils were punched out of this sheet and were cemented on one-inch OD by 1/16 inch thick Lucite discs.

The foils were then irradiated in a calibration tank at equal distances from a neutron source, counted, and by comparing the saturated activities correction factors were assigned to each foil to compensate for slight variations in foil thickness, density, impurities, and mounting imperfections.

The foils are counted by conventional techniques set up by CR&D personnel for indium foils. Foils are placed inside a two inch thick lead pig facing a thin end window Geiger tube. This feeds a decade scaler which counts the foils for a pre-determined time or number of counts.

The resulting activities are corrected for background, foil factor, coincidence loss and daily variations by conventional means. Saturated activities are computed on an IBM CPC computer (3).

Four of the gold foils were sent to Oak Ridge National Laboratory where they were irradiated in the Oak Ridge Standard Pile in a known flux and cadmium ratio. They were returned to CR&D where they were counted in seven pigs several times, and the corrected saturated activities were computed. It was then possible to relate the thermal activity of a gold foil (bare foil activity minus cadmium covered activity) to the thermal flux incident upon that foil. This relation has been determined to be: 3.60 ± 0.07 thermal neutrons per sq cm per second are equivalent to one count per minute corrected saturated activity. The details of this calculation are described in Appendix 1.

To determine the thermal neutron flux in a given position, two foils must be irradiated. One of these is a bare foil mounted as previously described. The other is an unmounted foil enclosed in a 0.030 inch thick cadmium box. The bare foil is responsive to neutrons of all energies while the cadmium covered foil is effectively screened by the cadmium from neutrons of energies less than 0.3 ev. The thermal activation is consequently the difference between the two foil activities.

A series of indium and gold foils were exposed within the sphere at varying distances from the center. Their activities normalized to the calibrated 500 watts are shown in Fig. 1. Also shown are the barium fission product activities from uranium foils exposed in various locations.

An equation of the following form has been fitted to the curve as a solution to the neutron distribution in the core:

$\phi = \phi_0 \frac{\sin Kr}{Kr}$ where $K = 0.31$ inches and r is the distance from the center of the sphere in inches. The accuracy of this curve fitting is shown in Fig. 1.

Integration of this equation describing the neutron distribution over the volume of the sphere gives a ratio of average to peak neutron, or power density in the core of 0.819.

The power is defined in the following manner (4):

$$P = \bar{\phi}_{th} \Sigma_{f25} CV$$

where, P is the power in watts

$\bar{\phi}_{th}$ is average thermal neutron flux in the core

Σ_{f25} is the macroscopic thermal fission cross section
for U-235

V is the volume of the fuel solution in cubic centimeters

C is a conversion factor to convert fissions per second to watts.

Since Σ_{25} , C , and V are known, and the thermal flux may be determined by exposing bare and cadmium covered gold foils, the power can be determined readily from the above expression. A solution of this equation shows that a flux of 4.22×10^7 thermal neutrons/cm²/sec ± 10 per cent at the

FIG. 1 - FLUX TRAVERSE IN CORE

center of the sphere is equivalent to one watt. In this solution the fission cross section of U-235 is assumed to be 549 barns (5), the volume of fissionable solution is about 14 liters, and the conversion factor is 3.7×10^{10} fissions per second per watt, assuming the energy release is 175 Mev per fission. This equation is solved more rigorously in Appendix 2.

A series of 12 gold foils alternately bare and cadmium covered were exposed in the center of the sphere at approximately one watt, and they were counted using the previously described techniques. Corrected saturated activities were computed and converted to thermal activities and thermal fluxes. The resulting power was $1.30 \text{ watts} \pm 0.14$. Several days later a series of six bare gold foils were exposed in the center of the sphere, and again the power was calculated using the cadmium ratio of 3.24 ± 0.09 as measured by gold which was determined from the preceding run. The result was $1.31 \text{ watts} \pm 0.14$.

It was thus felt that this method had proven feasible subject to the degree of its agreement with the other methods of power measurements. A detailed analysis of the gold foil activities is also presented in Appendix 2.

The predicted power level settings for 500 watts assuming linearity of the gamma compensated ionization chambers are as follows:

Ionization Chamber 1 - Beckman No. 1:24.8 on scale 500
Ionization Chamber 2 - Servo: 103 vernier on scale 200
Ionization Chamber 3 - Log N: 500

Fission Product Determination

All irradiations of these foils were made at approximately 500 watts in the sphere. A series of enriched uranium-235 foils were prepared by sealing a measured amount of uranium oxide powder inside a 0.001 in. thick aluminum foil. They were taped to Lucite backings one-inch diameter by 1/16 inch thick. The quantity of uranium in each foil was about one milligram.

