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PHYSICS VERIFICATION PROGRAM,
PART III, TASK 1,
FINAL REPORT

BY

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1.0 INTRODUCTION

In January of 1968, The Babcock & Wilcox Company initiated Part III, Task 1, of the Physics Verification Program. Its objective was to investigate the response of an all-solid self-powered incore detector, at temperatures approaching those of an operating power reactor. The program was jointly supported by the Company and the U. S. Atomic Energy Commission.

The measurements were performed inside a high-temperature test vessel located adjacent to a swimming pool reactor core. Measurements were made in a water environment and in a subcritical fueled lattice environment over a wide range of moderator boron concentrations.

This report summarizes all of the experimental results obtained during Part III, Task 1, of the program. In some instances, data previously reported in quarterly technical reports^(1,2,3) have been reanalyzed and the results given here may differ slightly from those reported earlier.

Related measurements were performed in 1967 in a critical assembly mock-up of a typical PWR design. These measurements are summarized in reference 4.

2.0 DESCRIPTION OF FACILITY

2.1 INTRODUCTION

The test facility (Figures 2.1 and 2.2) is principally a 3-foot-ID by 9-foot-long cylindrical pressure vessel with auxiliary equipment to pressurize the system to 700 psi and heat the moderator to approximately 500 F. Neutrons are supplied by the Lynchburg Pool Reactor (LPR). A general description of the facility is given in the following sections.

2.2 LYNCHBURG POOL REACTOR (LPR)

The LPR is a water moderated swimming pool research reactor with MTR fuel elements. Each full element consists of 10 plates of uranium-aluminum alloy with about 19 grams of ^{235}U in each plate. Each control element contains six plates. When operated in conjunction with the hot exponential facility, the LPR core is limited to a power level of 200 kW. This limits the neutron flux entering the test vessel to approximately $3 \times 10^{10} \text{ n/cm}^2\text{-sec.}$

2.3 TEST VESSEL ENCLOSURE

The test vessel enclosure is a steel shell with a square cross section, which penetrates the concrete wall of the LPR. A 1-inch-thick aluminum closure plate, secured to one end of the shell, prevents the loss of pool water. The closure plate is reinforced by horizontal and vertical metal ribs. A 4-inch-thick layer of lead brick is stacked on the ribs for gamma shielding of the reactor. Concrete blocks are stacked against the closure plate. A 2-foot-square opening in the center acts as a neutron beam aperture.

2.4 TEST VESSEL

Adjacent to the concrete blocks is the test vessel, which projects beyond the concrete wall. The 3-foot-ID by 9-foot-long cylindrical vessel is fabricated of stainless-steel clad 1-inch-thick carbon steel. The inside of the vessel is lined with 1/8-inch-thick steel containing about 1.25 wt% boron and separated from the vessel wall by a small space. The liner acts as a thermal shield during system letdown and also serves to reduce the activation of the steel vessel and to decrease the effect of neutron reflections from the walls.

2.5 TEST VESSEL INTERNALS

2.5.1 Lattice Support Structure

Five drilled aluminum (6061-T6) grid plates are aligned inside the test vessel as shown in Figure 2.2. Fuel rod positions are spaced on a 0.644-inch square lattice pitch. The end grids are 0.25-inch thick. Intermediate grids are 1/16-inch-thick, 3/16-inch-thick, and 1/16-inch-thick, respectively. Alignment of the grid plates is maintained by a stainless steel support rack.

The number, spacing, thickness, and material of the grid plates were based on a design requirement of supporting the fuel rods rigidly without introducing excessive perturbing material in the region where measurements were made.

2.5.2 Subcritical Lattice

About one-half of the measurements were made along the axis of a subcritical assembly of slightly enriched UO_2 fuel rods located inside the test vessel, i.e., a lattice environment. The remaining measurements were made with the fuel rods absent, i.e., a water environment.

The fuel rods were supported horizontally in the vessel by grid plates and the support structure. The cylindrical lattice was approximately 13 inches in diameter. A diagram of the subcritical lattice is presented in Figure 2.3. K_{eff} of the assembly ranged from about 0.77 to 0.95 depending on the moderator boron concentration.

