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NONDESTRUCTIVE ANALYSIS OF FUEL
IRRADIATED IN THE EBWR
BY GAMMA SCANNING

April 1969

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ERRATA

TABLE OF CONTENTS Page v

Under Section IV-A, insert

6. Symmetry 40

Page 20, last line, 3rd paragraph - cladding misspelled.

Page 35, last sentence of Figure 10 caption should read -

Each Rod is Normalized to its Own Highest Count.

Page 37, - Data symbols are undefined and should be

- Zone 1 - First Burnup Step
- o Zone 2 - Second Burnup Step
- x Zone 3 - Third Burnup Step

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Reactor Technology

NONDESTRUCTIVE ANALYSIS
OF FUEL IRRADIATED IN THE EBWR
BY GAMMA SCANNING

By

E. S. Murphy*
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Reactor Experiments Section
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April 1969

FIRST UNRESTRICTED
DISTRIBUTION MADE

MAY 28 '69

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NON-DESTRUCTIVE ANALYSIS
OF FUEL IRRADIATED IN THE EBWR BY GAMMA SCANNING

ABSTRACT

As a part of the Plutonium Recycle Demonstration experiment conducted in the Experimental Boiling Water Reactor with plutonium enriched fuel, several intact fuel elements and a number of fuel rods have been analyzed by counting the fission product gamma rays emitted by the fuel. This non-destructive method provided valuable data about the performance of the plutonium enriched fuel as a function of exposure. A large part of the data is relative count rates, having been taken with a NaI(Tl) detector, and is presented to indicate a) the relative power generation profiles of UO_2 -1.5 wt% PuO_2 , Al-3.35 wt% PuO_2 , and natural UO_2 fuel rods at varying exposures; b) the relative power generation profile of a fuel element as well as the profile of the plutonium enriched region of the core as a function of exposure; c) changes to power generation profiles and how the changes correlate to reactor operating history, i.e., power level changes and control rod movements; d) core symmetry; e) performance characteristics of different nuclear fuels which have been irradiated in the same environment with the same power history; and f) the contribution to the total gamma activity measured outside an intact fuel element from each rod in a six rod column inside the element.

Gamma ray energy spectra data were also obtained with a Ge(Li) detector for the different fuels which were part of the irradiation experiment and several spectra are presented. However, the spectrum analysis is not complete and absolute results are not presented.

TABLE OF CONTENTS

BNWL-1005

LIST OF FIGURES	v
LIST OF TABLES	vii
I. INTRODUCTION	1
II. DESCRIPTION OF FUEL	3
A. Core Loading	3
B. Reactor Operating History	7
III. EXPERIMENTAL PROCEDURE	15
A. PNL Gamma Scanning Facility	15
B. Procedure for Rod Scans	18
C. Data Reduction	20
D. Procedure for Element Scan	22
IV. RESULTS	25
A. Scans of Mixed Oxide Rods	25
1. General Features	26
2. Power Generation Compared	29
3. Rod Power Profile Changes	31
4. Power Profiles in the Plutonium Region	36
5. Control Rod Settings	40
B. Scans of Special Rods	43
C. Scans of Enriched and Natural Uranium Rods	46
D. Scan of Element Pu-59	49
E. Summary Diagram	57
F. Gamma Ray Spectra	57
V. CONCLUSIONS	68
ACKNOWLEDGEMENTS	70
REFERENCES	71
APPENDIX A	72
DISTRIBUTION	80

LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
1	EBWR Plutonium Recycle Experiment core loading diagram.	4
2	UO ₂ -PuO ₂ fuel element.	6
3	EBWR thermal power history	8
4	Designation of fuel rod locations within a fuel element.	16
5.	Detector housing, carriage, rails, collimator, and fuel tray of the Pacific Northwest Laboratory gamma scan facility at the PRTR.	17
6	Gamma ray spectrum of a mixed oxide fuel rod taken with a 2" x 2" NaI(Tl) detector.	19
7	Diagram of the plutonium region of the EBWR core showing positions of some fuel rods that were gamma scanned.	27
8	Gamma Scans of seven radial rods from the second burnup step.	28
9	Gamma scans of rods at center of core. Three burnup steps.	32
9a	Gamma scans of rods at outer corners of plutonium region for three burnup steps.	34
10	Gamma scans of two rods from element Pu-43. First and third burnup steps.	35
11	Radial burnup profiles 10 inches above the bottom of the fuel.	37
12	Gamma scans of six fuel rods on a radial traverse through element Pu-59.	38
13	Gamma scans of five rods from element Pu-59 located at the same radial distance from the center of the core.	39
14	Gamma scans of fuel rods nos. 1, 11, 7, and 12 for the first burnup step.	41
15	Gamma scans of fuel rods from corresponding positions in different quadrants of the plutonium region.	42
16	Gamma scans of the special rods from each burnup step.	44

<u>Figure No.</u>		<u>Page</u>
17	Gamma scans of five enriched uranium fuel rods.	47
18	Gamma scans of mixed oxide, enriched uranium, and natural uranium rods.	48
19	Schematic of fuel element Pu-59 showing locations of fuel rods in the element.	50
20	Three-dimensional plot of relative burnup for fuel element Pu-59.	51
21	Comparison of experimental and synthesized bundle scans for fuel element Pu-59.	52
22	Contribution of each rod in a column to the total activity of the column.	55
23	Summary diagram of the relative power distribution at a point approximately 10 inches above the bottom of the fuel.	58
24	Gamma ray spectra of mixed oxide and special EBWR rods from the third burnup step.	60
25	Gamma ray spectra of a mixed oxide and a natural UO_2 EBWR rod from the third burnup step at 11.5 inches and 35.0 inches above the bottom of the fuel.	61
26	Gamma ray spectra of an enriched uranium and a mixed oxide EBWR rod from the third burnup step.	62
27	Gamma ray spectra of mixed oxide EBWR rods which had received different amounts of exposure.	63
A-1	Schematic drawing of element guide and collimator used at ANL.	A-3
A-2	Gamma scans of intact EBWR uranium fuel elements at ANL	A-6
A-3	Gamma scan of intact EBWR plutonium fuel element, Pu-59, at ANL	A-7

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
I.	Average daily control rod settings during EBWR power operation.	9
II.	Summary of EBWR power operation	10
III.	Summary of EBWR rods that were gamma scanned.	12
IV	Summary of EBWR rods for which gamma-ray spectrum data are presented.	58
V.	Prominent gamma rays from long-lived fission products.	63
A-I	Summary of EBWR elements scanned intact	A-2
A-II	Summary of corrected count rates of EBWR fuel elements scanned intact at ANL.	A-4

I. INTRODUCTION

Gamma scanning of fission product activities has been utilized to determine the relative burnup distribution of plutonium and uranium fuels irradiated in the Experimental Boiling Water Reactor (EBWR). This has been accomplished by scanning selected fuel rods from 6 x 6 rod fuel assemblies as well as by scanning a limited number of fuel assemblies intact. The rods that were analyzed were selected to assist in demonstrating the performance characteristics of plutonium enriched fuel in a boiling light water reactor. The gamma scan measurements were undertaken as a part of the $\text{UO}_2\text{-PuO}_2$ experiment in the EBWR,⁽¹⁾ a joint program between Argonne National Laboratory (ANL) and Pacific Northwest Laboratory (PNL) under the USAEC Plutonium Recycle Program, with the participation of the National Committee for Nuclear Energy (CNEN) of Italy through a contract with the United States Atomic Energy Commission.

One of the most important facets of designing power reactors which are safe and economical is the ability to accurately predict the reactor power distributions. The EBWR experiment afforded a unique opportunity to obtain experimental information on the spatial variation of power within a plutonium fueled boiling water reactor as a function of irradiation. It was deemed important to obtain gamma scan data not only to learn the relative burnup profile of a rod or an element but also to investigate the following:

- Changes in burnup profile of a rod as a function of exposure.
- Relative burnup profile within a 6 x 6 rod fuel assembly and changes to the profile as a function of exposure.
- Relative burnup profile of the plutonium-enriched region of the EBWR and changes to the profile as a function of exposure.
- Symmetry of burnup within the core.
- Correlation of relative burnup data with control rod settings.
- Comparison of the performance of different fuels, e.g., natural UO_2 , mixed oxide and aluminum-plutonium (Al-Pu) fuels, in the same environment and with the same power history.

The fuel was irradiated in three steps during the period from October, 1966, through June, 1967. At the conclusion of each burnup step, selected fuel rods were removed from the core and shipped to PNL where they were gamma scanned using a NaI(Tl) detector in the period between June, 1967, and May, 1968. Relative burnup measurements were made on 106 individual fuel rods from both the plutonium and uranium regions of the EBWR core. Of this total, 36 rods came from one assembly which had been scanned intact before the individual rods were removed and scanned. A Ge(Li) detector and a 4096-channel analyzer were also used at PNL to obtain high resolution gamma ray spectra from natural UO_2 , enriched UO_2 , mixed oxide and Al-Pu fuels. In addition to the work performed at PNL, seven intact 36-rod assemblies were scanned at ANL.

Results of the analysis of a first set of 17 rods sent to PNL have already been published.⁽²⁾ This report presents results of the measurements made on the 89 additional fuel rods. Some results from the first set

of 17 rods are included for comparison purposes. The results of the scanning of one 36-rod assembly performed at PNL are included in the body of the report and the results of the scanning of the seven intact assemblies performed at ANL are presented in Appendix A.

A description of the plutonium-enriched demonstration core loading and its irradiation history are presented in Section II. The details of the experimental procedure are discussed in Section III, and the results of the measurements are presented in Section IV. Included in the results are representative gamma ray spectra obtained from the different fuel types with the Ge(Li) detector.

