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Neutronic Benchmarks for the Utilization of Mixed Oxide Fuel: Joint U.S./Russian Progress Report For Fiscal Year 1997 Volume 4, Part 3: Evaluation of the Relative Power Experiments for the SAXTON Partial Plutonium Core

Georgeta Radulescu

Fissile Materials Disposition Program

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NEUTRONIC BENCHMARKS FOR THE UTILIZATION OF MIXED OXIDE FUEL: JOINT U.S./RUSSIAN PROGRESS REPORT FOR FISCAL YEAR 1997—VOLUME 4, PART 3: EVALUATION OF THE RELATIVE POWER EXPERIMENTS FOR THE SAXTON PARTIAL PLUTONIUM CORE

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CONTENTS

Page

LIST OF FIGURES v
LIST OF TABLES vii
ACKNOWLEDGEMENTS ix

1. DESCRIPTION OF RELATIVE POWER EXPERIMENTS 1
   1.1 OVERVIEW 1
   1.2 POWER SHARING FACTOR 1
      1.2.1 Lanthanum-140 Measurements 2
      1.2.2 Calorimetric Measurements 3
   1.3 POWER SCAN DATA 4

2. RESULTS OF SAMPLE CALCULATIONS 23

3. REFERENCES 41

DISTRIBUTION LIST 43

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LIST OF FIGURES

Figure		Page
1	Relative pin power distribution for SX1.2.2	7
2	Relative pin power distribution for SX1.2.3	8
3	Relative pin power distribution for SX1.2.4	9
4	Relative pin power distribution for SX1.2.5	10
5	Relative pin power distribution for SX3.2.1	11
6	Relative pin power distribution for SX3.2.2	12
7	Relative pin power distribution for SX3.2.3	13
8	Relative pin power distribution for SX3.2.4	14
9	Relative pin power distribution for SX4.2.1	15
10	Relative pin power distribution for SX4.2.2	16
11	Relative pin power distribution for SX4.2.3	17
12	Relative pin power distribution for SX4.2.4	18
13	Relative pin power distribution for SX4.2.5	19
14	Relative pin power distribution for SX5.2.1	20
15	Relative pin power distribution for SX6.2.1	21
16	Relative difference of calculated and measured power for SX1.2.2	25
17	Relative difference of calculated and measured power for SX1.2.3	26
18	Relative difference of calculated and measured power for SX1.2.4	27
19	Relative difference of calculated and measured power for SX1.2.5	28
20	Relative difference of calculated and measured power for SX3.2.1	29
21	Relative difference of calculated and measured power for SX3.2.2	30
22	Relative difference of calculated and measured power for SX3.2.3	31
23	Relative difference of calculated and measured power for SX3.2.4	32
24	Relative difference of calculated and measured power for SX4.2.1	33
25	Relative difference of calculated and measured power for SX4.2.2	34
26	Relative difference of calculated and measured power for SX4.2.3	35
27	Relative difference of calculated and measured power for SX4.2.4	36
28	Relative difference of calculated and measured power for SX4.2.5	37
29	Relative difference of calculated and measured power for SX5.2.1	38
30	Relative difference of calculated and measured power for SX6.2.1	39

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LIST OF TABLES

Table **Page**

2.1 Relative power of UO_2 and MOX standard rods 23

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1. DESCRIPTION OF RELATIVE POWER EXPERIMENTS

1.1 OVERVIEW

One of the objectives of critical experiments for the SAXTON partial plutonium core was to provide relative power distribution data for single-region and multiregion cores with 1.4224-cm (0.56-in.) lattice pitch [1]. Local power peaking was measured for MOX single-region cores near the following perturbations: control rods, water slot, and aluminum plate. Power sharing measurements were performed for multiregion cores composed of MOX and UO_2 fuels in various patterns. The power produced in a fuel rod was determined by measuring the gamma activity of the fission products. Power sharing factors were previously determined in order for the fission product gamma activity of the fuel rods in multiregion cores to be normalized to that of the reference rod of one of the regions. Two methods were used to determine the power sharing factors as a function of time: the thermal method and the foil method. The power sharing factor as a function of time after shutdown for the foil method had the same shape but was about 5% lower than that for the thermal method. This discrepancy was explained by the difference in heat capacity between different types of fuel cladding, which had been neglected in the thermal method. Corrections for the heat capacity of the fuel cladding gave essentially identical power sharing factors for the two methods [2]. To evaluate the influence of spectrum shift at the zone interface on the power sharing factor, additional experiments were performed with different neutron spectra. The errors associated to the power sharing factors determined by the two methods were not provided in Ref. 1. The reader is referred to Ref. 2 for a discussion of the critical experiment configurations.

1.2 POWER SHARING FACTOR

The methods employed in relative power measurements are based on the direct proportionality between energy released per fission and gamma activity of the fission products. Gamma activities of the fuel rods were normalized to the gamma activity of a reference fuel rod of the same fuel type.[a] Since the fuel rods and the reference rod were not counted at the same time, a correction for the fission product decay was made. The decay correction was made by using a variable counting time, which was the time needed to reach 20,000 counts in an irradiated monitor rod of the same fuel type. However, for multiregion cores, composed of MOX and UO_2 fuels, the normalization of power generated in fuel rods of the two types to that of the reference rod of one of the regions cannot be achieved by simply relating the gamma activities of the rods.