Table 2.1 summarizes the physical properties of the fuel rods for the subcritical assembly inside the test vessel. The uncertainties are standard deviations of the means obtained from vendors' quality control data and check measurements on 50 to 100 randomly selected samples. The impurities are given as the summation of $N_i \sigma_i$, where N_i is the concentration of each impurity per cubic centimeter of the oxide fuel, and σ_i is the corresponding microscopic absorption cross section at 2200 m/sec. The end caps are 1/8-inch-thick aluminum plugs, and a 1-inch-long dead space between the top of the fuel pellet stack and the top end cap is filled with Kaowool.

2.6 ACCESS CONDUITS

2.6.1 Central Conduit

The central conduit is a 0.438-inch-OD by 0.120-inch-wall 6061-T6 aluminum tube welded closed at one end. It enters the test vessel through a flange in the vessel door and passes through the center hole of each support grid. The central conduit extends essentially the full length of the test vessel.

Flux measuring wires and/or detectors may thus be inserted and removed from the test vessel while the water system is maintained at elevated temperature and pressure. A 0.1875-inch-OD by 0.028-inch-wall aluminum guide tube located inside the central conduit ensures positioning reproducibility of detectors and flux measuring wires. The calculated thermal depression and shielding resulting from the presence of the conduit and guide tube is 0.5%.

2.6.2 Side Conduit

A second conduit enters through the side of the test vessel and runs along the vessel wall parallel to the axial center line of the vessel. This side conduit, fabricated from 0.3125-inch-OD by 0.083-inch-wall 304 stainless steel tubing provides an entrance for monitor wires.

2.7 MODERATOR SYSTEM

Figure 2.4 shows a flow diagram of the system for circulating, heating, and pressurizing the moderator. The equipment consists of the pressurizer, heater, circulating pump, letdown tank, sample cooler, and associated piping, valves, and connections. The moderator is circulated by a 50 gpm canned-rotor pump and is heated by two tubular resistance heaters having a total capacity of 120 kW. The loop is pressurized by nitrogen gas directly contacting the moderator in a 10-inch-diameter by 15-foot-long pressurizer. The total system volume is about 550 gallons.

TABLE 2.1. PHYSICAL PROPERTIES OF 2.46%-
ENRICHED UO_2 FUEL RODS

Parameter	Value
Outer diameter, in.	0.4748 ± 0.0006
Wall thickness, in.	0.032 ± 0.001
Wall material	6061 aluminum
Pellet (fuel) diameter, in.	0.4054 ± 0.0005
Total length, in.	61.59 ± 0.16
Active (fuel), length, in.	60.37 ± 0.35
Weight of fuel, gm/rod	1305.5 ± 1.0
U/ UO_2 , wt%	88.13 ± 0.01
Enrichment, $^{235}\text{U}/\text{U}$, wt%	2.459 ± 0.002
Weight of ^{235}U , gm/rod	$28.29 \pm .02$
Pellet (fuel) density, gm/cm^3	10.24 ± 0.04
$\sum N_i \sigma_i$ (summation of impurities), cm^2/cm^3 oxide	10^{-3}

FIGURE 2.1. LPR AND HOT EXPONENTIAL FACILITY—SCHEMATIC DIAGRAM

FIGURE 2.2. LPR AND HOT EXPONENTIAL FACILITY—HORIZONTAL SECTION

FIGURE 2.3. LOADING DIAGRAM FOR SUBCRITICAL LATTICE

FIGURE 2.4. MODERATOR FLOW SYSTEM

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3.0 DETECTOR RESPONSE MEASUREMENTS

3.1 THE ALL-SOLID SELF-POWERED DETECTOR

Since 1960, there has been considerable interest in developing all-solid (self-powered) incore neutron flux monitors for use in large central station pressurized water reactors.^(5,6,7) The detectors, similar to a thermocouple in construction, use a small rhodium wire as the active element and operate on the principle of beta emission following neutron capture. The detector is illustrated in Figure 3.1 and is described more fully in reference 4.

3.2 EXPERIMENTAL METHOD

3.2.1 Detector Signal Measurements

Detector signal measurements were made by inserting the detector a predetermined distance into the central access conduit of the test vessel and irradiating it at a constant power level until an equilibrium current was established (in 10 to 15 minutes). Reproducibility of the detector position was ensured by a solid 0.125-inch-OD aluminum rod in the closed end of the conduit, which provided a positive stop (Figure 3.2).

Detector background corrections were measured with a background detector identical in construction to the rhodium detector except that the Inconel lead wire extended into the region otherwise occupied by the rhodium emitter.

