Rhodium In-Core Detector Sensitivity Depletion

EPRI

MASTER

Keywords:
In-Core Detectors
Power Distribution
Fuel Utilization

EPRI NP-1405
Project 1397-1
Interim Report
May 1980

Prepared by
Babcock & Wilcox Company
Lynchburg, Virginia

ELECTRIC POWER RESEARCH INSTITUTE

Rhodium In-Core Detector Sensitivity Depletion

NP-1405
Research Project 1397-1

Interim Report, May 1980

Prepared by

BABCOCK & WILCOX COMPANY
Research and Development Division
P.O. Box 1260
Lynchburg, Virginia 24505

Principal Investigator
H. D. Warren

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
H. G. Shugars

Reliability, Availability and Economics Program
Nuclear Power Division

ORDERING INFORMATION

Requests for copies of this report should be directed to Research Reports Center (RRC), Box 50490, Palo Alto, CA 94303, (415) 965-4081. There is no charge for reports requested by EPRI member utilities and affiliates, contributing nonmembers, U.S. utility associations, U.S. government agencies (federal, state, and local), media, and foreign organizations with which EPRI has an information exchange agreement. On request, RRC will send a catalog of EPRI reports.

NOTICE

Prepared by
Babcock & Wilcox Company
Lynchburg, Virginia

EPRI PERSPECTIVE

PROJECT DESCRIPTION

Self-powered in-core neutron detectors that have rhodium emitters are used in many reactors to monitor power distribution within the core. With use, the supply of rhodium nuclei in these detectors is depleted, resulting in a loss of sensitivity.

Currently, utilities are required to replace the detectors before their sensitivities are reduced by 60 percent. This replacement conservatively limits depletion-related uncertainties, which contribute to the overall uncertainty in using the detector signals to compute core power distribution.

However, replacing the detectors is costly: used detectors are highly radioactive; new detectors are expensive; and replacing detectors often extends the length of the refueling outage. Utilities would benefit from being able to replace detectors less frequently. To date, uncertainties in understanding the rhodium depletion process have prevented this change.

PROJECT OBJECTIVE

The objective of Research Project 1397 is to accurately characterize rhodium depletion in a power reactor over as much of the operating life of the detector as is feasible. The data will be used to reduce uncertainties in detector sensitivity so that the detectors will not have to be replaced as frequently as they are now.

PROJECT RESULTS

Results in this interim report show that the sensitivity depletion curve is essentially linear. However, the slope of the line is different for each of the two reactor fuel cycles reported, a result that may be related to differences in the fuel burnup in the assemblies where the experimental detectors are located. Data from present and future reactor fuel cycles will be analyzed in this project to quantify this effect further.

This report will be of interest primarily to utility reactor engineers who support the operating staff and to reactor physicists who develop the computer codes for calculating core power distribution.

Gordon Shugars, Project Manager
Reliability, Availability and Economics Program
Nuclear Power Division

ABSTRACT

Sensitivity depletion of two rhodium (Rh) self-powered neutron detectors has been measured since July, 1976 at the Oconee 2 pressurized water reactor (PWR). The detectors were positioned inside the reactor core throughout the measurement period. Depletion has been determined as a function of electric charge expended (released) by each detector over the exposure period to the times of measurement.

The goal of the project is the empirical definition of the depletion characteristics over the operating life-time of the Rh detector. Results to date show that the depletion rate of the Rh detector in the PWR is linear with expended charge, but it is approximately 8% smaller than the depletion rate in a pool-type test reactor. There appears also to be an effect on the depletion rate that is traceable to the beginning-of-cycle burnup of the fuel assembly in which the Rh detectors are located. This "fuel effect" is not fully understood at this time.

ACKNOWLEDGMENTS

The author is grateful for the valuable assistance of D. R. Clutter of B&W's Lynchburg Research Center throughout the past 30 months of the experiment. Thanks are also due E. L. Glass, M. F. Sulcoski, and C. L. Gray, all of B&W, for their contributions at various times.

The cooperation and assistance of the Duke Power Company has been indispensable throughout the experiment at Oconee 2.

CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY

INTRODUCTION

Self-powered neutron detectors (SPNDs) that have rhodium (Rh) emitters are used in Babcock & Wilcox (B&W) and Combustion Engineering (CE) pressurized water reactors (PWRs) as power shape monitors. A typical B&W reactor has more than 350 Rh SPNDs positioned throughout the core to measure such quantities as quadrant power tilt, axial power imbalance, and the total distribution of power within the core.

After correction for background, Rh detector signals are proportional to local neutron flux densities at the emitter locations. (A gamma-induced background signal is generated within the section of a SPND cable that lies within the PWR core and leads to the emitter. The background signal is proportional to the integrated gamma flux over the length of the cable and must be subtracted to obtain a signal that is proportional to the neutron flux density at the emitter location.) The signal-to-flux proportionality factor changes with increasing exposure, because the sensitivities of the SPNDs to neutrons decrease with exposure. A rhodium emitter interacts with neutrons through the $^{103}Rh(n,\beta^-)^{104}Pd$ reaction. ^{104}Pd is a stable, non-neutron-sensitive isotope; hence, the decrease (or depletion) in detector sensitivity. After correction for background, the signal from a Rh detector is further corrected for this sensitivity depletion — a correction that is most accurate when it is based on measured depletion.

B&W has had a Rh depletion experiment underway since July, 1976 in Duke Power Company's Oconee 2 PWR at Seneca, South Carolina. The detectors are now approximately 25% depleted, and the depletion characteristics are becoming clear. The purpose of the experiment is to define those characteristics over as much as possible of the operating life of Rh detectors in the PWR.

The Oconee 2 experiment was supported solely by B&W during the first 30 months. But since the depletion results are applicable for Rh detectors in the nuclear reactors of many utilities (with two different reactor vendors involved), the Electric Power Research Institute has assumed support of the experiment so that the depletion results will be widely disseminated.

SCOPE OF WORK

Sensitivity depletion of two Al_2O_3-insulated Rh detectors in the Oconee 2 experimental detector assembly has been measured periodically since July, 1976. Seventy-one sets of data points have been obtained during fuel cycles 2 and 3 of reactor operation. A set of data points consists of the relative sensitivity of a fixed Rh detector — as measured with a movable, twin-leadwire, undepleted Rh calibration detector — and the current from the fixed detector integrated from time zero (in neutron exposure) to the time of measurement. ("Integrated current" is also called "expended charge.")

Regression analysis of the depletion data from fuel cycles 2 and 3 has been performed to find the analytical expression that best represents the measured results. A depletion correction factor for the Rh signal has been formulated from the analytical expression.

RESULTS

After two fuel cycles of neutron exposure, the combined depletion data from the two Rh detectors produce the following expression for relative detector sensitivity at time t versus expended charge, Q(t):

$$\frac{S(t)}{S(0)} = 1 - \frac{0.01318}{\sqrt{mL}} Q(t),$$

where m = emitter mass, g,
L = emitter length, cm.

This equation holds strictly only for Rh detectors whose emitters are approximately 0.046 cm (0.018 in.) in diameter. The detector sensitivity depletion correction factor at time t (in neutron exposure) is the inverse of this equation.

CONCLUSIONS

- The Oconee 2 experiment is producing high-quality data and is expected to define Rh depletion accurately when carried to completion.

- Through two fuel cycles, the depletion curve is essentially linear. However, there has been a difference in the slopes of depletion curves for the individual fuel cycles. Although presently unverified, this difference may be related to differences in the beginning-of-cycle burnup values for the two fuel assemblies used at the core locations of the Rh detectors during the two fuel cycles.
- The depletion rate of a Rh detector in the PWR is approximately 8% less than the rate in a pool reactor.

RECOMMENDATION

The experiment at Oconee 2 must continue for at least two additional fuel cycles to cover most of the operational life of a Rh detector in a PWR. Otherwise, the depletion correction to a detector signal will be based on extrapolated data during the last fuel cycles of exposure of the detector. As a consequence, uncertainty in the signal will become larger the more the sensitivity of the detector depletes.

Section 1

INTRODUCTION

Self-powered neutron detectors (SPNDs), or "incore detectors," have been widely used in recent years as incore power shape monitors in nuclear reactors. The characteristics of these detectors have been reported by other investigators (1). There are two kinds of SPNDs: prompt and delayed. Upon capture of a neutron, a prompt-responding incore detector immediately produces a signal through the (n,γ,e) reaction. Delayed-response incore detectors produce time delayed signals through the (n,β) reaction. A detector with a cobalt "emitter," the neutron sensitive element, is an example of a prompt-responding SPND. One with a rhodium (Rh) emitter is an example of a delayed-response detector. In each type of detector, the electric current produced by the capture of neutrons in the emitter is directly proportional to the incident neutron flux density.