[a] For each fuel region, one rod at the region boundary was selected as a standard rod, such that the two standard rods were in adjacent positions. Usually, the locations were on the flat direction of the core. The locations were adjacent in order for the flux not to have a significant gradient. The gamma activity of the standard rods was carefully measured as a function of time. For certain values of time, the ratio of gamma activity was multiplied by the power sharing factor (determined according to one of the formulas presented in the text). The average was exactly the relative power for the two adjacent rods, chosen as standard rods. Since the relative power within each region was previously determined, the power ratio for the standard rods allowed normalization to the reference rod of the core. In most of the cases the standard rods were also reference rods for relative power measurements within each fuel region.

The two fuel types have different fission yields and energy released per fission, which lead to different decay characteristics. Therefore, the relative power was attained by normalizing the gamma fission-product activity for each fuel region to the gamma fission-product activity of the reference rod of the same fuel type, and then the power sharing factor was applied to the standard rods. The locations chosen for the standard rods were usually at each side of the fuel region interface, so that the standards were adjacent. For most of the multiregion cores, the standard and reference rods were the same. The power sharing factor, C(t), is defined as the ratio of gamma activity per unit power generated in the UO_2 fuel to gamma activity per unit power generated in the MOX fuel [1]. It is a time-dependent quantity.

$$\frac{\gamma \text{ activity } (UO_2)}{\text{Power } (UO_2)} \Big/ \frac{\gamma \text{ activity (MOX)}}{\text{Power (MOX)}} = C(t) \qquad (1)$$

If gamma activities of the MOX and UO_2 standard rods and the power sharing factor are known for the same time after shutdown, the ratio of power generated in the two standard rods is determined from Eq. 1 as follows:

$$\frac{\text{Power(MOX)}}{\text{Power}(UO_2)} = C(t) * \frac{\gamma \text{ activity(MOX)}}{\gamma \text{ activity}(UO_2)} \qquad (2)$$

The power sharing factor is only weakly dependent on the flux since both fission product activity and power generated for a specific fuel are proportional to flux (there are some spectral effects). Therefore, once the power sharing factor as a function of time for two different fuel types is determined, it can be used in power normalization for multiregion cores, provided that the difference in neutron spectra does not bias the results. The power sharing factor as a function of time was determined using two different types of measurements: lanthanum-140 measurement in the foil method and calorimetric measurement in the thermal method. The two methods were used for the purpose of data accuracy verification. The correction for the differences in the fission product decay characteristics of the MOX and UO_2 fuels reaches a maximum value of 30% approximately four hours after shutdown.

1.2.1 Lanthanum-140 Measurements

The gamma activity of a fission product, whose yield from fission is well known, is proportional to the number of fissions that occur. Therefore, the relative gamma activity of ^{140}La, the daughter of ^{140}Ba produced in nuclear fission, can be measured for the two fuels after 12 days from the reactor shutdown, when the activity of ^{140}La is nearly maximized and its decay rate equals that of the ^{140}Ba precursor.

In this experiment aluminum alloy foils, containing fissile metal of the same enrichment as the MOX and UO_2 fuels, were irradiated in the peak thermal flux in the reflector of the CES research reactor and subsequently measured for gamma rays with energies above 0.5 MeV for

nine hours. The foils were measured after at least two weeks decay for the 1.6-MeV gamma peak that resulted from ^{140}La decay. The following equation was used to calculate the ratio of gamma activity per unit power in the uranium-bearing foil to gamma activity per unit power in the plutonium-bearing foil, as a function of the measured activities [1]:

$$\frac{(\gamma \text{ activity / relative thermal power unit})_U(t)}{(\gamma \text{ activity / relative thermal power unit})_{Pu}(t)} = \frac{A_U(t)}{A_{Pu}(t)} * \frac{^{140}La_{Pu}\, y_{Pu}^{Ba}}{^{140}La_U\, y_U^{Ba}} * \frac{(E/f)_{Pu}}{(E/f)_U} \quad (3)$$

where,
A(t) = the time dependent gamma activity (E>0.5 MeV) of the subscripted foil type;
^{140}La = the intensity of the lanthanum line from gamma spectrometric analysis of the subscripted foil type;
y^{Ba} = the fission yield of ^{140}Ba of the subscripted foil type; and
E/f = the energy per fission of the subscripted foil type.

In Eq. 3, the fission yields and energy released per fission were corrected for the presence of ^{238}U in the uranium foils and for the natural uranium in the plutonium foils using data provided by the diffusion code LEOPARD. Using the data obtained from fission product gamma activity measurements and ^{140}La analysis of the two foil types as a function of time, the power sharing factor was determined as a function of time.