Current produced by the detectors was measured with a Cary model 31 vibrating reed electrometer, using the steady deflection mode of operation. The electrometer is shown schematically in Figure 3.3. The current (I) was calculated by the equation:

$$I = \frac{V_e}{R_i}$$

The voltage, V_e , indicated by the electrometer was calibrated against a Leeds and Northrup type K-3 potentiometer, which was in turn calibrated against a low-temperature-coefficient standard cell manufactured by the Eppley

Laboratory, Incorporated. The 10^{12} -ohm rating of the precision input resistor, R_i employed in the measurements had been verified accurate to within 1% with a Keithley model 515 megohm bridge (having a quoted accuracy of 0.5%).

3.2.2 Wire Activation Measurements

Bare and cadmium covered activation wires were employed inside the central access conduit of the test vessel to measure the neutron flux and to determine the fraction of the detector signal produced by thermal neutrons. Three compositions of activation wire were employed in the experiments: dysprosium-aluminum (5 wt% dysprosium), gold, and rhodium. All were 0.020 inch in diameter.

Bare activations were made with the wire loaded inside a hollow 0.188-inch-OD flexible titanium cable manufactured by Teleflex, Incorporated. Cadmium covered activations were made with the wires loaded inside a 0.035-inch-ID by 0.020-inch-wall cadmium tube covered by snug fitting 0.111-inch-OD Teflon tubing to reduce friction.

During irradiation, the bare and cadmium covered activation assemblies described above were positioned inside a 0.132-inch-ID by 0.028-inch-wall aluminum guide tube, which in turn was inserted into the central access conduit of the test vessel.

Following activation, wires were cut into 1/2-inch lengths and counted in each of three end-window, gas-flow proportional counters.

3.3 THERMAL FLUX

Dysprosium aluminum wires were employed to measure the 2200-meter-per-second neutron flux (ϕ_0). Since thermal neutrons have a continuous distribution of energies, ϕ_0 is a somewhat artificial concept. Nevertheless, flux is often quoted in terms of ϕ_0 since it can easily be measured by a $1/v$ detector.^(8,9) Although dysprosium, which serves as the detector, deviates slightly from $1/v$ behavior, this deviation is not significant below the cadmium cutoff. The principal advantage gained by using ϕ_0 is that the thermal neutron energy distribution need not be known.

The standard technique normally employed at the Critical Experiment Laboratory for measuring ϕ_0 relates the saturated count rate induced by thermal neutron capture in a standard 0.259-inch by 0.005-inch-thick gold

foil to the absolute 2200-meter-per-second neutron flux. By intercalibration, a similar relationship was obtained for the dysprosium-aluminum wires used in the reported experiment. Intercalibration was achieved by mounting standard gold foils and dysprosium-aluminum wires on the periphery of a Lucite wheel, which rotated in a uniform thermal neutron flux. Activation caused by epicadmium neutrons was subtracted, employing data obtained with the foils and wires cadmium covered.

Random uncertainties in the determination of ϕ_0 were about 0.5%. In addition, a 3.5% systematic error was present because of uncertainty in the thermal flux value where the standard gold foils were originally calibrated.

3.4 RESULTS

The measured neutron flux profile along the axial center line of the test vessel is presented in Figure 3.4. The measurements were in a water environment and were made at ambient temperature (72 F) with bare dysprosium-aluminum wire and with cadmium covered gold wire. The observed tendency of the neutron spectrum to harden slightly as it is attenuated by water is supported by similar measurements in the Bulk Shielding Facility at ORNL.⁽¹⁰⁾

Detector sensitivity measurements were made with the detector positioned inside the central conduit, 12 inches from the closed end. The sensitive rhodium section therefore traversed the distance from 12.5 to 17.25 inches (Figure 3.4). Wire activation measurements traversed the same distance. This position was sufficiently far into the moderator to ensure an unperturbed ratio of thermal flux to fast flux at the maximum temperature condition, when the moderator density was reduced.

The signal produced by the detector is tabulated in Table 3.1 along with normalized wire activation measurements. The net rhodium detector signal is the algebraic difference between the signal generated by the rhodium detector and the signal generated by the background detector. In some cases, the thermally induced net detector signal was computed by employing cadmium ratio measurements made with 0.020-inch-diameter rhodium wire. The results are also presented graphically in Figure 3.5.

3.5 DISCUSSION

Since the observed large variation in detector sensitivity resulting from changes in the moderator boron concentration had not been anticipated, additional measurements and supporting calculations were performed to determine the cause of this unexpected result.