Power-shape-monitoring systems that are fixed inside the cores in pressurized water reactors (PWRs) in the United States are comprised almost exclusively of rhodium SPNDs. Nuclear reactors designed by the Babcock and Wilcox Company (B&W) and the Combustion Engineering Corporation (CE) have from 200 to 400 Rh incore detectors, the number in each plant depending upon the size and model of the reactor.

When a ^{103}Rh nucleus captures a neutron and releases a beta particle, left behind is a non-neutron-sensitive ^{104}Pd nucleus. Hence, by the nature of the neutron reaction, the neutron sensitivity of a Rh detector "depletes" or "burnsup" with exposure to neutrons. The theoretical nature of this depletion has been discussed by others (2). Experimental depletion of Rh detectors in a 6 MWt pool reactor has been reported by the writer (3).

For a Rh detector to be used in a PWR power-shape-monitoring system, its neutron sensitivity must be known at all times over its operational life. If the sensitivity depletion rate is well-defined through direct measurements in a PWR, then the actual neutron sensitivity of the Rh detector at any time is known. Aside from a correction for background, only a depletion correction to the detector signal is necessary to convert the signal to neutron flux.

In July, 1976, B&W, with the assistance and cooperation of the Duke Power Company, installed an experimental assembly of self-powered incore detectors in Duke Power's Oconee 2 PWR at Seneca, South Carolina. The assembly contained both prompt-responding and Rh SPNDs. The purpose of the experiment was to determine the sensitivity depletion of the prompt detectors as a function of exposure in the reactor core. As a by-product, the depletion of the Rh detectors would also be determined.

There are two Rh detectors in the Oconee 2 experimental assembly. The depletion of each of these detectors has been monitored throughout fuel cycles 2 and 3 of reactor operation. This report is an interim account of the measured Rh depletion throughout the period from July, 1976 to November, 1978, during the time the experiment was supported solely by B&W. In December, 1978, the Electric Power Research Institute assumed support of the experiment. This report is the first under EPRI sponsorship. The new objective for the experiment is to continue the depletion measurements long enough to define empirically and accurately the loss of sensitivity over as much as feasible of the operating life of the Rh detectors.

The data acquisition system (DAS) used in the Oconee 2 experiment is described in Section 2. Section 3 contains a description of the experimental procedure. Results and analyses are presented in Section 4, and conclusions and a recommendation in Section 5.

Section 2

DESCRIPTION OF EXPERIMENTAL EQUIPMENT

DETECTORS AND DETECTOR ASSEMBLY

Rh and Background Detectors

Table 2-1 lists physical characteristics of the two Rh and one background detectors in the Oconee 2 experimental SPND assembly (which is positioned inside fuel assembly L11).

Detector Assembly

Table 2-2 gives the composition and dimensions of the experimental assembly. The locations of the emitters of the Rh detectors with respect to the end of the assembly calibration tube and the top of the active fuel are listed. The distance from the tip of the leadwire in the background detector to the reference point also is given.

Fuel Assembly

Figure 2-1 shows the core location of Oconee 2 fuel assembly L11. The experimental detector assembly is positioned inside an instrument guide tube in the center of the 15x15-pin fuel assembly. The instrument tube is made of Zircaloy, and it supplants the central fuel pin. Its inside diameter is 1.120 cm (0.441 inch). The L11 fuel assembly itself changes from fuel cycle to fuel cycle as the fuel is shuffled during reloadings. Below are listed the initial enrichments and beginning-of-cycle (BOC) burnups of the fuel assemblies used in the L11 position during fuel cycles 2, 3, and 4 (cycle 4 began in December, 1978).

	L11 Fuel Assembly	
Oconee 2 Fuel Cycle	Initial Enrichment, wt % ^{235}U	BOC Burnup, MWd/mtU
2	2.75	17,834
3	2.64	6,957
4	3.03	9,769

Table 2-1

CHARACTERISTICS OF RHODIUM AND BACKGROUND SPNDs
IN OCONEE 2 EXPERIMENTAL INCORE DETECTOR
ASSEMBLY (L11 FUEL ASSEMBLY)

Item	Rh Det. L11-R3	Rh Det. L11-R5	Bkgd. Det. L11-B1
Sheath OD, cm., emitter region	0.157±0.005	0.157±0.005	---
Sheath OD, cm., cable region	0.140±0.003	0.140±0.003	0.140±0.003
Sheath wall, cm., emitter region	0.025±0.003	0.025±0.003	---
Sheath wall, cm., cable region	0.020±0.003	0.020±0.003	0.020±0.003
Sheath material	Inconel 600	Inconel 600	Inconel 600
Insulation material	Al_2O_3	Al_2O_3	Al_2O_3
Leadwire material	Zircaloy 2	Zircaloy 2	Zircaloy 2
Leadwire OD, cm	0.024±0.001	0.024±0.001	0.024±0.001
Emitter mass, mg	810±2	810±2	---
Emitter diam., cm	0.0462	0.0462	---
Emitter length, cm	38.99	39.40	

Table 2-2

CHARACTERISTICS OF EXPERIMENTAL SPND
ASSEMBLY IN OCONEE 2 FUEL ASSEMBLY L11

Assembly serial no.:	PRY-1
Assembly length, m:	31.51
Oversheath material:	Inconel 600
Oversheath OD, cm.:	0.752
Oversheath wall, cm:	0.046
Calibration tube material:	Inconel 600
Calibration tube OD, cm.:	0.318±0.005
Calibration tube wall, cm.:	0.041±0.005
Assembly contents:	4 B&W prompt detectors
	2 Rh detectors (see Table 2.1)
	1 bkgd. detector (see Table 2.1)

Detector emitter positions within the assembly:

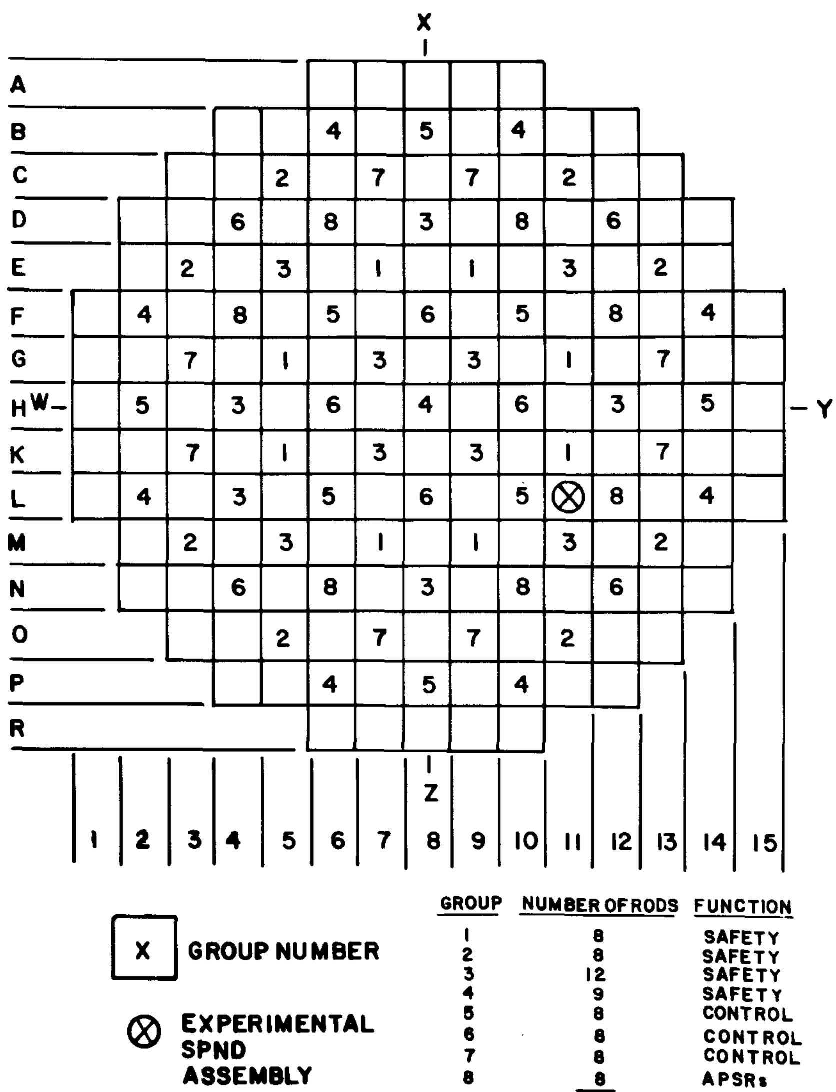
Detector Designation*	Center of Emitter to Tip End of Calibration Tube, m**
L11-R5	1.518
L11-R3	2.039
L11-B1	1.195†

- - - - -

* R — Rh detector
B — bkgd. detector

** Tip end of calibration tube is 20.0±0.3 cm above the active fuel

† From end of bkgd. det. leadwire



GROUP	NUMBER OF RODS	FUNCTION
1	8	SAFETY
2	8	SAFETY
3	12	SAFETY
4	9	SAFETY
5	8	CONTROL
6	8	CONTROL
7	8	CONTROL
8	8	APSRs
TOTAL	69	

Figure 2-1. Location of experimental SPND assembly in Oconee 2 core. Control rod configuration for fuel cycle 2.