In order to assess the influence of the spectrum shift at the zone interface on the power sharing factor, bare and cadmium covered foils were irradiated. The power sharing factors from the bare and cadmium covered foils were within ± 2.5%. Then the effects of spectrum shifts at fuel interfaces and of fuel density variations on the power sharing factor were studied using the gamma spectrometry technique, which was proved applicable without geometry corrections to two types of MOX fuel: precipitated MOX and vibratory compacted MOX both clad in Zircaloy. The results were again within ± 2.5%.

1.2.2 Calorimetric Measurements

In this method the energy deposited in an insulated fuel rod was determined by measuring the adiabatic temperature rise provided by thermocouples attached to the fuel rod. A gamma-activity-to-power-generated ratio curve as a function of time after shutdown was then determined from the measurement of the fission-product gamma rays with energies above 0.5 MeV, as a function of time and the energy deposition. The energy deposition was assumed the same as the energy generated in fuel rods. In the case of MOX and UO_2 fuels, the fractions of the energy releases per fission in the form of gamma rays for ^{235}U and ^{239}Pu are different. Also, the energy deposition from gamma rays originated in the surrounding lattice causes an increase in the apparent energy production in the test rod if its fission density is lower than that of the lattice or a decrease in the apparent energy production in the test rod if its fission density is higher than that of the surrounding lattice.

Six copper thermocouples were fixed at five axial positions on the standard MOX and UO_2 rods. Two out of the six thermocouples were placed at an identical axial position to determine the reproducibility of the thermocouple data. The standard rods were then packed in styrofoam in an aluminum thimble and placed in symmetric positions in the CES research reactor located at the WREC facilities at Waltz Mill, Pennsylvania. Each experiment consisted of a rapid

rise to power and measurement of each thermocouple temperature as quickly as possible before, during, and after control rod motion. After shutdown, the two standard rods were withdrawn and scanned periodically for their fission-product gamma rays with energies above 0.5 MeV. In this experiment, the energy deposition in each standard rod was related to the heating rate as follows:

$$\text{Thermal Power} = M\, c_p(\Delta T/\Delta t) \qquad (4)$$

The specific heats (c_p) of the MOX and UO_2 fuels and the heat capacities of the fuel claddings were assumed identical in this equation. Neglecting the differences in the heat capacity of stainless steel and Zircaloy 4 introduced a bias in the power sharing factor obtained by thermal method [2].

Concerned about the applicability of this method to the power sharing factor of the two different types of fuel, the authors applied the same procedure to 1.6 wt% and 3.7 wt% enriched UO_2 fuel rods. In this case no correction factor was necessary. If the measured heating rates were proportional to fission power, the gamma-to-power ratios for the 1.6 wt% and 3.7 wt% UO_2 fuel rods would be the same. The results were the same within the experimental errors. This proved that the axial thermal conduction along the fuel rods did not invalidate the technique.

The power sharing factor as a function of time after shutdown for the thermal method had the same shape but was about 5% higher than that for the foil method. Note that to calculate power in UO_2 rods relative to MOX rods, the UO_2 activity is divided by the power sharing factor and then normalized. "A reevaluation showed that the difference in heat capacities of the claddings of the two fuel rods had been neglected in the thermal method. With this correction the ratios from the two methods were essentially identical" [2].

1.3 POWER SCAN DATA

This section presents the relative power data for MOX single-region and multiregion configurations measured during the SAXTON Plutonium Program. For single-region cores, the relative power distribution was achieved by normalizing the gamma activity of fission products of selected rods to the gamma activity of fission products of a reference rod. For multiregion cores, the gamma activity of fission products of the selected rods was first normalized to that of the reference rod of the same type of fuel. Then the power sharing factor was applied to the standard rods of the two regions, which were MOX and UO_2 adjacent rods, in order to determine their relative power. This correction required measurement of fission-product gamma activity of the standard rods at the same time after shutdown. In order to normalize the entire core to the reference rod of one of the regions, the normalized gamma activities for the counted rods of the region that did not contain the reference rod were multiplied by the relative power of the standard rod. Gamma counts were performed at six axial positions, and data from five axial positions were used in the Power Scan Code to determine rod-averaged activity (Ref. 1, App. B, p. 7). There is no additional information about the meaning of the "rod-averaged activity" provided by this code.

Figures 1 through 15 present a subset of the relative power data provided by Ref. 1 for the core configurations used in relative power experiments. Criticality parameters and core designations are presented in Table 1.1, Ref. 3. Considering the symmetry of the core geometry, only one forth or a half of the core is shown. The central fuel rod position is marked by the letter C. The reference and the standard fuel rods are indicated by letters R and S, respectively, with a

subscript referring to the core region. For multiregion cores, where the rod power in one of the regions was normalized to the power of the reference rod of the other region, relative power values obtained by using power sharing factors provided by the foil method are shown. The relative power values obtained by the foil method are used for benchmark calculations due to studies reported in Ref. 2 and noted in the previous section. Different sizes for fuel rod locations have been used to fit the figures within page size.

