Rhodium In-Core Detector Sensitivity Depletion, Cycles 2-4

NP-1715
Research Project 1397-1

Interim Report, February 1981

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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 process have prevented this change.

PROJECT OBJECTIVE

The objective of RP1397 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

As opposed to results reported earlier (EPRI Interim Report NP-1405, May 1980), the linearity of the sensitivity depletion curve does not appear to vary with the fuel burnup in the assemblies where the experimental detectors are located. Furthermore, the uncertainty in the slope of the curve has been reduced by a factor of 3. These results are now being used in measuring the core power distribution in Babcock and Wilcox reactors; an additional benefit is that the measured power distribution is now closer to that predicted by the computer codes. The experiment will continue for at least one additional fuel cycle.

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
Nuclear Power Division

ABSTRACT

Sensitivity depletion of two rhodium (Rh) self-powered neutron detectors (SPNDs) 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.

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 sensitivity depletion rate of the Rh detector in the PWR is highly linear with charge released from the detector. In contrast to preliminary observations reported earlier, there appears to be no 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.

ACKNOWLEDGMENTS

The authors are grateful for the contribution of W. D. Ayres, M. L. Gilbert, E. L. Glass, and C. L. Gray, all of B&W.

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

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SUMMARY

INTRODUCTION

The Babcock and Wilcox Company (B&W) has had a rhodium (Rh) self-powered neutron detector (SPND) sensitivity depletion experiment underway since July 1976 in Duke Power Company's Oconee 2 pressurized water reactor (PWR) at Seneca, South Carolina. The detectors are now approximately 35% depleted, and the depletion characteristics are becoming well-defined. 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 neutron sensitivity of a Rh detector operating as part of an incore monitoring system in a PWR is continuously corrected for depletion by the plant on-line computer. The correction is based upon empirical data that defines sensitivity as a function of electric charge released from the detector (which is a function of integrated neutron exposure to the detector). The accuracy of the correction is directly related to the accuracy of the empirical data. Existing depletion data permit a PWR lifetime for the Rh detector of about "60% depletion" before correction errors become unacceptable. The Oconee 2 experiment will provide a new depletion data base that will permit accurate depletion corrections to 70% or 80% sensitivity depletion. Thus, the operational lifetime of the Rh detector can be significantly extended, and costs to the Utility for replacement detectors will be correspondingly reduced. This is the motivation for performing the Oconee 2 experiment.

SCOPE OF WORK

Sensitivity depletion of two alumina-insulated Rh detectors in the Oconee 2 experimental detector assembly has been measured periodically since July 1976. One hundred three sets of data points have been obtained for each detector during fuel cycles 2, 3, and 4 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.")

The depletion data have been corrected for the effects of neutron flux depression by the movable Rh detector on the signal of the fixed Rh detector and vice versa. Regression analysis of the depletion data from fuel cycles 2, 3, and 4 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 three fuel cycles of neutron exposure, the combined depletion data from the two Rh detectors produce the following expression for the relative detector sensitivity at time t versus expended charge, Q(t):

$$\frac{S(t)}{S(0)} = 1 - \frac{0.01313}{\sqrt{mL}} Q(t),$$

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

The detector sensitivity depletion correction factor at time t is the inverse of this equation. Error in the slope of the equation arises from errors in the measurements of relative sensitivity. By extending the experiment at Oconee 2 through a third fuel cycle (cycle 4), the error in the slope has been reduced by a factor of 3 from the value that existed at the end of only two fuel cycles (from 1.28% to 0.43%). Because the uncertainty in the slope is now smaller, depletion corrections to the Rh detector neutron sensitivity can be made with greater accuracy. Core power distributions measured by the Rh detectors of a PWR incore monitoring system will be more accurate as a consequence of more precise corrections for sensitivity depletion.

CONCLUSIONS

- No appreciable errors in the Rh depletion data were incurred from the loss of two movable calibration detectors during Oconee 2 fuel cycle 4. Normalization of the cycle 4 data to the cycles 2 and 3 data was accurately performed.

- After three fuel cycles the depletion curve continues to be well-behaved and have good accuracy. The curve remains highly linear.

- With the addition of depletion data from fuel cycle 4, uncertainty in the slope of the Rh sensitivity depletion curve has been reduced by a factor of 3 from its value at the end of fuel cycle 3. Therefore, corrections to Rh detector signals for sensitivity depletion are correspondingly more accurate. Depletion corrections based on this latest data have been implemented at B&W PWRs. Measurements of core power distributions in these reactors are now more accurate and beneficial to the PWR operators.

- After three fuel cycles the Rh detectors in the Oconee 2 experiment are about 35% depleted. The detectors have been in the reactor for almost 4 years. Another two or three years of exposure in the reactor will be required to deplete the detectors to $\sim$60%.

- There appears to be no effect on the Rh sensitivity depletion rate from changes in fuel assemblies (around the two fixed Rh detectors) during Oconee 2 refueling.

RECOMMENDATION

The experiment at Oconee 2 must continue for at least one additional fuel cycle 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 may become larger the more the sensitivity of the detector depletes.

Section 1

INTRODUCTION

The Rhodium Self-Powered Neutron Detector Sensitivity Depletion experiment continues at Oconee 2, funded by the Electric Power Research Institute (EPRI). The experiment began with fuel cycle 2 in July 1976, sponsored by the Babcock & Wilcox Company (B&W). In 1978, after two fuel cycles of exposure to the rhodium (Rh) SPNDs, EPRI assumed funding responsibility for the project.

The experimental equipment and arrangement and the measured depletion data for the first two fuel cycles of exposure of the SPNDs have been described in a previous report (1). Since that report, the two Rh detectors have undergone a third cycle of exposure (fuel cycle 4).

Sensitivity depletion of the two detectors is being measured by periodically using an undepleted movable Rh calibration detector to measure the remaining sensitivity of each detector as one of the variables of a depletion curve. An on-line computer continuously integrates the current signals from the fixed Rh detectors to form the second variable: the total charge released by a detector from initial neutron exposure to the present. The depletion curve is formed by plotting relative sensitivity (relative to movable Rh) versus charge released.

The last cycle of exposure (fuel cycle 4) began in January 1979 and was completed on March 4, 1980. Twice during the cycle, once at the beginning and again at mid-cycle, the movable Rh calibration detector was inadvertently broken and was replaced with a new detector. The effects on the measured sensitivity of the two fixed Rh detectors from these changes in calibration detector have been closely examined. The data from fuel cycle 4 have been analyzed to determine the magnitude of any effects from the changes.

This report gives the depletion data accumulated during fuel cycle 4, the analysis of that data, and the revised Rh depletion curve for three fuel cycles of exposure, incorporating the cycle 4 data.

