EBWR BURNUP DATA

NOVEMBER 1968

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UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

3 3679 00061 2376

BNWL-978

UC-80, Reactor Technology
Special Distribution

EBWR BURNUP DATA

By

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November 1968

PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON

Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

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ABSTRACT

Burnup data are presented from the plutonium enriched loading that was irradiated in the Experimental Boiling Water Reactor (EBWR). The data are plotted in order to detect mismeasurements and to spot subsets which have a pattern different from the remainder of the data. It was expected that the variation in the void fraction of the coolant along the rod might be detected in this way; however, the data do not seem to reflect this effect. The plots do identify seven samples that are different from the others. These samples are from rods that were surrounded by extra water moderator.

TABLE OF CONTENTSPage

LIST OF TABLES	v
LIST OF FIGURES	vi
I. INTRODUCTION	1
II. MEASUREMENT OF THE BURNUP DATA	2
III. PROCESSING THE EXPERIMENTAL DATA	4
IV. CONCLUSIONS	9
REFERENCES	11
APPENDIX A	33
DISTRIBUTION	42

<u>LIST OF TABLES</u>	<u>Page</u>
I. Irradiation History of EBWR during Plutonium Experiment	1
II. Initial Composition of Fuels	2
III. Results of Europium Analyses	4
IV. Differences Between ISODIL Analyses for Uranium and Plutonium Systems	5
V. Initial Compositions of the Fuel, Estimated from the Post-irradiation Data	7
VI. Tabulation of Outliers in $\text{UO}_2\text{-PuO}_2$ Data	8

<u>LIST OF FIGURES</u>	<u>Page</u>
1. Plutonium Loading in EBWR	12
2. Gamma Scan of a Typical Fuel Rod	13
3. $^{241}\text{Pu}/^{239}\text{Pu}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 -1.5wt% PuO_2	14
4. $^{242}\text{Pu}/^{239}\text{Pu}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 -1.5wt% PuO_2	15
5. $^{238}\text{Pu}/^{239}\text{Pu}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 -1.5wt% PuO_2	16
6. BURNUP (MWd/MTM) versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 -1.5wt% PuO_2	17
7. $\text{Pu}/\text{U}+\text{Pu}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 -1.5wt% PuO_2	18
8. $^{235}\text{U}/^{238}\text{U}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 -1.5wt% PuO_2	19
9. $^{236}\text{U}/^{238}\text{U}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 -1.5wt% PuO_2	20
10. $^{241}\text{Pu}/^{239}\text{Pu}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 (6% ^{235}U)	21
11. $^{242}\text{Pu}/^{239}\text{Pu}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 (6% ^{235}U)	22
12. $^{238}\text{Pu}/^{239}\text{Pu}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 (6% ^{235}U)	23
13. BURNUP (MWd/MTM) versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 (6% ^{235}U)	24
14. $\text{Pu}/\text{U}+\text{Pu}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 (6% ^{235}U)	25
15. $^{235}\text{U}/^{238}\text{U}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 (6% ^{235}U)	26
16. $^{236}\text{U}/^{238}\text{U}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 (6% ^{235}U)	27

(LIST OF FIGURES Cont.)

	<u>Page</u>
17. ^{152}Eu and ^{154}Eu versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for UO_2 (6% ^{235}U)	28
18. $^{241}\text{Pu}/^{239}\text{Pu}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for Al-Pu Fuel	29
19. $^{242}\text{Pu}/^{239}\text{Pu}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for Al-Pu Fuel	30
20. $^{238}\text{Pu}/^{239}\text{Pu}$ Ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for Al-Pu Fuel	31
21. BURNUP (% Depletion versus) $^{240}\text{Pu}/^{239}\text{Pu}$ Ratio for Al-Pu Fuel	32

EBWR BURNUP DATA*

R. P. Matsen

I. INTRODUCTION

This report presents burnup data from fuel irradiated during the Plutonium Recycle Experiment in the Experimental Boiling Water Reactor (EBWR). The experimental data are plotted and checked for consistency. They are also processed to obtain the burnup of each fuel sample in MegaWatt days per Metric Ton of heavy Metal (MWd/MTM) as well as for several other quantities of interest, and are presented here to be available for use in correlations with results of calculations for boiling water reactors.

Initial Loading, Irradiation, and Sampling of the Fuel. The core configuration for the EBWR is shown in Figure 1. The central thirty-six elements are loaded with depleted uranium which is enriched with plutonium. Fuel rods were removed and sent to Pacific Northwest Laboratory for analysis at three different periods of the irradiation. The pertinent data are shown in Table I.

TABLE I
IRRADIATION HISTORY OF EBWR DURING PLUTONIUM EXPERIMENT

<u>Interval</u>	<u>Start</u>	<u>End</u>	<u>Incremental MWd of Core</u>	<u>Total MWd of Core</u>	<u>Core Power</u>	<u>Incremental Pu Zone Expo- sure (MWd/MTM)</u>
1	10/66	2/11/67	3760	3760	42 MW	1320
2	3/67	4/29/67	3140	6900	42	940
3	5/67	6/29/67	1360	8260	~60	340

Four types of fuel elements have been destructively analyzed. They are listed in Table II.

* This work was sponsored by the USAEC under the Plutonium Utilization Program and the cooperative agreement between the National Committee for Atomic Energy (CNEN) of Italy and USAEC.

TABLE II
INITIAL COMPOSITION OF FUELS

<u>Fuel Type</u>	<u>U235(at%)</u>	<u>Pu/(U+Pu)</u>	<u>Pu 240(at%)</u>	<u>No.of Samples</u>
UO ₂ -1.5wt% PuO ₂	~.165*	0.015	7.77	31
Al-3.35wt% Pu	_____	1.000	8.08	6
Al-3.35wt% Pu	_____	1.000	27.1	6
UO ₂	5.96	0.000	_____	4

* The initial uranium-235 isotopic content of the UO₂-PuO₂ rods varies slightly among the rods. They have been separated into three groups. For rods EL-67 and EN-43; at% = .159; for rod EY-71; at% = .152; and for all other rods at% = .165.

