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IN-CORE ACTIVATION TRAVERSES DURING
THE PLUTONIUM RECYCLE EXPERIMENT IN
THE EXPERIMENTAL BOILING WATER REACTOR
AT POWER LEVELS OF 35 TO 70 MW

by

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Reactor Physics Division

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IN-CORE ACTIVATION TRAVERSES DURING THE PLUTONIUM RECYCLE EXPERIMENT IN THE EXPERIMENTAL BOILING WATER REACTOR AT POWER LEVELS OF 35 TO 70 MW

by

R. E. Grajek and K. E. Freese

I. INTRODUCTION AND SUMMARY

In-core activation traverses were made during the Plutonium Recycle Experiment¹ in the Experimental Boiling Water Reactor (EBWR) during power operation. This report gives the results of several traverses with bare and cadmium-covered manganese-aluminum alloy spheres, and a few traverses with copper, gold, iridium, and lutetium. Power levels of 37, 40, 61, and 70 MW were held during the various measurements.

These measurements provided information on flux distributions and on correlation between cadmium ratios and local steam-void fractions, and also permitted a comparison of physics experiments in plutonium-fueled systems with similar experiments in uranium-fueled reactors.

Traverses were obtained by inserting bead-chains into tubes that extended through the fuel region. The method has been described previously,² although some modifications were made for the plutonium-recycle core. The samples were withdrawn after momentary exposures to the reactor flux, and were then processed as indicated schematically in Fig. 1.

The change in power level from 40 to 70 MW increased the copper-cadmium ratios by as much as 50%; those of manganese and ^{177}Lu decreased substantially. On the other hand, the cadmium ratios of gold and ^{176}Lu were close to unity and were only slightly affected by the increase in power level and the accompanying increase in steam-void fraction.

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Fig. 1. Schematic Diagram of Irradiation-analysis Procedure Used in Study of EBWR Neutron-flux Distribution

II. DESCRIPTION OF EQUIPMENT

This method incorporates the use of five U-shaped tubes located in the northeast quadrant of the core. The five tubes are positioned in fuel assemblies No. Pu-22, Pu-27, Pu-32, Pu-37, and EU-2-42, as shown in Fig. 2. The 3/16-in.-OD Inconel tubes extend above the fuel assembly and are welded into 1/4-in.-OD Inconel tubing. At this junction there is an internal taper to provide a seat for the 5/32-in. terminal bead of a sample chain, as shown in Fig. 3. The samples are then precisely located relative to this point. These 1/4-in.-OD tubes then pass through the east instrument nozzle and terminate in a glovebox. The glovebox is kept at negative pressure by exhausting to the plant stack. Compressed helium gas was used to effect fast removal of the bead chain assemblies; vacuum was used for fast insertion and positive positioning.

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Fig. 2. EBWR Fuel-loading Diagram Showing Locations of Foil Irradiation Facilities

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Fig. 3. Scale Drawing of Reactor and East Instrument Nozzle, Showing Typical Irradiation Facility

III. FOIL PREPARATION

The spherical foils used were 0.0625 ± 0.002 -in.-diam high-purity aluminum alloy containing one of the following:

Gold	0.065%	Manganese	1.0%
Copper	1.00%	Lutetium	6.0%
Indium	0.035%	Iridium	0.25%
High-purity aluminum			

Bare and cadmium-covered foils were encapsulated in $3/8$ -in.-long, 0.116-in.-OD, 0.100-in.-ID aluminum tubing by forming the ends over the $3/32$ -in.-OD aluminum bead chain. Cadmium covers used were fashioned from tubing with a 15-mil thickness, and the end caps punched from a 15-mil sheet. Each chain assembly contained bare and cadmium-covered foils in alternate positions, as shown in Fig. 4.

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Fig. 4. Bead Chain Assemblies with Alternating Bare and Cadmium-covered Foils

During the early stages of the experiment, interference was found from ^{24}Na activity resulting from the $^{27}\text{Al}(n,\alpha)$ reaction, which has an effective threshold above 6 MeV. This problem was overcome by accompanying each foil-containing capsule with one capsule containing a high-purity aluminum foil to be used for background subtraction.