Section 2

ANALYSIS OF Rh DEPLETION DATA FROM OCONEE 2 FUEL CYCLE 4

There were 32 measurements of relative sensitivity of the two Rh detectors during fuel cycle 4 — sixteen using the first replacement movable Rh calibration detector during the first half of the cycle, and sixteen others using the second calibration detector over the last half of the cycle. Table 2-1 gives the physical characteristics of the two calibration detectors. Table 2-2 gives the relative sensitivity as measured with the two calibration detectors.

The first and second sets of 16 depletion data points for each detector in Table 2-2 were individually fit by a linear curve in a least-squares procedure. Then all the data for each detector and the two detectors together were least-squares fit. The curve-fitting parameters are listed in Table 2-3. To determine if any relative sensitivity "offset" was caused by the change at mid-cycle from calibration detector with serial number S/N 001 to the other with serial number S/N 002, the two least-squares curves for a detector were evaluated at a value of charge released from the detector, Q, approximately mid-way between the two sets of data. For example, the least-squares curves for detector L11-R3 were:

Cal. Det. S/N 001: Rel. Sens. = 0.96067 - 0.00187Q

Cal. Det. S/N 002: Rel. Sens. = 1.04597 - 0.00259Q

The value of Q = 124.0 coulombs occurred approximately half-way between the data taken with S/N 001 and that taken with S/N 002. Substituting the value into the above equations gives:

<u>Q = 124.0C</u>

Cal. Det. S/N 001: Rel. Sens. = 0.7288

Cal. Det. S/N 002: Rel. Sens. = 0.7248

Given the uncertainties in the slopes of the two linear curves, there is no significant difference in these two values of relative sensitivity. Hence, all the data for L11-R3 during fuel cycle 4 can be treated as a unified set with no distinction between data taken with calibration detectors S/N 001 and S/N 002. In other words, there was no significant difference in the neutron sensitivities of the two calibration detectors. This conclusion is substantiated by the result of least-squares fitting a linear curve to the total set of cycle 4 data for L11-R3. The fitting parameters — listed in Table 2-3 — show a closer fit to the total set of data than to either of the sets for the two calibration detectors treated individually.

A similar examination of the least-squares results for detector L11-R5 led to the same conclusion: the data for L11-R5 during fuel cycle 4 can also be treated as a unified set without consideration for which calibration detector was used.

The averaged experimental data from Table 2-2 for L11-R5 are plotted in Figure 2-1. The linear least squares curve is drawn through the data points.

Table 2-1

PHYSICAL CHARACTERISTICS OF MOVABLE TWIN-LEAD Rh CALIBRATION SPNDS USED IN OCONEE 2 EXPERIMENT DURING FUEL CYCLE 4

Item	Det. S/N 001*	Det. S/N 002**
Emitter, mass, g:	0.810	0.810
Emitter length, cm:	39.57	39.27
Emitter dia., cm:	0.0457	0.0460
Leadwire mat'l:	Inconel 600	Inconel 600
Leadwire diameters, cm:	0.024	0.023
Detector tip to emitter end, cm:	1.91	1.50
Detector OD, cm:	0.160	0.157
Detector insulation:	Al_2O_3	Al_2O_3
Detector length, m:	32.31	32.31

- - - - -

*Manufacturer Job No. 6007

**Manufacturer Job No. 9178

Table 2-2

MEASURED VALUES OF RELATIVE SENSITIVITY
VS EXPENDED CHARGE FOR TWO Rh
DETECTORS IN OCONEE 2 FUEL ASSEMBLY L11,
FUEL CYCLE 4

	Rh Det. L11-R3				Rh Det. 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
	Calibration Detector S/N 001							
2-25-79	0.7641	103.7			0.7527	111.7		
2-25	0.7650	103.7	0.7658	103.8	0.7537	111.7	0.7533	111.8
2-26	0.7645	103.8	±0.25%		0.7517	111.8	±0.16%	
2-26	0.7669	103.8			0.7533	111.9		
2-26	0.7686	103.9			0.7550	111.9		
3-27	0.7616	107.9			0.7470	116.4		
3-28	0.7613	108.0	0.7606	108.0	0.7461	116.5	0.7459	116.5
3-28	0.7613	108.0	±0.22%		0.7461	116.5	±0.15%	
3-28	0.7581	108.0			0.7444	116.5		
4-24	0.7531	111.6			0.7352	120.5		
4-24	0.7507	111.6	0.7508	111.6	0.7341	120.5	0.7342	120.5
4-24	0.7486	111.6	±0.30%		0.7332	120.5	±0.14%	
6-12	0.7473	114.7			0.7267	123.8		
6-12	0.7464	114.7	0.7466	114.7	0.7295	123.8	0.7282	123.8
6-12	0.7460	114.7	±0.09%		0.7285	123.8	±0.19%	
7-17	0.7367	119.2			0.7172	128.5		

Table 2-2 (Continued)

	Rh Det. L11-R3				Rh Det. 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
	Calibration detector S/N 001 broken. Replaced by S/N 002.							
10-30	0.7111	129.6			0.6938	139.0		
10-30	0.7134	129.6			0.6934	139.0		
10-30	0.7133	129.6	0.7117	129.6	0.6938	139.0	0.6933	139.0
10-30	0.7122	129.6	±0.21%		0.6933	139.0	±0.07%	
10-30	0.7108	129.6			0.6929	139.0		
10-30	0.7096	129.6			0.6925	139.0		
11-20	0.7045	132.4			0.6857	141.8		
11-20	0.7032	132.4	0.7035	132.4	0.6850	141.8	0.6847	141.8
11-20	0.7040	132.4	±0.14%		0.6846	141.8	±0.13%	
11-20	0.7023	132.5			0.6836	141.9		
12-18	0.6889	136.1			0.6765	145.6		
12-18	0.6903	136.1	0.6898	136.1	0.6752	145.7	0.6748	145.7
12-18	0.6903	136.1	±0.12%		0.6728	145.7	±0.28%	
1-18-80	0.6867	140.2			0.6619	149.8		
1-18	0.6855	140.2	0.6861	140.2	0.6628	149.8	0.6622	149.8
1-18	0.6861	140.2	±0.09%		0.6620	149.8	±0.07%	

Table 2-3

LINEAR REGRESSION ANALYSIS OF MEASURED
Rh DETECTOR RELATIVE SENSITIVITY VS EXPENDED
CHARGE IN OCONEE 2 REACTOR, FUEL CYCLE 4