The UO₂-PuO₂ and Al-Pu rods were irradiated in the plutonium zone. The locations of the rods that were destructively analyzed are shown in Figure 1.

Those fuel rods which were sampled were first gamma scanned using a NaI detector. A gamma scan plot⁽¹⁾ of one of the rods is shown in Figure 2. It gives a good indication of the flux shape in the EBWR. On the basis of the gamma scan results, the rods were sampled at the positions labeled 1, 2, 3, and 4. Some of the rods were sampled only at position 2 and the Al-Pu rods were sampled at 1, 2, and 4. Each sample was approximately three fourths of an inch in length.

II. MEASUREMENT OF THE BURNUP DATA

Each fuel sample was weighed and dissolved in a measured volume of dissolver solution in such a way that the clad material was not attacked. The cladding was then weighed and the grams of fuel per milliliter of solution was calculated for the sample.

The amount of uranium, plutonium, and neodymium (neodymium is used to determine the total number of fissions that have occurred) in the dissolver solution is measured by the isotopic dilution technique.⁽²⁾ Briefly, the procedure is as follows: The element to be measured is separated from a small amount of the dissolver solution by a chemical process. A portion of this separated material is then measured for isotopic ratios on a mass spectrometer. A measured amount of the remainder of the separated material is added to a measured amount of spike solution made up of the same chemical element as the separated material but with a different isotopic content. The spike contains a known number of atoms/ml of its principal isotope which is usually chosen as one of the minor isotopes of the separated material. The principal isotopes in the spike solutions are ^{233}U for uranium, ^{242}Pu for plutonium, and ^{150}Nd for neodymium. The spiked solution is also measured on a mass spectrometer. The experimental data and its one standard deviation uncertainties are reported in Appendix A.

The isotope used as a burnup indicator is ^{148}Nd . The amount of neodymium-142 present provides an estimate of the contamination that occurs during the chemical separation of neodymium since the 142 isotope is not formed in the fission process. Typically, this contamination amounts to several percent. Several samples also had their burnup determined by measuring the amount of ^{137}Cs present in the sample. This was done by gamma counting the ^{137}Cs extracted from a small amount of the dissolver solution. The ^{137}Cs results were in good agreement with the neodymium results.

Small amounts of natural europium and samarium were added as burnable poisons to the enriched UO_2 rods during the fabrication process. Measurements of the remaining isotopes of these elements indicate how fast the europium and samarium burn out as compared with the nuclear fuel. Therefore the UO_2 samples were analyzed for ^{152}Eu and ^{154}Eu . These serve as calibration measurements for other europium and samarium isotopes to be measured with the (uncalibrated) PNL Gamma Scan Facility. The europium was separated from a measured amount of dissolver solution and its gamma peaks were counted on a calibrated (both energy and intensity) Ge(Li) solid state detector. Although only one photopeak was needed for each isotope, six were measured for ^{152}Eu and four were measured for ^{154}Eu . The results are given in Table III.

TABLE III
RESULTS OF EUROPIUM ANALYSES

Rod	$^{152}\text{Eu}(\text{atoms/ml})$	$^{152}\text{Eu}(\text{gm/gmU})$	$^{154}\text{Eu}(\text{atoms/ml})$	$^{154}\text{Eu}(\text{gm/gmU})$
2089	9.26×10^{16}	0.221×10^{-3}	6.71×10^{16}	0.160×10^{-3}
1626	9.92	0.226	6.25	0.143
1305	8.95	0.214	5.25	0.125
2095	7.72	0.184	3.64	0.087

The half lives used to calculate these numbers were 12.7 years for ^{152}Eu and 16.0 years for ^{154}Eu . The data of analysis was August 28, 1968. Data reported in Table III have been corrected back to the time that they were removed from the reactor, June 24, 1967.

III. PROCESSING THE EXPERIMENTAL DATA

The experimental data from each sample was processed through the computer code ISODIL⁽³⁾ to convert the raw data into more useful numbers such as burnup and the absolute concentrations of the heavy isotopes. The ISODIL printout not only includes these calculated numbers but also lists the experimental

lists the experimental input data for each sample. It lists the fissions and the initial and final composition of each heavy isotope. One standard deviation errors are enclosed in parentheses. In reality there are two ISODIL programs, one for fuels that include uranium and the other for fuels made of plutonium alone (e.g., Al-Pu). The main differences between the two versions are shown in Table IV.

TABLE IV

<u>Uranium System</u>	<u>Item</u>	<u>Plutonium System</u>
One gram of heavy metal(U+Pu):	Initial fuel normalized to:	One atom of plutonium
MWd/MTM	: Burnup calculated as	: Fractional loss of plutonium
^{235}U	: Ratio of capture to fission cross sections calculated for	: ^{239}Pu

A given sample can be normalized to either the sample weight data or to the pertinent isotope dilution data. For the uranium data these two results are usually in good agreement. However, for Al-Pu data, they frequently disagree and thus for the EBWR data the usually reliable isotopic dilution approach has been applied consistently. The ISODIL printout for the EBWR data is available on request.

In order to detect spurious points, plots of the measured data were made. The other measured quantities were plotted against the $^{240}\text{Pu}/^{239}\text{Pu}$ ratio. This ratio changes smoothly with burnup and the individual measurements of this quantity are uniformly spaced over the full range of the data. The $^{240}\text{Pu}/^{239}\text{Pu}$ ratio is also the most accurate item that is measured.

Plots of the measured data are shown in figures 3 through 21. The one standard deviation error flags have been plotted for each point. In some cases they are smaller than the symbol marking the event. Each sample has been assigned a number and some of the associated data points are so labeled. The samples have also been assigned symbols to indicate which part of the rod they come from ($\square$ at 4", $\odot$ at 11", Δ at 22", and x at 32"). Each type of fuel has its own set of plots except that the two Al-Pu sets of data are shown together in one set.