The chain used to transport the foils is designed to position the top sample even with the top of the active fuel zone, and the bottom sample at the bottom of the fuel zone. The samples are spaced at 4-in. intervals, to give a total of 13 foil positions throughout the fuel zone. Foils are positioned by attaching a ball-stop at a premeasured distance above the first sample.

IV. FOIL IRRADIATION

Sample chain assemblies were inserted in selected U tubes. This is accomplished by inserting the chain in one leg of the U tube and using vacuum on the opposite leg to fully insert the chain. The start of an irradiation was timed from the moment the chain assembly was released at the top of the U tube. At the end of the irradiation time, the chain is blown from the reactor core directly to a lead storage facility about 6 ft from the glovebox. A cylinder of helium gas was used for this operation.

V. RECOVERY OF ACTIVATED FOILS

After sufficient storage time, depending upon the half-life of the material, the chain assemblies were transported to the Reactor Physics Laboratory and prepared for analysis. The foils were recovered from the irradiated sample assemblies by using a small Unimat lathe and a hollow collet chuck. This operation was performed in a glovebox to prevent contamination of the work area. Individual foils were placed in specially designed aluminum planchets and nylon sample holders used in conjunction with an automatic sample changer.

VI. DESCRIPTION OF COUNTING FACILITY

Up to 82 individual foils could be analyzed by using an Argonne automatic turret-type sample changer. During the counting cycle, the sample is positioned between two detectors, which are shielded on all sides by a 4-in. lead cave. Each counting channel consists of a detector (typically a 2 x 2-in. NaI(Tl) crystal or a Pilot-B scintillating plastic), photomultiplier tube, high-voltage power supply, preamplifier, linear amplifier, single-channel pulse-height analyzer, and scaler. The data from all channels are recorded automatically on IBM cards. A block diagram of the foil-counting facility is shown in Fig. 5.

* SCPHA SINGLE-CHANNEL PULSE-HEIGHT ANALYZER

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Fig. 5

Foil-counting Facility, Block Diagram

VII. COUNTING TECHNIQUE

In order that the ^{24}Na activity from each sample could be directly subtracted with negligible decay loss, the high-purity aluminum foil accompanying each sample foil was counted immediately preceding it. All 40-MW irradiations were gamma-counted with the single-channel pulse-height analyzer in the differential mode, with the intention of further decreasing the error due to the ^{24}Na activity. Since no significant reduction was observed, further studies at 70 MW were analyzed in the integral mode for improved

counting statistics. In both cases, the lower-level discriminator was set just below the principal gamma-energy peak.

Lutetium and iridium, each of which contained two active isotopes, required special counting considerations.³ These foils were initially counted shortly after irradiation, which yielded the total activation of both isotopes. The individual activity of each isotope was determined by recounting the foils at the same discriminator bias after the short half-lived isotope had decayed. To reproduce the discriminator level setting, a standard americium source was used for calibration of each isotope. For lutetium, the bias was set just below the ^{241}Am 0.06-MeV energy peak; for iridium, the ^{243}Am 0.106-MeV energy peak was used. Identical foils were irradiated simultaneously in the Argonne Thermal Source Reactor (ATSR) graphite pile for calibration.

VIII. DATA AND RESULTS

The raw counting data, punched automatically on IBM cards, were processed on the DDP-24 computer. For each count of the foil, the data-reduction code computes the relative activity corrected for analyzer dead time, ^{24}Na subtraction, background subtraction, and decay corrected to the end of the irradiation.⁴

Relative activation plots for each foil material at 40 and 70 MW are shown in Figs. 6-18. Since the sample chains were constructed with bare and cadmium-covered foils in alternate positions, it was necessary to apply a least-squares polynomial fit (LSPF) to determine the activity of those points that could not be measured directly. Initial data for manganese and copper showed unusual peaks at both ends of the traverse, as shown in the unfitted curves of Figs. 19-24. These high points were dropped in order to use the LSPF. The resulting activities and cadmium ratios for all foil materials are listed in Tables I and II and shown in Figs. 25-29. All measurements were made in the west leg of the U tube installed in fuel assembly No. Pu-32, unless specified otherwise.