The foils were exposed to approximately 1.5×10^{13} nvt. They were then sent to the CR&D Nuclear Chemistry Group. There the foils were disassembled and using standard carrier techniques, the zirconium-97 atoms formed as fission products were extracted and counted relative to a standardized 4π counter. As a further refinement of the technique barium-139 was extracted and counted in addition to zirconium-97 for traverse data. The accuracy of this method is estimated to be within $\pm$ ten to fifteen per cent.

Three foils were exposed successively in the center of the sphere at approximately 500 watts, and they gave an average flux of 2.45×10^{10} thermal neutrons/cm²/sec, which when converted to power and normalized to 100 on scale 200 on detector 2 gives a power estimate of 434 watts $\pm$ 12 per cent.

In addition a number of foils were irradiated within the sphere at varying distances from the center. The results are plotted in Fig. 1, with the gold and indium traverse points.

Sample calculations and an analysis of the results are given in detail in Appendix 3.

Calorimetric Method

The most straightforward and, therefore, presumably the simplest method for measuring the power of a system such as this is to make a calorimetric determination. However, some difficulties are encountered at this low power since small temperature differences exist in the coolant inlet and outlet lines for reasonable flow rates.

The usual equation defining specific heat governs this application:

$$P = Kw \quad c_p \Delta t$$

where:

P is the power in watts

W is the mass flow rate in lb/min = (density-lb/ft³) (volume-ft³/min)

c_p is the specific heat in $\frac{\text{Btu}}{\text{lb}^\circ \text{F}}$

Δt is the temperature difference between inlet and outlet coolant in degrees Fahrenheit

K is a conversion constant in watts per Btu per min.

Copper wells for the temperature measuring devices were inserted into the flow path of the coolant at the inlet and outlet lines outside the reflector, about three feet from the core.

A Fischer-Porter-type flowrator of 0.15 to 1.81 gpm capacity with a least count of 0.002 gpm was installed on the inlet cooling line.

The flowrator was calibrated volumetrically prior to its installation, and a deviation curve was prepared.

Flow rates were usually established at about 0.4 gpm giving temperature differences of about 8 F at 500 watts.

Prior to taking data the temperature of the refrigerated heat exchanger was adjusted so that the temperature of the fuel coincided with the ambient temperature to minimize heat loss to the graphite reflector.

Two types of temperature sensing devices were used: two sets of Leeds and Northrup iron-constantan thermocouple wires were connected in opposition to read temperature difference directly. A Leeds and Northrup-Type 8667 potentiometer was used to measure the emf generated.

The other temperature measuring device consisted of two thermistors Type 51A1 manufactured by Victory Engineering Corporation. They were calibrated against precision thermometers, and their resistances were measured on a Leeds and Northrup-Type 5300 Wheatstone Bridge.

A detailed analysis of the above data is presented in Appendix 4.

The average power as determined by thermocouple measurements was 503 ± 50 watts. Thermistor readings gave an average power of 509 ± 25 watts, for detector number 2 setting of 100 on scale 200.

CONCLUSIONS

It seems from the final results as though power detectors one and two, Beckman one and the Servo respectively, may be relied upon for true power indication. Power detector three connected to a Log N amplifier and recorder, has shown considerable daily variation, and, in addition, it has been demonstrated that the amplifier has a high degree of temperature sensitivity. Measurements made with gold foils from one hundred to five hundred watts during gamma compensation of power detector two have shown little departure from linearity, if any, in this region. Periodic exposure of gold foils during an eight hour, 500 watt run show little, if any, drift in power.

Sources of possible error in this experiment are for the most part apparent from the discussion. No correction has been made to the gold and uranium foil data for flux perturbation. Error in the gold foil data due to this occurs because the foils were calibrated in a graphite medium whose diffusion length is significantly different from that in the core. Thin Lucite holders were used to support the gold and uranium foils. A preliminary evaluation shows no apparent difference between using the holder and laying the foils in place with no holder. Foils of both types were exposed horizontally and vertically in the core, and no measureable difference was detected in their activities.