Most of the $\text{UO}_2\text{-PuO}_2$ data (figures 3 through 9) fall close to a definite curve. However samples 2, 3, 10, 11, 16, 25, and 26 are consistently displaced from the rest of the data. These samples were taken from regions where extra water perturbs the neutron spectrum and causes them to arrive at a state of slightly different nuclear composition. Samples 11 and 25 are from rods in a corner position of the plutonium zone and samples 10 and 26 are from rods at the edge of this zone. Samples 2, 3, and 16 are from fuel rods that were in the interior of the plutonium zone but were from the bottom end of rods that were in the corner position of one of the fuel boxes. There is no discernable pattern in any of the $\text{UO}_2\text{-PuO}_2$ plots that distinguishes samples taken at one elevation from those taken at any other elevation.

The $^{238}\text{Pu}/^{239}\text{Pu}$ ratio (Figure 5) breaks into two separate curves because the $\text{UO}_2\text{-PuO}_2$ data was (except for sample 31) analyzed in two batches. A substantial contributor to the ^{238}Pu content is the alpha decay of ^{242}Cm (163 day half life). Since the two batches were irradiated for different lengths of time (and therefore had different amounts of

^{242}Cm) and were allowed to cool for different lengths of time, two curves appear for this ratio.

Several of the measurement variables were unknown at the beginning of the irradiation. These may be estimated from the plots. The results of these estimates are shown in Table V.

TABLE V
INITIAL COMPOSITIONS OF THE FUEL, ESTIMATED FROM
THE POST-IRRADIATION DATA

<u>Fuel Type</u>	<u>Estimate</u>	<u>Figure</u>
UO_2 -1.5 wt% PuO_2	$^{238}\text{Pu}/^{239}\text{Pu} = 1.2 \times 10^{-4}$	5
Natural UO_2	$^{234}\text{U}/^{238}\text{U} = 3.6 \times 10^{-4}$	-
	$^{236}\text{U}/^{238}\text{U} = 6 \times 10^{-4}$	16
Al-1.35 wt% Pu(27% ^{240}Pu)	$^{238}\text{Pu}/^{239}\text{Pu} = 5 \times 10^{-4}$	20

Outliers in the UO_2 - PuO_2 data are recorded in Table VI.

A large proportion of the outliers involve the $\text{Pu}/(\text{U}+\text{Pu})$ ratio for samples in the high void region (i.e., 32 inches above the bottom of the rod). Remeasurement of the plutonium content of two of the samples (9 and 23) reproduced the original results within their experimental uncertainties. Thus, there is no explanation of these anomalous $\text{Pu}/(\text{U}+\text{Pu})$ results at the present time.

Outliers in the enriched UO_2 data and in the Al-Pu data are difficult to identify since there are fewer measurements to establish where the data should lie. Of course, gross errors could be detected but there does not seem to be any of these. The data for the enriched UO_2 samples are shown in Figures 10 through 17 and the Al-Pu data are shown in Figures 18 through 21.

The Al-Pu data possibly shows some evidence for neutron flux shape changes along the rod. The samples taken at four inches seem to have a consistently higher value (relatively) for the $^{240}\text{Pu}/^{239}\text{Pu}$ ratio than those at eleven inches. If true, this indicates that the neutron spectrum is

TABLE VI
TABULATION OF OUTLIERS IN UO₂-PuO₂ DATA

<u>Rod</u>	<u>Position⁺</u>	<u>Sample Number</u>	<u>Outlying Data</u>
EX42 -	1	6	None
	2	7	$^{236}\text{U}/^{238}\text{U}$
	3	8	None
	4	9	$^{236}\text{U}/^{238}\text{U}$, Pu*
EV71 -	2	1	None
EL67 -	1	27	$^{235}\text{U}/^{238}\text{U}$
	2	28	None
	3	29	None
	4	30	$^{238}\text{Pu}/^{239}\text{Pu}$, U by Isotopic Dilution
EY32 -	2	11	None
EO16 -	1	2	None
	2	3	Pu
	3	4	$^{236}\text{U}/^{238}\text{U}$
	4	5	Pu
EK66 -	1	20	None
	2	21	None
	3	22	$^{240}\text{Pu}/^{239}\text{Pu}$
	4	23	$^{242}\text{Pu}/^{239}\text{Pu}$, Pu*
EK19 -	2	24	Pu, U by Isotopic Dilution
EI53 -	1	12	U by Sample Weight
	2	13	None
	3	14	None
	4	15	Pu
EH24 -	2	10	None
ER72 -	1	16	None
	2	17	$^{235}\text{U}/^{238}\text{U}$
	3	18	U by Sample Weight
	4	19	None
ES78 -	2	26	None
EJ47 -	2	25	Pu, U by Isotopic Dilution
EN43 -	2	31	U by Sample Weight

* Items that were remeasured.

+ The sample position is identified follows: 1 = 4" above the bottom end of the fuel, 2 = 11", 3 = 22", and 4 = 32".

slightly softer for the four-inch samples than for the eleven-inch samples. Such an effect is not unexpected since a sample near the bottom (4 inches) of the reactor should be surrounded by more water than a sample higher up (11 inches) where there are more steam voids. The data at thirty-two inches is too far separated from the rest of the data to be successfully compared with it for spectrum effects.

The $\text{UO}_2\text{-PuO}_2$ data is poorly suited for fitting⁽⁴⁾ isotopic transmutation equations to the data with the least squares fitting code, program LIKELY. Such an analysis must be based upon solid data for a monotonically decreasing isotope (i.e., one that is not replenished by neutron capture in another isotope) which, for a $\text{UO}_2\text{-PuO}_2$ system, is either ^{235}U or ^{238}U . Since the $\text{UO}_2\text{-PuO}_2$ fuel was made with depleted uranium, it contains very little ^{235}U . Consequently, the ^{235}U is a poor competitor for neutrons when compared with the more abundant plutonium isotopes. Thus, the ^{235}U content, which is small to begin with, changes slowly and is therefore a less than ideal variable on which to base a least squares fitting analysis. Further difficulties arise because the $^{235}\text{U}/^{238}\text{U}$ ratio for the unirradiated fuel was not the same for all rods. The ^{238}U isotope is also a poor candidate since it decreases in content by much less than its measurement uncertainty. However, the isotopic concentration data are still very useful for testing the reliability of burnup calculation for a boiling water reactor fueled with a $\text{UO}_2\text{-PuO}_2$ mixture.