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Fig. 6. Copper Activation Traverse at 40 MW

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Fig. 7. Manganese Activation Traverse at 40 MW

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Fig. 8. Gold Activation Traverse at 40 MW

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Fig. 9. ^{176}Lu Activation Traverse at 40 MW

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Fig. 10. ^{177}Lu Activation Traverse at 40 MW

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Fig. 11. Indium Activation Traverse at 70 MW

Fig. 12

Gold Activation Traverse at 70 MW

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Fig. 13. Copper Activation Traverse at 70 MW

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Fig. 14. Manganese Activation Traverse at 70 MW

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Fig. 15. ^{176}Lu Activation Traverse at 70 MW

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Fig. 16. ^{177}Lu Activation Traverse at 70 MW

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Fig. 17. ^{194}Ir Activation Traverse at 70 MW

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Fig. 18. ^{192}Ir Activation Traverse at 70 MW

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Fig. 19. Thermal Flux at Approximately 70 MW

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Fig. 20. Thermal Flux at Approximately 37 MW

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Fig. 21. Thermal Flux at Approximately 61 MW

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Fig. 22. Relative Gamma Activity for Manganese (Bare) Element No. Pu-32

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Fig. 23. Relative Gamma Activity for Manganese (Bare) Element No. Pu-42

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Fig. 24. Relative Gamma Activity for Manganese (Bare) Element No. Pu-27

TABLE I. Results of Measurements at 40 MW

Date	Foil Material	Run Time, min	Control-rod Position, in.		Boric Acid	MWd/tonne (approx)	Distance from Bottom of Fuel Zone, in.	Bare Activity	Cadmium-covered Activity	Cadmium Ratio
			1-8	9						
2-2-67	Cu	5	20.1	31.2	0	1160	48	42.31	7.694	5.49909
							44	78.25	21.20	3.69103
							40	141.95	45.40	3.09259
							36	238.28	80.96	2.94318
							32	379.51	126.76	2.99392
							28	586.47	181.00	3.24016
							24	855.13	241.08	3.54707
							20	1148.95	301.76	3.80749
							16	1395.20	352.17	3.96172
							12	1508.21	374.47	4.02758
							8	1435.67	349.10	4.11248
							4	1195.47	270.43	4.42062
							0	868.75	162.48	5.34681
2-6-67	Mn	1	20.1	31.2	0	1216	48	1242.97	326.96	3.80160
							44	2257.19	545.56	4.13738
							40	3612.08	888.91	4.06349
							36	5334.49	1403.21	3.80163
							32	7517.11	2128.03	3.53243
							28	10316.03	3072.74	3.35727
							24	13892.03	4184.23	3.32009
							20	18260.17	5319.24	3.43285
							16	23005.45	6245.80	3.68335
							12	26931.00	6697.83	4.02085
							8	28033.97	6482.67	4.32445
							4	24516.15	5593.17	4.38323
							0	16798.91	4246.37	3.95606
2-8-67	Au	5	20.1	31.2	0	1244	48	312.06	239.93	1.30063
							44	544.87	454.71	1.19828
							40	916.95	795.94	1.15203
							36	1485.25	1301.65	1.14105
							32	2306.21	2002.27	1.15179
							28	3409.56	2903.09	1.17445
							24	4754.23	3956.89	1.20150
							20	6176.52	5032.85	1.22724
							16	7365.72	5902.08	1.24798
							12	7922.08	6275.50	1.26238
							8	7529.82	5921.35	1.27163
							4	6180.80	4830.10	1.27964
							0	4269.92	3302.52	1.29292
2-8-67	^{176}Lu	2	20.1	31.2	0	1244	48	4311.93	4237.74	1.01751
							44	7958.78	7316.67	1.08776
							40	14034.52	12736.17	1.10194
							36	23476.24	21375.04	1.09830
							32	37016.15	33792.36	1.09540
							28	54680.74	49813.26	1.09771
							24	75056.84	68176.49	1.10092
							20	94682.20	86222.63	1.09811
							16	108107.29	99451.64	1.08703
							12	109432.14	101591.71	1.07718
							8	95388.79	87377.89	1.09168
							4	69006.72	58332.89	1.18298
							0	39577.51	26859.01	1.47353
2-8-67	^{177}Lu	2	20.1	31.2	0	1244	48	89.60	5.23	17.13193
							44	181.13	11.29	16.04340
							40	356.21	20.41	17.45271
							36	602.99	33.49	18.00508
							32	983.16	52.08	18.87788
							28	1450.14	77.48	18.71631
							24	2070.29	108.88	19.01442
							20	2711.94	140.87	19.25137
							16	3188.31	163.18	19.53861
							12	3276.93	165.99	19.74173
							8	2862.61	147.67	19.38518
							4	2061.65	109.84	18.76957
							0	1185.37	58.67	20.20402