II. DESCRIPTION OF FUEL

A. Core Loading

A schematic diagram of the EBWR Plutonium Recycle Experiment core loading is shown in Figure 1. The mixed oxide test fuel was located in 36 elements in a 6 x 6 square array in the center of the core. In Figure 1, the plutonium enriched fuel elements are labeled Pu _____. An intermediate region, comprising the two rows adjacent to the central plutonium-enriched region, contained 52 elements fueled with enriched uranium and eight spiked uranium elements. The enriched uranium elements are labeled EU____, and the spiked elements are labeled SP____. The outer region of the core contained 51 natural uranium elements, which are labeled NU____. All fuel elements, except spiked elements, contained 36 fuel rods in a 6 x 6 square lattice. Spiked elements contained a 7 x 7 array of fuel rods. In-core positions of all fuel rods that were gamma scanned are indicated in Figure 1. All the rods of assembly Pu 59 were scanned.

FIGURE 1
EBWR Plutonium Recycle Experiment Core Loading Diagram. The Dots Indicate In-Core Positions of Fuel Rods that were Gamma Scanned.

The plutonium-enriched test fuel was depleted UO_2 -1.5 wt% PuO_2 that had been loaded into Zircaloy-2 tubes by vibrational compaction.⁽³⁾ A sketch giving dimensions of a fuel element and a fuel rod is shown in Figure 2. The normal plutonium composition included 8.0 at% ^{240}Pu , and the depleted uranium content was nominally 0.16 at% ^{235}U . The active fuel length was 48.5 inches and began at approximately 1.8 inches above the bottom of a rod.

Five special rods were loaded into the central element of each quadrant of the plutonium region. These special rods had the following fuel compositions:

1. Natural uranium dioxide
2. Depleted UO_2 - 1.5 wt% PuO_2 with 20 at% ^{240}Pu .
3. Depleted UO_2 - 1.5 wt% PuO_2 with 26 at% ^{240}Pu
4. Aluminum - 3.35 wt% plutonium alloy, with 8 at% ^{240}Pu .
5. Aluminum - 3.35 wt% plutonium alloy, with 26 at% ^{240}Pu .

All of the special rods had the same dimensions as the mixed oxide rods and were clad in the same manner with Zircaloy-2.

Fuel for the enriched uranium portion of the uranium shim zone was in the form of UO_2 pellets enriched to 6.0 wt% ^{235}U . The pellets contained 0.158 wt% Eu_2O_3 and 0.0288 wt% Sm_2O_3 as burnable poisons. Pellets were stacked in a 48-inch long column inside Zircaloy-2 tubes. The active fuel began at 1.53 inches above the bottom of a rod. Spiked fuel elements contained enriched UO_2 with 93 wt% ^{235}U .

Outer elements of the EBWR Plutonium Recycle Experiment core contained rods loaded with natural UO_2 pellets. The dimensions

FIGURE 2
 $\text{UO}_2\text{-PuO}_2$ Fuel Element

and cladding of these natural UO_2 rods were the same as for the enriched UO_2 rods.

B. Reactor Operating History

With the core loading described above, the EBWR was operated from October, 1966 through June, 1967. The average daily power level is shown graphically in Figure 3. Average daily control rod settings are tabulated in Table I. Core locations of the control rods are shown in Figure 1. It can be seen that the daily setting of the central control rod (control rod number 9) was different from the settings of the eight outer control rods. During most of the reactor operation, the central control rod was withdrawn a greater distance than the eight outer control rods.

The first burnup step ended February 11, 1967. For this step the reactor was operated at a nominal power of 42 MW_t , and the estimated average burnup achieved in the plutonium region was approximately 1300 MWd/MTM. A summary of the exposure achieved during operation is shown in Table II. At the conclusion of the first step, 17 fuel rods were removed from the north-west quadrant of the plutonium region and shipped to PNL for analysis. The 17 rods included 12 mixed oxide rods and 5 special rods. Results from gamma scanning of these rods have been reported previously.⁽²⁾

The second burnup step ended April 29, 1967, with an estimated average burnup in the plutonium region of approximately 2300 MWd/MTM. During this period the reactor operated at a nominal power of 70 MW_t . At the conclusion of this step, 17 fuel rods were moved from the south-west quadrant of the plutonium region. These rods were shipped to

FIGURE 3
EBWR Thermal Power History

TABLE I

AVERAGE DAILY CONTROL ROD SETTINGS DURING EBWR POWER OPERATION

	OCT. 66		NOV. 66		DEC. 66		JAN. 67		FEB. 67		MARCH 67		APRIL 67		MAY 67		JUNE 67	
Day	Rods 1 - 8	Rod 9	Rods 1 - 8	Rod 9	Rods 1 - 8	Rod 9	Rods 1 - 8	Rod 9	Rods 1 - 8	Rod 9	Rods 1 - 8	Rod 9	Rods 1 - 8	Rod 9	Rods 1 - 8	Rod 9	Rods 1 - 8	Rod 9
1	-	-	-	-	18.0	35.0	19.5	31.2	20.0	31.2	-	-	31.6	31.6	-	-	21.5	21.5
2	-	-	-	-	20.0	31.2	19.5	31.2	20.0	31.2	18.8	28.0	29.5	22.5	-	-	22.5	22.5
3	-	-	18.5	28.0	20.0	31.2	19.5	31.2	20.2	31.2	21.0	28.0	29.5	30.0	-	-	23.0	23.0
4	-	-	24.0	28.0	20.0	31.2	19.5	31.2	20.2	31.2	19.0	28.0	31.4	31.4	-	-	23.0	23.0
5	-	-	25.5	28.0	20.0	31.2	19.5	31.2	20.2	31.2	21.5	28.0	31.9	31.9	-	-	23.0	23.0
6	-	-	25.7	28.0	20.0	31.2	19.5	31.2	20.2	31.2	28.0	28.0	31.9	31.9	-	-	27.0	39.0
7	-	-	26.0	28.0	19.0	31.2	19.5	31.2	20.4	31.2	25.8	28.0	31.9	31.9	-	-	30.0	39.0
8	-	-	25.5	28.0	19.3	31.2	19.5	31.2	20.2	31.2	24.0	28.0	31.9	31.9	-	-	30.0	39.0
9	-	-	24.5	28.0	19.5	31.2	19.5	31.2	20.2	31.2	27.0	28.0	32.3	32.3	-	-	30.0	39.0
10	-	-	24.0	28.0	19.7	31.2	19.7	31.2	19.6	31.2	30.0	28.0	30.4	30.4	-	-	31.0	39.0
11	-	-	23.6	28.0	19.7	31.2	19.7	31.2	19.8	31.2	28.5	28.0	31.9	31.9	-	-	31.5	39.0
12	15.0	28.0	27.0	28.0	19.7	31.2	19.7	31.2	-	-	-	-	32.0	32.0	-	-	31.5	39.0
13	16.0	28.0	27.7	28.0	19.5	31.2	19.7	31.2	-	-	-	-	32.0	32.0	14.5	14.5	27.0	39.0
14	16.5	28.0	28.0	28.0	19.6	31.2	19.7	31.2	-	-	11.9	28.0	33.0	32.5	31.0	30.5	31.5	39.0
15	17.0	28.0	28.0	28.0	19.6	31.2	19.7	31.2	-	-	19.5	28.0	32.5	32.5	25.5	25.5	31.5	39.0
16	17.2	28.0	27.0	28.0	19.6	31.2	19.7	31.2	-	-	33.7	28.0	32.6	32.7	25.0	25.0	31.5	39.0
17	18.0	28.0	-	-	19.6	31.2	19.7	31.2	-	-	34.5	28.0	32.7	32.7	29.5	29.0	31.5	39.0
18	19.5	28.0	-	-	19.6	31.2	19.7	31.2	-	-	27.0	29.0	32.7	32.7	30.0	29.0	31.5	39.0
19	20.0	28.0	20.0	20.0	19.6	31.2	19.7	31.2	-	-	31.0	32.2	32.7	32.7	-	-	31.5	39.0
20	19.5	28.0	23.0	23.0	19.6	31.2	19.7	31.2	-	-	32.4	27.5	32.7	32.7	-	-	31.5	39.0
21	-	-	24.0	24.0	19.6	31.2	19.7	31.2	-	-	32.4	27.5	32.7	32.7	-	-	31.5	39.0
22	-	-	27.0	27.0	19.5	31.2	19.7	31.2	-	-	-	-	32.7	32.7	-	-	31.5	39.0
23	-	-	27.0	27.0	19.5	31.2	19.0	31.2	-	-	17.5	18.0	32.7	32.7	-	-	31.5	39.0
24	16.0	28.0	28.5	28.5	19.5	31.2	19.5	31.2	-	-	24.0	25.0	33.0	33.0	-	-	31.5	39.0
25	19.7	28.0	28.0	28.0	19.4	31.2	19.7	31.2	-	-	29.0	29.0	33.2	33.2	-	-	31.5	39.0
26	20.5	28.0	27.0	27.0	19.3	31.2	19.7	31.2	-	-	31.0	31.0	33.2	33.2	-	-	31.5	39.0
27	21.3	28.0	24.0	24.0	17.7	31.2	19.8	31.2	-	-	31.5	31.5	32.2	32.2	-	-	31.5	39.0
28	23.0	28.0	21.0	38.7	18.5	31.2	19.8	31.2	-	-	32.0	32.0	32.2	32.2	-	-	31.5	39.0
29	24.5	28.0	18.5	38.7	19.3	31.2	19.8	31.2	-	-	31.5	31.5	32.2	32.2	20.0	20.0	31.5	39.0
30	25.5	28.0	17.5	38.7	19.5	31.2	19.8	31.2	-	-	31.5	31.5	-	-	22.5	22.5	-	-
31	26.0	28.0	-	-	19.5	31.2	19.8	31.2	-	-	31.6	31.6	-	-	21.5	21.5	-	-

The numbers are dial readings in inches. A reading of zero inches for a control rod setting corresponds to 0.5 inches above the bottom of the active fuel length. Because control rod number 9 is different from the others, the position of its starting poison section inside the reactor is 2 inches higher than the reading on its dial. Therefore, a zero reading for control rod number 9 corresponds to 2.5 inches above the bottom of the active fuel.