IV. CONCLUSIONS

Most of the EBWR data was taken from $\text{UO}_2\text{-PuO}_2$ rods. All data was processed through the ISODIL data reduction code. The $\text{UO}_2\text{-PuO}_2$ data (31

samples) seems to be internally consistent when it is plotted. Some outliers in the data were identified from the plots. Correlations due to spectrum changes along the rod could not be detected in the $\text{UO}_2\text{-PuO}_2$ data but some spectrum effects were noted for rods located in regions of extra water moderator. The $\text{UO}_2\text{-PuO}_2$ data are poorly suited for a least squares fit to the uranium-plutonium transmutation equations because the key isotope, ^{235}U , changes too slowly. Other methods of correlation may prove to be more successful. The data do provide valuable tests of current burnup calculation methods.

Four samples from enriched UO_2 rods (6% ^{235}U) were analyzed for ^{152}Eu and ^{154}Eu in addition to the usual measurements. Twelve samples from Al-Pu rods were also analyzed. Checks on the internal consistency of the UO_2 and Al-Pu data were hindered by the small number of samples available for plotting. Nevertheless, it is clear that there are no gross errors in these data. As is explained in the main text, a weak case can be made for spectrum change effects along the Al-Pu rods. The Al-Pu rods, with 8 and 27 at % ^{240}Pu initially, were designed to prove data for extrapolation of the 8% rods to high burnup, via the results from the 27% rods. A cursory review of the data suggests that the planned result was obtained.

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4. L. C. Schmid, D. E. Christensen, B. H. Duane, R. C. Liikala, and R. P. Matsen. "Experimental and Theoretical Methods Used for Burnup Analyses at Battelle Northwest," Proceedings of the Joint International Conference on the Physics Problems in Thermal Reactor Design. London, England, June 1967.

<div style="display: inline-block; width: 15px; height: 15px; background-color: black; margin-right: 5px;"></div> ENRICHED UO_2 (95% U^{235}) <div style="display: inline-block; width: 15px; height: 15px; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); margin-right: 5px;"></div> ENRICHED UO_2 (6% U^{235}) <div style="display: inline-block; width: 15px; height: 15px; border: 1px solid black; margin-right: 5px;"></div> NATURAL UO_2	1 EH-24	8 EU-07	15 EU-22
	2 EL-67	9 ES-78	16 EU-20
	3 EO-16	10 EI-53	17 EN-43
	4 EV-71	11 ER-72	18 2089
	5 EX-42	12 EK-19	19 1626
	6 EY-32	13 EK-66	20 1305
	7 EU-10	14 EJ-47	21 2095

FIGURE 1
Plutonium Loading in EBWR

FIGURE 2
Gamma Scan of a Typical Fuel Rod

FIGURE 3

$^{241}\text{Pu}/^{239}\text{Pu}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for UO₂-1.5% PuO₂ fuel. Samples 2,3,10,11,16,25, and 26 are from positions surrounded by extra water moderator.

FIGURE 4

$^{242}\text{Pu}/^{239}\text{Pu}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for UO_2 -1.5% PuO_2 fuel. Samples 2,3,10,11, 16,25, and 26 are from positions surrounded by extra water moderator. Sample 23 is an outlier.

FIGURE 5

$^{238}\text{Pu}/^{239}\text{Pu}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for $\text{UO}_2-1.5\%\text{PuO}_2$ fuel. Samples 2,3,10,11, 16,25, and 26 are from positions surrounded by extra water moderator. Sample 30 is an outlier. The difference between the data for batch 1 and batch 2 is related to the different irradiation and cooling times for two batches with regard to the production of ^{242}Cm and its decay into ^{238}Pu .

FIGURE 6

BURNUP in MWd/MTM versus the $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for UO_2 -1.5% PuO_2 fuel. Samples 2,3,10,11, 16,25, and 26 are from positions surrounded by extra water moderator.

FIGURE 7

The $\text{Pu}/(\text{U} + \text{Pu})$ ratio versus the $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for $\text{UO}_2-1.5\% \text{PuO}_2$ fuel. Samples 2,3,10, 11,16,25, and 26 are from positions surrounded by extra water moderator. Samples 5,7,9,15, 23,24, 25, and 30 are outliers.

FIGURE 8

$^{235}\text{U}/^{238}\text{U}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for UO_2 -1.5% PuO_2 fuel. Samples 2, 3, 10, 11, 16, 25, and 26 are from positions surrounded by extra water moderator. Samples 1, 17, and 27 are outliers.

FIGURE 9

$^{236}\text{U}/^{238}\text{U}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for $\text{UO}_2-1.5\%\text{PuO}_2$ fuel. Samples 2, 3, 10, 11, 16, 25, and 26 are from positions surrounded by extra water moderator. Samples 4, 7, 9, and 22 are outliers.

FIGURE 10

$^{241}\text{Pu}/^{239}\text{Pu}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for UO_2 (6% ^{235}U) fuel.

FIGURE 11

$^{242}\text{Pu}/^{239}\text{Pu}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for UO_2 (6% ^{235}U) fuel.

FIGURE 12

$^{238}\text{Pu}/^{239}\text{Pu}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for UO_2 (6% ^{235}U) fuel.

FIGURE 13

BURNUP in MWd/MTM versus ²⁴⁰Pu/²³⁹Pu ratio for the UO₂(6%²³⁵U) fuel.

FIGURE 14

Pu/(U + Pu) ratio versus ²⁴⁰Pu/²³⁹Pu ratio for the UO₂ (6%²³⁵U) fuel.

FIGURE 15

$^{235}\text{U}/^{238}\text{U}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for the UO_2 (6% ^{235}U) fuel.

FIGURE 16

$^{236}\text{U}/^{238}\text{U}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for the UO_2 (6% ^{235}U) fuel.

FIGURE 17

¹⁵²Eu and ¹⁵⁴Eu versus ²⁴⁰Pu, ²³⁹Pu ratio for the UO₂ (6% ²³⁵U) fuel.