TABLE II Results of Measurements at 70 MW

Date	Foil Material	Run Time min	Control-rod Position in 1-9	Boric Acid	MWd/tonne (approx)	Distance from Bottom of Fuel Zone in	Bare Activity	Cadmium-covered Activity	Cadmium Ratio
4-4-67	In	1	31 4	0	1719	48	13254 14	11125 00	1 19138
						44	22695 17	19919 10	1 13936
						40	39566 98	33464 41	1 18235
						36	65479 63	55577 25	1 17817
						32	98930 75	84398 93	1 17218
						28	134681 97	114115 38	1 18022
						24	166059 01	138404 67	1 19980
						20	187863 39	154129 09	1 21887
						16	198632 63	161804 49	1 22760
						12	198366 73	161344 47	1 22946
						8	187065 67	148907 99	1 25625
						4	163134 03	117885 94	1 38382
						0	125322 04	69255 51	1 80956
4-5-67	Au	1	31 9	0	1743	48	189 71	110 66	1 71443
						44	312 73	252 30	1 23951
						40	531 92	474 96	1 11993
						36	858 70	765 75	1 12138
						32	1260 91	1093 10	1 15352
						28	1668 52	1419 03	1 17581
						24	2011 07	1707 77	1 17759
						20	2251 63	1926 70	1 16864
						16	2382 11	2040 32	1 16751
						12	2390 96	2008 65	1 19033
						8	2228 54	1798 99	1 23876
						4	1821 32	1415 02	1 28712
						0	1175 08	930 29	1 26313
4-13-67	Cu	3	32 1	0	1937	48	131 67	15 66	8 40882
						44	225 88	36 61	6 16996
						40	362 89	71 64	5 06540
						36	550 55	122 39	4 49824
						32	792 15	188 49	4 20262
						28	1081 06	267 51	4 04111
						24	1393 67	354 09	3 93597
						20	1683 40	437 97	3 84364
						16	1881 87	502 17	3 74745
						12	1915 00	524 12	3 65372
						8	1737 58	484 13	3 58909
						4	1371 35	380 93	3 59998
						0	914 53	243 30	3 75891
4-14-67	Mn	1	32 3	0	1961	48	654 66	124 57	5 25547
						44	1065 35	265 54	4 01206
						40	1625 03	478 55	3 39571
						36	2344 15	753 96	3 10909
						32	3214 84	1066 38	3 01472
						28	4198 71	1380 39	3 04168
						24	5212 74	1655 44	3 14884
						20	6119 03	1848 73	3 30985
						16	6730 78	1918 64	3 50810
						12	6851 07	1833 55	3 73649
						8	6350 43	1587 54	4 00016
						4	5255 64	1216 48	4 32036
						0	3794 74	800 21	4 74220
4-25-67	^{176}Lu	1	33 2	0	2229	48	15153 17	12808 33	1 18307
						44	31007 41	26227 90	1 18222
						40	55164 75	45753 25	1 20570
						36	86652 58	70645 60	1 22658
						32	121802 40	99262 60	1 22707
						28	154952 17	129159 01	1 19970
						24	180070 37	156727 68	1 14893
						20	192564 20	176806 57	1 08912
						16	190475 37	182890 30	1 04147
						12	174835 24	169391 22	1 03213
						8	149077 33	135708 80	1 09850
						4	117987 68	89949 02	1 31171
						0	86413 67	46678 87	1 85123