The accuracy of relative power data for the multiregion cores was not reported and the accuracy (2 Standard Deviations) for single-region configurations was ± 1.4% [1]. From the analysis of provided normalized gamma activity for standard rods and rods irradiated in symmetric positions of the multiregion cores, a scattering in data of about ± 2% can be observed. Also, the accuracy associated with power sharing factors was not reported but should be nearly the same as for the relative power.

For the multiregion configuration that contained aluminum slab at regions boundary, the time after shutdown when the gamma count was made for the standard rods has not been recorded. In this case, the power sharing factor obtained from the unperturbed core was used. For single-region configurations and some of the multiregion configurations, the gamma counts were corrected for background and renormalized.

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R_{MOX} 1.000									
		1.1220							
		1.2101		1.1190		0.9791		0.9552	
	1.2385	1.2357							
C			1.2013	1.1520	1.1007	1.0232	0.9390		

Figure 1. Relative pin power distribution for SX1.2.2.

R_{MOX} 1.0000							0.7367		
		1.0954			0.9703				
		1.3620				1.1135			
	2.0005	1.7921	1.4236						
Water Slot **C**			1.6152	1.2527	1.1550	1.0662	0.9840		

Figure 2. Relative pin power distribution for SX1.2.3.

		0.9308		0.8700			0.7168		
R_{MOX} 1.0000									
			1.0283		0.9256				
		1.2484		1.1245					
		1.4552		1.1570					
Al Plate **C**			1.3973	1.1734	1.0816	1.0002	0.9401		

Figure 3. Relative pin power distribution for SX1.2.4.

						0.8492				
				1.0449						
			1.0788							
		1.0774				1.0816				
	0.9283	0.9507		1.0399						
Ag-In-Cd Control Rods **C**			1.0003	1.0768	1.0413	**R_{MOX}** 1.0000		0.8863		

Figure 4. Relative pin power distribution for SX1.2.5.

									C **R_{MOX}** 1.3182
								1.4772	**S_{MOX}** 1.4036
							1.2234	1.1792	**S_{UO2}** 1.1985
						1.1877			1.2288
				0.9608					1.1440
		R_{UO2} 0.7400							1.0000

Figure 5. Relative pin power distribution for SX3.2.1[1].

[1] Power ratio of MOX to UO_2 standard rods by foil method: 1.1711.
Source: Ref. 1, Appendix B, Table A-6, Page 30.

1.1703			1.1236		0.9993				0.9960
0.8395		0.8092		0.7512				0.6207	
0.8045							0.6073		
S_{UO2} **R_{UO2}** 0.7701		0.7589				0.6697			
S_{MOX} 0.9592			0.9239		0.8940				
0.9250		0.9038		0.8594					
0.9657	0.9570		0.9126						
0.9735		0.9433							
0.9927	0.9881								
C **R_{MOX}** 1.0000									

Figure 6. Relative pin power distribution for SX3.2.2[2].

[2] Power ratio of UO_2 to MOX standard rods by foil method: 0.8029
Reference 1 is ambiguous. Appendix B, page 25, references the power ratio noted previously. Page 26 contains time dependent power ratios in which the average of the reported thermal method measurements is 0.8029 and the average of the reported foil method measurements is 0.7574. It is presumed that the columns on page 26 are mislabeled.

			0.8630	1.0749					**C** 1.1108	1.0970	1.0971	1.1405	1.3579	Al P	1.1173	0.9567	0.9300	1.2944
													1.3437	l a	1.0954			
													1.2893	t e	1.0277	0.9028		
													1.0697	1.2036	0.8831		0.8790	
													0.9763	1.0265		0.8101		
				S_{MOX} **R_{MOX}** 1.0000										0.9966			0.7801	
			S_{UO2} **R_{UO2}** 0.7504												0.7489			

Figure 7. Relative pin power distribution for SX3.2.3[3, 4].

[3] Power ratio of UO_2 to MOX standard rods by foil method: 0.8029.
Source: Ref. 1, Appendix B, Table A-9. Page 33.
[4] The time after shutdown when the gamma count was made was not recorded. The relative power in the two regions is based on the power relationship of the standard rods of unperturbed configuration.

				R_{UO2} **S_{UO2}** 0.8183	**R_{MOX}** **S_{MOX}** 1.0000					**C** 0.9354	0.8697	0.8519	0.7773	0.6263	Ag-In-Cd	0.5309	0.6105	0.6196	0.6552	0.9467
														0.6264	Rods	0.5495				
												0.9472		0.6619		0.5548	0.6169		0.6540	
														0.7323	0.7197	0.6000		0.6167		
		UO_2 Region					**MOX Region**							0.7755	0.7815		0.6408		0.6237	
															0.8255			0.5948		
				0.7335												0.6427				
																				0.8167 0.7705

Figure 8. Relative pin power distribution for SX3.2.4[5].

[5] Power ratio of UO_2 to MOX standard rods by foil method: 0.8183.
Source: Ref. 1, Appendix B, Table A-10, Page 34.