TABLE II⁽⁴⁾

OUTLINE OF POWER OPERATION
EBWR Pu EXPERIMENT

<u>Date</u>	<u>~Reactor Exposure (MWD)</u>	<u>Assumed Power From Pu Zone (% of Reactor Power)</u>	<u>~Pu Zone[*] Exposure (MWD/Tonne)</u>
Oct. 1966 to Feb. 1967	3760	35	1320
Mar. 1967 to May 1967	3140	30	940
May 1967	310	25	80
June 1967	1050	25	<u>260</u>
		Total	2600

*Since there is ~1 tonne of PuO₂ in the EBWR, the exposures are quoted in megawatt days per metric ton.

PNL in August, 1967, and were gamma scanned during October and November, 1967. Results from the gamma scanning of these rods are described in this report. The 17 rods from the second burnup step occupied positions in the south-west quadrant that were analogous to positions occupied in the north-west quadrant by the 17 rods from the first burnup step and included 5 special rods.

At the programmed end of the EBWR irradiations, on June 29, 1967, an additional rod sampling of 54 fuel rods from the plutonium region of the core and 18 fuel rods from the enriched and natural regions of the core were shipped to PNL to be gamma scanned. The average estimated burnup for rods from the plutonium region was 2600 MWd/MTM. The rods arrived at PNL during November, 1967, and gamma scanning was completed in April, 1968. The 54 fuel rods from the plutonium region included 12 mixed oxide fuel rods that had occupied positions in the south-east quadrant analogous to the positions occupied in the north-west and south-west quadrants by mixed oxide fuel rods from the first two rod samplings. Also included in the group of 54 rods were six rods from elements Pu-08 and Pu-45 in the south-east quadrant, and one rod from element Pu-43 in the north-west quadrant. Fuel element Pu-59, the center element in the south-east quadrant of the plutonium region, was shipped intact with its complement of 36 fuel rods which included 5 special rods.

A summary of all EBWR rods that were gamma scanned is presented in Table III. Positions of fuel rods within the EBWR core can be determined by reference to Figure 1 which shows the

TABLE III

SUMMARY OF EBWR RODS THAT WERE GAMMA SCANNED

Rod Serial Number	Location		Fuel Composition	P.N.L. Ident. Number	Cooling Time (days)
	Element Number	Position in Element			
I. First Burnup Step					
EP-98	Pu-46	36	UO ₂ -PuO ₂ (8% ²⁴⁰ Pu)	1	138
EL-67	Pu-46	15	"	2	139
EO-16	Pu-46	1	"	3	139
EV-71	Pu-43	22	"	4	144
EX-42	Pu-34	22	"	5	144
EY-22	Pu-34	8	"	6	145
EY-32	Pu-34	1	"	7	145
EI-16	Pu-07	21	"	8	150
ET-54	Pu-44	21	"	9	151
EQ-51	Pu-44	3	"	10	151
EH-24	Pu-46	35	"	11	166
EX-89	Pu-34	7	"	12	151
EX-01	Pu-43	34	UO ₂ -PuO ₂ (20% ²⁴⁰ Pu)	13	164
EX-55	Pu-43	10	UO ₂ -PuO ₂ (26% ²⁴⁰ Pu)	14	165
EU-07	Pu-43	26	Al-Pu (8% ²⁴⁰ Pu)	15	164
EU-10	Pu-43	8	Al-Pu (26% ²⁴⁰ Pu)	16	179
EX-65	Pu-43	18	Natural UO ₂	17	167
II. Second Burnup Step					
EM-42	Pu-26	31	UO ₂ -PuO ₂ (8% ²⁴⁰ Pu)	1	174
EI-53	Pu-26	16	"	2	174
ER-72	Pu-26	6	"	3	178
EK-19	Pu-18	21	"	4	180
EK-66	Pu-02	21	"	5	184
EP-27	Pu-02	11	"	6	184
EJ-47	Pu-02	6	"	7	180
EJ-53	Pu-09	22	"	8	178
ER-04	Pu-03	22	"	9	178
EL-73	Pu-03	4	"	10	177
ES-78	Pu-26	32	"	11	174
EK-02	Pu-02	12	"	12	181
EX-46	Pu-18	33	UO ₂ -PuO ₂ (20% ²⁴⁰ Pu)	13	179
EX-64	Pu-18	9	UO ₂ -PuO ₂ (26% ²⁴⁰ Pu)	14	177
EU-20	Pu-18	29	Al-Pu (8% ²⁴⁰ Pu)	15	180
EU-22	Pu-18	11	Al-Pu (26% ²⁴⁰ Pu)	16	178
EX-07	Pu-18	13	Natural UO ₂	17	180

TABLE III (Continued)

Rod Serial Number	Element Number	Position in Element	Fuel Composition	P.N.L. Ident. Number	Cooling Time (days)
III. Third Burnup Step					
EU-15	Pu-43	15	UO ₂ PuO ₂ (8% ²⁴⁰ Pu)		187
EJ-34	Pu-36	6	"	1	190
EK-62	Pu-36	21	"	2	190
EN-43	Pu-36	31	"	3	190
ES-15	Pu-42	16	"	5	190
EQ-50	Pu-42	26	"	6	189
ER-58	Pu-42	31	"	7	189
EH-47	Pu-28	22	"	8	190
EU-73	Pu-08	16	"	9	188
EH-11	Pu-08	34	"	10	189
EJ-84	Pu-36	12	"	11	190
ER-90	Pu-42	32	"	12	189
EQ-21	Pu-08	25	"		191
EQ-37	Pu-08	31	"		190
EI-34	Pu-08	32	"		188
EQ-88	Pu-45	1	"		189
ET-37	Pu-45	2	"		190
EH-31	Pu-45	7	"		189
EK-68	Pu-59	1	UO ₂ -PuO ₂ (8% ²⁴⁰ Pu)		284
ER-83	"	2	"		287
EX-48	"	3	UO ₂ -PuO ₂ (20% ²⁴⁰ Pu)	13	286
EK-72	"	4	UO ₂ -PuO ₂ (8% ²⁴⁰ Pu)		287
EL-18	"	5	"		288
EJ-46	"	6	"		288
EK-34	"	7	"		285
EG-42	"	8	"		286
EP-24	"	9	"		286
EM-48	"	10	"		287
EU-55	"	11	Al-Pu (8% ²⁴⁰ Pu)	15	287
EG-82	"	12	UO ₂ -PuO ₂ (8% ²⁴⁰ Pu)		288
EJ-26	"	13	"		285
EK-94	"	14	"		286
EI-73	"	15	"		284
EN-47	"	16	"	4	287
EL-66	"	17	"		287
EH-03	"	18	"		288
EX-62	"	19	Natural UO ₂	17	286

TABLE III (Continued)

Rod Serial Number	Element Number	Position in Element	Fuel Composition	P.N.L. Ident. Number	Cooling Time (days)
EJ-27	Pu-59	20	UO ₂ -PuO ₂ (8% ²⁴⁰ Pu)		286
ET-27	"	21	"		285
EK-47	"	22	"		288
EQ-89	"	23	"		288
ET-53	"	24	"		287
EM-53	"	25	"		286
EQ-31	"	26	"		286
EW-90	"	27	UO ₂ -PuO ₂ (26% ²⁴⁰ Pu)	14	286
EN-48	"	28	UO ₂ -PuO ₂ (8% ²⁴⁰ Pu)		288
EU-44	"	29	Al-Pu (26% ²⁴⁰ Pu)	16	288
EQ-01	"	30	UO ₂ -PuO ₂ (8% ²⁴⁰ Pu)		287
EN-73	"	31	"		284
EQ-07	"	32	"		286
EN-44	"	33	"		285
EN-05	"	34	"		288
EM-43	"	35	"		287
ER-55	"	36	"		288
1076	EU-46	15	Enriched UO ₂ (6 wt% ²³⁵ U)		189
2240	EU-25	15	"		188
717	EU-43	16	"		201
1571	EU-47	21	"		201
682	EU-30	22	"		201
1242	EU-64	22	"		202
1626	EU-29	22	"		202
1305	EU-18	22	"		202
1098	EU-57	22	"		202
2095	EU-78	22	"		202
666	EU-34	22	"		203
2394	EU-92	22	"		203
2089	EU-76	16	"		203
776	EU-20	22	"		203
4503	NU-125	22	Natural UO ₂		201
4012	NU-116	22	"		201
4249	NU-86	22	"		202
2604	NU-114	22	"		202

Scan data for all fuel rods from the first burnup step were normalized to rod count rates at 182 days cooling time.

Scan data for all fuel rods from the second burnup step were normalized to rod count rates at 186 days cooling time.

Scan data for fuel rods from the plutonium region for the third burnup step were normalized to rod count rates at 291 days cooling time.

Scan data for fuel rods from the uranium regions for the third burnup step were normalized to rod count rates at 203 days cooling time.

location of each fuel element and to Figure 4 which illustrates the method used to designate rod positions within a fuel element. It should be noted that for fuel elements from the first two quadrants of the plutonium region (the north-west and south-west quadrants) the notch in the element shroud was oriented north-west. For most of the fuel elements from the third quadrant of the plutonium region (the south-east quadrant), the notch in the element shroud was oriented north-east.

III. EXPERIMENTAL PROCEDURE

A. PNL Gamma Scanning Facility

The Pacific Northwest Laboratory Gamma Scanning Facility is located in the fuel storage basin at the Plutonium Recycle Test Reactor (PRTR). A diagram of the scanner is shown in Figure 5. Several feet of water provide an adequate gamma radiation shield for operating personnel during the scanning process.

The gamma scan facility has been described in a previous report⁽²⁾ and the details will not be repeated here. Modifications incorporated for the present experiments included a new rod positioner of solid aluminum which replaced the teflon holders used previously. A mechanical stop at one end of the new rod holder insured reproducible positioning of the fuel rods on the holder. Positioning of the scanner along a rod was accurate to $\pm 1/16$ in. The collimator used for these measurements had a circular aperture 0.25 in. in diameter.

FIGURE 4

Designation of Fuel Rod Locations Within a Fuel Element. The Shroud Notch is Oriented Northwest for all Fuel Elements from the First and Second Burnup Steps (Northwest and Southwest Quadrants of the Plutonium Region). For Fuel Elements from the Third Burnup step (Southeast Quadrant of the Plutonium Region), the Shroud Notch is Oriented Northwest for Element Pu-08 and Oriented Northeast for Elements Pu-28, Pu-36, Pu-42, Pu-45, and Pu-59. The Shroud Notch is Oriented Northwest for all Elements from the Uranium Regions.

