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Albert Hanson and David Diamond

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Albert Hanson
Brookhaven National Lab
PO Box 5000, Upton, NY
Phone : 631-344-3999
Fax : 631-344-3957
alh@bnl.gov

David Diamond
Brookhaven National Lab
PO Box 5000, Upton, NY
Phone : 631-344-2604
Fax : 631-344-3957
diamond@bnl.gov

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ABSTRACT

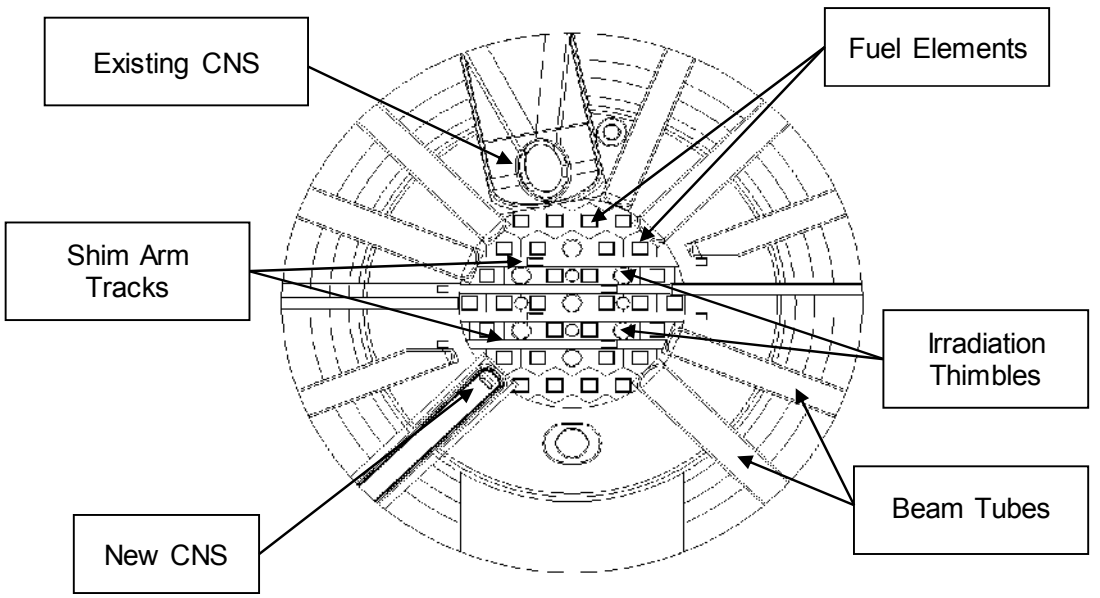
A methodology for calculating inventories for the NBSR has been developed using the MCNPX computer code with the BURN option. A major advantage of the present methodology over the previous methodology, where MONTEBURNS and MCNP5 were used, is that more materials can be included in the model. The NBSR has 30 fuel elements each with a 17.8 cm (7 in) gap in the middle of the fuel. In the startup position, the shim control arms are partially inserted in the top half of the core. During the 38.5 day cycle, the shim arms are slowly removed to their withdrawn (horizontal) positions. This movement of shim arms causes asymmetries between the burnup of the fuel in the upper and lower halves and across the line of symmetry for the fuel loading. With the MONTEBURNS analyses there was a limitation to the number of materials that could be analyzed so 15 materials in the top half of the core and 15 materials in the bottom half of the core were used, and a half-core (east-west) symmetry was assumed. Since MCNPX allows more materials, this east-west symmetry was not necessary and the core was represented with 60 different materials. The methodology for developing the inventories is presented along with comparisons of neutronic parameters calculated with the previous and present sets of inventories.

1. NBSR FUEL MANAGEMENT SCHEME

Figure 1 shows a planar view of the NBSR at the core midplane with some of the key structures identified. North and south are top and bottom of the page, east to the right and west is to the left. There are four cadmium shim arms that are rotated through the core in a semaphore fashion. Two pivot from the east and two pivot from the west. At the end of cycle, they are fully withdrawn from the core in a horizontal position and at shutdown they are inserted at an angle of 41° from horizontal. In the startup (SU) position, the shim arms are partially inserted in the top half of the core. Therefore there is an asymmetry between the top and bottom halves of the core in addition to the asymmetry between the east and west halves of the core. The latter asymmetry is exacerbated by differences in structures outside the core. With thirty fuel elements in the NBSR, the model requires 60 different materials to have each half fuel element with its own inventory. Within the half-fuel elements the assumption is that the fuel composition is uniform.

Figure 2 shows how the positions in the NBSR core are identified. The positions are identified with 13 columns, denoted with letters, and seven rows denoted with numbers. The space denoted with <RR> is the position of the regulating rod and the six positions denoted with <> are the 8.89-cm (3½-inch) in-core irradiation thimbles. These thimbles are aluminum tubes assumed to be filled with D_2O only. The four 6.35-cm (2½-inch) in-core irradiation thimbles located in positions D4, G3, G5, and J4 are not included in Figure 2, but are included in the neutronics model as is evidenced in Figure 1.

The fuel management scheme for the NBSR is shown in Figure 3. Each fuel position is identified with two numbers and one letter. The letters are either E or W for the east or west side of the core noting that a fuel element always stays in the east side or in the west side of the core. Since there are thirty fuel elements, 16 stay in the core for eight cycles and 14 stay in the core for seven cycles. The first number denotes how many cycles the element will be in the core (either 8 or 7) and the second number denotes the cycle in which the fuel element resides. Therefore at the beginning of a cycle (BOC), the 8-1 and 7-1 fuel elements are fresh, unirradiated fuel elements, 8-8 and 7-7 are in their final cycles and will be removed when the cycle is completed.