	Movable	Linear Regression Analysis Results				
Fixed Rh Det.	Cal. Det S/N	Intercept	Slope	Std. Dev. of Slope	Coeff. of Multi. Corr.	Std. Dev. of Est.
L11-R3	001	0.96067	-0.00187	0.00011	0.97805	0.00202
L11-R3	002	1.04597	-0.00259	0.00016	0.97295	0.00260
L11-R5	001	0.99620	-0.00217	0.00008	0.99063	0.00166
L11-R5	002	1.08880	-0.00285	0.00006	0.99725	0.00092
L11-R3	001/002	1.00507	-0.00228	0.00004	0.99573	0.00281
L11-R5	001/002	1.01943	-0.00236	0.00003	0.99800	0.00207
L11-R3 +L11-R5	001/002	1.00661	-0.00228	0.00003	0.99540	0.00309

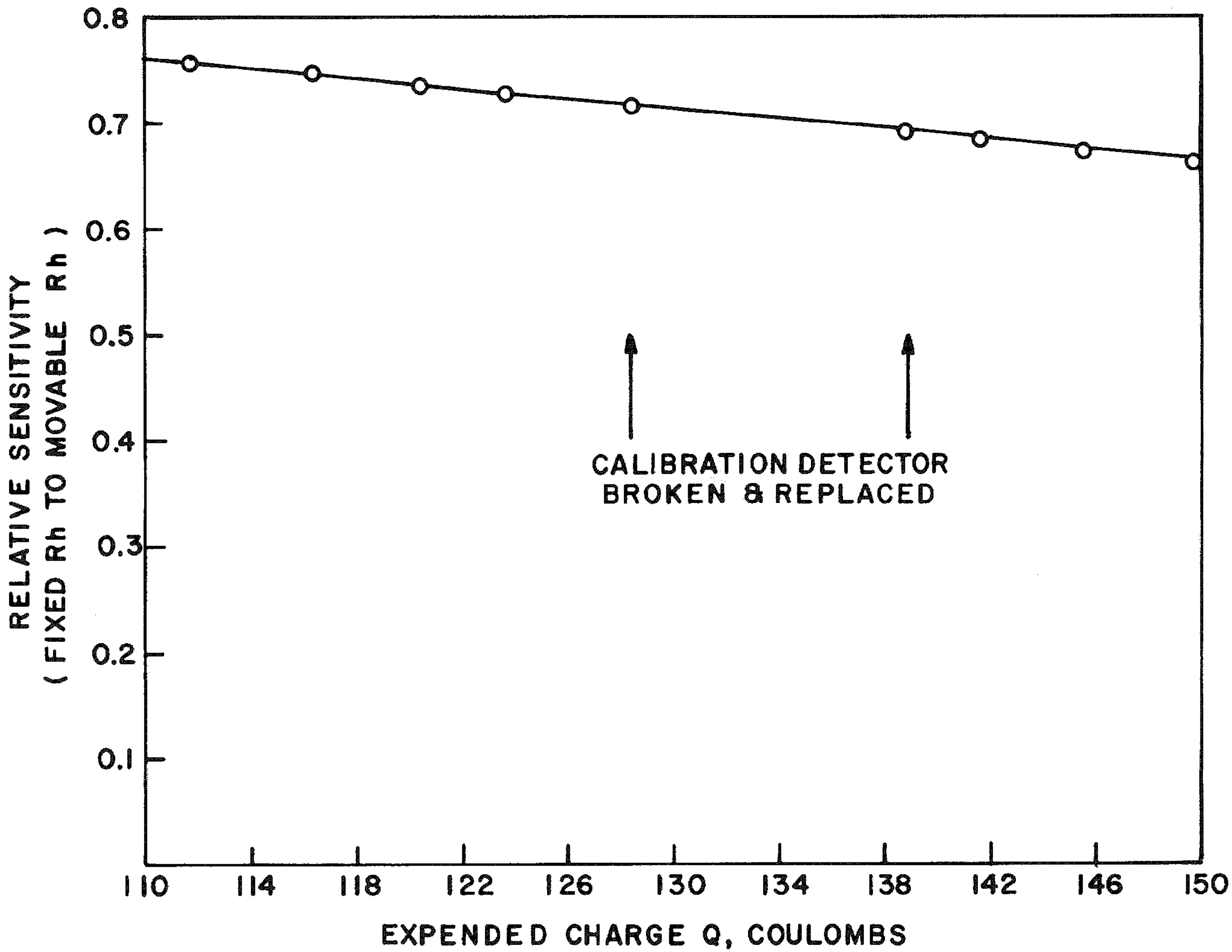

Figure 2-1. Measured Sensitivity Depletion for Rh Detector L11-R5 During Oconee 2 Fuel Cycle 4. Two different movable calibration detectors were used during the cycle, but there was no "offset" in relative sensitivity between the two sets of data.

Section 3

ANALYSIS OF Rh DEPLETION DATA FROM OCONEE 2 FUEL CYCLES 2, 3, AND 4

NORMALIZATION OF CYCLE 4 DATA

Figure 3-1 shows the averaged depletion data for all three fuel cycles of detector exposure for detector L11-R3. Data for the first two cycles were taken from Reference 1. Cycle 4 data came from Table 2-2. There is a distinct offset between the linear least-squares curve for the fuel cycles 2 and 3 data and the curve for the cycle 4 data. However, the slopes of the two curves are essentially the same.

To normalize the cycle 4 data to the data from the other two cycles, the relative sensitivities measured during cycle 4 were multiplied by a "normalizing factor." This factor was defined to be the one that resulted in the "best fit" of a linear curve to the total set of data; i.e., data from cycles 2 and 3 and the normalized cycle 4 data.

The normalizing factor that gave the best fit of all the data to a linear curve was

$$\overline{NF} = 0.966.$$

Table 3-1 lists the coefficient of multiple correlation (i.e., the "closeness of fit") versus the normalizing factor.

Table 3-2 contains fuel cycle 4 depletion data normalized to the data of cycles 2 and 3; i.e., each relative sensitivity value from Table 2-2 was multiplied by 0.966 to form the relative sensitivity in Table 3-2.

The resulting linear least-squares fitting parameters for the three cycles of data are given in Table 3-3. By comparing these parameters against the corresponding ones in Table 4-2 or Reference 1 (the curve-fitting parameters for fuel cycles 2 and 3), it is clear that adding cycle 4 depletion data to the depletion curve improved the curve. The multiple correlation coefficient improved from 0.99101 to 0.99704, indicating a better linear fit with cycle 4 data included. Hence, the normalized cycle 4 data are consistent with the cycle 2 and 3 data.

Table 3-1

FACTOR USED TO NORMALIZE OCONEE 2 FUEL CYCLE 4 Rh DEPLETION DATA TO CYCLE 2 AND 3 DATA VS COEFFICIENT OF MULTIPLE CORRELATION (CLOSENESS-OF-FIT PARAMETER) FOR LINEAR LEAST SQUARES FIT TO DATA FROM ALL 3 CYCLES (AFTER THIS NORMALIZATION)

Normalizing Factor, Cycle 4 Data	Coefficient of Multiple Correlation*
0.955	0.99686
0.959	0.99697
0.960	0.99699
0.961	0.99701
0.962	0.99702
0.963	0.99703
0.964	0.99703
0.965	0.99704
0.966	0.99704
0.967	0.99704
0.968	0.99703
0.969	0.99702
0.970	0.99700
0.971	0.99698
0.975	0.99688

*When the coefficient of multiple correlation $\equiv$ 1.00000, the fitting curve passes through each data point.