One supplementary measurement was a determination of the equilibrium beta emission from an activated rhodium wire at several selected conditions of boron concentration and temperature. Based on past measurements in a critical assembly, ⁽⁴⁾ the background corrected equilibrium detector signal should be approximately equivalent to the equilibrium beta emission; however the two measurements were grossly at variance when measured in the test vessel. Detector background corrections were therefore suspected.

The background current results principally from gamma radiation interacting with the detector sheath, insulation, emitter, and lead wire to produce photoelectric and Compton electrons. (The positive and negative signals from pair production are presumed to cancel.) The background detector is identical in construction to the rhodium detector except that the Inconel lead wire extends into the region otherwise occupied by the rhodium emitter. The signal from a background detector has always been observed to be negative (i.e., a signal in opposition to the beta signal produced by rhodium decay).

To test the adequacy of the background detector signal for background corrections under extreme conditions, a rhodium detector and a background detector were located in the LPR during shutdown so that their ends terminated near the core center. The region of the detectors where the internal structure differed was thus subjected to a very large gamma dose (20,000 r/hr). Neutron flux in the shutdown core was negligible. Signals from the two detectors were roughly equal in absolute magnitude but were of opposite sign. This difference presumably resulted from property differences and size variations of rhodium and Inconel.

Detector background corrections can therefore be significantly in error if the background correction is a large fraction of the total signal (high

gamma-to-neutron flux ratio), particularly if the gamma flux is preferentially higher in the detector's end region, where the differences in the rhodium and background detectors exist. Both of these conditions existed in the reported program, since a large fraction of the gamma radiation originated from the LPR core. These same conditions may also exist in pressurized water reactor cores following a significant reduction in power. Table 4.2 compares the ratio of gamma dose rate in roentgens per hour (D_γ) to the 2200 m/sec neutron flux in $\text{n/cm}^2\text{-sec}$ (ϕ_0) in the reported experiment to the ratio present in previous critical experiments and to the ratio for a current B&W pressurized water reactor design.

In order to circumvent the erroneous background detector signal, all subsequent data were taken by activating rhodium wire. These measurements are described in the following section.

TABLE 3.1. IN-CORE DETECTOR MEASUREMENTS

Temperature, F	Moderator Boron Concentration, ppm	Rhodium Detector Signal, 10^{-13} ampere	Background Detector Signal, 10^{-13} ampere	$10^7 \phi_0$, n/cm ² -sec	Ratio of Net Detector Signal to Thermal Flux, 10^{-20} ampere/ ϕ_0	Cadmium Ratio of Rhodium Wire	Ratio of Thermally Induced Net Signal to Thermal Flux, 10^{-20} ampere/ ϕ_0
71	0	3.969	-0.579	2.364	1.924	-----	-----
100	0	4.070	-0.599	2.486	1.878	25.65	1.806
200	0	5.280	-0.699	3.298	1.804	-----	-----
350	0	9.308	-1.003	6.152	1.676	-----	-----
100	488	2.486	-0.452	1.147	2.561	11.81	2.344
200	488	2.984	-0.497	1.439	2.419	-----	-----
350	504	4.668	-0.762	2.498	2.174	-----	-----
100	942	1.912	-0.395	0.748	3.084	9.34	2.754
200	942	2.289	-0.431	0.963	2.824	-----	-----
350	941	3.624	-0.789	1.655	2.667	-----	-----
100	1344	1.695	-0.331	0.592	3.422	7.19	2.946
200	1344	1.873	-0.331	0.708	3.113	-----	-----
350	1344	2.809	-0.654	1.219	2.841	-----	-----
450	1344	4.191	-0.989	1.977	2.620	-----	-----

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TABLE 3.2. COMPARISON OF GAMMA-TO-NEUTRON FLUX RATIOS

<u>Facility</u>	<u>D_γ/ϕ_0</u>	<u>Method</u>
CX-10	1×10^{-5}	Calculation
Current PWR Design	1×10^{-5}	Calculation (11)
Hot Exponential	5×10^{-2} to 2×10^{-4} depending on moderator tempera- ture and boron concentration	Measurement

FIGURE 3.1. ALL-SOLID INCORE NEUTRON DETECTOR

Note: For background detector, extend Inconel lead wire to occupy region shown here for rhodium.