0.5753													0.2969
0.5258												0.2763	
0.5586			0.5370			0.4741					0.3146		
S_{UO2} **R_{UO2}** 0.5718										0.3830			
S_{MOX} 0.7594			0.7231			0.6441			0.5604				
0.7535													
0.8010							0.6480						
0.8603													
0.9038					0.8053								
0.9467													
0.9679			0.9424										
0.9893													
0.9845													
C **R_{MOX}** 1.0000													

UO_2 Region

MOX Region

Figure 9. Relative pin power distribution for SX4.2.1[6].

[6] Power ratio (corrected for background and renormalized) of UO_2 to MOX standard rods by foil method: 0.7504. Source: Ref. 1, Appendix B, Table 250.3, Page 9.

C **R_{UO2}** 0.9050	**S_{UO2}** 0.8533	**R_{MOX}** **S_{MOX}** 1.0000	0.9166	0.8832	0.8387		0.7560		0.7055	0.5476			
	0.8146	0.9887											
	1.0143*												

Figure 10. Relative pin power distribution for SX4.2.2[7].

* Symmetric location yields relative power value of 0.9372.

[7] Power ratio (corrected for background and renormalized) of UO_2 to MOX standard rods by foil method: 0.8533.
Source: Ref. 1, Appendix B, Table A-3, Page 27.

0.3022													0.5906												
	0.2767																								
		0.3230											0.5671												
			0.3809																						
				0.5517									0.7629												
		0.4210																							
						0.6425							0.8263												
		0.5218				0.7197		0.8071					1.0490		0.7551										
				0.7056																					
						0.7920				0.9507															
		0.5726							0.9740																
				0.7556		0.8363						0.9984													
		0.5930		0.7624				1.0605		**R_{MOX}** **S_{MOX}** 1.0519			**C** 1.0000								0.8565				
									R_{UO2} **S_{UO2}** 0.8098																
									0.7920																
											0.7960		0.7800												

Figure 11. Relative pin power distribution for SX4.2.3[8].

[8] Power ratio of UO_2 to MOX standard rods by foil method: 0.7698.
Source: Ref. 1, Appendix B, Table A-8, Page 32.

0.7811	0.6994	0.7452	**R_{UO2}** **S_{UO2}** 0.7597	**R_{MOX}** **S_{MOX}** 1.0000					1.2404				**C** 1.3046		1.2988		1.2257	1.1664	1.1314	1.1121	1.3713	W a t e r	1.1168	0.8233	0.7064	0.7621
																					1.3375		1.0921			
																					1.2508		0.9883*			
																					1.0516	1.1410	0.8145			
																						0.9478				
													1.0188													
													0.7701										0.5067			

Figure 12. Relative pin power distribution for SX4.2.4[9].

* Symmetric position yields relative power of 0.97568.

9 Power ratio of UO_2 to MOX standard rods by foil method: 0.7597.

Source: Ref. 1, Appendix B, Table A-11, Page 35.

				1.0052					1.2449				**C** 1.3065		1.3012		1.2329	1.1806	1.1251	1.1051	1.2049	Al P l a t e	0.9751	0.7861	0.7037	0.7768
																					1.2273		0.9366			
																					1.1549		0.8943			
																					1.0204	1.0961	0.7837			
																						0.9558				
													R_{MOX} **S_{MOX}** 1.0000													
													R_{UO2} **S_{UO2}** 0.7654													

Figure 13. Relative pin power distribution for SX4.2.5[10].

[10] Power ratio of UO_2 and MOX standard rods by foil method: 0.7654.
Source: Ref. 1, Appendix B, Table A-12, Page 36.

1.0949			1.0419		0.9591				1.0092
0.7070		0.7060		0.6543		0.5580		0.5326	
0.7189			0.6810		0.6133		0.5176		
R_{MOX} **S_{MOX}** 0.8798		0.8547		0.7744		0.6173			
S_{UO2} 0.7752			0.7213		0.6027				
0.8758		0.8516		0.7797					
0.9433	0.9307		0.8871						
0.9849		0.9517							
0.9916	0.9807								
C **R_{UO2}** 1.0000									

Figure 14. Relative pin power distribution for SX5.2.1[11].

[11] Power ratio of MOX to UO_2 standard rods by foil method: 1.0731.
Source: Ref. 1, Appendix B, Table A-4, Page 28.

0.5959													0.3432
0.4771												0.2537	
0.5260			0.5054			0.4531					0.2896		
R_{MOX} **S_{MOX}** 0.6558										0.3789			
S_{UO2} 0.6110			0.5652			.5088			0.3833				
0.6970													
0.7640							0.6053						
0.8157			0.7842										
0.8406													
0.8886													
0.9047			0.8814										
0.9250													
0.9479													
C **R_{UO2}** 1.0000										0.6590			

Figure 15. Relative pin power distribution for SX6.2.1[12].

[12] Power ratio of MOX to UO_2 standard rods by foil method: 1.0733.
Source: Ref. 1, Appendix B, Table A-5, Page 29.