During cycle 2, a group 5 control rod was positioned in core location L10, a fuel assembly adjacent to the L11 test position. In fuel cycle 3, L10 contained a group 7 control rod. In cycle 4, the group 7 rod remains in L10. Group 5 rods usually are fully withdrawn, but group 7 rods usually are partially inserted into the core during power operation. The presence or absence of a control rod in an adjacent fuel assembly is not expected to have an appreciable effect on the depletion rate of the Rh detectors.

DATA ACQUISITION SYSTEM (DAS)

Figure 2-2 shows the instrumentation channel for the Rh detector in the experimental SPND assembly. The signal from each Rh detector is input to a current-sensitive solid state amplifier. The amplifier is a differential input circuit with a full scale range of 5000 nA. The amplifier is stable to ±1/2% over the full current range. The circuit is essentially a current-to-voltage converter that loads the detector with an effective impedance of about 300 ohms.

One of the two parameters needed to establish a Rh detector depletion curve is the expended charge, $Q(t)$, from the detector at time t in reactor exposure. (The other is the relative sensitivity of the detector at time t.) Expended charge is the integral of detector current from time zero to time t. Shown in Figure 2-2 is an electronic integrator that uses as input the 0 to 10V output of the input amplifier.

The integrator consists of a voltage-to-frequency converter followed by a 36-bit binary counter chain. The last 16 bits of the chain are readable. The counter is battery-backed by mercury cells that supply power to counter memory whenever circuit power supply voltages are off. The batteries have a shelf life of about 4 years. Since the counters drain very small currents, the batteries can power the counters for a full shelf life. The counters have 1% accuracy, and are used only as backup to the Nova 800 computer in providing expended charge information. The counters are read by attaching a "charge reader" to the amplifier card connector (the counters are mounted on the input amplifier card).

There are 64 data channels in the DAS. A multiplexer scans all channels in one second, and inputs signals through interface circuitry to the Nova 800 computer, which controls the logging and display of data. Current signals from the rhodium detectors are integrated over time within the computer. Integrated current values

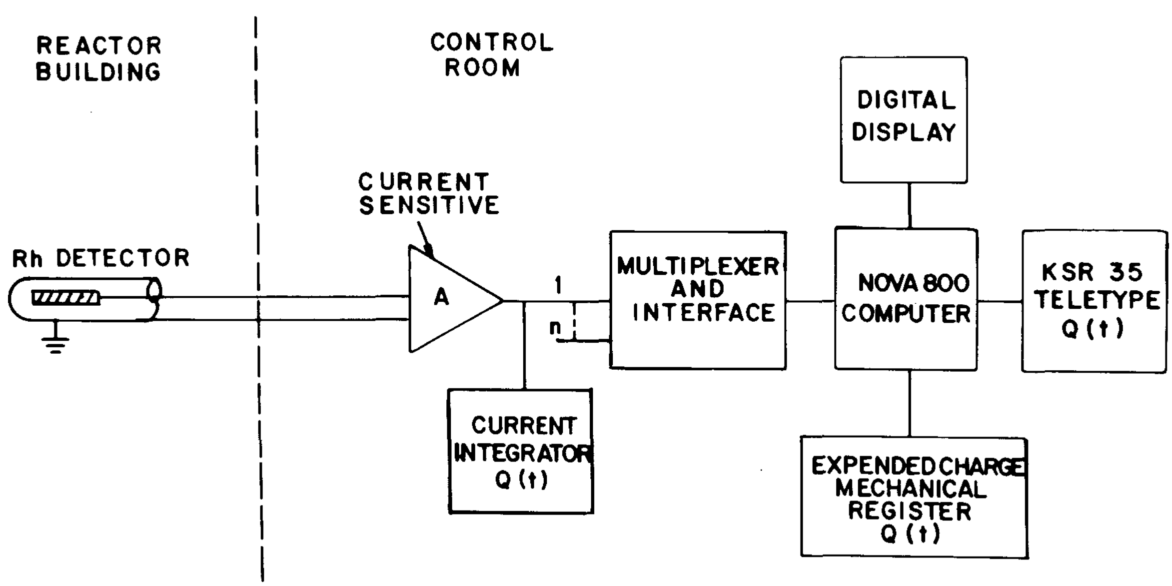


Figure 2-2. Instrumentation channel for data logging of expended charge, Q(t), and other parameters from rhodium SPNDs in Oconee 2 experimental assembly.

Q(t), are registered in front-panel mechanical counters, are printed once-a-day on the teletypewriter, and are displayed on demand in a digital register. All other variables in the computer program can also be digitally displayed on demand.

Having accurate values of expended charge is crucial in reaching the desired goal of well-defined Rh depletion data. With dual current integrations and multiple displays of expended charge, this experiment is providing an accurate accounting of Q(t).

Figure 2-3 is a photograph of the data acquisition system.

MOVABLE RHODIUM DETECTOR DRIVE SYSTEM (MRDDS)

The second quantity in a depletion curve for a Rh SPND is the relative neutron sensitivity of the SPND. To form a depletion curve, relative sensitivity is measured at periodic intervals and plotted as a function of expended charge at the times of measurement. Relative sensitivity is measured using a movable twin-lead rhodium detector, which is mechanically driven into the reactor core via the calibration tube of the experimental SPND assembly. The movable Rh detector is parked in the core with its emitter alongside that of the fixed Rh detector. The movable and fixed detector signals are recorded simultaneously, providing the relative sensitivity data.

Figure 2-4 is a block diagram of the equipment used to drive the movable Rh detector and to record its signal.

Table 2-3 lists the physical characteristics of the movable twin-lead Rh calibration detector used during fuel cycles 2 and 3 at Oconee 2 and those of the backup movable detector that is held in reserve. Although the movable detector has MgO insulation, there has been no significant effect from insulation leakage. The resistive load on the detector has been small compared to the insulation resistance. When not in use, the movable detector is parked 3 meters below the core. The MgO insulation has not deteriorated with the detector in the parked position.

The movable calibration detector is driven into the reactor core by the machine shown in Figure 2-5. The detector is mounted on the grooved reel of the machine, underneath a rubber timing belt that is driven by a DC stepping motor. Frictional