TABLE II (Contd)

Date	Foil Material	Run Time, min	Control-rod Position, in 1-9	Boric Acid	MWd/tonne (approx)	Distance from Bottom of Fuel Zone, in	Bare Activity	Cadmium-covered Activity	Cadmium Ratio
4-25-67	^{177}Lu	1	33.2	0	2229	48	190.99	16.95	11.26785
						44	426.43	34.04	12.52732
						40	803.70	59.31	13.5503
						36	1322.51	92.27	14.33304
						32	1951.82	130.79	14.92331
						28	2635.97	171.14	15.40242
						24	3301.07	207.83	15.88351
						20	3858.07	233.80	16.50158
						16	4206.46	241.38	17.42761
						12	4247.70	224.87	18.88958
						8	3917.21	184.50	21.23149
						4	3230.89	129.15	25.01657
						0	2318.23	74.17	31.25563
						ATSR Graphite Pile (8 in)	273.50	2.27389	120.27846
4-26-67	^{194}Ir	1	33.2	0	2254	48	514.09	284.67	1.80589
						44	1029.01	676.62	1.52059
						40	1746.30	1271.39	1.37354
						36	2611.10	2004.09	1.30288
						32	3542.71	2777.85	1.27534
						28	4447.87	3503.03	1.26972
						24	5242.58	4105.08	1.27709
						20	5799.55	4507.80	1.28655
						16	5989.00	4617.43	1.29704
						12	5686.59	4335.81	1.31131
						8	4842.99	3621.02	1.33746
						4	3580.45	2576.01	1.38991
						0	2202.53	1476.06	1.49216
						ATSR Graphite Pile (8 in)	1112.57	239.278	4.64969
4-26-67	^{192}Ir	3	33.2	0	2254	48	118.09	45.77	2.58017
						44	194.20	90.54	2.14491
						40	309.17	159.44	1.93910
						36	468.65	251.21	1.86557
						32	667.31	356.08	1.87405
						28	883.65	456.50	1.93571
						24	1081.05	532.36	2.03067
						20	1217.92	568.09	2.14389
						16	1263.85	558.13	2.26444
						12	1212.37	508.07	2.38623
						8	1082.62	431.37	2.50972
						4	909.40	343.93	2.64414
						0	728.55	259.31	2.80961
						ATSR Graphite Pile (8 in)	211.60	14.86	14.23521

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Fig. 25

Gold-Cadmium Ratios at 40 and 70 MW

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Fig. 26

Manganese-Cadmium Ratios at 40 and 70 MW

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Fig. 27

 ^{176}Lu -Cadmium Ratios at 40 and 70 MW

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Fig. 28. ^{177}Lu -Cadmium Ratios at 40 and 70 MW

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Fig. 29. Copper-Cadmium Ratios at 40 and 70 MW

Because of the complications and time loss involved in foil preparation and data analysis in order to compensate for the interference of ^{24}Na activity, it is suggested for future studies of this type that the spherical foils be fabricated in ceramic or glass spheres instead of the aluminum alloy.

IX. DISCUSSION OF THE ACTIVATION TRAVERSES

The traverse shapes are determined partly by the level to which the control blades are raised for operation, and also by the steam-void distribution. Both of these factors tend to shape the power distribution, the peak power density occurring about 12 in. from the bottom of the fuel.

The effect of control-blade positions is readily evident in comparison of Figs. 20 and 21, the blades being farther withdrawn during the irradiation corresponding with Fig. 21. Although the activation peaks are much broader in Fig. 21 than in Fig. 20, the vertical locations of the maxima of Fig. 21 are only slightly displaced from the locations indicated by Fig. 20.

The normalized curves for bare manganese activities are shown in Figs. 22-24, one figure showing the distributions at three different power levels for a single traverse location. The reactor conditions for these measurements are shown in Table III.