Table 3-2

RELATIVE SENSITIVITY VS EXPENDED CHARGE FOR TWO Rh DETECTORS IN OCONEE 2 FUEL ASSEMBLY L11, FUEL CYCLE 4. RELATIVE SENSITIVITY NORMALIZED BY MULTIPLYING BY 0.966.

	Rh Det. L11-R3				Rh Det. 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
2-25-79	0.7381	103.7			0.7271	111.7		
2-25	0.7390	103.7			0.7281	111.7		
2-26	0.7385	103.8	0.7398	103.8	0.7261	111.8	0.7276	111.8
2-26	0.7408	103.8	±0.25%		0.7277	111.9	±0.16%	
2-26	0.7425	103.9			0.7293	111.9		
3-27	0.7357	107.9			0.7216	116.4		
3-28	0.7354	108.0	0.7347	108.0	0.7207	116.5	0.7205	116.5
3-28	0.7354	108.0	±0.22%		0.7207	116.5	±0.14%	
3-28	0.7323	108.0			0.7191	116.5		
4-24	0.7275	111.6			0.7102	120.5		
4-24	0.7252	111.6	0.7253	111.6	0.7091	120.5	0.7092	120.5
4-24	0.7231	111.6	±0.30%		0.7083	120.5	±0.13%	
6-12	0.7219	114.7			0.7020	123.8		
6-12	0.7210	114.7	0.7212	114.7	0.7047	123.8	0.7035	123.8
6-12	0.7206	114.7	±0.09%		0.7037	123.8	±0.19%	
7-17	0.7117	119.2			0.6928	128.5		

Table 3-2 (Continued)

	Rh Det. L11-R3				Rh Det. 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
10-30	0.6869	129.6			0.6702	139.0		
10-30	0.6891	129.6			0.6698	139.0		
10-30	0.6890	129.6	0.6875	129.6	0.6702	139.0	0.6697	139.0
10-30	0.6880	129.6	±0.21%		0.6697	139.0	±0.07%	
10-30	0.6866	129.6			0.6693	139.0		
10-30	0.6855	129.6			0.6690	139.0		
11-20	0.6805	132.4			0.6624	141.8		
11-20	0.6793	132.4	0.6796	132.4	0.6617	141.8	0.6615	141.8
11-20	0.6801	132.4	±0.14%		0.6613	141.8	±0.13%	
11-20	0.6784	132.5			0.6604	141.9		
12-18	0.6655	136.1			0.6535	145.6		
12-18	0.6668	136.1	0.6664	136.1	0.6522	145.7	0.6519	145.7
12-18	0.6668	136.1	±0.11%		0.6499	145.7	±0.28%	
1-18-80	0.6634	140.2			0.6394	149.8		
1-18	0.6622	140.2	0.6628	140.2	0.6403	149.8	0.6397	149.8
1-18	0.6628	140.2	±0.09%		0.6395	149.8	±0.08%	

*Relative sensitivity in this table is 0.966 times the corresponding relative sensitivity in Table 2-2. This multiplication normalizes the data from fuel cycle 4 to the data from cycles 2 and 3.

Table 3-3

LINEAR REGRESSION ANALYSIS OF Rh DETECTOR RELATIVE SENSITIVITY VS EXPENDED CHARGE IN OCONEE 2 REACTOR, FUEL CYCLES 2, 3 AND 4. (NORMALIZED CYCLE 4 DATA WERE USED. CORRECTION FOR "MUTUAL-FLUX-DEPRESSION" NOT YET APPLIED.)

	Linear Regression Analysis Results				
Fixed Rh Det.	Intercept	Slope	Std. Dev. of Slope	Coeff. of Mult. Corr.	Std. Error of Est.
L11-R3	0.99133	-0.00236	0.00002	0.99685	0.00835
L11-R5	0.99328	-0.00234	0.00002	0.99740	0.00804
L11-R3 +L11-R5	0.99211	-0.00235	0.00001	0.99704	0.00831