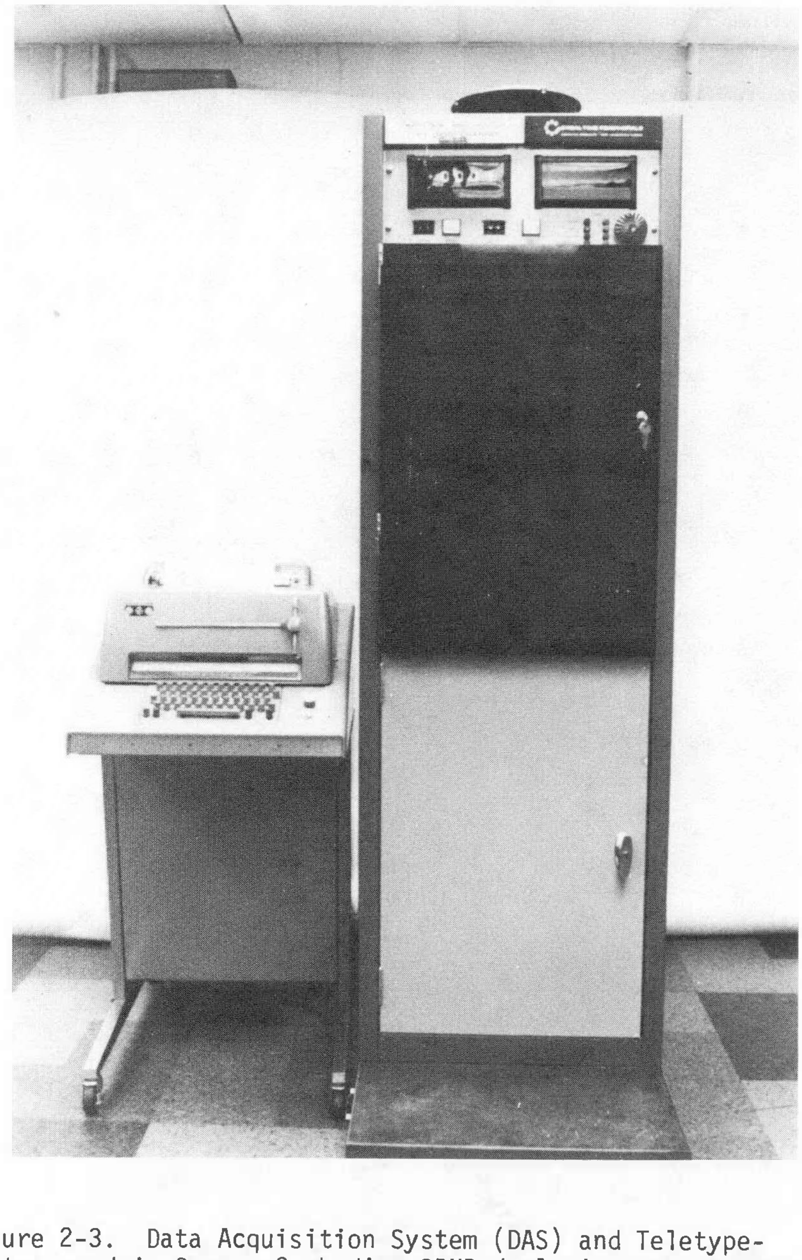


Figure 2-3. Data Acquisition System (DAS) and Teletype-writer used in Oconee 2 rhodium SPND depletion measurements.

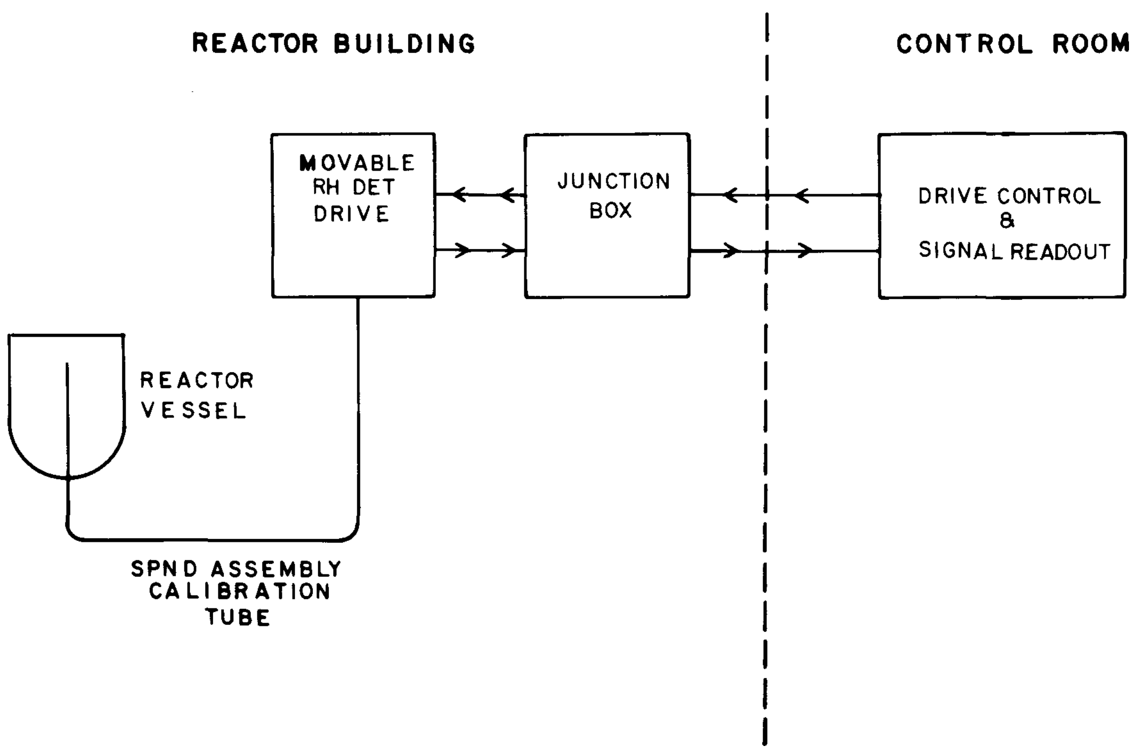


Figure 2-4. Block diagram of apparatus for measurement of relative sensitivity of fixed Rh incore detector using a movable Rh detector.

Table 2-3

PHYSICAL CHARACTERISTICS OF MOVABLE TWIN-LEAD Rh CALIBRATION SPND USED IN OCONEE 2 EXPERIMENT IN FUEL CYCLES 2 AND 3 AND THOSE OF RESERVE Rh CALIBRATION SPND

Item	Movable Rh Cal. Det. Used In Cycles 2 & 3	Movable Rh Cal. Det. Held In Reserve
Emitter mass, g:	0.850	0.810
Emitter length, cm:	40.01	39.57
Emitter dia., cm:	0.0467	0.0457
Leadwire mat'l:	Inconel 600	Inconel 600
Leadwire diameters, cm:	0.024	0.024
Detector tip to emitter end, cm.	1.68	1.91
Detector OD, cm	0.157	0.160
Detector insulation	MgO	Al_2O_3
Detector length, m	32.31	32.31

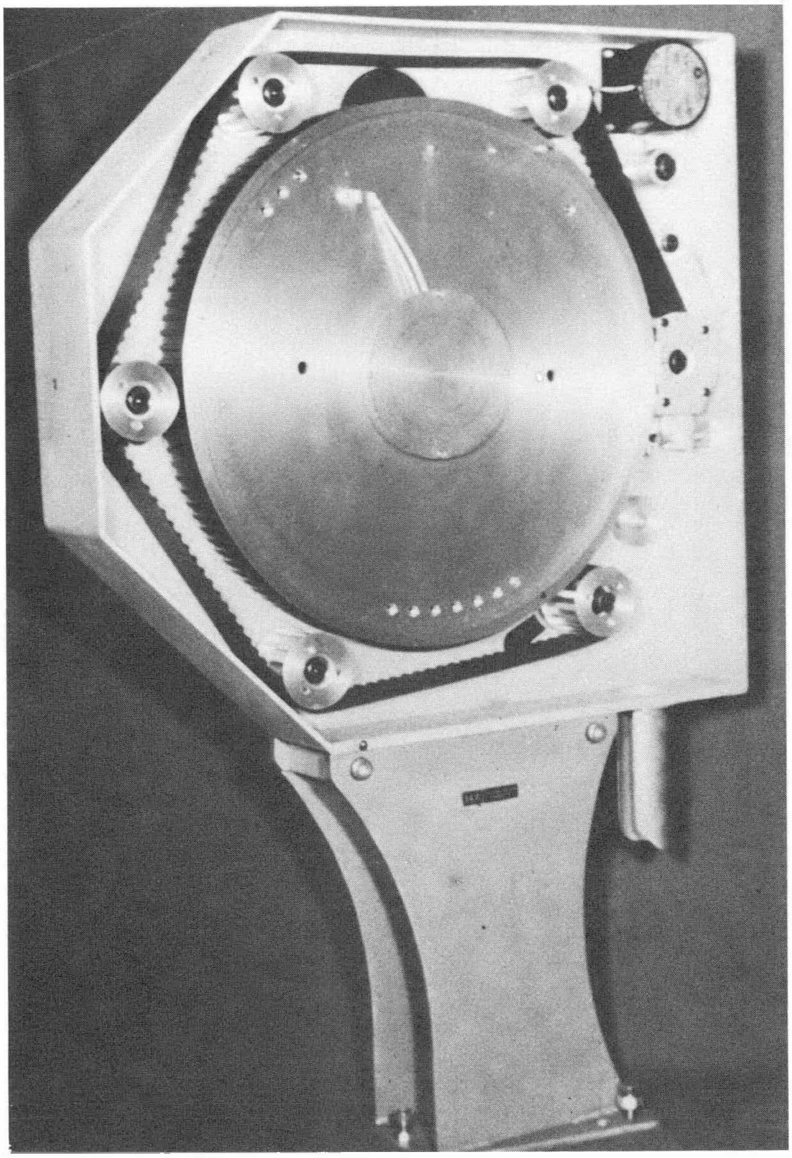


Figure 2-5. Movable detector drive machine. Movable detector is driven by friction from rotating reel into experimental SPND assembly calibration tube.

forces between the belt and the detector impel the detector from the reel and into the reactor core via the calibration tube of the experimental SPND assembly. Signals generated in the emitter and background leads of the twin-lead detector are transmitted from the moving detector through a slip ring assembly to a stationary signal cable. The slip ring assembly is shown in Figure 2-6.