In the case of the calorimetric measurements, the thermocouples and thermistors were carefully calibrated over the full range used to minimize this possible source of error. The flowrator also was calibrated over its full scale. Loss of heat to the graphite reflector was minimized by maintaining the core at approximately ambient temperature. The largest source of error in this method is the change in properties of the coolant water due to its circulation through the cooling circuit. Distilled water was used, but visual observation indicated that impurities were present after many hours of circulation.

The final power results are tabulated below, and are shown graphically in Fig. 2. Taking all methods into consideration, the power for a setting of 100 on the vernier, scale 200, on detector two (servo) and 25.2, scale 500, on detector one (Beckman one) has been determined to be 494 watts plus or minus six per cent for 95 per cent confidence limits. The method involving fission product analysis gives the maximum deviation from the above power, or about 10 per cent lower.

More weight was attached to the thermistor measurement than any other, since it was felt that this was the most inherently accurate method of all because it involved the fewest variables.

Summary of Data

The following power data are normalized in this table to a reading of 100 on the vernier, scale 200, on power detector two (servo) for purposes of comparison. The data are presented graphically in Fig. 2.

Method	Power Setting Detector 2	Power, Watts	Normalized Power, Watts
Gold 1	027.5/2	1.30	473
2	027.5/2	1.31	476
Fission Product	124/200	581	434
Thermistor			
1	98/200	505	515
2	98/200	502	512
3	98/200	491	501
Thermocouple			
1	98/200	506	516
2	120/200	562	469
3	134/200	714	532

FIG. 2 - POWER LEVELS AT STANDARD DETECTOR SETTING

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APPENDIX 1Absolute Standardization of Gold Foils

Four of the CR&D bare gold foils mounted on Lucite backings were sent to Oak Ridge National Laboratory. They were irradiated in slot 3 of the Standard Graphite Pile 33.95 cm from the source. The thermal flux in this position was 9.466×10^3 neutrons/cm²/sec, and the cadmium ratio as measured by gold foils was 7.98 (6) (7-Appendix D).

Each of the above foils was counted in seven pig-scaler combinations by CR&D. Corrected saturated activities were determined and the final average activity was 3012 counts per minute $\pm$ 2 per cent for 95 per cent confidence limits.

If A_{th} = thermal activity

A_b = bare activity

A_c = cadmium covered activity

CR = cadmium ratio

B = ratio between thermal flux and
saturated thermal activity

Then

$$CR = \frac{A_b}{A_c}$$

and

$$\begin{aligned} A_{th} &= A_b - A_c \\ &= A_b \frac{(CR-1)}{CR} \end{aligned}$$

Since the foils were irradiated in a cadmium ratio of 7.98:

$$A_{th} = 3012 \times \frac{6.98}{7.98} = 2635 \text{ counts per minute}$$

The thermal flux at this position was 9.466×10^3 neutrons/cm²/sec.

Then

$$B = \frac{\phi_{th}}{A_{th}} \frac{9.466 \times 10^3}{2635} \quad 3.60 \text{ neutrons/cm}^2/\text{sec)/cpm}$$

The error in B is the previously quoted ± 2 per cent plus the error in ORNL's flux measurement which may be assumed to be on the order of five per cent (7).

APPENDIX 2

Power Calibration by Gold Foils

It is necessary to determine the average thermal neutron flux in the sphere to be able to calculate the average power generated. Since the flux measured is the maximum flux at the center of the sphere, an expression must be secured relating the ratio of the maximum to the average thermal flux. This was done by integrating the curve shown in Fig. 1 and the result was:

$$\frac{\phi_{avg}}{\phi_{max}} = 0.819$$

As previously was shown (4):

$$P = \phi_{th} \Sigma_{f25} CV \text{ watts}$$

$$\phi_{th max} = \frac{P}{\Sigma_{f25} CV \times 0.819}$$

The flux corresponding to one watt may be computed by:

$$V = \frac{M}{\rho}$$

where V is the volume of the fuel solution in cm^3

M is the critical mass of U-235 in grams

ρ is the density of the fuel solution in grams per cm^3

$$\Sigma_{f25} = N_{25} \sigma_{f25} = \frac{\rho \cdot Av}{A} \sigma_{f25}$$

Av is Avogadro's number equals number of atoms of uranium per gram atom weight.