FIGURE 5
Detector Housing, Carriage, Rails, Collimator and Fuel Tray
of the Pacific Northwest Laboratory Gamma Scan Facility in
the PRTR Fuel Storage Basin.

A 2 x 2 in. NaI(Tl) crystal with a resolution of 10% FWHM for the 662 keV gamma ray from ^{137}Cs was used as the detector for the fuel rod scans. In addition, a Ge(Li) detector of 9 cm² cross section and 1 cm depletion depth was used to obtain gamma ray spectra from several of the EBWR fuel rods. The Ge(Li) detector was oriented such that gamma rays from the fuel traversed the long dimension of the detector, (3 cm) in order to increase efficiency and the ratio of photoelectric to compton events. The detector had a resolution of 4.0 keV FWHM for the 662 keV gamma ray from ^{137}Cs . Transistorized electronic equipment including linear amplifiers, single channel analyzers, and scalers was used with the NaI(Tl) detector. The use of transistorized equipment served to reduce the electronic drift which had been a serious problem during scanning of the first set of EBWR rods. To obtain gamma ray spectra, output pulses from the Ge(Li) detector were analyzed using a 4096-channel analyzer.

B. Procedure for Rod Scans

A typical EBWR fuel rod gamma ray spectrum taken with the NaI(Tl) detector is shown in Figure 6. Because of the long cooling times associated with the scans of these rods, only two intermediate-energy gamma ray intensity peaks are easily detected. The peak at about 500 keV is due primarily to the 512 keV gammas from $^{106}\text{Ru}/^{106}\text{Rh}$, with a small contribution from the 497 keV gamma ray from ^{103}Ru . The peak at about 750 keV is due to the 725 keV and 756 keV gamma rays from ^{95}Zr and to the 765 keV gamma rays from ^{95}Nb . For measurements on fuel rods from the second burnup step, the window of the single channel analyzer

FIGURE 6
Gamma ray Spectrum of a Mixed Oxide Fuel Rod Taken with the 2" x 2" NaI(Tl) Detector. For Fuel Rods from the Second Burnup step, and Energy Window from 660 to 880 keV was used for the Gamma Scans. For Fuel Rods from the Third Burnup Step, an Energy Window from 710 to 885 keV was used for the Gamma Scans.

was set to accept pulses in the energy range from 660 to 880 keV. For measurements on the last set of EBWR fuel rods, gamma activity in the energy range from 710 to 885 keV was counted. Thus, in both cases, the $^{95}\text{Zr}/^{95}\text{Nb}$ gamma activity of the rods was measured.

A one minute count was taken at each rod position where a measurement was made. The count rate on the zirconium peak at 750 keV was typically of the order of 50,000 counts per minute. As part of the normal operating routine, calibration of the apparatus with ^{137}Cs and ^{60}Co sources was made at frequent intervals. Repeated counts at several positions were also made to check the reproducibility of the measurements and to evaluate the statistical accuracy of the data collected. As many as 50 measurements were made along the length of each fuel rod.

C. Data Reduction

The procedure for reduction of data from the fuel rod scans consisted of background subtraction, correction for the activity due to the Zircaloy cladding, and a decay correction.

Measurements of background were made before, during, and after the scanning of each fuel rod. Background count rates were of the order of one percent of the gross count rate for the energy range selected and were practically constant during all measurements. The background level resulted primarily from the presence of other fuel elements stored in the basin. No background changes were observed to result from the presence of EBWR fuel rods on the scanning tray.

The correction for the count rate contribution due to the Zircaloy rod cladding was determined by the formula

$$ZC_i = \frac{C_o V_1}{C_1 V_o} C_i$$

where

ZC_i is the cladding correction at the i^{th} point being scanned,

C_o is the count, minus background, at approximately 0.25 in. below the starting point of the active fuel,

C_1 is the count, minus background, at approximately 0.25 in. above the starting point of the active fuel,

C_i is the count, minus background, at the i^{th} point along the fuel rod being scanned, and

V_1/V_o is the ratio of the cladding volume at the +0.25 in. position to the end cap volume at the -0.25 in. position.

The cladding corrections so determined ranged from about 1.4% to about 1.8% of the total count rate at the measured point. A calculated cladding activity using cross sections given by the RIBOT Code⁽⁵⁾ leads to a value of 1.65% of the total activity at any point along a fuel rod.

At the conclusion of the rod scans for each set of rods, data were taken to permit internormalization of all rod data within a set to the same cooling time. The experimental procedure consisted in repeating, on a single day, measurements at several fixed points on each rod of the set. In cases where several

rods had previously been scanned on the same day, only one of the rods was re-measured. The average ratio of the latest count rates to the earlier count rates at the repeated measurement points was assumed as the decay factor. The theoretical value of the ^{95}Zr decay, using a 65.5 day half life was also evaluated. In most instances, the difference between theoretical and experimental values of the decay correction was less than 2%. The experimental decay correction was always applied to the data.

An adequate description of propagated errors to account for the scatter of repeated counts was obtained from error equations that included the uncertainty of the decay correction ($\sim 1.5\%$) and an assumed 1% error identified with electronic drift and positioning. For a 50,000 count rate, a one standard deviation of $\pm 2.2\%$ results.

D. Procedure for Element Scan

Fuel element Pu-59 was one of seven elements scanned at ANL after termination of the third burnup step. It was also scanned as a complete element at PNL. However, the methods of scanning the fuel element were different at ANL and at PNL. At ANL, longitudinal scans were made (see Appendix A) with a collimator aperture which encompassed the width of the whole element. At PNL, two transverse scans were made on each side of the element, one at 12 in. and the other at 32 in. above the bottom of the active fuel.

Gamma scanning of element Pu-59 was performed with the same equipment as that used to scan individual fuel rods. A special element holder was fabricated which made it possible to place the fuel element in a horizontal position and which permitted transverse movement of the element under the collimator. A new collimator

head was also built to permit the scanning of flat surfaces. Following the normal procedure for scanning of fuel rods, the gamma activity of the $^{95}\text{Zr}/^{95}\text{Nb}$ peak in the range from 710 keV to 885 keV was monitored.

After the transverse scans were completed on the intact assembly, measurements were made to evaluate the contributions to the total observed gamma activity for a 6-rod column from the individual rods in that column. The technique was as follows: With the fuel element held in a vertical position, wires were attached to the top end caps of 12 rods in two different columns. With the element in its horizontal counting position, the rods were removed one by one, from the bottom up, by pulling the wires. Gamma activity measurements were made above the column from which rods were being removed before and after each rod was pulled from the element. After the column measurements were completed, each rod from the element was scanned individually.

Counting data from scanning of element Pu-59 were corrected for background, for differences in cooling times, and for zirconium activity of the rod cladding and the bundle shroud. The correction for the activity of the zirconium bundle shroud and the rod cladding was evaluated by the following procedure: Gamma activity in the energy range from 710 keV to 885 keV was measured at a point 12.5 in. above the bottom of the bundle shroud. Since this point is below the bottom of the active fuel, the measured count rate represents the total zirconium activity of the bundle shroud and the fuel rod end caps. The bundle shroud activity was also

measured after all fuel rods had been removed from one column. With these data, the zirconium correction can be computed from the following formula:

$$Z_c = A \cdot VF + A_B(1 - VF)$$

where

Z_c is the zirconium activity due to the bundle shroud and rod cladding,

A is the total measured activity at 12.5 in.,

A_B is the activity of the bundle shroud only, and

VF is the volume fraction of the cladding of the rods.

The average value for this correction to the peak activity of a column of six rods was $3.16 \pm 0.06\%$ of the total measured activity. This value was taken as a constant for all of the measured points along a transverse scan. Because the collimator has a 0.25 in. diameter aperture whereas the diameter of a fuel rod is 0.476 in., only when the rods are directly beneath the collimator aperture does the measured count rate represent the real activity of the rod column being measured. The zirconium correction will also be in error for those points in which the collimator aperture is not centered over a rod and overlaps the water gap. Because of the lesser importance of the off-center points which are used only to establish the position of the peak activity, no effort was made to calculate the zirconium correction at positions other than at the rod center.

IV. RESULTS

A. Scans of Mixed Oxide Rods

The results of the gamma scanning measurements provide a significant body of data for testing the accuracy of methods utilized in calculating power distributions in plutonium fueled boiling water reactors. The data are obtained in sufficient detail to allow an assessment of the problem areas in the calculational method(s). The data are also an indicator of the history of reactor operation (e.g., control rod positions).

Absolute comparisons of burnup for fuel rods from different burnup steps are not made from data presented in this report. This results from the following factors: Although the $^{95}\text{Zr}/^{95}\text{Nb}$ gamma ray peak at approximately 750 keV was used for gamma scans of rods from each burnup step, ^{95}Zr has a half life of 65 days which is relatively short in comparison with irradiation times for fuel rods in this experiment. The first burnup step involved full power operation at 42 MW_t for 90 days. At the conclusion of the third burnup step, the fuel rods had been in the reactor for a total of 261 days and had been irradiated for a total of 175 days, much of the time at a power level of 70 MW_t . Thus, whereas an approximately linear relationship existed between zirconium gamma ray activity and burnup during the first burnup step, the ^{95}Zr activity was approaching saturation at the conclusion of the third burnup step. In addition, although $^{95}\text{Zr}/^{95}\text{Nb}$ activity was monitored, the gamma energy intervals were not identical for scans of rods from different burnup steps.

Changes in relative power profile can, however, be observed by examining rods at comparable locations in the core for the different burnup steps. A diagram of the plutonium region of the EBWR core is presented in Figure 7 and shows the locations and PNL identification numbers of the 17 fuel rods from each of three zones that were gamma scanned. Fuel rods scanned following the first burnup step came from zone 1; rods scanned following the second burnup step came from zone 2; and rods scanned following the third burnup step came from zone 3.