The drive machine is remotely operated from a control panel mounted at the "control and readout" station. The drive moves forward or in reverse at two speeds: 2.5 cm/s and 0.2 cm/s. The slower speed is used to position the movable detector within 3 mm of the desired position. The accuracy of the movable detector position is ±6 mm.

Signals from the movable detector are amplified in a Keithly Instrument Model 604 Differential Electrometer and Model 6041 Current Shunt. Detector load resistors used in the current shunt are 10^4 ohm. Gain of the amplifier is normally set at 333. The differential action of the amplifier eliminates background and common mode noise from the movable detector signals. The drive control and signal readout instrumentation is shown in Figure 2-7.

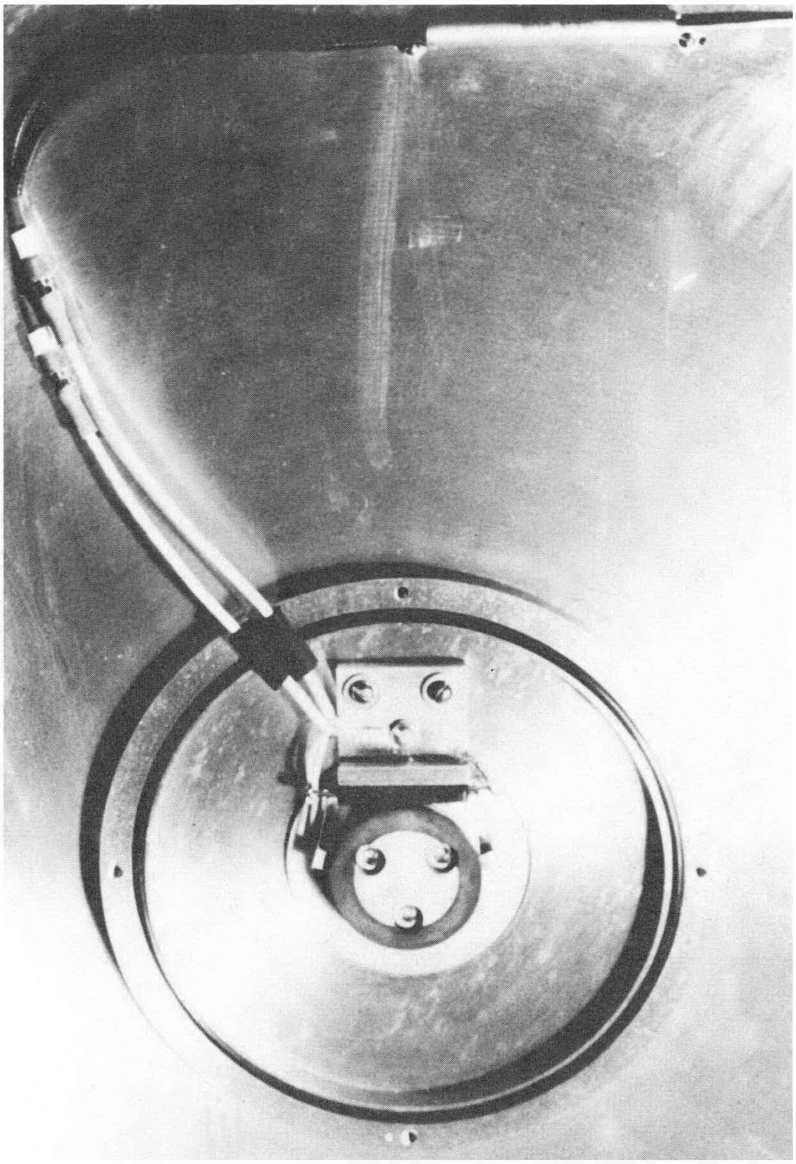


Figure 2-6. Slip ring assembly used to transfer signals from moving Rh calibration detector to stationary cable leading to signal readout instrumentation.

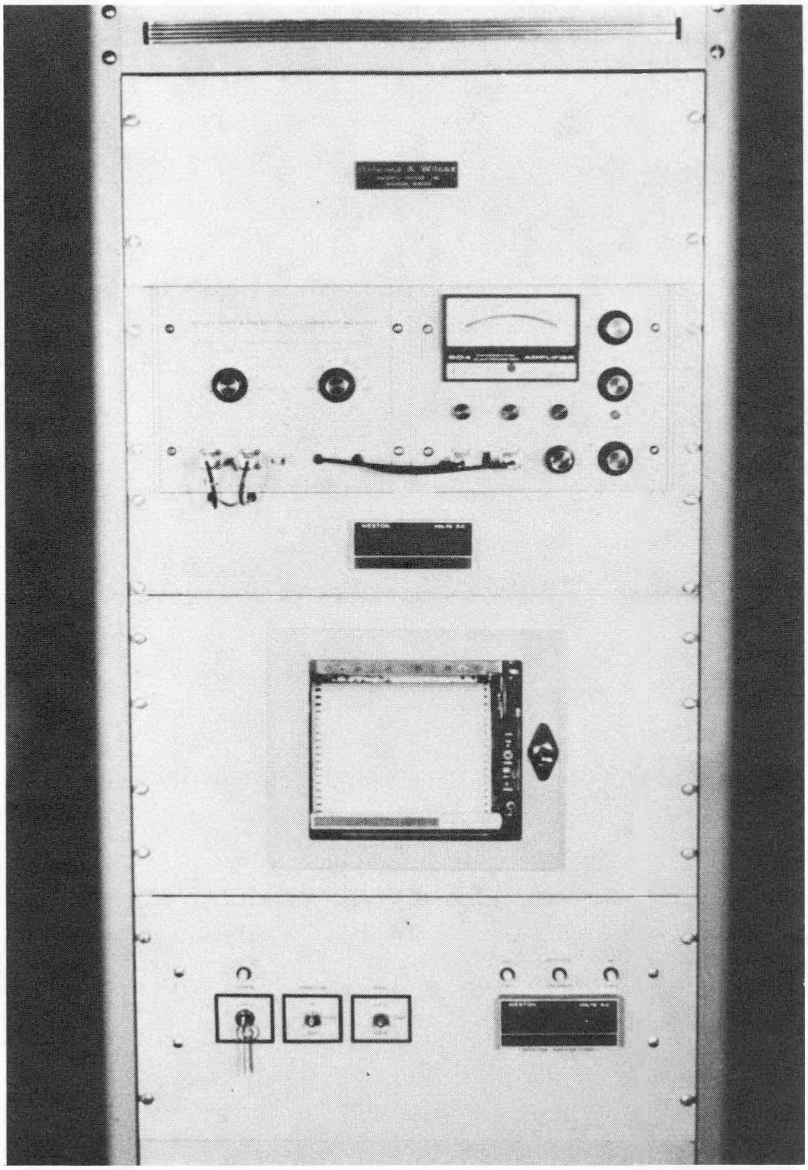


Figure 2-7. Instrumentation for drive control and movable Rh detector signal readout.

Section 3

DATA LOGGING AND CALIBRATION PROCEDURES

EXPENDED CHARGE

In the discussion of equipment in Section 2, integration of the fixed Rh detector currents over time was described. Current integrators mounted on the input amplifier cards integrate background-uncorrected signals, providing backup Q(t) values. However, the main current integration is performed by the software of the Nova 800 computer. The computer first corrects the Rh detector signals for background (less than a 0.5% correction), then integrates the background-corrected currents over time. Expended charge values are stored in the computer memory, on the teletypewriter hard copy (printed once-a-day), and in mechanical registers. The backup charge values are stored in the integrators on the input amplifier cards.

DAILY PRINTOUT

Each day at noon, the data acquisition system prints a hard copy of all input incore detector signals being monitored at that time, both uncorrected and corrected for background. Expended charge values are printed, along with information on reactor power, control rod positions, core inlet temperatures, reference voltages within the DAS, the date and time. Hard copies also are printed on demand.

If for any reason the DAS computer stops running, a battery-powered red light begins flashing. Once, in the 30 months the experiment has been in operation, while Oconee 2 was shutdown, the flashing light was activated. Within a short period, the computer was restarted with no loss of expended charge data.

FIXED Rh DETECTOR CALIBRATION PROCEDURE

The relative neutron sensitivity of each of the Rh detectors fixed in the experimental SPND assembly is measured periodically. The calibration procedure is as follows:

1. The control and readout station for the movable Rh calibration detector is activated and allowed to warm up for at least 30 minutes (the MRDDS).