The copper-cadmium ratio increased markedly near the top of the plutonium zone, where the steam-void fraction was high. Figure 29 shows the copper-cadmium ratios measured at 40 and 70 MW. In the lower quarter

of the core, the 70-MW cadmium ratio curve is lower than the 40-MW curve, but higher in the core, the 70-MW curve crosses over and reaches much higher values than the 40-MW curve. This sensitivity to steam-void fraction is attributed⁵ to the effect of the $1/v$ resonance of ^{240}Pu , which reduces the $1/v$ portion of epicadmium foil activation. The foil is shielded from the resonance in the fuel by the intervening water. Copper-cadmium ratios are more sensitive than those of the other materials because the other materials have resonance activation in addition to the $1/v$ portion of epicadmium activation.

TABLE III. Reactor Conditions for Thermal-flux Measurements

Date	Foil Material	Reactor AWR, MW	Run Time, min	Control-rod Position, in.		Boric Acid	MWd/tonne	U-tube ^a Position
				1-8	9			
4-27-67	Mn-bare	70	4	33.2	33.2	0	2278	EU-2-42
4-27-67	Mn-bare	70	1	33.2	33.2	0	2278	Pu-27
4-27-67	Mn-bare	70	1	33.2	33.2	0	2278	Pu-32
6-5-67	Mn-bare	37	5	23.2	23.2	0	2495	EU-2-42
6-5-67	Mn-bare	37	3	23.2	23.2	0	2495	Pu-27
6-5-67	Mn-bare	37	2	23.2	23.2	0	2495	Pu-32
6-27-67	Mn-bare	61	2	31.5	39.0	0	2950	EU-2-42
6-27-67	Mn-bare	61	1	31.5	39.0	0	2950	Pu-27
6-27-67	Mn-bare	61	1	31.5	39.0	0	2950	Pu-32

^aSee Fig. 2.

The cadmium ratio of ^{177}Lu activity (plotted in Fig. 28) was also strongly affected by the change from a power of 40 MW to a power of 70 MW. However, a resonance of ^{176}Lu is at about 0.14 eV, which is thought to be shadowed by the 0.26-eV resonance of ^{241}Pu and the 0.3-eV resonance of ^{239}Pu ; thus the subcadmium activity of ^{177}Lu decreased with increased steam-void fraction.⁵ As a consequence, the ^{177}Lu activity cadmium ratio decreased with increased steam void, in contrast to the copper-cadmium ratio, which increased.

Two activation traverses are plotted in Fig. 30, and a comparison with Fig. 21, in which the control blades were further withdrawn (because of higher power operation), indicates a substantial redistribution of the flux. Figure 31 compares a traverse through the plutonium loading with one from

113-305

Fig. 30. Measured Power Distributions

113-324

Fig. 31. Comparison of Activation Distributions in Plutonium-fueled and Uranium-fueled Cores

an earlier EBWR loading. The operating conditions were similar during the two measurements. The traverses indicate no significant difference that might be attributed to the difference in core composition.

The gamma activity of selected fuel elements was scanned along the length of the elements approximately 60 days after shutdown to provide additional information on the power distribution of the fuel.⁷

Figures 32-35 show the plots of the postirradiation gamma-scanning measurements of the selected EBWR fuel elements. Figures 32 and 33 show the plots of the gamma activities for the uranium-enriched elements.

113-327

Fig. 32. Gamma Scanning of Uranium-enriched Fuel Elements; Differential Counts at 165 ± 0.02 MeV

113-309

Fig. 33. Gamma Scanning of Uranium-enriched Fuel Elements; Differential Counts at 2.55 ± 1.04 MeV

113-311

Fig. 34. Gamma Scanning of Plutonium Fuel Elements

113-322

Fig. 35. Gamma Scanning of Natural-uranium Fuel Elements

Figures 34 and 35 show the similar plots for the plutonium element and the natural uranium element. Figure 2 shows the core locations of these elements. Figure 36 is a power-distribution comparison using bare manganese at 61 and 70 MW in element No. Pu-32 and gamma scanning of element No. Pu-59.

113-308

Fig. 36. Power-distribution Comparison Using Manganese-Subcadmium Activation and Element-Gamma Scanning

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