FIGURE 3.2. LOADING ARRANGEMENT FOR DETECTORS AND ACTIVATION ASSEMBLIES

FIGURE 3.3. THE CARY VIBRATING REED ELECTROMETER

FIGURE 3.4. FLUX TRAVERSE ALONG CENTER CONDUIT—WATER ENVIRONMENT

FIGURE 3.5. NET EQUILIBRIUM DETECTOR SIGNAL PER UNIT 2200 m/s
THERMAL NEUTRON FLUX

4.0 WIRE ACTIVATION MEASUREMENTS

4.1 INTRODUCTION

Bare and cadmium covered activation wires were employed inside the central access conduit of the test vessel to measure the 2200-meter-per-second neutron flux, the equilibrium beta emission from a rhodium sample simulating a detector emitter, and the fraction of the beta emission produced by subcadmium neutrons. Measurements were made in a lattice environment (i.e., with the subcritical lattice in place and surrounding the position of measurement) and in a water environment (i.e., with all fuel rods removed from the lattice support structure). Three compositions of activation wire were employed: dysprosium-aluminum (~5wt% dysprosium), gold, and rhodium. All were 0.020 inch in diameter.

4.2 THEORY

Current from the rhodium detector type under study is the result of beta emission from the detector's activated rhodium element. Detector sensitivity changes resulting from changes in the incident neutron spectrum may therefore be determined directly from beta emission measurements with activated rhodium wire. The equations employed to obtain equilibrium beta emission from the decay of the rhodium sample are presented below. They are derived in reference 4.

Except for a 0.18% contribution from ^{104m}Rh (which can be neglected), the beta count rate R_β from an activated rhodium sample is entirely the result of ^{104}Rh decay, and following irradiation can be expressed as the sum of two exponentials:

$$R_\beta(t_w) = I_1 e^{-\lambda_1 t_w} + I_2 e^{-\lambda_2 t_w} \quad (4-1)$$

where t_w = the time lapse following irradiation

If the observed beta count rate of an irradiated sample is fitted to equation 4-1, the fitting constants λ_1 , λ_2 , I_1 , and I_2 are obtained. The

equilibrium beta emission E_β can then be obtained from the fitting constants, the detector efficiency η , and the irradiation time t_E :

$$E_\beta = \frac{1}{\eta} \left[\frac{I_1}{[1 - e^{-\lambda_1 t_E}]} + \frac{I_2}{[1 - e^{-\lambda_2 t_E}]} \right] \quad (4-2)$$

4.3 EXPERIMENTAL RESULTS

Bare activations were made with the wires loaded inside a hollow 0.188-inch-OD flexible titanium cable manufactured by Teleflex, Incorporated. Cadmium covered activations were made with the wire loaded inside a 0.035-inch-ID by 0.020-inch-wall cadmium tube covered by snug fitting 0.111-inch-OD Teflon tubing to reduce friction. During irradiation, these bare and cadmium covered activation assemblies were positioned inside a 0.132-inch-ID by 0.028-inch-wall aluminum guide tube, which in turn was inserted into the central access conduit of the test vessel.

The selection of a suitable irradiation position for the water environment measurements has been discussed in section 3. To determine a suitable position for the lattice environment measurements, bare and cadmium covered gold wires several feet in length were activated inside the central access conduit with the subcritical lattice in place. The neutron flux profile, obtained under conditions of ambient temperature and zero moderator boron concentration, is shown in Figure 4.1. The asymptotic region begins about 2-1/2 inches inside the lattice, a value consistent with past measurements in a critical assembly having the same lattice spacing and fuel composition.

Data from past experiments ⁽¹²⁾ show that the nonasymptotic span increases about 20% at the elevated temperatures sometimes employed in the present measurements. To circumvent this slight reduction in the size of the asymptotic region at elevated temperatures, all beta emission measurements were made at least 5.5 inches into the lattice. The addition of boric acid to the moderator of course increases the size of the asymptotic region

since the mean free path of thermal neutrons is shortened and since the thermal neutron peaking is less severe in a borated reflector.

The bare and cadmium covered rhodium wire irradiations were made with three 1/2-inch lengths of wire placed end to end. During measurements of equilibrium beta emission in the lattice environment, the wires were positioned to span the distance from 18 to 19.5 inches (Figure 4.1). During measurements in the water environment, they were positioned to span the distance from 13 to 14.5 inches (Figure 3.4). All rhodium irradiations were 10 minutes in duration.