2. Support data on plant conditions and core power distribution are obtained from the station computer.

3. Movable detector signal amplifier settings are checked and the amplifier is zeroed.

4. The movable detector is driven into the reactor core to the "in-limit" position. (The in-limit is the reference point for positioning the emitter of the movable Rh detector alongside the emitters of the fixed Rh detectors. In relation to the reference in-limit, the locations of the emitters of the fixed Rh detectors are known within ±6 mm).

5. The movable Rh detector is withdrawn a known distance and parked with its emitter alongside that of the first fixed Rh to be calibrated.

6. After waiting at least 10 minutes, currents from the movable and fixed Rh detectors are simultaneously recorded. (The effective time constant of the response of a Rh detector to a step change in incident neutron flux is 1.38 minutes. A wait-time of 10 minutes ensures that 99.9% of the change in flux is registered in the output of the detector.) Both the uncorrected and corrected-for-background fixed signals are recorded. The fixed detector expended charge is recorded from the mechanical registers and teletypewriter printout.

7. The movable Rh detector is withdrawn farther and parked with its emitter alongside the emitter of the second fixed Rh detector.

8. After waiting 10 minutes, movable and fixed Rh detector currents are recorded as before. The fixed detector expended charge is recorded from the mechanical registers and the teletypewriter printout.

9. The current signal from the background detector in the experimental SPND assembly is recorded.

10. The movable Rh detector is withdrawn to approximately 3 meters below the reactor core (the out-limit position) and parked there until next usage.

11. Using a special electronic instrument, which attaches to the end connector of the input amplifier card, the expended charge stored in the input current integrator is read for each of the fixed Rh detectors. (These data are used as backup information.)

12. Cables from the fixed Rh detectors to the DAS are disconnected. Using a special switch box, voltage source, and picoammeter, the insulation leakage of each of the fixed detectors is measured. The insulation leakage of the movable Rh calibration detector is similarly measured.

13. Supporting data on plant conditions and core power distribution are obtained from the station computer.

14. Steps 1 through 13 are repeated at least twice (step 12 is done once).

15. The accuracies of the movable detector position meter and signal amplifier are checked at regular intervals against instruments whose calibrations are traceable to the National Bureau of Standards. The accuracies of the DAS current signal channels also are checked regularly against a calibrated picoammeter.

The foregoing procedure for the calibration of the fixed Rh detectors produces relative neutron sensitivities. When these quantities are plotted versus expended charge, emitter depletion curves for the fixed Rh detectors are obtained.

Section 4

RESULTS AND ANALYSIS

RESULTS

Table 4-1 presents the measured values of relative sensitivity of the two Rh detectors in the L11 test detector assembly in Oconee 2 as a function of measured expended charges from the two detectors. Average values of relative sensitivity and expended charge, and the standard deviation on the relative sensitivity, are tabulated from the set of readings taken during each trip to the reactor site. The average relative sensitivity values are plotted in Figures 4-1 and 4-2 against their corresponding average expended charges.

The relative sensitivity values in Table 4-1 were corrected only for background in the two fixed Rh detectors. Aside from a minor correction (∿0.5%) for the effects on detector signals of differential flux depression between the unburned movable Rh calibration detector and the partially burned fixed Rh detector, no other signal corrections were necessary. A differential-flux-depression correction will be applied to the depletion data when it is complete (after two more fuel cycles); however, it is not applied at this point because it is not significant enough to justify the effort required.

As discussed in Section 2, the data acquisition system contains a hardwired current integrator as well as software current integration in the NOVA 800 computer (see Figure 2-2). Comparison of the expended charges indicated by these two independent integrators defines the accuracy of the integrations. On October 24, 1978 – after nearly two complete fuel cycles of detector exposure – the two results were:

	Expended Charge, C	
Detector	Hardwired Integrator	Software Integrator
L11-R3	95.067	95.006
L11-R5	102.277	101.89

Table 4-1

MEASURED VALUES OF RELATIVE SENSITIVITY VS EXPENDED CHARGE FOR TWO Rh INCORE DETECTORS IN OCONEE 2 FUEL ASSEMBLY L11

	Rh Detector L11-R3				Rh Detector L11-R5			
Date	Rel. Sens.	Expended Charge, C	Average Rel. Sens.	Average Exp. Charge, C	Rel. Sens.	Expended Charge, C	Average Rel. Sens.	Average Exp. Charge, C
7-20-76	0.9992	1.0			1.0152	1.1		
7-21	0.9991	1.1			1.0127	1.3		
7-21	1.0002	1.1	0.9995	1.2	1.0135	1.3	1.0138	1.4
7-23	0.9995	1.3	±0.04%		1.0147	1.4	±0.11%	
7-23	0.9995	1.5			1.0128	1.8		
8-17	0.9687	4.4			0.9668	5.2		
8-17	0.9770	4.4	0.9737	4.4	0.9770	5.2	0.9712	5.2
8-18	0.9755	4.5	±0.45%		0.9698	5.3	±0.52%	
9-9	0.9588	8.1			0.9539	9.5		
9-9	0.9315	8.1	0.9574	8.1	0.9377	9.5	0.9525	9.5
9-10	0.9818	8.2	±2.63%		0.9656	9.6	±1.49%	
9-30	0.9833	11.7			0.9731	13.5		
9-30	0.9650	11.7	0.9870	11.7	0.9593	13.6	0.9744	13.6
10-1	1.0127	11.8	±2.44%		0.9908	13.7	±1.62%	
10-23	0.9397	15.2			0.9417	17.5		
10-23	0.9545	15.2	0.9496	15.3	0.9477	17.5	0.9462	17.5
10-24	0.9545	15.4	±0.90%		0.9492	17.6	±0.42%	
11-21	0.9424	20.3			0.9352	22.9		
11-21	0.9414	20.3	0.9413	20.4	0.9343	22.9	0.9343	23.0
11-22	0.9400	20.5	±0.13%		0.9334	23.1	±0.10%	
12-29	0.9444	23.1			0.9277	25.9		
12-30	0.9297	23.2	0.9370	23.3	0.9248	26.0	0.9278	26.1
12-30	0.9378	23.3	±0.65%		0.9289	26.1	±0.23%	
12-31	0.9359	23.4			0.9296	26.2		

Table 4-1 Cont'd.

	Rh Detector L11-R3				Rh Detector L11-R5			
Date	Rel. Sens.	Expended Charge, C	Average Rel. Sens.	Average Exp. Charge, C	Rel. Sens.	Expended Charge, C	Average Rel. Sens.	Average Exp. Charge, C
1-23-77	0.9391	27.4			0.9130	30.4		
1-23	0.9265	27.4	0.9271	27.5	0.9164	30.4	0.9156	30.5
1-24	0.9213	27.5	±0.90%		0.9155	30.5	±0.21%	
1-24	0.9215	27.5			0.9176	30.5		
2-21	0.9140	32.3			0.9144	35.4		
2-22	0.9119	32.4	0.9127	32.4	0.9070	35.5	0.9098	35.5
2-22	9.9121	32.4	±0.13%		0.9079	35.5	±0.44%	
3-26	0.8996	37.3			0.8971	40.5		
3-26	0.9002	37.3	0.9004	37.3	0.8958	40.6	0.8961	40.6
3-27	0.9013	37.4	±0.10%		0.8953	40.7	±0.10%	
4-24	0.8889	42.1			0.8816	45.3		
4-24	0.8881	42.2	0.8888	42.2	0.8833	45.3	0.8827	45.3
4-25	0.8894	42.3	±0.07%		0.8831	45.4	±0.09%	
5-23	0.8784	47.1			0.8755	50.0		
5-24	0.8787	47.2	0.8785	47.2	0.8743	50.1	0.8739	50.1
5-24	0.8785	47.3	±0.02%		0.8718	50.1	±0.22%	
	END OF OCONEE 2 FUEL CYCLE 2							
9-3-77	0.8689	48.7	0.8662	48.8	0.8710	51.6	0.8704	51.7
9-4	0.8634	48.8	±0.45%		0.8697	51.7	±0.11%	
11-3	0.8627	52.3	0.8625	52.4	0.8598	55.9	0.8591	56.0
11-3	0.8623	52.4	±0.03%		0.8583	56.0	±0.12	
11-30	0.8611	54.2			0.8580	58.0		
11-30	0.8589	54.2	0.8596	54.2	0.8571	58.1	0.8575	58.1
12-1	0.8588	54.3	±0.15%		0.8575	58.1	±0.05%	

Table 4-1 Cont'd.