FIGURE 18

$^{241}\text{Pu}/^{239}\text{Pu}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for Al-Pu fuel

FIGURE 19

$^{242}\text{Pu}/^{239}\text{Pu}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for Al-Pu fuel

FIGURE 20

$^{238}\text{Pu}/^{239}\text{Pu}$ ratio versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for Al-Pu fuel

FIGURE 21

BURNUP in percent depletion of Pu versus $^{240}\text{Pu}/^{239}\text{Pu}$ ratio for Al-Pu fuel

APPENDIX A

APPENDIX A

Tables 1A through 9A list the EBWR experimental data in its raw form. Three groups or batches of samples were analyzed. Separate tables are presented for the uranium, plutonium and neodymium results from each batch. In addition, the grams of fuel per liter of dissolver solution is recorded for each sample.

The one standard deviation uncertainty for each measurement is shown either in parentheses or after a $\pm$ sign. The errors refer to the last one or two places of the measured numbers (e.g., $.02043(22) = .02043 \pm .00022$).

TABLE A1

ISOTOPIC ANALYSIS SUMMARY OF URANIUM SAMPLES
From EBWR Rods, First Group (Removed from Reactor 2-11-67)

Rod No.	Lab No.	Grams Fuel/1	Sample Vol.(1) U & Pu	Spike Vol.(2) U	Spike Vol.(2) Pu	U Sample		U Sample + Spike 238/233
						235/238	236/238	
EU 07	1	4943	41.023	1.487	.1001	-	-	-
	2	4944	37.122	1.487	.10011	-	-	-
	4	4945	35.346	1.487	.1001	-	-	-
EU 10	1	4946	33.960	1.487	.10011	-	-	-
	2	4947	38.497	1.487	.1001	-	-	-
	4	4948	36.220	1.487	.10011	-	-	-
EL 67	1	4949	110.568	0.9897	.1001	.001550(5)	.0000578(18)	0.9536(16)
	2	4950	111.435	0.9897	.10011	.001423(3)	.0000591(6)	0.9510(6)
	3	4951	116.630	0.9897	.1001	.001467(3)	.0000468(10)	0.9916(4)
	4	4952	135.889	0.9897	.10011	.001542(5)	.0000376(10)	1.2119(15)
EO 16	1	4953	131.369	0.9915	.1001	.001385(5)	.0000628(18)	1.115 (1)
	2	4954	125.364	0.9912	.10015	.001376(8)	.0000680(7)	1.080 (1)
	3	4955	138.353	0.9915	.1001	.001461(6)	.0000841(19)	1.189 (2)
	4	4956	119.036	0.9915	.10011	.001531(8)	.0000454(30)	1.031 (1)
EX 42	1	4957	116.062	0.9915	.1001	.001513(4)	.0000533(10)	0.9945(16)
	2	4958	118.367	0.9915	.10011	.001499(5)	.0000690(10)	1.032 (1)
	3	4959	116.367	0.9915	.1001	.001560(4)	.0000425(5)	1.000 (1)
	4	4960	117.440	0.9915	.10011	.001610(5)	.0000425(47)	1.008 (1)
EH 24	2	4961	123.701	0.9915	.1001	.001307(4)	.0000697(11)	1.055 (1)
EV 71	2	4962	119.716	0.9915	.10015	.001384(8)	.0000578(12)	1.018 (1)
EY 32	2	4963	120.093	0.9915	.1001	.001372(5)	.0000621(4)	1.038 (1)

A-2

(1) Sample Volume in 10^{-3} ml units

(2) Spike volumes in ml

 ^{233}U Spike Ratio: $238/233 = 0.002404$ (ID-2), Calib.: 5.1458×10^{18} atoms U^{233}/ml ^{242}Pu Spike Ratio: $239/242 = 0.0001078$ (ID-8), Calib.: 5.004×10^{16} atoms $\text{Pu}^{242}/\text{ml}$

TABLE A2

ISOTOPIC ANALYSIS SUMMARY OF PLUTONIUM SAMPLES
From EBWR Rods, First Group (Removed from Reactor 2-11-67)

*Corrected Data - Based on NBS 948 STD
Spike Calibration Sample No. Y-1008 B 242/239 Ratio = 1.0459 $\pm$ 10