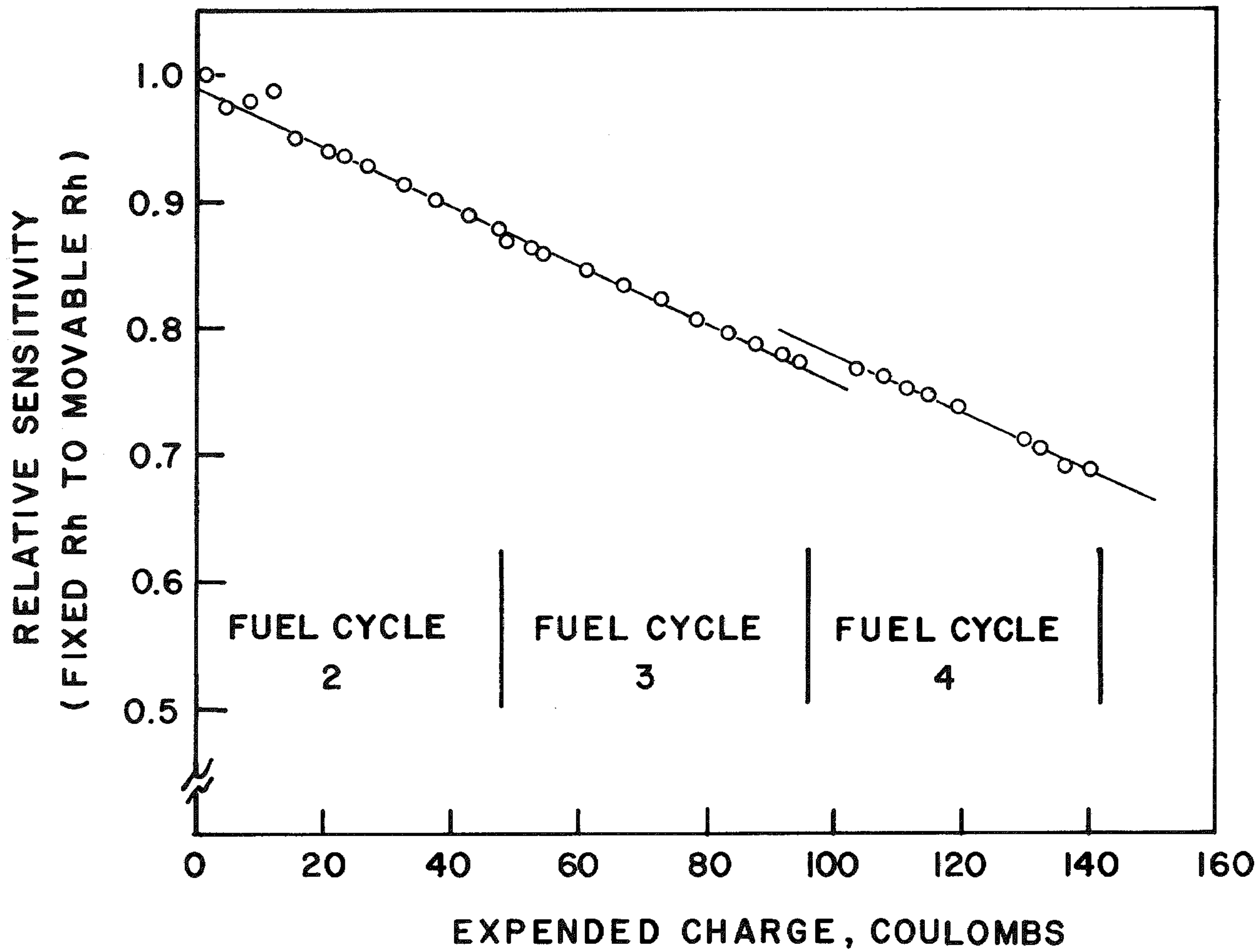

Figure 3-1. Sensitivity Depletion Curve for Rh Detector L11-R3 as Measured Over Three Oconee 2 Fuel Cycles. Replacement of movalbe calibration detector between cycles 3 and 4 caused offset in depletion curves. Curves are linear least squares fit to data.

CORRECTION TO RELATIVE SENSITIVITY FOR MUTUAL-FLUX-DEPRESSION BY THE Rh DETECTORS

When a Rh detector is placed in the neutron flux in the PWR, the flux at the detector location is depressed slightly because of neutron absorption within the Rh emitter. The signal of any other incore detector positioned adjacent to the Rh detector will be affected by the depression in the flux. When a movable Rh detector is used to calibrate a fixed Rh detector – as in this experiment – the presence of each detector adjacent to the other causes a small error in the signal of each detector. The movable Rh detector has no sensitivity depletion so the effect on the fixed Rh signal from the presence of the movable Rh is always constant; i.e.,

$$I_{fixed,meas.} = a\, I_{fixed,unperturbed} \quad (3\text{-}1)$$

where $I_{fixed,meas.}$ = current measured from the fixed Rh detector while the movable Rh detector is adjacent to it,

$I_{fixed,unperturbed}$ = current measured from the fixed Rh detector when movable Rh detector is not adjacent to it (but no change in overall neutron flux shape),

a = constant of proportionality.

The fixed Rh detector has a continuously decreasing neutron sensitivity, so the effect of the fixed Rh detector on the movable Rh detector signal (when the movable is adjacent to the fixed) also decreases; i.e.,

$$I_{movable,\ meas.} = f(Q)\, I_{movable,unperturbed} \quad (3\text{-}2)$$

where $I_{movable,meas.}$ = current measured from movable Rh detector while it is positioned adjacent to the fixed Rh detector,

$I_{movable,unperturbed}$ = current that would be measured for the movable detector at the fixed detector location if the fixed detector were not there (but no change in overall neutron flux shape),

$f(Q)$ = function that defines the relationship between the two current signals at any given value of expended charge, Q, from the adjacent fixed detector.

From experimental measurements (1) we know that the neutron sensitivity depletion of the fixed Rh detector is a linear function of its expended charge. Hence, the amount of depression in the neutron flux caused by the fixed detector, or the effect of the fixed detector on the signal of the movable detector, will also be a linear function of the expended charge of the fixed detector; i.e.,

$$f(Q) = b + cQ, \tag{3-3}$$

where b and c are constants.

The boundary conditions for Equation (3-3) are as follows:

$$f(0) = a \quad \text{[as in Equation (3-1)]},$$

$$f(Q_\infty) = 1.$$

When Q=0, the fixed detector has no sensitivity depletion, and its effect on the movable detector is the same as the effect of the movable detector on the fixed. When $Q=Q_\infty$, the fixed detector is completely depleted and has no significant effect on the movable detector signal. Therefore, Equation (3-3) becomes

$$f(Q) = a + \frac{(1-a)}{Q_\infty} Q, \tag{3-4}$$

where Q_∞ is the total charge that can be released from a fixed Rh detector.

The relative sensitivity of the fixed Rh detector to the movable Rh detector corrected for mutual-flux-depression can be found by dividing Equation (3-1) by Equation (3-2), then cross multiplying:

$$\frac{I_{\text{fixed,unperturbed}}}{I_{\text{movable,unperturbed}}} = \frac{f(Q)}{a} \times \frac{I_{\text{fixed,meas.}}}{I_{\text{movable,meas.}}} \tag{3-5}$$

Substituting Equation (3-4) for f(Q), and defining the current ratios as "Rel. Sens.," the corrected relative sensitivity is

$$\text{Rel. Sens.}_{corr.} = \frac{a+(1-a)\frac{Q}{Q_\infty}}{a} \times \text{Rel. Sens.}_{meas.}$$

$$= [1 + (\frac{1-a}{aQ_\infty})Q] \times \text{Rel. Sens.}_{meas.} \qquad (3\text{-}6)$$

Thus, if constant a and Q_∞ are known, the measured relative sensitivity can be corrected for the mutual-flux-depression effect of the fixed and movable detectors.

Table 3-4 lists ten values for constant a as determined from the currents from the two fixed Rh detector in the Oconee 2 experiment. The data were recorded shortly after the detectors were first installed in the reactor core in July 1976. The average of the 10 values is:

$$a = 0.9830 \pm 0.0010 \qquad (3\text{-}7)$$

Spot checks of the data from the experiment since June 1976 have shown that this value for constant a has not changed throughout the experiment.