Following exposure, the wires were beta counted in three end-window gas-flow proportional counters. Count rates varied from 400,000 to 15,000 cpm during the time interval of 2 to 15 minutes following irradiation. All data were corrected for counter losses of 2.8% per 100,000 cpm and for background.

Bare and cadmium covered dysprosium-aluminum wires were employed to measure the 2200-meter-per-second neutron flux, ϕ_0 . These wires, also 1/2-inch in length, were positioned at precisely the same location held by their rhodium counterparts. After a 30-minute delay following irradiation (to allow the activated aluminum to decay), they were counted in each of three end-window gas-flow proportional counters. ϕ_0 is assumed to be directly proportional to the saturated count rate induced in the Dy-Al wire by subcadmium neutrons.

4.4 DATA ANALYSIS

A least squares fit of the rhodium wire decay data to equation 4-1 gave the fitting constants I_1 , I_2 , λ_1 , and λ_2 . In all instances, values obtained for λ_1 and λ_2 were consistent with those previously reported by this Laboratory.⁽⁴⁾ The value of η required in equation 4-2 for the end-window gas-flow proportional counters was obtained by comparison counting with a 4π gas flow proportional counter, which was assumed 100% efficient. The average counting efficiency of the three counters measured in this manner was 0.493. This value is estimated to have an uncertainty of about 4%.

Since the rhodium emitter of a detector is 0.018 inch in diameter by 4.75 inches long, an appropriate scaling factor was employed to make E_β (equation 4-2) comparable to the equilibrium emission from an actual detector element. From previous measurements ⁽⁴⁾, the beta emission rate from a 0.018-inch-diameter rhodium emitter is 88% of that from a 0.020-inch-diameter rhodium emitter of identical length and exposure. Equilibrium beta emission measurements, scaled to correspond to the dimensions of an actual detector emitter, are presented in Table 4.1 and Figures 4.2 through 4.5. Although the total uncertainty for these values is 10%, most of this results from systematic errors. Random uncertainty on each point is estimated at 1.3%.

Figures 4.2 through 4.5 show that the data can reasonably be plotted as linear functions of temperature. The equilibrium beta emission data have therefore been fitted by least squares to equations of the form:

$$E_\beta (T) = E_0 [1 + \alpha (T - T_0)] \quad (4-3)$$

where $T_0 = 68 \text{ F}$

$T =$ temperature of detector and its environment

$E_\beta(T) =$ equilibrium beta emission at T

Values of the fitting constants E_0 and α resulting from the least squares analysis are presented in Table 4.2. Since there is no observable trend in the values of α as the moderator boron concentration is changed, average values for this parameter have been computed.

Detector signal measurements taken last year in a critical assembly at ambient temperature are presented in Table 4.3. Since the lattice spacing and fuel composition of this critical assembly were identical to those of the subcritical assembly employed in the present measurements, data taken in the two assemblies should be comparable. Both sets of ambient temperature data are plotted in Figure 4.6, and compared numerically in Table 4.4. Least squares analysis shows that both sets of data are consistent with a linear relationship to within a standard deviation of 0.6%.

The ratio of critical assembly measurements to subcritical assembly measurements is remarkably constant, attesting to the excellent internal consistency of both sets of data. There are two principal reasons why this ratio is not unity: (1) there are systematic experimental uncertainties for the measured quantities, and (2) some of the beta particles escaping from the emitter do not contribute to the detector signal.

The beta emission and detector signal measurements have total uncertainties of 10 and 5% respectively. These values include systematic errors common to both totaling about 4% and an additional 5% systematic error, presented only in the beta emission measurements. The ratio of detector signal to beta emission can therefore be expected to deviate from unity by as much as 5 to 6% because of experimental uncertainties for the measured quantities.

Warren ⁽¹³⁾ has formulated a space charge model to describe the effect of an insulator upon the current of the self-powered incore monitors. The model predicts that 300 keV is required by the beta particle to traverse from the detector emitter to beyond the potential peak within the insulator. Beta particles which do not traverse beyond the potential peak are forced back to the emitter, thus resulting in no net current. Approximately 15% of the beta particles escaping from the emitter are below 300 keV in energy and do not contribute to the net current.