	Rh Detector L11-R3				Rh Detector L11-R5			
Date	Rel. Sens.	Expended Charge, C	Average Rel. Sens.	Average Exp. Charge, C	Rel. Sens.	Expended Charge, C	Average Rel. Sens.	Average Exp. Charge, C
2-9-78	0.8446	60.8			0.8356	65.8		
2-9	0.8458	60.8	0.8449	60.8	0.8394	65.8	0.8379	65.8
2-9	0.8444	60.9	±0.09%		0.8387	65.8	±0.24%	
3-15	0.8338	66.4			0.8258	72.1		
3-15	0.8324	66.4	0.8330	66.4	0.8246	72.1	0.8249	72.1
3-15	0.8329	66.4	±0.09%		0.8242	72.1	±0.10%	
5-10	0.8220	72.2			0.8129	78.5		
5-11	0.8203	72.3	0.8210	72.3	0.8109	78.6	0.8115	78.6
5-11	0.8207	72.3	±0.11%		0.8108	78.6	±0.15%	
6-20	0.8061	78.6			0.7950	85.4		
6-21	0.8066	78.7	0.8064	78.7	0.7962	85.4	0.7947	85.4
6-21	0.8065	78.7	±0.03%		0.7929	85.5	±0.21%	
7-24	0.7973	83.0			0.7871	90.0		
7-25	0.7962	83.1	0.7966	83.1	0.7870	90.1	0.7871	90.1
7-25	0.7963	83.1	±0.08%		0.7871	90.1	±0.01%	
9-5	0.7865	87.5			0.7747	94.7		
9-5	0.7894	87.5	0.7875	87.5	0.7757	94.7	0.7753	94.7
9-5	0.7866	87.5	±0.21%		0.7755	94.7	±0.07%	
10-2	0.7793	91.8			0.7615	99.0		
10-3	0.7797	91.9	0.7793	91.9	0.7657	99.1	0.7639	99.1
10-3	0.7790	91.9	±0.05%		0.7644	99.1	±0.28%	
10-23	0.7740	94.8			0.7584	101.8		
10-24	0.7709	94.9	0.7723	94.9	0.7565	101.8	0.7572	101.8
10-24	0.7719	95.0	±0.20%		0.7567	101.8	±0.14%	

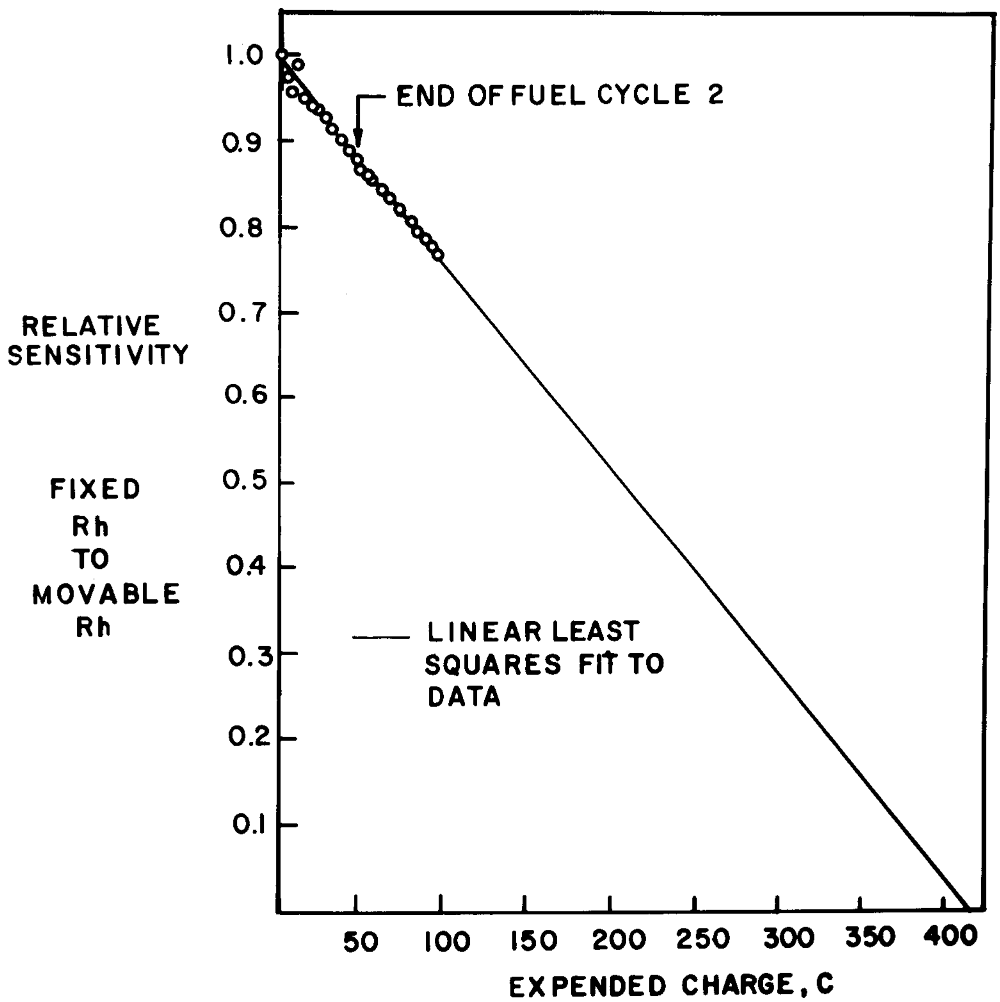


Figure 4-1. Measured relative sensitivity of Rh detector L11-R3 vs charge expended by detector in Oconee 2 reactor. L11-R3 emitter length: 38.99 cm.

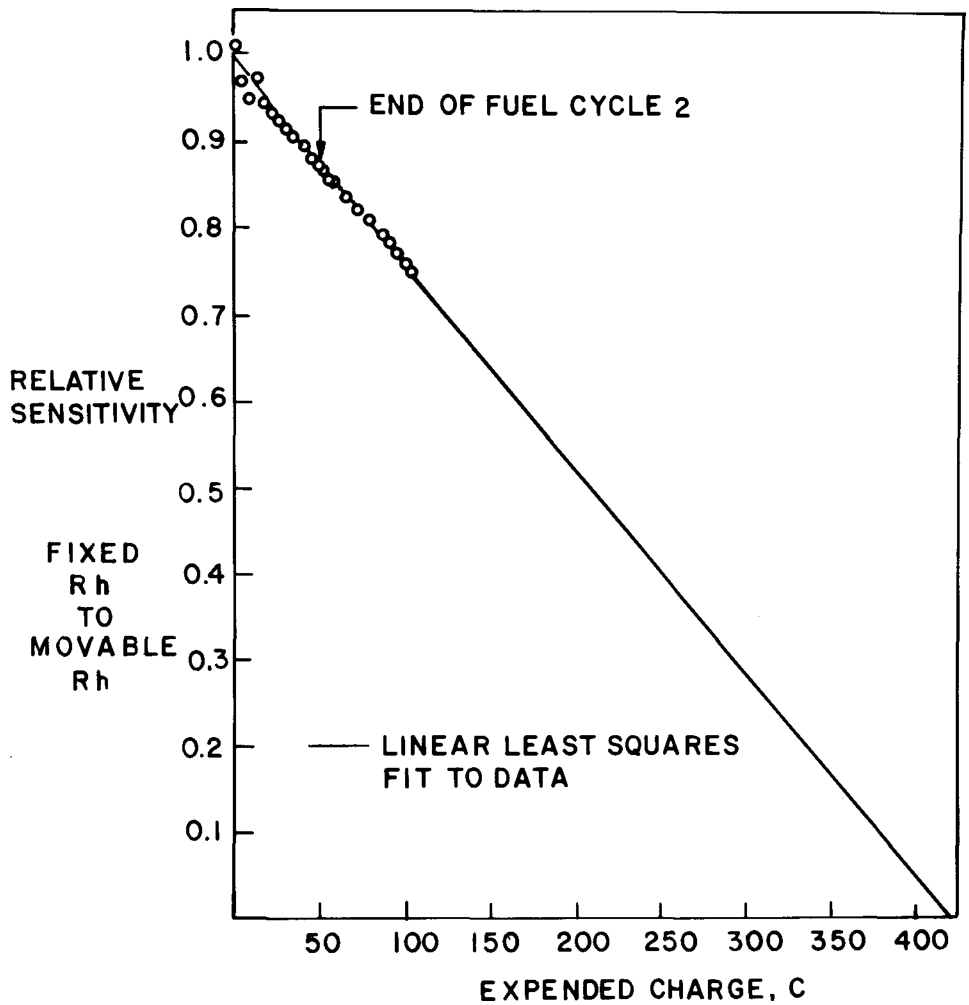


Figure 4-2. Measured relative sensitivity of Rh detector L11-R5 vs charge expended by detector in Oconee 2 reactor. L11-R5 emitter length: 34.40 cm.