Table 3-4

CONSTANT OF PROPORTIONALITY "a" THAT RELATES SIGNAL MEASURED FOR FIXED Rh DETECTOR (WITH MOVABLE Rh DETECTOR ADJACENT TO IT) TO SIGNAL OF FIXED Rh DETECTOR WITH MOVABLE Rh DETECTOR NOT PRESENT

Date	Fixed Rh Det. Current Without Movable Rh Det. Adjacent, nA		Fixed Rh Det. Current With Movable Rh Det. Adjacent,nA		Constant of Proportionality, "a"	
	L11-R3	L11-R5	L11-R3	L11-R5	L11-R3	L11-R5
7-20-76	1940	2336	1906	2294	0.9825	0.9820
7-21-76	1923	2339	1891	2300	0.9834	0.9833
7-21-76	1921	2333	1888	2291	0.9828	0.9820
7-23-76	2036	2449	2004	2404	0.9843	0.9816
7-23-76	2023	2478	1992	2437	0.9847	0.9835

Average "a" = 0.9830 ± 0.0010

The value of Q_∞ to be first inserted in Equation (3-6) is the inverse of the slope of the depletion curve (i.e., relative sensitivity versus expended charge) without the mutual-flux-depression correction applied. The inverse of the slope given in the third entry in Table 3-3 is:

$$Q_\infty = 425.5C.$$

Hence, the relative sensitivity of the fixed rhodium detectors corrected for the effects of mutual-flux-depression is given by

$$\text{Rel. Sens.}_{\text{corr.}} = (1 + 4.064 \times 10^{-5} Q)\text{Rel. Sens.}_{\text{meas.}} \quad (3\text{-}8)$$

(first application)

When Equation (3-8) is applied to all the measured relative sensitivity values for this experiment (data from Oconee 2 fuel cycles 2, 3, and 4), and the cycle 4 data is again normalized to the cycle 2 and 3 data as described previously, linear least squares fitting of relative sensitivity versus expended charge defines a new slope for the depletion curve and, therefore, a new value for Q_∞. Thus, an iterative procedure is required to determine the exact effect of mutual-flux-depression.

Only two iterations were needed to make Q_∞ converge to a unique value. The final equation for the relative sensitivity was:

$$\text{Rel. Sens.}_{\text{corr.}} = (1 + 4.030 \times 10^{-5} Q)\text{Rel. Sens.}_{\text{meas.}} \quad (3\text{-}9)$$

(final iteration)

Throughout the iterative process, the factor needed to normalize the cycle 4 relative sensitivity values to those of cycles 2 and 3 did not change from its initial value of 0.966.

Table 3-5 gives the relative sensitivity values corrected for the effects of mutual-flux-depression by the fixed and movable Rh detectors. The corresponding values of expended charge for the fixed Rh detectors are also given. Data from Oconee 2 fuel cycles 2, 3 and 4 are included. The cycle 4 relative sensitivity values were normalized to the cycles 2 and 3 data by multiplying the cycle 4 values by the factor 0.966. The data in Table 3-5 are the data to be used to determine the latest neutron sensitivity depletion curve for the Rh detector.

Table 3-5

CORRECTED VALUES OF RELATIVE SENSITIVITY VS EXPENDED CHARGE FOR TWO Rh INCORE DETECTORS IN OCONEE 2 FUEL ASSEMBLY L11, FUEL CYCLES 2, 3, AND 4. RELATIVE SENSITIVITIES CORRECTED FOR "MUTUAL-FLUX-DEPRESSION." CYCLE 4 DATA NORMALIZED TO CYCLES 2 AND 3 DATA BY MULTIPLYING FACTOR 0.966.

	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			1.0128	1.3		
7-21	1.0002	1.1	0.9995	1.2	1.0136	1.3	1.0139	1.4
7-23	0.9996	1.3	±0.04%		1.0148	1.4	±0.11%	
7-23	0.9996	1.5			1.0129	1.8		
8-17	0.9689	4.4			0.9670	5.2		
8-17	0.9772	4.4	0.9739	4.4	0.9772	5.2	0.9714	5.2
8-18	0.9757	4.5	±0.45%		0.9700	5.3	±0.54%	
9-9	0.9591	8.1			0.9543	9.5		
9-9	0.9318	8.1	0.9577	8.1	0.9381	9.5	0.9529	9.5
9-10	0.9821	8.2	±2.63%		0.9663	9.6	±1.49%	
9-30	0.9838	11.7			0.9736	13.5		
9-30	0.9655	11.7	0.9875	11.7	0.9598	13.6	0.9749	13.6
10-1	1.0132	11.8	±2.44%		0.9913	13.7	±1.62%	
10-23	0.9403	15.2			0.9424	17.5		
10-23	0.9551	15.2	0.9502	15.3	0.9484	17.5	0.9469	17.5
10-24	0.9551	15.4	±0.90%		0.9499	17.6	±0.42%	
11-21	0.9432	20.3			0.9361	22.9		
11-21	0.9422	20.3	0.9421	20.4	0.9352	22.9	0.9352	23.0
11-22	0.9408	20.5	±0.13%		0.9343	23.1	±0.10%	

Table 3-5 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
12-29	0.9453	23.1			0.9287	25.9		
12-30	0.9306	23.2	0.9379	23.3	0.9258	26.0	0.9288	26.1
12-30	0.9387	23.3	±0.65%		0.9299	26.1	±0.23%	
12-31	0.9368	23.4			0.9306	26.2		
1-23-77	0.9401	27.4			0.9141	30.4		
1-23	0.9275	27.4	0.9281	27.5	0.9175	30.4	0.9167	30.5
1-24	0.9223	27.5	±0.90%		0.9166	30.5	±0.21%	
1-24	0.9225	27.5			0.9187	30.5		
2-21	0.9152	32.3			0.9157	35.4		
2-22	0.9131	32.4	0.9139	32.4	0.9083	35.5	0.9111	35.5
2-22	0.9133	32.4	±0.13%		0.9092	35.5	±0.44%	
3-26	0.9010	37.3			0.8986	40.5		
3-26	0.9016	37.3	0.9018	37.3	0.8973	40.6	0.8976	40.6
3-27	0.9027	37.4	±0.10%		0.8968	40.7	±0.10%	
4-24	0.8904	42.1			0.8832	45.3		
4-24	0.8896	42.2	0.8903	42.2	0.8849	45.3	0.8843	45.3
4-25	0.8909	42.3	±0.07%		0.8847	45.4	±0.11%	
5-23	0.8802	47.1			0.8773	50.0		
5-24	0.8804	47.2	0.8802	47.2	0.8761	50.1	0.8757	50.1
5-24	0.8801	47.3	±0.02%		0.8736	50.1	±0.22%	