A is the atomic weight = 235

$$\text{Therefore } \Sigma_{f25} V = \frac{M Av}{A} \sigma_{25}$$

$$C = 175 \text{ Mev/fission} \times 1.6 \times 10^{-13} \text{ joules/Mev} \times 1 \frac{\text{watt second}}{\text{joule}}$$

$$= 2.80 \times 10^{-11} \text{ watts/fission/second}$$

Using data derived from reference (7), seven percent of the total fissions occur above 0.3 ev.

$$\phi_{th} = \frac{A}{M Av \sigma_{f25} \times 0.819 \times 1.07 \times 2.80 \times 10^{-11}}$$

Taking:

$$A = 235 \text{ grams/gram atomic weight}$$

$$Av = 6.02 \times 10^{23} \text{ atoms per gram atomic weight}$$

$$M = 687.3 \text{ grams of U-235}$$

$$\sigma_{f25} = 549 \times 10^{-24} \text{ cm}^2$$

Solving the above, it is determined that the thermal neutron flux at the center of the sphere for 1 watt power equals 4.22×10^7 neutrons/cm²/sec $\pm$ 10 per cent.

Gold Foil DataCASE I

<u>Bare Foils</u> <u>Corrected Sat. Activity</u>	<u>Cadmium Covered Foils</u> <u>Corrected Sat. Activity</u>	<u>Thermal</u> <u>Activity</u>	<u>Cadmium</u> <u>Ratio</u>
$2.146 \times 10^7 \text{ cpm}$	$0.669 \times 10^7 \text{ cpm}$	$1.477 \times 10^7 \text{ cpm}$	3.21
2.224	0.662	1.562	3.36
2.262	0.679	1.583	3.34
2.187	0.690	1.497	3.17
2.190	0.699	1.491	3.13
2.258	0.702	1.556	3.22

$$\bar{A}_{th} = 1.528 \times 10^7$$

$$\overline{CR} = 3.24$$

The precision of both figures is $\pm 3\%$ for 95% confidence levels

$$P = \frac{1.528 \times 10^7 \times 3.60}{4.22 \times 10^7} = 1.30 \text{ watts} \pm 10\%$$

CASE II

Bare Foils Corrected
Sat. Activity

$2.261 \times 10^7 \text{ cpm}$
2.219
2.207
2.240
2.256
2.156

$$\bar{A}_b = 2.223 \times 10^7 \text{ cpm}$$

$$\bar{A}_{th} = A_b \times \frac{(CR-1)}{CR} = 2.223 \times 10^7 \times \frac{2.24}{3.24} = 1.540 \times 10^7 \text{ cpm}$$

The precision of this figure is also $\pm 3\%$ for 95% confidence levels.

$$P = \frac{1.540 \times 10^7 \times 3.60}{4.22 \times 10^7} = 1.31 \text{ watts} \pm 10\%$$

APPENDIX 3Fission Product Foil AnalysisAnalytical Procedure

A series of U_3O_8 foils containing U-235 was irradiated in the center of the sphere.

The foils were dissolved individually in nitric and hydrochloric acids, and a known amount of zirconium (about 10 mg) was added to the U_3O_8 as a carrier. The nitric acid was then boiled off to 6N and the remaining solution made up to 10 ml of 4N HCl; and 10 ml of a solution of 0.4N TTA and benzene was thoroughly mixed in. Phases were separated by centrifuging, the water was discarded and the zirconium organic compound in benzene remained. This was then washed several times with hydrochloric and nitric acids, repeating the centrifuging and discarding the aqueous phase.

The remaining solution was then evaporated to dryness and ignited. The residue was accurately weighed and counted. Counting was done with chlorine filled Geiger tubes standardized to a 4π counter. Counts were taken for about three weeks, and the zero time activity was extrapolated graphically.

Sample Calculation

The governing equation relating the activity $\frac{dI}{dt}$ in counts per minute of a fission product when exposed to a flux of ϕ neutrons/cm²/second is:

$$\frac{dI}{dt} = \phi N\sigma - \lambda I \quad (I)$$

therefore, by integrating with respect to time

$$I = \frac{\phi N\sigma}{\lambda} (1 - e^{-\lambda t}) \quad (II)$$

and when λt is $\ll 1$

$$I = \phi N\sigma t \quad (III)$$

where I is the number of Zr 97 atoms found at the end of the irradiation
 N is the number of U-235 atoms in the sample
 σ is the production cross section for Zr-97 = fission cross section of U-235 x fission yield of Zr-97
 t is the time of irradiation in seconds

and
$$N = 2.163 \times 10^{18} \text{ atoms} = \frac{A_v \times \text{Mass}}{A}$$

$$\sigma = \sigma_{25} \times \text{FY} = 549 \times 10^{-24} \times .062 = 3.40 \times 10^{-23} \text{ cm}^2 \quad (5)(8)$$

$$t = 900 \text{ seconds}$$

$$\left(\frac{dI}{dt} \right)_{t=0} = 3.61 \times 10^4 \text{ counts per minute} = C_o$$