TABLE 4.1. EQUILIBRIUM BETA EMISSION FROM ACTIVATED RHODIUM WIRE

Environment	Moderator Boron Concentration, ppm	Temperature, F	10^4 cps		ϕ_0 , 10^6 n/cm ² -s	Cadmium Ratio of Dysprosium Wire	Equilibrium Beta Emission Per Unit Flux, 10^{-20} A/ ϕ_0 $\pm 10\%$	Cadmium Ratio of Rhodium Wire	Subcadmium Component of Equilibrium Beta
			I ₁	I ₂					Emission Per Unit Flux, 10^{-20} A/ ϕ_0 $\pm 10\%$
Lattice	0	70	2.45	38.11	62.69	41.0	1.784	3.93	1.330
		100	2.70	41.98	66.92	41.2	1.841	4.03	1.384
		300	3.64	56.60	84.54	37.7	1.965	3.62	1.422
		450	5.31	82.63	114.93	32.0	2.110	3.43	1.495
Lattice	499	96	0.82	12.81	20.12	40.0	1.868	3.73	1.367
		300	1.19	18.48	26.75	35.7	2.027	3.52	1.451
		450	1.82	28.23	37.05	29.0	2.236	3.24	1.546
Lattice	976	100	0.47	7.30	11.29	36.2	1.897	3.49	1.353
		300	0.71	10.99	15.45	32.4	2.087	3.39	1.471
		450	1.19	18.46	24.23	29.0	2.236	3.31	1.560
Lattice	1453	100	0.33	5.07	7.57	33.6	1.965	3.31	1.371
		300	0.50	7.79	10.79	29.6	2.119	3.15	1.446
		450	0.83	12.93	16.49	25.9	2.301	2.98	1.529
Water	0	104	1.25	19.47	43.19	239.0	1.323	27.3	1.275
		300	2.34	36.45	80.56	266.0	1.328	30.3	1.284
		450	5.47	85.12	173.16	248.0	1.443	35.5	1.402
Water	1483	100	0.31	4.81	9.34	80.3	1.511	7.11	1.298
		300	0.56	8.78	16.21	81.3	1.589	7.42	1.375
		450	1.11	17.19	31.19	77.0	1.617	7.78	1.409

TABLE 4.2. RESULTS OF LEAST SQUARES ANALYSIS--
WIRE ACTIVATION MEASUREMENTS

Parameter	Environment	Moderator Boron Concentration, ppm	E_0 , $10^{-20} \text{ A}/\phi_0$	α , $10^{-4} \text{ deg}^{-1} \text{ F}$
Equilibrium beta emission	Lattice	0	1.795 ± 0.015	4.48 ± 0.38
Equilibrium beta emission	Lattice	499	1.824 ± 0.044	5.62 ± 0.94
Equilibrium beta emission	Lattice	976	1.865 ± 0.003	5.19 ± 0.07
Equilibrium beta emission	Lattice	1453	1.924 ± 0.032	4.94 ± 0.65
			Unweighted avg	5.06 ± 0.24
Equilibrium beta emission	Water	0	1.293 ± 0.054	2.56 ± 1.62
Equilibrium beta emission	Water	1483	1.506 ± 0.015	2.04 ± 0.38
			Unweighted avg	2.30 ± 0.26
Subcadmium component of equilibrium beta emission	Lattice	0-1453	1.346 ± 0.010	3.54 ± 0.29
Subcadmium component of equilibrium beta emission	Water	0-1483	1.268 ± 0.027	2.64 ± 0.82

TABLE 4.3. RESULTS OF DETECTOR SIGNAL MEASUREMENTS
IN CRITICAL ASSEMBLY

Moderator Boron Concentration, ppm	Equilibrium Signal, Per Unit Flux $10^{-20} \text{ A}/\phi_0$ ($\pm 5.7\%$)	Subcadmium Component of Equilibrium Signal, Per Unit Flux $10^{-20} \text{ A}/\phi_0$
0	1.531	1.167
291	1.553	1.163
858	1.617	1.187
1280	1.624	1.145
1547	1.640	<u>1.155</u>
	Unweighted avg	1.163 $\pm$ 0.055

TABLE 4.4 COMPARISON OF BETA EMISSION AND DETECTOR
SIGNAL MEASUREMENTS AT 68 F --- LATTICE
ENVIRONMENT

Moderator Boron Concentration, ppm	Component	Equilibrium Signal, Per Unit Flux $10^{-20} \text{ A}/\phi_0$	Equilibrium Beta Emission Per Unit Flux, $10^{-20} \text{ A}/\phi_0$	Ratio
0	Total	1.536	1.787	0.860
1500	Total	1.644	1.919	0.857
0-1500	Subcadmium	1.163	1.346	0.864
Average:				0.860 ± 0.002