1. General Features

Power profiles of radially positioned rods of mixed oxide fuel from zone 2 of the plutonium region removed following the second burnup step (rods numbered 1 through 7 in Figure 7) are shown in Figure 8. Included in the insert shown in Figure 8 are relative power values at the point of peak activity of all radially positioned rods for each burnup step. All rod scan data are normalized to the highest count of rod number 1 of that particular burnup step. Thus, only relative changes in power shape within a given burnup step can be inferred and compared from the figure.

Certain features are common to each of the burnup steps. In each case, rod number 1 exhibits the highest power and rod number 5 exhibits the least power. Thus the power distribution within the plutonium zone peaked in the center of the core. Peak power occurs approximately 11 in. above the bottom of the fuel, although it appears to shift slightly upward with each

FIGURE 7
The Plutonium Region of the EBWR Core Showing Positions of some Fuel Rods that were Gamma Scanned. The Numbers are PNL Rod Identification Numbers.

FIGURE 8

Relative Power Generation Profiles from Gamma Scans of Seven Radially Positioned Mixed Oxide Fuel Rods from the Second Burnup Step. The Insert Compares Relative Power Generation Values at the Point of Peak Activity of Rods 1 Through 7 for each Burnup Step. Rod Scan Data from each Burnup Step are Normalized Separately to the Highest Count of Rod Number 1 of that Particular Step.

burnup step (not shown). The upper portion of each fuel rod experiences very little burnup as typically, 5-10% of the total burnup occurs in the upper one-third of the active fuel. The effect of a control rod in depressing the fission rate in rods adjacent to it can also be seen. The burnup profile of fuel rod number 7 compared with the profiles of fuel rods numbers 5 and 6 indicates that the active portion of control rod number 8 ended near 32.5 in. above the bottom of the fuel. The position as recorded in Table I for the second burnup step verifies this.

2. Power Generation Compared

The data contained in the insert of Figure 8 provide information on the changes in spatial fission rates during burnup and the mechanism causing the changes.

If leakage was the only effect on the power distribution in the x-y plane, then it would be expected that fuel rod number 1 would generate the most power and fuel rod number 7 the least. The data from zone 1 show that the power distribution does not decrease uniformly as a function of position from the center of the reactor. Rather, the power distribution is peaked at the corners of each element and dipped in the center of the element. This is due to the existence of water gaps outside the elements which peak the power in the adjacent fuel rods. Because of the larger water gap next to rod 7, the power generation in rod 7 is higher than that for rods 2, 4, 5, and 6.

Looking at the relative differences between rods 2, 4, and 5, it is noted that the power distribution shifts with exposure. the order of power generation is 2, 4, and 5 for the first two burnup steps and then goes to 4, 2, and 5 for the third step. This is a significant change in that the shift occurred during the last 300 MWd/tonne of exposure. Another shift occurs for rods 2, 4, and 6 where the order of power generation is 2, 6, and 4 for the first burnup step; 6, 2, and 4 for the second; and 6, 4, and 2 for the third step. The power generation of rods near the outer edge of the plutonium region not only increased with exposure relative to the power generation of the center rod, but increased relative to the rods in the interior of the plutonium region as well. The power generation of the interior rods did not follow this trend of a continuing increase relative to the center rod as a slight decrease in power generation relative to the center rod occurred during the third burnup step.

The shifts in power generation with exposure can be correlated with changes in reactor power level and control rod changes. The reactor power was increased from 42 MW_t to 70 MW_t for the second burnup step and the eight outer control rods were withdrawn from approximately 19.8 in. to the same approximate elevation (32.5 in. See Table I) as the center control rod which was not raised appreciably. The withdrawal of the outer eight control rods, accompanied by the requirements of increased power density, flattened the power generation profile in the core such that all the rods away from the center of the core increased

in power generation relative to rod 1. Since rods 2, 3, 4, and 5 are surrounded by smaller water gaps than rod 7, their rate of power generation increase was not as large relative to rod 1 as the increase incurred in rods 6 and 7. The power level of the third burnup step was maintained near 65 MW_t and the approximate positions of the outer eight control rods did not change. However, the center control rod was withdrawn to its full-out position which would tend to peak the power generation at the center of the core as evidenced by the decrease in power generation of rods 2, 3, 4, and 5 relative to rod 1. However, the requirements of the maintained power density increased the power generation of rods 6 and 7 relative to rod 1 since the plutonium at the center of the core was more depleted.

3. Rod Power Profile Changes

Power profiles of plutonium enriched rods from the center of the core (rods numbered 1) are shown in Figure 9 for the three burnup steps. Each rod is normalized to its own highest count, hence no information about absolute burnup is implied in the figure. An upward shift of about two inches in the position of peak gamma ray activity and a marked increase in relative power generation in the upper two-thirds of the rod is evident from a comparison of the profile of the fuel rod from the second burnup step with the profile of the rod from the first burnup step. Except in the top twelve inches of fuel, very little change in relative power generation profile is evident in a comparison of fuel rods from the second and third burnup steps. Similar changes

FIGURE 9
Gamma Scans of Rods from Center of Core, Position Number 1,
for each of the Three Burnup Steps. The Data of each Rod
are Normalized to its own Highest Count

in power profiles are observed when other sets of rods (e.g., rods numbered 2 or rods numbered 7) from the three burnup steps are compared, Figure 9A. However, the increased power generation is more pronounced in rod 7 as the result of power flattening due to withdrawal of the eight outer control rods and an increased void concentration present at the higher power level.

The effect of the withdrawal of the center control rod to its full-out position during the third burnup step can be seen in Figure 9. Some shift in power generation to the outer rods of the plutonium region during the third burnup step is seen in Figure 9A.

Power profiles for two mixed oxide fuel rods from fuel element Pu-43 are shown in Figure 10. Fuel element Pu-43 was the center element in zone 1 of the plutonium region. One mixed oxide fuel rod (rod number EV-71) from the center of this element (location 22) was removed and scanned following the first burnup step, and a second mixed oxide rod (rod number EU-15, location 15) was removed and scanned following the third burnup step. In the figure, each rod is normalized to a different count rate, hence only changes in power profile are significant. For the mixed oxide rod scanned following the third burnup step, there is an upward shift in the point at which peak power occurs and also a significant increase in power along the upper two-thirds of the fuel. It has been pointed out that most of the observed change in relative power profile occurred during the second burnup step and was caused by the

FIGURE 9A

GAMMA SCANS OF RODS FROM THE OUTER CORNER OF THE PLUTONIUM REGION, POSITION NUMBER 7, FOR EACH BURNUP STEP. THE DATA FROM EACH ROD ARE NORMALIZED TO ITS OWN HIGHEST COUNT.

FIGURE 10
Gamma Scans of Two Rods from Element Pu-43. One Rod was Removed After the First Burnup Step and the Other Rod After the Third Burnup Step. Each Rod is Normalized to Rod Number 1 of its set.

change in void concentration and the withdrawal of the outer eight control rods which accompanied the increase in reactor power.

4. Power Profiles in the Plutonium Region

Power generation profiles within the plutonium region at a single position in the x-y plane can be observed by presenting the data in a different format as shown in Figure 11. The figure is constructed by plotting the relative power generation observed at 10 in. above the bottom of the fuel as a function of rod position for rods 1 through 7 for each burnup step. The figure then represents the radial power distribution for each burnup step (the dashed lines are drawn by inspection). The flattening of the distribution during the second and third burnup steps due to the rise in reactor power and control rod movement is evident. A profile of the plutonium region at 30 in. above the bottom of the fuel (not shown) shows more markedly the effect of control rod settings and void concentration changes.

Gamma scan profiles of six rods on a radial traverse through element Pu-59 are presented in Figure 12 in the normal format which shows again the flux depression existing within an element. From considerations of symmetry, if all fuel rods had the same composition, the power profiles for fuel rod EU-55 should be slightly higher than the power profile for fuel rod EQ-31. However, because rod EU-55 is an Al-Pu fuel rod, it has the lowest power of any of the rods in this traverse.

FIGURE 11
Radial Power Generation Profiles at 10 Inches Above the Bottom of the Fuel are Compared for the Three Burnup Steps. Data for each Burnup Step are Normalized Separately. The Fuel Elements have been Rotated about the Core Center in this Figure. Since each Rod from Element Pu-59 was Scanned, the Figure Shows Additional Data for Third Burnup Step to Correspond with Rod Marked with Vertical Straight Lines

FIGURE 12
Gamma Scans of Six Fuel Rods on a Radial Traverse Through
Element Pu-59.

FIGURE 13
Gamma Scans of Five Rods from Element Pu-59 Located at the
same Radial Distance from the Center of the Core

Information about the power distribution in an element can also be obtained from the gamma scan profiles of five additional mixed oxide fuel rods from element Pu-59 which are presented in Figure 13. All five of the fuel rods were at the same radial distance from the center of the core. Since rods EM-43 and EK-34 are outer rods while rods EN-48, ET-27, and EK-94 are interior rods, this figure illustrates both the symmetry of the thermal flux distribution and also the thermal neutron flux depression in fuel element Pu-59.

5. Control Rod Settings

The use of gamma scan data to correlate control rod settings is illustrated in Figure 14. The figure shows power profiles from the first burnup step for two mixed oxide fuel rods at the center of the core and two mixed oxide fuel rods at the edge of the plutonium zone. The average daily positions of the ends of active poison sections for control rods adjacent to these fuel rods are shown as dashed vertical lines. A definite correlation between fission product activity and control positions is apparent from the shapes of the profiles. Similar correlations between fuel rod power profile data and control rod positions can be made for the second and third burnup steps (not shown).

6. Symmetry

The power profile of a mixed oxide rod from the center element of zone 3 of the plutonium region is compared to that of a corresponding rod from the center element of zone 1 in Figure 15. Both rods were removed at the conclusion of the third burnup step, and both rods are normalized to the same count. The

FIGURE 14
Gamma Scans of Fuel Rods Nos. 1, 11, 7, and 12 for the First Burnup step. Average Daily Positions of the ends of Active Poison Sections for Control Rods Adjacent to these Fuel Rods are Shown as Dashed Vertical Lines.