The software integration is made after background is subtracted. The hardwired integration includes the integration of background currents. Hence, the difference in the two integrations demonstrates the cumulative effects of background over the entire time of detector exposure. As the foregoing tabulation shows, there is only a minor difference in the two integrated results for each detector. This indicates not only that expended charge values are precise, but also that background has been almost negligible throughout. In regression analysis of the depletion data, expended charge values were assumed to be exact.

ANALYSIS

Linear Regression Analysis

In Table 4-1 there are 71 sets of depletion data points for each Rh detector (the unaveraged data). These data were subjected to a linear regression analysis. The results are given in Table 4-2. Nine cases were run as tabulated in the table. The results of the first two cases are plotted in Figures 4-1 and 4-2, respectively, demonstrating the linear least squares fits to the depletion data.

The multiple correlation values given in Table 4-2 show the correlation of detector relative sensitivity to expended charge is indeed highly linear. The results for the slopes of the linear curves show little or no difference between the two detectors for Oconee 2 fuel cycle 2 and for the combination of cycles 2 and 3. There may be some difference in the depletion rates for the two detectors during fuel cycle 3. There is a definite difference between the depletion rate for each detector in fuel cycle 2 as compared to the corresponding rate in cycle 3. The rate for each was lower in cycle 3 by an average of approximately 15%. The reason for this decrease is unclear. More depletion data are needed during fuel cycles 4 and 5 to elucidate the cause of this change.

Depletion Correction Factors

If the correlation of detector relative sensitivity with expended charge is linear, then the factor that is used at time t to correct a measured signal for emitter depletion is

$$f(t) = 1 \Bigg/ \left[1 - \frac{Q(t)}{Q_\infty} \right] \qquad (4\text{-}1)$$

Table 4-2

LINEAR REGRESSION ANALYSIS OF MEASURED Rh DETECTOR
RELATIVE SENSITIVITY VS EXPENDED CHARGE IN OCONEE 2 REACTOR

Detector	Oconee 2 Fuel Cycle(s)	Linear Regression Analysis Results				
		Intercept	Slope	Std. Dev. of Slope	Mult. Corr.	Std. Error of Est.
L11-R3	2+3	0.99133	-0.00236	0.00004	0.99044	0.00986
L11-R5	2+3	0.99299	-0.00233	0.00004	0.99182	0.00966
L11-R3 + L11-R5	2+3	0.99201	-0.00234	0.00003	0.99101	0.00979
L11-R3	2	0.99474	-0.00250	0.00014	0.94739	0.01258
L11-R5	2	0.99845	-0.00259	0.00012	0.95883	0.01214
L11-R3 + L11-R5	2	0.99651	-0.00255	0.00009	0.95336	0.01225
L11-R3	3	0.97244	-0.00211	0.00002	0.99890	0.00156
L11-R5	3	0.98571	-0.00223	0.00002	0.99911	0.00162
L11-R3 + L11-R5	3	0.97763	-0.00215	0.00002	0.99712	0.00269

where $f(t)$ = depletion correction factor at time t in detector exposure,

$Q(t)$ = charge expended in coulombs by detector throughout its exposure,

Q_∞ = total charge available in coulombs for release from the detector = inverse of the slope of the linear depletion curve.

The detector signal corrected for depletion is given by

$$I_c(t) = f(t)\, I_m(t), \tag{4-2}$$

where $I_c(t)$ = detector signal corrected for emitter depletion at exposure time t,

$I_m(t)$ = measured detector signal at exposure time t (corrected for background, if any).

Define Q_∞ as follows:

$$Q_\infty = q_\infty\, S, \tag{4-3}$$

where q_∞ = total charge available in coulombs per unit of lateral surface area of emitter,

S = lateral surface area of emitter (excludes surfaces at ends of emitter).

Now

$$S = \pi d L = \sqrt{\frac{4\pi m L}{\rho}} \tag{4-4}$$

where d = emitter diameter,

L = emitter length,

m = emitter mass,

ρ = emitter density.

The handbook value for the density of Rh is:

$$\rho = 12.41 \text{ g/cm}^3.$$

Hence,

$$S = 1.0063 \sqrt{mL} \text{ in cm}^2, \tag{4-5}$$

when m is in grams and L is in centimeters; and,

$$S = 0.2486 \sqrt{mL} \text{ in in}^2, \tag{4-6}$$

when m is in grams and L is in inches.

Expressed in square centimeters of emitter surface area

$$Q_\infty = 1.0063 \, q_\infty \sqrt{mL} , \tag{4-7}$$

and the depletion correction factor is

$$f(t) = 1 \Bigg/ \left[1 - \frac{0.9937}{q_\infty \sqrt{mL}} \, Q(t) \right] , \tag{4-8}$$

where m is in grams and L is in centimeters.

Is q_∞ a constant for Rh emitters that have the same mass but slightly different lengths? Results from a previous Babcock & Wilcox measurement of Rh depletion in a 6-MWt pool reactor showed (3):

$$\underset{\text{(pool react.)}}{q_\infty} = 69.77 \text{ C/cm}^2 \pm 1.24\% \tag{4-9}$$

for six emitter lengths between 11.25 and 12.67 centimeters and an emitter mass of 0.250 g. The error in this quantity is the standard deviation in the measured values of q_∞ for the six detectors. From the third entry in Table 4-2, the absolute value of the inverse of the slope gives a Q_∞ for the Oconee 2 Rh detectors of 427.4C±2.56%. The Oconee 2 emitters have a mass of 0.810 g and an average length of 39.20 cm. Therefore, from Eq. 4-5

$$q_\infty = 427.4\ C \pm 2.56\%/5.670\ cm^2 = 75.38\ C/cm^2 \pm 2.56\%\ . \qquad (4\text{-}10)$$
(OCO-2)

The error of 2.56% was calculated using the standard deviation in the linear-least-squares slope as listed in Table 4-2.

Hence, the Oconee 2 value for q_∞ is 8.0% larger than the pool-reactor value. The reason for this difference is unclear at this writing, but differences in the neutron energy spectra in the two reactors may be responsible. The reader is cautioned that q_∞ in Eq. 4-10 holds strictly only for Rh emitters of approximately 0.046 cm (.018 in.) diameter. The quantity may be different for emitters with diameters significantly different from this.

Through Eq. 4-8, the Oconee 2 experimental q_∞ value can be used to construct a depletion correction factor for a given-size Rh detector in the PWR. Babcock & Wilcox's standard Rh detector has an emitter mass of 0.250 g and length of 12.19 cm. The depletion correction factor for this detector is

$$f(t) = 1 \bigg/ \left[1 - 0.00755\ Q(t)\right] \ . \qquad (4\text{-}11)$$

Eq. 4-8 provides the means of comparing depletion correction factors for Rh emitters of different lengths. The emitter length and mass appear in the equation because the lateral surface area of the emitter was introduced in Eq. 4-3. The introduction of emitter surface area as a normalizing factor has been proven justified in calculations of Rh emitter sensitivities (4), in measurements of sensitivities at the B&W test reactor, and in B&W's previous depletion measurements in the 6 MW test reator (3).

Section 5

CONCLUSIONS AND RECOMMENDATION

CONCLUSIONS

- The Oconee 2 experiment is producing high-quality data, and is expected to define accurately Rh depletion when the experiment is carried to completion.

- Through two fuel cycles of detector exposure, the depletion curve is essentially linear. However, there has been a decrease in the slope of the curve (the burnout rate) between fuel cycles 2 and 3 of approximately 15%. At this time the cause of this change is uncertain, but the decrease may be related to differences in the beginning-of-cycle burnup of the two fuel assemblies used during the two cycles at the core location where the Rh detectors are positioned.

- The Rh depletion rate in the PWR is approximately 8% less than the rate in a pool reactor.

RECOMMENDATION

- The Oconee 2 Rh depletion experiment must continue for at least two additional fuel cycles of detector exposure to cover most of the operational life of a Rh detector in a PWR. Otherwise, the depletion correction to a Rh detector signal will be based on extrapolated data during the last fuel cycles of exposure of the detector. As a consequence, the uncertainty in the detector signal will be larger.

Section 6

REFERENCES

1. Proceedings of the IAEA Specialists' Meeting On In-Core Instrumentation and Failed Fuel Detection and Location, AECL-1524, May 1974, pp 7-177.

2. T. Laaksonen and J. Saastamoinen. Ibid. p. 111.

3. H. D. Warren. "Depletion Characteristics of Beta-Decaying SPNDs." In Transactions of the American Nuclear Society, Vol. 23, June 1976, p. 460.

4. H. D. Warren. "Calculational Model For Self-Powered Neutron Detector." Nuclear Science & Engineering, Vol. 48, 1972, pp. 331-342.