Rod No.	Sample	238/239	240/239	241/239	242/239	239/242 Spike
EU-07	No. 1	.0003880 $\pm$ 116	.19781 $\pm$ 59	.035354 $\pm$ 177	.002352 $\pm$ 24	.6177 $\pm$ 15
	No. 2	.0004193 $\pm$ 126	.21667 $\pm$ 65	.043255 $\pm$ 216	.003115 $\pm$ 31	.60572 $\pm$ 151
	No. 4	.0001970 $\pm$ 86	.11524 $\pm$ 35	.013980 $\pm$ 105	.0008239 $\pm$ 165	.72754 $\pm$ 182
EU-10	No. 1	.003187 $\pm$ 32	.58689 $\pm$ 176	.12739 $\pm$ 38	.028165 $\pm$ 141	.43812 $\pm$ 110
	No. 2	.003805 $\pm$ 38	.61019 $\pm$ 183	.14566 $\pm$ 44	.03147 $\pm$ 16	.44593 $\pm$ 111
	No. 4	.001307 $\pm$ 26	.45587 $\pm$ 137	.07446 $\pm$ 30	.017733 $\pm$ 133	.54407 $\pm$ 137
EL-67	No. 1	.0003631 $\pm$ 73	.15919 $\pm$ 48	.025546 $\pm$ 128	.001495 $\pm$ 15	.57902 $\pm$ 145
	No. 2	.0004141 $\pm$ 83	.17192 $\pm$ 52	.031305 $\pm$ 157	.001883 $\pm$ 19	.56824 $\pm$ 142
	No. 3	.0003091 $\pm$ 93	.13995 $\pm$ 42	.021566 $\pm$ 108	.001096 $\pm$ 11	.63355 $\pm$ 158
	No. 4	.000886 $\pm$ 39	.10811 $\pm$ 32	.012317 $\pm$ 92	.000571 $\pm$ 15	.77999 $\pm$ 196
EO-16	No. 1	.0004419 $\pm$ 88	.19980 $\pm$ 60	.03404 $\pm$ 17	.002399 $\pm$ 24	.63392 $\pm$ 158
	No. 2	.0004933 $\pm$ 99	.21390 $\pm$ 64	.041685 $\pm$ 208	.003151 $\pm$ 40	.56109 $\pm$ 140
	No. 3	-	.16309 $\pm$ 49	.02729 $\pm$ 14	.001599 $\pm$ 32	.71424 $\pm$ 179
	No. 4	-	.11787 $\pm$ 35	.014387 $\pm$ 108	.000873 $\pm$ 17	.66542 $\pm$ 166
EX-42	No. 1	.0002930 $\pm$ 88	.14580 $\pm$ 44	.02197 $\pm$ 16	.001548 $\pm$ 31	.63691 $\pm$ 159
	No. 2	.0003177 $\pm$ 94	.15340 $\pm$ 46	.025649 $\pm$ 128	.001452 $\pm$ 18	.67332 $\pm$ 177
	No. 3	.0002295 $\pm$ 94	.11887 $\pm$ 38	.016042 $\pm$ 120	.000809 $\pm$ 16	.66809 $\pm$ 167
	No. 4	.0001486 $\pm$ 45	.09516 $\pm$ 29	.009353 $\pm$ 70	.0004638 $\pm$ 93	.66661 $\pm$ 167
EH-24	No. 2	.0005948 $\pm$ 119	.25194 $\pm$ 76	.04608 $\pm$ 23	.004124 $\pm$ 41	.52599 $\pm$ 131
EV-71	No. 2	.0003421 $\pm$ 65	.16662 $\pm$ 50	.030679 $\pm$ 162	.001825 $\pm$ 18	.6298 $\pm$ 22
EY-32	No. 2	- .0004290 $\pm$ 12	.20139 $\pm$ 74	.034437 $\pm$ 181	.002415 $\pm$ 24	.5754 $\pm$ 17

A-3

Note: Mass spectrometer analyses were performed between 12/22/67 and 1/19/68.

TABLE A3

ISOTOPIC ANALYSIS SUMMARY OF NEODYMIUM SAMPLES
From EBWR Rods, First Group (Removed from Reactor 2-11-67)

Rod No.	Lab. No.	Nd Sample				Nd Sample + Spike			
		150/142	150/145	150/146	150/148	142/150	145/150	146/150	148/150
EU 07	1 4943	9.410(47)	.3216(7)	.3817(6)	.5814(5)	.01194(6)	.1776 (10)	.1547 (4)	.1020 (1)
	2 4944	12.34 (7)	.3188(9)	.3784(10)	.5760(7)	.01812(11)	.2051 (10)	.1815 (4)	.1188 (2)
	4 4945	2.466(7)	.3310(6)	.3803(7)	.6008(5)	.01398(5)	.05582(16)	.05552(14)	.03627(4)
EU 10	1 4946	9.681(35)	.3262(6)	.3851(8)	.5845(7)	.01518(4)	.1427 (2)	.1285 (1)	.08451(7)
	2 4947	4.638(17)	.3278(6)	.3732(7)	.5877(7)	.03050(14)	.1797 (5)	.1655 (4)	.1058 (1)
	4 4948	1.023(4)	.3591(7)	.3760(7)	.6369(8)	.01283(6)	.04465(14)	.04600(9)	.03069(6)
EL 67	1 4949	11.32 (3)	.2930(6)	.3668(5)	.5683(10)	.01780(7)	.2109 (11)	.1882 (8)	.1225 (14)
	2 4950	6.109(21)	.3199(4)	.3721(4)	.5790(6)	.01388(4)	.2575 (10)	.2251 (6)	.1461 (4)
	3 4951	8.673(24)	.3108(3)	.3673(5)	.5744(9)	.01518(4)	.1812 (4)	.1609 (3)	.1043 (2)
	4 4952	5.230(13)	.3191(4)	.3754(6)	.5855(9)	.01206(3)	.09400(24)	.08393(20)	.05707(30)
EO 16	1 4953	7.721(39)	.3136(8)	.3704(3)	.5718(8)	.03051(15)	.3347 (12)	.2949 (10)	.1887 (4)
	2 4954	1.487(3)	.3353(5)	.3632(7)	.5998(8)	.08449(26)	.3707 (11)	.3459 (10)	.2109 (4)
	3 4955	5.794(24)	.3115(5)	.3662(5)	.5726(7)	.01968(9)	.2755 (7)	.2403 (5)	.1546 (2)
	4 4956	1.210(14)	.3394(23)	.3654(19)	.6147(22)	.02844(13)	.1157 (3)	.1104 (2)	.06881(13)
EX 42	1 4957	5.237(36)	.3126(7)	.3671(7)	.5760(10)	.02202(6)	.1980 (3)	.1765 (2)	.1125 (1)
	2 4958	4.268(28)	.3189(11)	.3693(10)	.5805(14)	.02006(4)	.2340 (2)	.2067 (2)	.1328 (1)
	3 4959	1.472(4)	.3312(4)	.3639(5)	.6060(8)	.01972(6)	.1289 (3)	.1185 (2)	.07559(14)
	4 4960	2.503(15)	.3231(9)	.3702(10)	.5952(7)	.01433(5)	.04724(10)	.04873(9)	.03146(5)
EH 24	2 4961	16.37 (5)	.3088(6)	.3645(5)	.5633(6)	.01554(8)	.3995 (11)	.3456 (3)	.2258 (4)
EV 71	2 4962	9.649(45)	.3168(9)	.3715' 4)	.5762(6)	.01115(3)	.2564 (5)	.2235 (5)	.1456 (2)
EY 32	2 4963	12.72 (6)	.3111(8)	.3685(9)	.5666(10)	.01282(2)	.3075 (4)	.2648 (2)	.1725 (2)