FIGURE 15

GAMMA SCANS OF FUEL RODS FROM CORRESPONDING POSITIONS IN DIFFERENT QUADRANTS OF THE PLUTONIUM REGION. BOTH RODS WERE SCANNED FOLLOWING THE THIRD BURNUP STEP AND WERE NORMALIZED TO THE HIGHEST ACTIVITY IN ROD NUMBER 1 FROM THE THIRD BURNUP STEP.

symmetry of power generation at corresponding points of the plutonium region is evident.

B. Scans of Special Rods

Power profiles for the special fuel rods from element Pu-18 from zone 2 of the plutonium region are shown in Figure 16. These are rods of differing initial fuel composition from the second burnup step. In addition, the insert of Figure 16 compares the relative activities of fission products at the point of peak activity for all special rods from each burnup step. Data for each set of rods are normalized to the highest count of fuel rod number 1 of that particular burnup step. Data from a normal mixed oxide rod, rod number 4, from each central element are presented with data from the special rods for purposes of comparison. Differences in activity observed for the various rods from a particular burnup step result in part from differences in initial fuel composition and in part from differences in locations of the fuel rods within a fuel element since the power generation changes as a function of position. For example, rods 4, 13 and 14 differ in the percentage of ^{240}Pu present in the plutonium oxide and thus differ in the amount of initial fissile plutonium. However, fuel rod number 13 is located at an edge of a fuel element whereas fuel rod number 14 is located one row in and fuel rod number 4 is located two rows in from the edge. Because of undermoderation of the neutrons in the interior of a fuel element and the resultant depression of the thermal neutron flux, fuel rod number 13 achieves a higher fission product activity than either fuel rod number 4 or fuel rod number 14

FIGURE 16

Power Generation Profiles from Gamma Scans of the Special Rods from the Second Burnup Step. The Insert Compares Relative Power Generation Values at the Point of Peak Activity for the Special Rods from each Burnup Step. Rod Scan data from each Burnup step are Normalized Separately to the Highest Count of Rod Number 1 of that Particular Burnup step.

although its fissile content is not as great as rod number 4. Fuel rod number 4 started with the greater content of fissile Pu whereas fuel rod number 14 started with the least amount, and, therefore, rod number 4 achieves a higher fission product activity than rod number 14. However the burnup of rod 4, based on the percentage of initial fissile atoms that have fissioned may not be as great as the burnup of rod 14.

Rod number 17, located at the edge of a fuel element, has the smallest fission product activity of any of the special rods because it is fueled with natural UO_2 and contains the least initial fissile material.

An increase in power generation is seen for the second burnup step for each rod relative to rod number 1. The power generation of each rod relative to rod number 1 decreases for the third burnup step, except for the natural UO_2 rod, rod number 17. The increase in power generation shown for this rod relative to rod number 1 is not considered significant within the errors of the experiment.

A feature that is significant from the rod scan data presented in Figure 16 is the change in relative activity observed during the three burnup steps for the Al-Pu fuel rods (numbers 15 and 16) as compared to the other special rods. As burnup proceeds, the fission product activity of the Al-Pu rods does not increase at as fast a rate as does the fission product activity of the other special rods because the fissionable isotopes are not being replaced in an Al-Pu rod as they are in mixed oxide or uranium rods.

C. Scans of Enriched and Natural Uranium Rods

Some results of scans of fuel rods from the enriched and natural uranium regions of the EBWR core are presented in Figures 17 and 18. Activity profiles of four enriched uranium rods symmetrically located in elements along the four sides of the plutonium region are shown in Figure 17. Data from these scans were normalized to the highest count for rod number 2089 from the enriched uranium region. The data presented in Figure 17 illustrates the symmetry in the burnup profile for the EBWR core. The fluctuations in profile observed in the figure are not statistically significant within the errors of the experiment. Symmetry in the power profile was also evident from scans (not shown) of four enriched uranium rods (rods numbers 2240, 717, 1305, and 1571) located in elements at the four corners of the plutonium region. For comparison purposes, the scan of one enriched UO_2 fuel rod from a corner element is shown in Figure 17. The reduced power of the fuel rod from the corner element is due to a combination of factors, e.g., the greater distance of this rod from the center of the core and its proximity to a natural uranium element (see Figure 1).

Gamma scans of two enriched uranium and two natural uranium rods that were positioned in a line outward from the center of the EBWR core toward the edge are shown in Figure 18. Gamma scans of two mixed oxide rods from the plutonium region are also shown for purposes of comparison. In Figure 18, both the mixed oxide rod data and the uranium rod data are normalized to the same cooling time. The higher activity achieved by the enriched uranium rods in comparison with the

FIGURE 17
Gamma Scans of Five Fuel Rods from the Enriched Uranium
Region of the EBWR Core.

FIGURE 18
Gamma Scans of Mixed Oxide, Enriched Uranium, and Natural Uranium Rods from Different Regions of the EBWR Core. The Mixed Oxide Rods were Normalized to the same Cooling Time as the Uranium Rods.

mixed oxide rods indicates that the EBWR core was being driven by the enriched uranium elements that surrounded the plutonium region. However, the differences in fission product activity between mixed oxide and enriched uranium rods do not necessarily indicate that more fissions occurred in the enriched uranium. In this experiment, power was related to the measured intensities of gamma rays from $^{95}\text{Zr}/^{95}\text{Nb}$. The thermal neutron fission yield for ^{95}Zr is approximately 6.2% for ^{235}U as compared to approximately 5.2% for ^{239}Pu .⁽⁵⁾ Thus the use of $^{95}\text{Zr}/^{95}\text{Nb}$ gamma rays for gamma scanning causes differences in fission product activity between the enriched uranium and the mixed oxide fuel rods to appear to be relatively larger than they actually are. The yields of ^{95}Zr from uranium and plutonium need to be used to modify the data before it can be concluded absolutely that more fissions occurred in the enriched uranium fuels than in the plutonium enriched fuels.

D. Scan of Element Pu-59

Locations of fuel rods within element Pu-59 are shown in Figure 19. In this figure, the special rods are indicated. The orientation shown is the orientation of the element in the reactor.

Transverse scans were made at two positions on each side of element Pu-59. Results of the scans performed at 12 inches above the bottom of the active fuel are shown in Figures 20 and 21. A three-dimensional representation of the gamma activity is shown in Figure 20 where the data are normalized to the highest count at the east side of the column of rods headed by rod EK-68. Since each corner rod heads two

Special Rods:

- * EX-48 $\text{UO}_2\text{-PuO}_2$ (20% ^{240}Pu)
- * EW-90 $\text{UO}_2\text{-PuO}_2$ (26% ^{240}Pu)
- * EU-55 Al-Pu (8% ^{240}Pu)
- * EU-44 Al-Pu (26% ^{240}Pu)
- * EX-62 Natural UO_2

FIGURE 19
Schematic of Fuel Element Pu-59 Showing Locations of Fuel Rods in the Element. Both the rod Identification Numbers (e.g., EJ-46) and the Rod Bundle Location Numbers (e.g., 6) are Given.

FIGURE 20
Three-Dimensional plot of Relative Power Generation for
Fuel Element Pu-59 from Transverse Scans at 12 Inches Above
the Bottom of the fuel.

FIGURE 21
Comparison of Experimental and Synthesized Bundle Scans for Fuel Element Pu-59.
The Solid Horizontal Lines Represent Synthesized Results. The Dashed Horizontal
Lines Represent Synthesized Results when Account was Taken of the Reduced Gamma
Ray Absorption in the Al-Pu Rods.

columns, two activities are associated with it. To designate these activities, in Figure 20, the lower activity is denoted by the flat top box area and the higher activity is denoted by extending the sides of the box in the direction from which the higher value was obtained.

Looking at the symmetry of the relative power profile for element Pu-59, it is apparent that, within the uncertainty of the measurement, the north and south sides of the element exhibit the same shape, and the activity of the south side is consistently lower than that of the north side.

Comparing data for rod columns that are symmetric with respect to the corner rod, EJ-46, it is evident that gamma activity differences exist between a column that contains a special rod and symmetric column that does not. For example, the presence of the natural UO_2 rod EX-63 in an outer-ring position is clearly denoted by a 23% decrease in activity for the column headed by that rod as compared to the activity of the symmetric column of rods headed by EN-44.

The activity of the column of rods headed by EM-43 is 6% higher than the activity of the symmetrically placed column of rods headed by EK-34. A reasonable explanation is apparent when the rods behind EM-43 and EK-34 are considered. (See Figure 19.) Rod EU-44 is an Al-Pu rod and its gamma contribution is lower than that of the mixed oxide rod EG-42. However, the density of rod EU-44 is lower than that of rod EG-42, and the attenuation of gamma radiation from rods behind EU-44 is less than the attenuation of gamma radiation

from rods behind EG-42. The net result is that the inner rods in the column headed by rod EM-43 contribute more to the total activity of that column than is contributed by the inner rods to the total activity of the column headed by EK-34. Similar comments apply to data from columns of rods headed by EL-18, EG-82, and EQ-01. Thus the observable power profile of a fuel element is not determined solely by the outer-ring rods of the element but also by the fuel rods within the element.

The ability of a detector to record gamma activity from the interior of a fuel assembly was investigated by counting the activity of two columns of rods while removing rods sequentially from the columns. The procedure for removing the rods has been outlined in Section III. The two columns chosen for this investigation were the column in element Pu-59 that included rods in positions 1, 7, 13, 19, 25, and 31 and the column that included rods in positions 3, 9, 15, 21, 27, and 33. (See Figure 19.) Results of these measurements are presented in Figure 22 which shows the relative contribution of each rod in a column to the total activity of the column. In Figure 22, the activity contributions from each rod are normalized to unity for the first rod in the column. Figure 22 shows that, for EBWR fuel element Pu-59, slightly over 60% of the measured activity of the bundle scan is contributed by the outer rod. About 24% of the activity is contributed by the second rod in a column and about 10% is contributed by the third rod in a column. The fourth rod contributes about 4%, the fifth rod contributes about 1%, and the sixth rod contributes only about 0.4% of the total measured activity.