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2. RESULTS OF SAMPLE CALCULATIONS

Total prompt energy released per fission, averaged over each fuel rod, was calculated with MCNP-4B and continuous-energy cross-section libraries from ENDF/B-V and ENDF/B-VI evaluations. The calculated and the measured (by the foil method) power sharing factors are presented in Table 2.1 for comparison. Figures 16 through 30 present the measured relative pin power by the foil method, followed by the relative difference of calculated and measured relative power, (Calc.-Meas.)/Meas., in percent, using ENDF/B-V and ENDF/B-VI, respectively. A discussion about these results is available in Ref. 4.

Table 2.1. Relative power of UO_2 and MOX standard rods

Core	Measurements	MCNP4B ENDF/B-V	MCNP4B ENDF/B-VI
SX3.2.2	0.8029	0.8051 ± 0.0126	0.8030 ± 0.0126
SX3.2.3	0.8029	0.7959 ± 0.0127	0.8144 ± 0.0128
SX3.2.4	0.8183	0.8219 ± 0.0127	0.8123 ± 0.0108
SX4.2.1	0.7504	0.7460 ± 0.01343	0.7631 ± 0.0139
SX4.2.5	0.7654	0.7600 ± 0.0137	0.7607 ± 0.0137
SX4.2.4	0.7597	0.7531 ± 0.0136	0.7555 ± 0.0136
SX4.2.3	0.7698	0.7663 ± 0.0138	0.7493 ± 0.0135
SX4.2.2	0.8533	0.8226 ± 0.0132	0.8388 ± 0.0134
SX5.2.1	0.9318	0.9355 ± 0.0151	0.9340 ± 0.0150
SX3.2.1	0.8539	0.8269 ± 0.0137	0.8376 ± 0.0134
SX6.2.1	0.9312	0.9072 ± 0.0163	0.9210 ± 0.0166

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1.000									
		1.122 -1.9 -0.8							
		1.210 -1.9 -1.4		1.119 -0.2 -0.2		0.979 -1.0 +0.3		0.955 -2.9 -2.3	
	1.239 -0.4 -0.5	1.236 -2.2 -2.4							
			1.201 -0.7 -0.2	1.152 -1.2 -1.4	1.101 -2.2 -3.2	1.023 -2.7 -2.4	0.939 -0.7 -0.2		

Center

Fig. 16. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX1.2.2. The error in calculations is ± 1.6%.

1.000							0.737 0.0 -0.6		
		1.095 +3.5 +2.1			0.970 +2.3 -0.9				
		1.362 +2.1 +1.4							
	2.001 +3.8 +2.2	1.792 +4.0 +1.9	1.424 +1.5 +1.5						
Water Slot			1.615 +2.9 +2.8	1.253 +3.2 +2.6	1.155 +0.5 +1.6	1.066 +1.6 +1.9	0.984 +3.1 +3.1		

Center

Fig. 17. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX1.2.3. The error in calculations is ± 1.6%.

		0.931 0.0 -3.2		0.870 -1.5 -2.9			0.717 -2.5 -1.0		
1.000									
			1.028 +0.1 -2.1		0.926 -0.6 -1.8				
		1.248 +1.2 -1.5		1.125 -0.4 -0.8					
		1.455 +2.3 +0.5		1.157 +0.2 +0.2					
Al Plate			1.397 +1.4 -0.9	1.173 -1.4 +0.1	1.082 +1.1 +0.4	1.000 +0.3 +0.6	0.940 -0.1 -0.6		

Center

Fig. 18. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX1.2.4. The error in calculations is ± 1.6%.

						0.849 +2.0 +0.8				
				1.045 -2.1 +0.3						
			1.079 -0.6 +0.2							
		1.077 -1.2 -1.5								
	0.928 -4.9 -3.4	0.951 -2.6 -0.8		1.040 -2.0 +1.4						
Ag-In-Cd Control Rods			1.000 -3.0 -3.0	1.077 -2.9 -0.6	1.041 -0.1 +0.5	1.000		0.886 +0.6 +0.6		

Center

Fig. 19. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX1.2.5. The error in calculations is ± 1.6%.

1.000							0.740 -0.8 -1.5		
1.144 +0.1 -0.1					0.961 +0.4 +2.3				
1.229 +1.1 +0.7			1.188 +0.2 +1.5						
1.199 -1.2 -1.2	1.179 +2.0 +1.2	1.223 -0.4 +0.5							
1.404 +2.1 +0.8	1.477 +1.2 +1.0								
1.318 +1.6 -0.6									

Center

Fig. 20. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX3.2.1. The error in calculations is ± 1.6%.

1.170 +1.7 +0.1			1.124 -0.6 -1.7		0.999 -0.5 -2.1				0.996 +0.3 -0.5
0.840 -0.5 -2.4		0.809 -3.6 -0.6		0.751 -0.3 -0.9				0.621 +0.0 +0.5	
0.805 -1.4 -3.2							0.607 -1.0 -1.8		
0.770 +0.8 -0.1		0.759 -1.4 -1.2				0.670 -1.8 +1.5			
0.959 +0.5 +0.2			0.924 -2.1 -2.1		0.894 -2.0 -0.3				
0.925 -0.8 -0.1		0.904 +1.0 0.0		0.859 +1.2 0.0					
0.966 -1.7 -1.7	0.957 -1.5 -1.1		0.913 +0.6 -1.3						
0.974 -0.9 +0.1		0.943 +2.1 +1.4							
0.993 -0.2 +0.7	0.988 +0.3 +0.4								
1.000									

Center

Fig. 21. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V (middle) and ENDF/B-VI (bottom), respectively, for core SX3.2.2. The error in calculations is ± 1.6%.