FIGURE 4.1. FLUX TRAVERSE ALONG CENTER CONDUIT—LATTICE ENVIRONMENT

Saturated Activity, Relative Units

FIGURE 4.2. EQUILIBRIUM BETA EMISSION PER UNIT FLUX FROM ACTIVATED RHODIUM WIRE—
LATTICE ENVIRONMENT

FIGURE 4.3. EQUILIBRIUM BETA EMISSION PER UNIT FLUX FROM ACTIVATED RHODIUM WIRE-
WATER ENVIRONMENT

FIGURE 4.4. EQUILIBRIUM BETA EMISSION PER UNIT FLUX FROM ACTIVATED RHODIUM WIRE—
SUBCADMIUM COMPONENT—LATTICE ENVIRONMENT

FIGURE 4.5. EQUILIBRIUM BETA EMISSION PER UNIT FLUX FROM ACTIVATED RHODIUM WIRE—
SUBCADMIUM COMPONENT—WATER ENVIRONMENT

FIGURE 4.6. COMPARISON OF BETA EMISSION AND DETECTOR CURRENT MEASUREMENTS

5.0 NORMALIZED RESULTS

The foregoing discussion serves to show that the beta emission measurements, although systematically displaced by about 15% from detector signal measurements, are quite consistent and can be reliably employed to predict changes in detector sensitivity resulting from temperature and moderator boron concentration. Accordingly, the least squares fits of beta emission measurements have been normalized to the critical assembly measurements of the detector signal.

Since equilibrium beta emission has been shown to vary linearly with the moderator boron concentration and temperature, the normalized sensitivity $S(T,B)$ may be expressed by equations of the form:

$$S(T,B) = A_0 [1 + \beta(T - T_0)] [1 + \gamma B]$$

where $T_0 = 68 \text{ F}$

T = temperature of the detector and its environment

β = temperature coefficient

B = moderator boron concentration

γ = moderator boron coefficient

A_0 = detector sensitivity at 68 F and 0 ppm moderator boron concentration

Best values for the fitting constants A_0 , β , and γ , based on a linear least squares analysis of the data, are presented in Table 5.1.

It should be noted from Table 5.1 that for the lattice and water environments the subcadmium neutron sensitivity of a detector does vary more than two standard deviations. The subcadmium neutron sensitivity of a detector is therefore not substantially affected by reactor lattice parameters and can be used in current PWR designs with confidence.

Thus, if the detector signal and rhodium cadmium ratio are known, the 2200 m/sec flux can be calculated.

$$\phi_0 = \frac{I}{Q} \left[\frac{CR - 1}{CR} \right]$$

I = detector signal

CR = rhodium cadmium ratio

Q = subcadmium neutron sensitivity of detector

$$= [1.163 \pm 0.055] [1 + (T - T_0) (3.5 \pm 0.3) \times 10^{-4}] \times 10^{-20} \text{ A}/\phi_0$$

ϕ_0 = 2200 m/sec flux measured with a 1/v detector

(Dysprosium was used as the 1/v detector, and the slight non-1/v nature of dysprosium was ignored.)

It should be noted also that the total neutron sensitivity of a detector depends upon the lattice parameters and cannot be used in current PWR designs without the performance of a complete neutron spectrum comparison between the PWR design and the exponential facility.

TABLE 5.1. NORMALIZED BEST VALUES OF FITTING CONSTANTS

<u>Parameter</u>	<u>Environment</u>	$10^{-20} \frac{A_0}{A/\phi_0}$	$10^{-4} \frac{\beta}{\text{deg}^{-1} \text{ F}}$	$10^{-5} \frac{\gamma}{\text{ppm}^{-1}}$
Total neutron sensitivity of detector	Lattice	1.536 ± 0.074	5.1 ± 0.3	4.8 ± 0.6
Total neutron sensitivity of detector	Water	1.112 ± 0.093	2.3 ± 0.3	11.0 ± 5.0
Subcadmium neutron sensitivity of detector	Lattice	1.163 ± 0.055	3.5 ± 0.3	0.0
Subcadmium neutron sensitivity of detector	Water	1.090 ± 0.069	2.6 ± 0.9	0.0

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