A-4

Nd sample volume (all samples): 0.03497 ml
¹⁵⁰Nd spike volume (all samples): 0.35007 ml, Calib.: (ID-14, : 7.8398×10^{15} atoms Nd¹⁵⁰/ml)
¹⁵⁰Nd spike ratios: 42/50 45/50 46/50 48/50
 .008056 .004383 .011422 .008679

TABLE A4

ISOTOPIC ANALYSIS SUMMARY OF URANIUM SAMPLES

EBWR Rods - Second Group (Discharged From Reactor 4-29-67)

Rod No.	Lab. No.	Sample ⁽¹⁾ Vol.(U&Pu)	Spike ⁽²⁾ Vol.(U)	Spike ⁽³⁾ Vol.(Pu)	U Sample		U Sample + Spike
					235/238	236/238	238/233
EI-53-1	5486	.00198	.10004	.14995	.001362 (4)	.0000723 (6)	0 .9197 (6)
2	5487	"	"	.14998	.001340 (5)	.0000747 (6)	0 .7531 (5)
3	5488	"	"	.14995	.001416 (6)	.0000647 (14)	0 .9070 (7)
4	5489	"	"	.14998	.001520 (5)	.0000463 (7)	0 .9149 (6)
ER-72-1	5490	"	"	.14995	.001323 (5)	.0000903 (12)	0 .5816 (7)
2	5491	"	"	.14998	.001424 (6)	.0000984 (14)	0 .9985 (5)
3	5492	"	"	.14995	.001382 (6)	.0000775 (11)	0 .6241 (6)
4	5493	"	"	.14998	.001514 (3)	.0000527 (5)	0 .7218 (7)
EK-66-1	5494	"	"	.14995	.001431 (4)	.0000648 (8)	0 .9160 (6)
2	5495	"	"	.14998	.001387 (5)	.0000707 (7)	1.090 (1)
3	5496	"	"	.14995	.001472 (3)	.0000627 (22)	0 .9965 (11)
4	5497	"	"	.14998	.001570 (3)	.0000401 (9)	0 .8797 (8)
EK-19-2	5498	"	"	.14995	.001360 (13)	.0000789 (14)	0 .7300 (36)
EJ-47-2	5499	"	"	.14998	.001275 (10)	.0000889 (9)	0 .9887 (20)
ES-78-2	5500	"	"	.14995	.001172 (7)	.0001032 (7)	1.049 (3)
EU-20-1	5501	"	"	.14995			
2	5502	"	"	.14998			
3	5503	"	"	.14995			
EU-22-1	5504	"	"	.14995			
2	5505	"	"	.14998			
3	5506	"	"	.14995			

(1) Sample Volume in ml

(2) U-233 Spike (ID-2) Volume in ml, Calibration: 5.1458×10^{18} atoms $^{233}\text{U}/\text{ml}$, Ratio: $238/233 = .002404$ (3) Pu-242 Spike (ID-8) Volume in ml, *Calibration: 4.958×10^{16} atoms $^{242}\text{Pu}/\text{ml}$, Ratio: $239/242 = .0001078$

TABLE A5

ISOTOPIC ANALYSIS SUMMARY OF EBWR FUEL RODS

Customer Ident.	Chemical Serial #	238/239 Ratio	240/239 Ratio	241/239 Ratio	242/239 Ratio	Spike 239/242 Ratio
EI-53-1	5486	.000597*17	.21598*43	.04297*11	.003283*25	.6994*14
EI-53-2	5487	.000671*20	.22999*46	.04993*12	.004837*36	.5661*11
EI-53-3	5488	.000490*15	.18148*36	.034981*87	.002285*19	.7150*14
EI-53-4	5489	.0002570*77	.12689*30	.018209*87	.000848*17	.7379*15
ER-72-1	5490	.000789*24	.28013*56	.05844*15	.005914*44	.39310*79
ER-72-2	5491	.000920*28	.29475*59	.06949*22	.007573*57	.6229*13
ER-72-3	5492	.000634*19	.22514*45	.04903*12	.003973*30	.45114*90
ER-72-4	5493	.0003143*94	.15167*30	.024341*82	.001297*12	.6161*12
EK-66-1	5494	.000493*15	.18898*38	.034890*87	.002321*19	.7322*15
EK-66-2	5495	.000590*18	.20632*41	.04372*11	.003228*25	.8493*17
EK-66-3	5496	.000387*12	.15226*30	.027377*72	.001463*13	.8538*17
EK-66-4	5497	.0002057*62	.10915*22	.013857*38	.002073*14	.6402*13
EK-19-2	5498	.000646*19	.21836*44	.04867*12	.003842*29	.6707*13
EJ-47-2	5499	.000822*16	.28969*58	.06148*15	.006359*48	.5655*11
ES-78-2	5500	.001134*11	.36261*73	.08034*20	.010880*27	.6108*12
EU-20-1	5501	.000566*17	.27687*55	.05919*15	.005186*39	.41962*84
EU-20-2	5502	.000723*22	.31562*63	.07783*19	.007799*58	.39906*80
EU-20-4	5503	.0002469*74	.14588*29	.023026*58	.0011415*86	.47190*94
EU-22-1	5504	.006360*48	.7138*14	.18296*37	.04249*11	.32311*65
EU-22-2	5505	.007992*60	.7691*15	.22415*45	.05168*13	.27898*56
EU 22 4	5506	.002385*23	.49656*99	.09616*19	.020930*52	.45143*90