Center

			0.863 +1.2 +0.5	1.075 +1.3 -0.3					1.111 +1.7 -0.3	1.097 +1.4 +2.1	1.097 +1.0 -1.1	1.141 -1.8 -1.7	1.358 +0.1 -1.7	Al	1.117 +0.9 0.0	0.957 +0.1 +0.2	0.930 +2.9 +2.8	1.294 +0.8 +1.8
													1.344 -0.2 -0.9	P l a	1.095 +1.8 +1.9			
													1.289 -2.5 -3.5	t e	1.028 +0.5 +1.3	0.903 +1.9 +0.9		
													1.070 +0.7 -0.7	1.204 +0.2 +0.3	0.883 +1.9 -0.7		0.879 +0.1 +0.7	
													0.976 +1.6 0.0	1.027 -1.7 +0.2		0.810 +1.6 -0.9		
				1.000										0.997 +0.7 +1.0			0.780 +1.4 +1.4	
			0.750 +0.4 +0.1												0.749 +0.8 -1.1			

Fig. 22. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX3.2.3. The error in calculations is ± 1.6%.

Center

				0.818 +0.5 -0.7	1.000					0.935 -1.2 -1.3	0.870 +2.6 +4.1	0.852 +0.4 0.0	0.777 -0.5 -0.3	0.626 -1.9 -1.0	Ag- In- Cd	0.531 -5.2 -4.9	0.611 -3.1 -0.5	0.620 -2.4 -0.8	0.655 -1.8 -2.0	0.947 -3.7 -2.9
														0.626 -1.4 +0.3	R o d s	0.550 -7.7 -6.5				
												0.947 -10.2 -9.0		0.662 -0.6 -1.4		0.555 -4.5 -3.8	0.617 -1.6 -1.6		0.654 -1.5 -2.0	
														0.732 -1.0 -1.9	0.720 -2.5 -1.4	0.600 -0.5 -2.0		0.617 -2.6 +0.3		
														0.776 -0.3 -2.1	0.782 -1.0 -0.3		0.641 -2.9 -2.2		0.624 +0.3 -0.2	
															0.826 -0.5 -2.3			0.595 -0.7 -2.7		
				0.734 -1.1 -1.2												0.643 -2.3 -2.5				
																				0.817 +0.4 -1.1

Fig. 23. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX3.2.4. The error in calculations is ± 1.6%.

0.575 -0.7 -1.7													0.297 -3.7 -3.0
0.526 -4.0 -3.4												0.276 -4.3 -4.8	
0.559 -1.8 -2.0			0.537 -3.7 0.0			0.474 -2.3 -2.3					0.315 -5.7 -5.7		
0.572 -1.9 -0.9										0.383 -2.3 -5.5			
0.759 -0.9 -2.1			0.723 -1.1 +0.3			0.644 -1.7 -2.6			0.560 -1.3 -4.5				
0.754 -3.7 -3.3													
0.801 -2.0 -0.5							0.648 -0.8 0.0						
0.860 -2.7 -2.0													
0.904 -1.0 -1.7					0.805 -1.1 -0.3								
0.947 -2.9 -2.5													
0.968 -0.8 -2.5			0.942 -2.6 -1.4										
0.989 -0.7 -2.0													
0.985 +0.7 +0.4													
1.000													

Center

Fig. 24. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX4.2.1. The error in calculations is ± 1.8%.

	1.014 -3.9 -2.7												
	0.815 -1.6 -2.1	0.989 -1.5 -1.7											
0.905 -3.9 -4.3	0.853 -3.5 -1.6	1.000	0.917 -2.1 -2.2	0.883 -2.0 -2.2	0.839 -0.8 -1.8		0.756 -2.0 -1.2		0.706 -0.6 -0.8	0.548 -4.1 -4.0			

Center

Fig. 25. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX4.2.2. The error in calculations is ± 1.7%.

0.302 -2.7 -0.3											0.591 -2.9 -0.1		
	0.277 -6.2 -2.5												
		0.323 -3.5 -2.4									0.567 -2.6 -1.6		
			0.381 -2.1 -0.2										
				0.552 +0.6 +3.2							0.763 -1.1 -0.8		
		0.421 +0.5 +0.2											
					0.643 -0.9 +0.6						0.826 -2.0 -0.6		
		0.522 -5.0 -2.4			0.720 +1.0 +1.8	0.807 -1.9 +1.6					1.049 -10.0 -8.0		0.755 -2.1 -0.6
				0.706 +0.4 -0.3							Mn wire		
					0.792 -2.0 +0.9			0.951 -2.2 -1.4					
		0.573 -4.7 -3.8					0.974 -5.3 -4.8						
	Mn wire			0.756 -0.6 +1.3	0.836 -3.8 -1.8	Mn wire				0.998 -0.4 -0.6			
		0.593 -4.9 -4.9		0.762 -1.2 -1.0		1.061 -11.3 -8.0		1.052 -3.6 +0.7			1.000 Center		
							0.810 -4.0 -2.5						
							0.792 -3.9 -1.0						
									0.796 -2.9 -0.6		0.780 -1.6 -1.5		

Fig. 26. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core Sx4.2.3. The error in calculations is ± 1.6%.