FIGURE 22

Contribution of each rod in a Column to the Total Activity of the Column. Values are Normalized to Unity for the First rod in the Column

A synthesis of the transverse bundle scan of element Pu-59, using average values of the rod weight factors shown in Figure 22 and data obtained by scanning each rod individually, was made to evaluate the accuracy and usefulness of the rod weight factors. To synthesize the bundle scan, it was necessary to normalize all data to a particular rod in the element. Fuel rod number EK-68 was chosen for this purpose. The results of the synthesis are shown as solid horizontal lines in Figure 21.

In general, the synthesized results agree well with measured values. In most cases the agreement is better than $\pm 3\%$. Exceptions occur at fuel rod EL-18 on the north side of the fuel element, at fuel rods EG-82 and EQ-01 on the west side of the element, and at fuel rod EM-43 on the south side of the element. Inspection of Figure 19 which shows the locations of fuel rods within element Pu-59 indicates that columns where there is lack of agreement between experimental and synthesized scan results are those columns which contain one of the Al-Pu rods, either EU-55 or EU-44, in the second row. Since the experimental scan results give higher activities than the synthesized scan results, this suggests that, for the four columns which contain Al-Pu rods, the weight factors of some of the lower rods in the column should be increased. In particular, the weight factor assigned to the third rod in each of those columns is too low since the weight factor was determined for gamma radiation which had traversed two mixed oxide rods before being detected. However, for the four columns in question, gamma rays from the third rod traverse one mixed oxide rod and one fuel rod in which

the principal absorbing material is aluminum. For these columns, a better approximation to the experimental situation might be to assign the same weight factor to the third rod in a column as is assigned to the second rod. When this assignment is made, the synthesized bundle scan result is as shown by the dashed horizontal lines in Figure 21. Substantial improvement in agreement between experiment and synthesis is achieved.

E. Summary Diagram

In all, 106 fuel rods have been examined in detail by gamma scanning. A summary of the relative power generation of each rod at the point of maximum activity is shown in Figure 23.

F. Gamma Ray Spectra

Fission product gamma ray spectra of selected fuel rods also were obtained with a Ge(Li) detector. For the gamma ray spectrum measurements, the NaI(Tl) detector was removed from the lead shield at the top of the collimator tube (see Figure 5) and the Ge(Li) detector described in Section III was put into place.

The choice of fuel rods for spectral analysis was made to cover all combinations of fuel types and irradiation conditions that were possible with EBWR rods still available (several rods had been removed for destructive analysis). Spectra were obtained at the position of peak activity along a fuel rod and also near the top of the active fuel. Information about fuel rods for which gamma ray spectra are shown is listed in Table IV. The corresponding gamma-ray spectra are shown in Figures 24-27.

FIGURE 23

FIGURE 23

Summary Diagram Showing the Spatial Distribution of the Relative Power Generation at the Point of Peak Gamma Activity

FIGURE 23

Summary Diagram Showing the Spatial Distribution of the Relative Power Generation at the Point of Peak Gamma Activity of Each Fuel Rod. Data from Rods of a Given Burnup Step are Normalized Separately to the Rod Removed from the Center of the Core for that Particular Burnup Step. No Corrections to Account for Different Fission Product Yields from Fuels of Differing Initial Fuel Compositions have been made.

TABLE IV

SUMMARY OF EBWR RODS FOR WHICH GAMMA-RAY SPECTRUM DATA ARE PRESENTED

Rod Serial Number	Fuel Composition	Burnup Step	Cooling Time (days)	Position of Spectrum (inches above bottom of Fuel)	Counting Time (minutes)
EX-62	Natural UO_2	3rd	322	12.6	920
EU-44	Al-Pu (26% ^{240}Pu)	3rd	321	12.6	900
EI-73	UO_2 - PuO_2 (8% ^{240}Pu)	3rd	318	12.6	880
EJ-34	UO_2 - PuO_2 (8% ^{240}Pu)	3rd	317	12.6	80
EJ-34	UO_2 - PuO_2 (8% ^{240}Pu)	3rd	361	11.5	220
EJ-34	UO_2 - PuO_2 (8% ^{240}Pu)	3rd	361	35.0	930
EX-62	Natural UO_2	3rd	362	11.5	330
EX-62	Natural UO_2	3rd	362	35.0	940
1076	Enriched UO_2 (6% ^{235}U)	3rd	320	8.9	80
1076	Enriched UO_2 (6% ^{235}U)	3rd	320	14.9	80
1076	Enriched UO_2 (6% ^{235}U)	3rd	320	34.9	80
EP-98	UO_2 - PuO_2 (8% ^{240}Pu)	1st	451	11.1	80
EM-42	UO_2 - PuO_2 (8% ^{240}Pu)	2nd	374	11.1	80

Because of the long cooling times associated with the EBWR fuel rods, only gamma rays which follow decay of long-lived fission products were observed. A tabulation of the principal gamma rays from long-lived fission products is given in Table V.

FIGURE 24.
Gamma Ray Spectra of Mixed Oxide and Special EBWR Rods from the Third Burnup Step. Each Rod had Cooled 317 to 322 Days.

FIGURE 25

Gamma Ray Spectra of a Mixed Oxide and a Natural UO₂ EBWR Rod from the Third Burnup step at 11.5 Inches and 35.0 Inches Above the Bottom of the Fuel. Each Rod had Cooled 361 Days.

FIGURE 26

Gamma Ray Spectra of an Enriched Uranium and a Mixed Oxide EBWR Rod from the Third Burnup step. Each Spectrum was Accumulated for 80 Minutes. Each Rod had Cooled 317 to 320 Days.

FIGURE 27
Gamma Ray Spectra of Mixed Oxide EBWR Rods Which had Received Different Amounts of Exposure. Each Rod was at the Center of the Core While it was Being Irradiated.

TABLE V
PROMINENT GAMMA RAYS FROM LONG LIVED FISSION PRODUCTS

Gamma Energy (MeV)*	Fission Product	Half Life	Fission Yield From Thermal Fission (%)**	
			²³⁵ U	²³⁹ Pu
0.134	¹⁴⁴ Ce	284 d	5.41	3.82
0.497	¹⁰³ Ru	39.6 d	3.0	5.6
0.512	¹⁰⁶ Ru/ ¹⁰⁶ Rh	367 d/30 s	0.39	4.4
0.605	¹³⁴ Cs	From ¹³³ Cs 2.05 y	6.69	6.5
0.622	¹⁰⁶ Ru/ ¹⁰⁶ Rh	367 d/30 s	0.39	4.4
0.662	¹³⁷ Cs	30.0 y	6.20	6.56
0.695	¹⁴⁴ Ce/ ¹⁴⁴ Pr	284 d/17.3 m	5.41	3.82
0.724	⁹⁵ Zr	65 d	6.2	5.2
0.756	⁹⁵ Zr	65 d	6.2	5.2
0.764	⁹⁵ Zr/ ⁹⁵ Nb	65 d/35 d	6.2	5.2
0.796	¹³⁴ Cs	From Cs 2.05 y	6.69	6.5
0.815	¹⁴⁰ Ba/ ¹⁴⁰ La	12.8 d/40.2 h	6.30	5.33
0.874	¹⁰⁶ Ru/ ¹⁰⁶ Rh	367 d/30 s	0.39	4.4
0.884	¹¹⁰ Ag	From ¹⁰⁹ Ag 253 d	0.03	1.2
1.050	¹⁰⁶ Ru/ ¹⁰⁶ Rh	367 d/30 s	0.39	4.4
1.128	¹⁰⁶ Ru/ ¹⁰⁶ Rh	367 d/30 s	0.39	4.4
1.164(1)	¹⁴⁴ Ce/ ¹⁴⁴ Pr	284 d/17.3 m	5.41	3.82
1.21	⁹¹ Y	58.8 d	5.9	2.6
1.278	¹⁵⁴ Eu	From ¹⁵³ Eu 16 y	0.158	0.36
1.365	¹³⁴ Cs	From ¹³³ Cs 2.05 y	6.69	6.5
1.487	¹⁴⁴ Ce/ ¹⁴⁴ Pr	284 d/17.3 m	5.41	3.82
1.562	¹⁰⁶ Ru/ ¹⁰⁶ Rh	367 d/30 s	0.39	4.4
1.596	¹⁴⁰ Ba/ ¹⁴⁰ La	12.8 d/40.2 h	6.30	5.33
1.675(2)	¹⁴⁴ Ce/ ¹⁴⁴ Pr	284 d/17.3 m	5.41	3.82
2.13	¹⁰⁶ Ru/ ¹⁰⁶ Rh	367 d/30 s	0.39	4.4
2.186	¹⁴⁴ Ce/ ¹⁴⁴ Pr	284 d/17.3 m	5.41	3.82

*From C. M. Lederer, J. M. Hollander, and I. Perlman. TABLE OF ISOTOPES, (Sixth Edition), John Wiley and Sons, Inc., New York. 1967.

**Fission yield data is from M. E. Meek and B. F. Rider, APED-5398 (1968).

(1) Double escape peak, 2.186 MeV gamma-ray

(2) Single escape peak, 2.186 MeV gamma-ray

Half lives and fission yields for thermal neutron fission of both ^{235}U and ^{239}Pu are also shown. Fission yield data are from Meek and Rider.⁽⁶⁾

In some of the fuel rod spectra, the 1173 keV and 1332 keV gamma rays from ^{60}Co are observed. These gamma rays result because of ^{60}Co contamination in the fuel storage basin where the gamma scan facility was located. The ^{60}Co gamma rays are especially prominent in spectra taken near the top of a fuel rod where, because of low gamma activity, long counting times were used.

When making comparisons between gamma ray spectra from different fuel rods, account must be taken of differences in cooling times. This is particularly important for gamma rays from ^{91}Y , $^{95}\text{Zr}/^{95}\text{Nb}$, and ^{103}Ru which all have half lives that are short compared to rod cooling times for the fuel rods of this experiment. Because ^{140}Ba has a half life of only 12.8 days, gamma rays from $^{140}\text{Ba}/^{140}\text{La}$ are not observed in any of the spectra shown in Figures 24-27.