Table 3-5 Cont'd

Date	Rh Detector L11-R3 Rel. Sens.	Expended Charge, C	Average Rel. Sens.	Average Exp. Charge, C	Rh Detector L11-R5 Rel. Sens.	Expended Charge, C	Average Rel. Sens.	Average Exp. Charge, C
	END OF OCONEE 2 FUEL CYCLE 2							
9-3-77	0.8706	48.7	0.8679	48.8	0.8728	51.6	0.8722	51.7
9-4	0.8551	48.8	±0.45%		0.8715	51.7	±0.11%	
11-3	0.8645	52.3	0.8643	52.4	0.8617	55.9	0.8610	56.0
11-3	0.8641	52.4	±0.03%		0.8602	56.0	±0.12	
11-30	0.8630	54.2			0.8600	58.0		
11-30	0.8608	54.2	0.8615	54.2	0.8591	58.1	0.8595	58.1
12-1	0.8607	54.3	±0.15%		0.8595	58.1	±0.05%	
2-9-78	0.8467	60.8			0.8378	65.8		
2-9	0.8479	60.8	0.8470	60.8	0.8416	65.8	0.8401	65.8
2-9	0.8465	60.9	±0.09%		0.8409	65.8	±0.24%	
3-15	0.8360	66.4			0.8282	72.1		
3-15	0.8346	66.4	0.8352	66.4	0.8270	72.1	0.8273	72.1
3-15	0.8351	66.4	±0.09%		0.8266	72.1	±0.10%	
5-10	0.8244	72.2			0.8155	78.5		
5-11	0.8227	72.3	0.8234	72.3	0.8135	78.6	0.8141	78.6
5-11	0.8231	72.3	±0.11%		0.8134	78.6	±0.15%	
6-20	0.8087	78.6			0.7977	85.4		
6-21	0.8092	78.7	0.8090	78.7	0.7989	85.4	0.7974	85.4
6-21	0.8091	78.7	±0.03%		0.7956	85.5	±0.21%	
7-24	0.8000	83.0			0.7977	90.0		
7-25	0.7989	83.1	0.7993	83.1	0.7899	90.1	0.7900	90.1
7-25	0.7990	83.1	±0.08%		0.7900	90.1	±0.01%	

Table 3-5 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
9-5	0.7893	87.5			0.7777	94.7		
9-5	0.7922	87.5	0.7903	87.5	0.7787	94.7	0.7783	94.7
9-5	0.7894	87.5	±0.21%		0.7785	94.7	±0.07%	
10-2	0.7822	91.8			0.7645	99.0		
10-3	0.7826	91.9	0.7822	91.9	0.7688	99.1	0.7669	99.1
10-3	0.7819	91.9	±0.04%		0.7675	99.1	±0.29%	
10-23	0.7770	94.8			0.7615	101.8		
10-24	0.7738	94.9	0.7752	94.9	0.7596	101.8	0.7603	101.8
10-24	0.7749	95.0	±0.21%		0.7598	101.8	±0.14%	
END OF OCONEE 2 FUEL CYCLE 3								
2-25-79	0.7412	103.7			0.7304	111.7		
2-25	0.7421	103.7			0.7314	111.7		
2-26	0.7416	103.8	0.7429	103.8	0.7294	111.8	0.7310	111.8
2-26	0.7439	103.8	±0.25%		0.7310	111.9	±0.16%	
2-26	0.7456	103.9			0.7326	111.9		
3-27	0.7389	107.9			0.7250	116.4		
3-28	0.7386	108.0	0.7379	108.0	0.7241	116.5	0.7239	116.5
3-28	0.7386	108.0	±0.22%		0.7241	116.5	±0.14%	
3-28	0.7355	108.0			0.7225	116.5		
4-24	0.7308	111.6			0.7137	120.5		
4-24	0.7285	111.6	0.7286	111.6	0.7126	120.5	0.7127	120.5
4-24	0.7264	111.6	±0.30%		0.7117	120.5	±0.14%	

Table 3-5 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
6-12	0.7253	114.7			0.7055	123.8		
6-12	0.7243	114.7	0.7245	114.7	0.7082	123.8	0.7070	123.8
6-12	0.7239	114.7	±0.10%		0.7072	123.8	±0.19%	
7-17	0.7150	119.2			0.6964	128.5		
10-30	0.6905	129.6			0.6740	139.0		
10-30	0.6927	129.6			0.6736	139.0		
10-30	0.6926	129.6	0.6911	129.6	0.6740	139.0	0.6735	139.0
10-30	0.6916	129.6	±0.21%		0.6735	139.0	±0.08%	
10-30	0.6902	129.6			0.6731	139.0		
10-30	0.6890	129.6			0.6727	139.0		
11-20	0.6842	132.4			0.6662	141.8		
11-20	0.6830	132.4	0.6832	132.4	0.6655	141.8	0.6652	141.8
11-20	0.6837	132.4	±0.14%		0.6651	141.8	±0.13%	
11-20	0.6820	132.5			0.6641	141.9		
12-18	0.6691	136.1			0.6574	145.6		
12-18	0.6705	136.1	0.6700	136.1	0.6561	145.7	0.6558	145.7
12-18	0.6705	136.1	±0.12%		0.6538	145.7	±0.28%	
1-18-80	0.6671	140.2			0.6433	149.8		
1-18	0.6660	140.2	0.6665	140.2	0.6441	149.8	0.6436	149.8
1-18	0.6665	140.2	±0.08%		0.6434	149.8	±0.07%	

END OF OCONEE 2 FUEL CYCLE 4

Table 3-6 gives the resulting linear least-squares fitting parameters for the three fuel cycles of corrected data given in Table 3-5. Figure 3-2 shows a plot of the linear least-squares curve superimposed on the data of Table 3-5.

Table 3-6

LINEAR REGRESSION ANALYSIS OF CORRECTED Rh DETECTOR RELATIVE SENSITIVITY VS EXPENDED CHARGE IN OCONEE 2 REACTOR, FUEL CYCLES 2, 3 AND 4. (RELATIVE SENSITIVITY DATA CORRECTED FOR "MUTUAL-FLUX-DEPRESSION." CYCLE 4 DATA NORMALIZED TO CYCLES 2 AND 3 DATA).

	Linear Regression Analysis Results				
Fixed Rh Det.	Intercept	Slope	Std. Dev. of Slope	Coeff. of Mult. Corr.	Std. Error of Est.
L11-R3 +L11-R5	0.99242	-0.00233	0.00001	0.99698	0.00829

DEPLETION CORRECTION FACTOR

Reference 1 contains the following equation for a "depletion correction factor" to be applied to a measured, background-corrected Rh detector signal to correct that signal for emitter sensitivity depletion:

$$f(t) = 1/[1 - \frac{0.9937}{q_\infty \sqrt{mL}} Q(t)], \qquad (3\text{-}10)$$

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

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

m = emitter mass in grams,

L = emitter length in centimeters,

$Q(t)$ = charge released from initial exposure to exposure time t.