Center

0.781 -2.6 -1.0	0.699 -4.8 -1.4	0.745 -1.7 -1.2	0.760 -0.9 -0.5	1.000	1.240 -0.9 +0.5	1.305 -1.0 +1.1	1.299 -1.7 -0.3	1.226 -2.9 -0.8	1.166 +0.6 -0.3	1.131 -1.7 -2.0	1.112 +0.2 +1.0	1.371 +1.4 +1.1	W	1.117 -4.1 -3.5	0.823 -3.5 -2.8	0.706 -3.8 -2.4	0.762 -3.8 -2.8
												1.337 0.0 +2.9	a t e	1.092 -3.7 -3.6			
												1.251 -1.8 -0.7	r	0.988 -3.6 -1.8			
												1.052 -1.5 -2.3	1.141 -1.6 -0.9	0.815 -3.8 -4.4			
													0.948 -1.3 -1.2				
						1.019 -3.3 -2.7											
						0.770 -3.6 -3.6								0.507 -4.4 -2.0			

Fig. 27. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX4.2.4. The error in calculations is ± 1.8%.

Center

				1.005 -2.0 -0.7				1.245 -0.9 -0.1				1.307 +1.6 -0.1		1.301 +0.8 +1.0		1.233 -2.6 -0.7	1.181 -1.5 +0.9	1.125 -0.5 -0.8	1.105 -2.4 -2.1	1.205 +1.9 +1.8	Al	0.975 -1.4 -3.0	0.786 -1.3 -1.4	0.704 -3.9 -3.9	0.777 -3.3 -2.6
																				1.227 -1.7 -0.5	P l a	0.937 -1.5 +0.8			
																				1.155 -0.1 +1.6	t e	0.894 -1.4 -1.1			
																				1.020 +0.8 +1.1	1.096 +1.2 +0.7	0.784 -1.3 0.0			
																					0.956 -0.6 -1.5				
												1.000													
												0.765 -0.7 -0.6													

Fig. 28. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX4.2.5. The error in calculations is ± 1.8%.

1.095 -2.3 -0.8			1.042 -1.9 -1.7		0.959 -4.0 -2.0				1.009 -2.7 -2.3
0.707 -4.7 -5.3		0.706 -6.0 -4.8		0.654 -6.6 -6.0		0.558 -3.0 -2.3		0.533 -4.2 -6.7	
0.719 -5.1 -5.3			0.681 -2.4 -2.8		0.613 -6.1 -4.6		0.518 -4.0 -2.6		
0.880 -7.2 -6.8		0.855 -5.3 -5.6		0.774 -5.9 -3.1		0.617 -4.3 -4.4			
0.775 -1.6 -1.6			0.721 -1.1 -1.0		0.603 +0.2 -1.5				
0.876 -0.4 -0.2		0.852 -0.5 +0.9		0.780 +0.1 -0.6					
0.943 +0.3 -0.1	0.931 -0.3 +0.1		0.887 -0.9 -1.8						
0.985 -1.5 -1.3		0.952 -0.5 -1.5							
0.992 +0.1 +0.4	0.981 +0.3 0.0								
1.000									

Center

Fig. 29. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX5.2.1. The error in calculations is ± 1.6%.

0.596 2.1 4.5													0.343 5.6 2.8
0.477 5.4 2.8												0.254 2.4 -0.5	
0.526 2.3 2.3			0.505 4.1 2.6			0.453 3.8 4.2					0.290 1.6 3.9		
0.656 5.2 4.3										0.379 2.1 4.3			
0.611 +2.5 +3.1			0.565 +5.5 +8.3						0.383 +5.5 +3.3				
0.697 +4.8 +6.7													
0.764 +5.0 +5.5							0.605 +6.8 +7.8						
0.816 +5.0 +6.1			0.784 +5.8 +6.2										
0.841 +7.6 +7.2					0.765 +7.4 +4.2								
0.889 +4.7 +4.3													
0.905 +5.8 +7.8			0.881 +5.8 +6.1										
0.925 +6.2 +6.7													
0.948 +4.7 +5.2													
1.000										0.659 2.4 4.0			

Center

Fig. 30. Measured relative pin power followed by the relative difference of calculated and measured relative power, (Calc.- Meas.)/Meas. in percent, using ENDF/B-V and ENDF/B-VI, respectively, for core SX6.2.1. The error in calculations is ± 1.8%.

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