Fission product gamma ray spectra for mixed oxide rods and special rods from the third burnup step are compared in Figure 24. Each spectrum was taken 12.6 inches above the bottom of the fuel and was accumulated for different live time counting periods. Three of the rods are from element Pu-59 and rod EJ-34 is the mixed oxide rod from the center of the core (PNL position no. 1, Figure 7). Differences between the spectra are especially evident in Figure 24 from the peaks of $^{106}\text{Ru}/^{106}\text{Rh}$. The $^{106}\text{Ru}/^{106}\text{Rh}$ gamma rays are relatively more intense for rods containing plutonium fuel than they are for rods containing uranium fuel since the fission yield for

^{106}Ru is approximately ten times greater for thermal fission of ^{239}Pu than it is for thermal fission of ^{235}U . Because of diverse fission product yields, selected gamma rays can be used to indicate the relative number of plutonium fissions in the mixed oxide rod.

A hardening of the neutron spectrum near the top of the EBWR core might be expected to result in observable changes in fission yields for some fission product isotopes. This should cause changes in the relative intensities of some fission product gamma rays when a gamma ray spectrum taken near the top of a fuel rod is compared with a spectrum taken at the point of maximum burnup. However, when gamma spectra from different points along an EBWR fuel rod are compared, as shown in Figure 25, very little change in relative gamma ray intensities is noted by inspection.

An exception to this general statement is the gamma rays from beta decay of ^{134}Cs at 605 and 796 keV. The spectra of all fuel rods on which measurements were made showed that the ^{134}Cs gamma rays were relatively less intense near the top of the fuel than they were at the point of maximum burnup. The ^{134}Cs is not formed directly in a fission process, but occurs as a result of a thermal neutron (n,γ) capture reaction with ^{133}Cs which is a fission product. (In Table V the tabulated fission yield is that of ^{133}Cs .) Lederer et al.⁽⁷⁾ quote a 2200 meter/second capture cross section of 28 barns for ^{133}Cs . The ratio of $^{134}\text{Cs}/^{137}\text{Cs}$, which varies with position along the length of the rods, is proportional to the thermal neutron flux at each position. In this way, selected gamma rays can be used to infer exposure and flux values in the core.

Both Eu_2O_3 and Sm_2O_3 were present as burnable poisons in the enriched uranium rods. Hence some of the gamma rays observed in the spectra of an enriched uranium fuel are not fission product gamma rays but instead are gamma rays that follow beta decay of radio-isotopes of europium. Spectra from evaluations of 8.9, 14.9, and 34.9 inches above the bottom of the active fuel for enriched uranium rod 1076 are compared in Figure 26. The gamma ray spectrum from a mixed oxide rod is shown for comparison. The 1.21 MeV peak from ^{91}Y is only evident in spectra of the enriched uranium rod. Yttrium-91 has a higher fission yield for uranium than it does for plutonium. The short half life of ^{91}Y (58.8 days) and the long cooling times employed for fuel rods in this experiment made counting statistics on the 1.21 MeV peak very poor.

Fission product gamma ray spectra for mixed oxide fuel rods from each of the three burnup steps are shown in Figure 27. The rods were scanned after different cooling periods and it is not possible to infer any spectrum differences due to exposure by inspection. Spectrum analysis is underway for all the spectra presented and these results will be presented at a later date.

V. CONCLUSIONS

Gamma ray measurements obtained with a NaI(Tl) detector from various types of fuel irradiated in the EBWR have been presented in this report to indicate the relative power distributions within the fuel. The results demonstrate the feasibility of using gamma scanning procedures to map the relative power generation profiles of a reactor core. The data show that core symmetry makes it possible to determine relative power profiles by looking at a relatively small number of rods and/or assemblies from a total core. Gamma scan data for selected individual rods can be used to construct power profiles within an assembly and then to construct the core profile. Because of differences in fission yields, it is necessary to correct gamma ray intensity data to obtain power comparisons for rods of differing initial fuel composition.

In the case of power reactors that do not exhibit the symmetry of the EBWR, gamma scanning procedures can be used to investigate the non-symmetry. It is not necessary to scan all the fuel to accomplish the core mapping as careful selection of fuel assemblies and rods will give the information needed.

Changes in relative power generation profiles as a function of exposure have been correlated with reactor power levels, varying void concentrations, and control rod positions. The influence of a control rod on the power production of neighboring fuel rods has been observed. Correlations between fuel rod power profiles and control rod settings indicate that gamma scan techniques can be utilized to determine control rod positions.

Comparisons among rods with different initial fuel compositions and thus with varying amounts of initial fissile materials are really comparisons of the reaction rates occurring in the special rods. In this experiment, the natural UO_2 rods had the lowest initial reaction rates. However, the reaction rates of the Al-Pu rods exhibited the greatest rate of decrease as the fuel was irradiated.

Results of transverse scans of element Pu-59 indicated that the observed power profile for the assembly was a weighted average of the power of the individual rods within the assembly. When gamma rays with energies of approximately 750 keV were monitored, it was found that a power profile of an element is influenced by fuel rods as far into the assembly as the fourth rod in a column of rods. The possibility exists that an average reading might be taken at a position which would indicate the average power of an assembly. Results from the transverse scan of element Pu-59 suggest the feasibility of using gamma scan methods to locate positions of fuel rods which cause a difference in count rates (i.e., fuel rod ruptures within an element) without dismantling the assembly.

Gamma ray spectrum data obtained with the Ge(Li) detector can be used to obtain information about intensities of gamma rays from individual fission products. These results can be correlated with data obtained by destructive analysis to obtain absolute calibrations of the data.

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APPENDIX A

SCANNING OF INTACT FUEL BUNDLES AT ANL

At ANL, intact 6 x 6 rod fuel elements were scanned along their length to provide an indication of the power generation profile of EBWR fuel elements. The experiment was done to investigate the possibility of gamma scanning with a wide collimator aperture. Seven elements were scanned; 5 enriched UO_2 elements, 1 natural UO_2 element, and 1 plutonium-enriched element. The elements are identified in Table A-I.

The measurements were made under 15 feet of water in the EBWR fuel storage pit. The scan along an element was accomplished by moving the element vertically through an element guide at one end of a collimator as shown in Figure A-1. Gamma rays were directed from the fuel to the detector via a rectangular air collimator 6 feet long whose cross section area was 4 in. by 0.25 in. A 2 in. by 2 in. NaI(Tl) detector was housed inside a water tight box surrounded by lead shielding at the opposite end of the collimator. A marked scale on the element handling tool was used to indicate to within ± 0.25 in. the position of the element being scanned. Data were obtained only every 4 in. along one side of each element. The side scanned is indicated in Table A-I.

The $^{140}\text{Ba}/^{140}\text{La}$ gamma rays were monitored in the energy range of 1.6 MeV with an energy window of 40 keV. A ^{60}Co source was used to check the calibration of the system, but no evaluation was made of the efficiency or resolution of the detector. Repeated measurements were made to check the reproducibility of the count rates.

Because of the large collimator aperture the measured activity can be defined as an average activity over the element width at the point being measured. Table A-II lists the corrected count rates for each point

TABLE A-I

Bundle Ident. No.	Core Location	Fuel Composition	Removed from Reactor	Side Scanned	Cooling time to the normalization day
EU-34	63-418	Enriched UO ₂ (6 wt% ²³⁵ U)	29 June 1967	North	75
EU-64	59-381	"	"	West	75
EU-92	54-390	"	"	West	75
EU-18	74-414	"	"	West	75
EU-20	44-392	"	"	West	75
NU-116	27-361	Natural UO ₂	"	West	75
Pu-59	101-54	UO ₂ -1.5 wt% PuO ₂ (8% ²⁴⁰ Pu)	"	North	75

FIGURE A-1
 Detector Housing, Collimator, and Fuel Element Guide of Gamma Scan Facility
 Installed in EBWR Storage Basin

TABLE A-II

Distance Bottom of element (inches)	Element EU-64	Element EU-34	Element EU-92	Element EU-20	Element EU-18	Element NU-116	Element PU-59
0	4615	5805	4773	3491	5186	584	2662
8	6641	7635	6178	4739	5889	879	3791
12	10641	13152	10435	8245	10417	2012	6956
14	37052	42758	37400	31005	34451	6005	24083
18	46384	51573	46655	42289	45004	8819	32929
22	52037	55432	49975	46474	51050	11270	38050
26	52819	55322	50453	47746	51836	12451	38972
30	52048	53563	48583	46434	50767	12111	38816
34	48173	50474	46222	42047	47058	11105	36006
39	42294	43898	39011	36288	39825	9247	31320
42	36590	37009	33210	31059	33190	7613	25912
46	29457	29352	27483	23694	23729	5738	22182
50	22551	21041	20903	17506	14993	4204	16326
54	17291	16092	16111	13504	11729	3575	12206
58	13224	12139	11969	9762	9046	2443	9222
62	9053	8185	7377	6213	6514	1280	5956
66	7091	6315	5595	4646	4990	913	4587

Corrected count rates at 1.6 MeV for the EBWR fuel elements scanned intact at ANL.

measured. Relative burnup profiles for the uranium fuel elements are obtained by normalizing the corrected count rates to the highest count rate of the set. Figure A-2 shows these profiles. Figure A-3 shows the relative burnup profile for the plutonium fuel element. The count rates are normalized to the highest count of the Pu element. Because of the short half life of ^{140}La (40.2 hr.) and its parent ^{140}Ba (12.8 days) the measurements indicate the burnup profile for the last month of reactor operation. Since the $^{140}\text{Ba}/^{140}\text{La}$ yield from uranium (6.3%) is greater than the yield from plutonium (5.4%), no absolute comparison between burnups of fuel having different composition was made. The effect of an outer control can also be noted from the data of element EU-18 in comparison with the data of element EU-92. Thus, the use of a wide aperture permits a quick determination of the element average burnup profile along the length of the element.

After the elements were scanned, one rod, see Table III, was removed from each of the UO_2 elements and sent to PNL. Element Pu-59 was sent intact to PNL.

FIGURE A-2
Gamma Scans of Intact EBWR Uranium Fuel Elements at ANL

FIGURE A-3
Gamma Scan of Intact EBWR Plutonium Fuel Element, Pu-59, at
ANL

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