At the end of irradiation the activity is:

$$-\frac{dI}{dT} = I\lambda = A_o \quad (IV)$$

$$\frac{dI}{dt} = (C_o) (\text{chemical yield}) (\text{geometry } 4\pi \text{ correction}) (\text{self absorption correction}) (\text{daughter correction}) = A_o$$

C_o is the actual counting rate of the isolated zirconium sample extrapolated back to zero time. The chemical yield factor is the correction for the known calibrated amount of zirconium lost during chemical analysis. The geometry factor converts the number of counts observed to a count which would be obtained for a zirconium-97 sample on the 4π counter. The self absorption correction was determined experimentally and is self explanatory. The daughter correction is due to the necessity of subtracting out the niobium-97 activity. Substituting the proper values we find

$$A_o = 3.61 \times 10^4 \times 2.91 \times 31.6 \times 0.714 \times 0.485 = 1.15 \times 10^6$$

Since $\lambda \text{ for Zr-97} = 6.80 \times 10^{-4} \text{ min}^{-1} \quad (9)$

it is seen from equation (IV)

$$I = \frac{A_o}{\lambda} = \frac{1.15 \times 10^6}{6.80 \times 10^{-4}} = 1.69 \times 10^9$$

And from equation III

$$\begin{aligned} \phi &= \frac{I}{N\sigma t} = \frac{1.69 \times 10^9}{2.16 \times 10^{18} \times 3.40 \times 10^{-23} \times 9.0 \times 10^2} = \\ &= 2.56 \times 10^{10} \text{ neutrons/cm}^2/\text{sec} \end{aligned}$$

Tabulated Results

Thermal Neutron Flux

<u>Sample No.</u>	
1.	2.11×10^{10}
2.	2.68
3.	2.56

Mean Flux = 2.45×10^{10}

Power equals 581 watts ± 12 per cent

Power Settings

Ionization Chamber 1 - Beckman 1 - 33.6 on scale 500

Ionization Chamber 2 - Servo - 134 on Vernier scale 200

Ionization Chamber 3 - Log N - 410

APPENDIX 4Power Calibration by Calorimetric Method

The usual calorimetric equation as given previously is:

$$P = k w C_p \Delta t = k \rho V C_p \Delta t$$

C_p is 0.999 Btu per pound per degree Fahrenheit at 60 F.

Δt is the temperature difference in degrees Fahrenheit.

V is the flow rate in cubic feet per minute

k is 17.58 watts per Btu per minute

ρ is 62.30 pounds per cubic foot at 60 F.

Therefore:

$$P = 1.091 V \Delta t \text{ watts}$$

Tabulated ResultsCase I - Thermistors

<u>Run</u>	<u>Inlet</u>		<u>Outlet</u>		<u>Δt</u>	<u>Power</u>
	<u>Resistance</u>	<u>Temperature</u>	<u>Resistance</u>	<u>Temperature</u>		
1	192200	49.63 F	148500	57.45 F	7.82 F	505 Watts
2	195200	49.05	150900	56.83	7.78	502
3	195800	48.95	152100	56.55	7.60	491

The flow rate for the above runs was 0.442 gpm or 0.0591 cfm.

Power Detector settings were 24.7/500, 98/200, and 280 for detectors one, two and three respectively.

Case II - Thermocouples

<u>Run</u>	<u>EMF</u>	<u>Δt</u>	<u>Flow Rate</u>	<u>Power</u>	<u>Detector</u>	<u>Settings</u>	<u>Power</u>
			<u>CFM</u>	<u>1</u>	<u>2</u>	<u>3</u>	
1	0.225 MV	7.5 F	0.0618	24.2/500	98/200	280	506 watts
2	0.250	8.33	0.0618	30	120	340	562
3	0.325	10.82	0.0605	33.5	134	390	714

σ-21