Calibration Standard Y-1008B

Average 242/239 Ratio 1.03628 ± 61

ISOTOPIC ANALYSIS SUMMARY OF NEODYMIUM SAMPLES

Rod No.	Lab. No.	Grams Fuel/1	Sample Vol.(ml)	Spike Vol.(ml)	Nd Sample		Nd Sample + Spike*	
					150/142	150/148	142/150	148/150
EI-53-1	5486	119.1	.02503	.35009	9.770 (151)	.5770 (8)	.01551 (17)	.1431 (2)
2	5487	89.4	.02503	.35009	9.514 (87)	.5821 (7)	.02147 (16)	.1355 (3)
3	5488	106.8	.02503	.35009	5.272 (45)	.5861 (6)	.04589 (40)	.1237 (3)
4	5489	107.9	.10000	.69967	20.40 (7)	.5761 (5)	.01160 (5)	.1073 (2)
ER-72-1	5490	68.5	.02503	.35009	6.438 (27)	.5814 (8)	.01466 (5)	.1218 (2)
2	5491	118.1	.02503	.69967	11.52 (13)	.5965 (73)	.01313 (5)	.1155 (2)
3	5492	93.4	.02503	.35009	5.316 (50)	.5907 (13)	.02243 (9)	.1086 (2)
4	5493	84.3	.10000	.69967	7.388 (23)	.5793 (11)	.01033 (3)	.1215 (2)
EK-66-1	5494	109.5	.02503	.35009	3.773 (35)	.5826 (12)	.01832 (17)	.1219 (3)
2	5495	130.2	.03495	.69967	16.16 (9)	.5708 (7)	.01231 (6)	.1202 (2)
3	5496	118.6	.03495	.35009	0.8856 (315)	.6338 (18)	.03314 (26)	.1352 (6)
4	5497	104.3	.10000	.35009	4.256 (68)	.5844 (7)	.02352 (30)	.1191 (5)
EK-19-2	5498	90.3	.02503	.35009	2.488 (4)	.5858 (10)	.02777 (22)	.1298 (5)
EJ-47-2	5499	121.4	.02503	.69967	10.45 (6)	.5742 (8)	.01820 (7)	.1119 (9)
ES-78-2	5500	124.8	.02503	.69967	8.950 (21)	.5716 (11)	.01157 (2)	.1376 (2)
EU-20-1	5501	32.29	.03495	.35009	15.09 (4)	.5964 (7)	.01293 (8)	.1340 (5)
2	5502	33.98	.02503	.35009	7.946 (42)	.5842 (6)	.01588 (12)	.1189 (3)
4	5503	26.72	.10000	.35009	16.47 (15)	.5892 (7)	.01427 (4)	.1213 (3)
EU-22-1	5504	35.52	.02503	.35009	6.604 (17)	.5888 (6)	.03391 (11)	.0944 (8)
2	5505	33.98	.02503	.35009	22.82 (1.30)	.5902 (24)	.01611 (8)	.1007 (2)
4	5506	34.51	.07501	.35009	8.450 (106)	.5880 (11)	.02546 (14)	.0984 (7)

7/26/68

TABLE A7

ISOTOPIC ANALYSIS SUMMARY OF URANIUM SAMPLES
EBWR - CNEN SAMPLES

ROD NO.	LAB. NO.	SAMPLE(1) VOL.(U& Pu)	SPIKE(2) VOL.(U)	SPIKE(3) VOL.(Pu)	U SAMPLE			U SAMPLE + SPIKE
					234/238	235/238	236/238	238/233
1305-A	5898	.003960	.24997	.1001	.0003730 (54)	.06005 (24)	.001353 (14)	.8306 (25)
1626-A	5899	"	"	"	.0003565 (54)	.05855 (23)	.001559 (16)	.8639 (17)
2089-A	5900	"	"	"	.0003589 (54)	.05896 (24)	.001684 (17)	.8242 (16)
2095-A	5901	"	"	"	.0004593 (86)	.06148 (25)	.001124 (11)	.8274 (16)
EN-43-A	5902	.001982	.10010	.14995	-	.001151 (5)	.0001076 (32)	.9825 (29)

A-8

(1) Sample Volume in ml

(2) U-233 Spike (ID-2) Volume in ml, Calibration: 5.1458×10^{18} atoms $^{233}\text{U}/\text{ml}$, Ratio: $238/233 = .002404$

(3) Pu-242 Spike (ID-8) Volume in ml, *Calibration: 4.958×10^{16} atoms $^{242}\text{Pu}/\text{ml}$, Ratio: $239/242 = .0001078$

TABLE A8

ISOTOPIC ANALYSIS SUMMARY OF EBWR FUEL RODS

<u>Customer Ident</u>	<u>Chemical Serial #</u>	<u>238/239 Ratio</u>	<u>240/239 Ratio</u>	<u>241/239 Ratio</u>	<u>242/239 Ratio</u>	<u>Spike 239/242 Ratio</u>
1305-A	5898	.000409±12	.037480±94	.005059±38	.0001131±45	.31844±64
1626-A	5899	.000561±17	.04704±12	.007960±60	.0001592±64	.40040±80
2089-A	5900	.000673±20	.05011±13	.009471±71	.0002085±83	.42706±85
2095-A	5901	.0002727±92	.027956±70	.002530±26	.0000409±41	.21245±42
EN-43-A	5902	.0011635±98	.34680±69	.09041±23	.011682 ±35	.59170±99

Calibration Standard Y-1008B

Average 242/239 Ratio 1.03628±61

TABLE A9

ISOTOPIC ANALYSIS SUMMARY OF NEODYMIUM SAMPLES

EBWR - CNEEN SAMPLES

<u>Rod No.</u>	<u>Lab. No.</u>	<u>Grams Fuel/l</u>	<u>Sample Vol.(ml)</u>	<u>Spike Vol.(ml)</u>	<u>Nd Sample</u>		<u>Nd Sample + Spike*</u>	
					<u>150/142</u>	<u>150/148</u>	<u>142/150</u>	<u>148/150</u>
1305-A	5898	129.7	.0202	.69967	3.332 (20)	.4253 (17)	.01794 (20)	.07362 (28)
1626-A	5899	132.4	"	"	1.050 (8)	.4678 (17)	.02445 (38)	.09197 (37)
2089-A	5900	125.9	"	"	4.792 (40)	.4269 (17)	.01758 (42)	.09544 (38)
2095-A	5901	126.5	"	"	3.075 (28)	.4238 (17)	.01426 (14)	.05509 (22)
EN-43-A	5902	112.4	"	"	7.164 (102)	.5736 (23)	.01611 (16)	.1127 (4)

*¹⁵⁰Nd Spike (ID 14) calibration: 7.8398×10^{15} atoms ¹⁵⁰Nd/ml Isotopic ratios: $\frac{142}{150}$ $\frac{148}{150}$
.008056 .008679

8-1-68

A-10

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