The term $\frac{0.9937}{q_\infty \sqrt{mL}}$ is equal to the inverse of the absolute value of the slope of the depletion curve. For the two fixed Rh detectors in the Oconee 2 experiment,

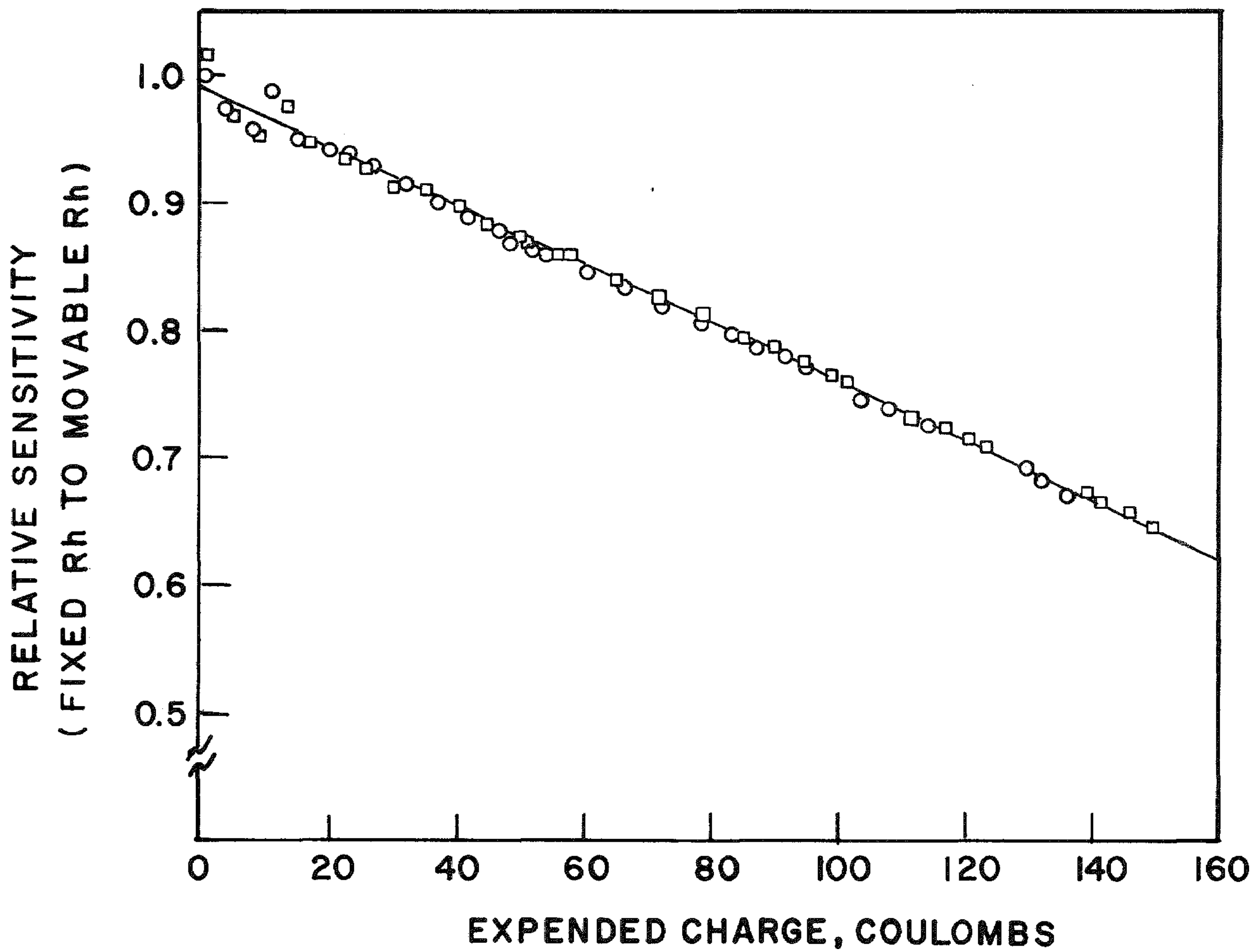

Figure 3-2. Sensitivity Depletion Curve for Rh Detectors L11-R3 (O) and L11-R5 (□) Over Three Oconee 2 Fuel Cycles. Curve drawn through data is the linear least squares fit.

$\bar{m}$ = 0.810 g

$\bar{L}$ = 39.20 cm.

Using the latest value of the depletion curve slope (from Table 3-6),

$$q_{\infty} = 429.2C \pm 0.43\%/5.670\ cm^2 = 75.70\ C/cm^2 \pm 0.43\%.$$

This value agrees within 0.43% with the value reported previously (1). The uncertainty on q_{∞} is one standard deviation and, in percentage, is the same as the uncertainty on the slope of the depletion curve. (In the previous report the uncertainty in q_{∞} was inadvertently given as two standard deviations.)

Through Equation (3-10), 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

$$f(t) = 1/[1 - 0.00752\ Q(t)]. \qquad (3\text{-}11)$$

Thus, adding data from fuel cycle 4 to the depletion curve for the B&W standard detector and making a correction to relative sensitivity for "mutual-flux-depression" have changed the slope of the curve (compared to the value reported in Reference 1) by 0.40%.

Section 4

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

- No appreciable errors in the Rh depletion data were incurred from the loss of two movable calibration detectors during Oconee 2 fuel cycle 4. Normalization of the cycle 4 data to the cycles 2 and 3 data was accurately performed.

- After three fuel cycles, the depletion curve continues to be well-behaved and have good accuracy. The curve remains highly linear, showing as yet no tendency to curve downward as predicted by some experimenters (2).

- With the addition of depletion data from fuel cycle 4, uncertainty in the slope of the Rh sensitivity depletion curve has been reduced by a factor of 3 from its value at the end of fuel cycle 3. Therefore, corrections to Rh detector signals for sensitivity depletion are correspondingly more accurate. Depletion corrections based on this latest data have been implemented at B&W PWRs. Measurements of core power distributions in these reactors are now more accurate and beneficial to the PWR operators.

- After three fuel cycles the Rh detectors in the Oconee 2 experiment are about 35% depleted. The detectors have been in the reactor for almost 4 years. Another two or three years of exposure will be required to deplete the detectors to ∿60%.

- In contrast to preliminary observations reported in Reference 1, there appears to be no effect on the Rh sensitivity depletion rate from changes in fuel assemblies (around the two fixed Rh detectors) during Oconee 2 refuelings.

RECOMMENDATION

The experiment at Oconee 2 must continue through at least one more fuel cycle 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 upon extrapolated data during the last fuel cycles of exposure of the detector. As a consequence, uncertainty in the corrected signal may become larger the more the sensitivity of the detector depletes.

Fuel Cycle 5 at Oconee 2 is scheduled to begin June 4, 1980. It is an 18-month cycle.

Section 5

REFERENCES

1. Rhodium In-Core Detector Sensitivity Depletion. Palo Alto, California: May 1980. Electric Power Research Institute, Interim Report NP-1405.

2. T. Laaksonen and J. Saastamoinen, "Calculational Studies of Sensitivity Characteristics and Their Burnup Behavior for Rhodium Self-Powered Neutron Detectors," Proceedings of the IAEA Specialists' Meeting On In-Core Instrumentation and Failed Fuel Detection and Location, ACEL-1524, May 1974, p. 111.