COLD SOURCE

			D1		F1		H1		J1			
		C2		E2		<>		I2		K2		
	B3		<>		F3		H3		<>		L3	
A4		C4		E4		<>		I4		K4		M4
	B5		<>		F5		H5		<>		L5	
		C6		E6		<RR>		I6		K6		
			D7		F7		H7		J7			

COLD SOURCE

			8-1W		7-2W		7-2E		8-1E			
		8-3W		7-5W		<>		7-5E		8-3E		
	7-3W		<>		8-7W		8-7E		<>		7-3E	
7-1W		8-6W		7-7W		<>		7-7E		8-6E		7-1E
	8-4W		<>		8-8W		8-8E		<>		8-4E	
		7-4W		7-6W		<RR>		7-6E		7-4E		
			8-2W		8-5W		8-5E		8-2E			

After a cycle is finished the 8-8 and 7-7 fuel elements are removed and the 8-7 elements are moved into the 8-8 positions, the 7-6 elements are moved into the 7-7 positions. Likewise the 8-6 and 7-5 fuel elements are moved into the 8-7 and 7-6 positions, respectively. This keeps occurring until the 8-1 and 7-1 fuel elements are moved into the 8-2 and 7-2 positions and new, unirradiated fuel is placed in the 8-1 and 7-1 positions.

2. DETERMINATION OF INVENTORIES

Previously, (Hanson, 2005) inventories were obtained using the MONTEBURNS (Poston, 2002) program used in conjunction with the MCNP5 (LANL, 2003) and ORIGEN2 (Ludwig, 2002) computer codes. Since the release of MONTEBURNS as its own program package, its methodology has been incorporated as the BURN option of MCNPX Version 2.6.0 (Pelowitz, 2008). MCNPX makes use of the CINDER'90 (Wilson, 1997) code instead of ORIGEN2 for solving the burnup equations. As such, some of the limitations that were evident in the MONTEBURNS code remain in the MCNPX code. The most important item is that not every fission product can be included in the inventory. Any isotope that is not in the library of isotopes is necessarily ignored by MCNPX, since MCNPX does not use any "representative" fission products. The result is a reduction of the mass that is tracked for each material. The total mass of each material is decreased every time CINDER'90 returns an isotope that MCNPX does not recognize. Therefore, for this work, in order to generate each inventory, based on the relative mass of the material, the amount of each isotope is extracted and the "missing mass" is added to the mass of ^{133}Cs. It should be noted that using the ENDF libraries available with the MONTEBURNS/MCNP codes, the amount of mass that was unaccounted for using the MONTEBURNS analyses was previously reported to ~1.2% per cycle. Using the present libraries for the analyses resulted in unaccounted mass of ~0.02% per cycle.

In considering differences between the calculations presented in the previous and the present efforts, one should note there were differences in the model of the reactor and different versions of each code were used. The work presented in (Hanson, 2005) used the ENDF66 or ENDF60 cross-section files wherever possible and the present effort makes use of the ENDF70 cross-section files wherever possible. The earlier work was performed on a PC system and the present analysis was performed on a LINUX cluster.

There are several differences between the previous geometric model and the present model, including a new cold neutron source that is scheduled to be installed as shown in Fig. 1. The present model also now has the moderator dump line and the fuel transfer chute included. The latter two items are aluminum tubes filled with D_2O. The differences between the methodology being presented here and the methodology presented earlier include:

- Increasing the number of fuel materials from 30 to 60
- Explicitly including an 11-day cooling time at the end of each cycle
- Increasing the number of isotopes in the inventory from an average of 55 (max 63) to an average of 198 (max 210)
- Performing the analyses at three different time steps during a cycle with each time step having its own shim arm position and extracting the inventories at the end of each time step

Each time step is represented with the same NBSR model with the exception that shim arms are in different positions and the inventory is extracted from the previous time step. The three different time steps used for the analysis were the SU, BOC and middle-of-cycle (MID) cores. Table 1 shows four distinct times of the NBSR cycle that have been used for the reactor analysis. SU is the startup core without equilibrium ^{135}Xe. BOC is the core soon after startup where the ^{135}Xe has come into equilibrium which is ~1.5 days into the cycle. During that initial 1.5 day time span, the shim arms move ~5°. The next two steps are MID or midway through the 38.5 day cycle and EOC is the end-of-cycle equilibrium core with the shim arms fully withdrawn. The angles for the beginning of each of those times are shown in the third column of Table 1. For the generation of the inventories, three models are used with the shim arms placed half way between those four positions. After each step the inventory is extracted, adjusted for the unaccounted mass, normalized to unity weight fraction and copied into the subsequent model.

Table 1 Shim Arm Positions

	Days into Cycle	Angle from Horizontal	Angle set for BURN
		(degrees)	(degrees)
SU	0	-19.7	-17.0
BOC	1.5	-14.6	-11.9
MID	19	-9.2	-4.6
EOC	38.5	0	

The flow chart for the methodology to calculate the inventories is shown in Figure 4. In all cases the regulating rod is placed at 50% withdrawn. The determination of the SU inventory is different from the other inventories. At the end of the cycle, the fuel is allowed to decay for 11 days. The inventories for the 7-7 and 8-8 fuel elements are deleted. The other fuel elements are shifted according to the fuel management scheme shown in Figure 3, and fresh, unirradiated fuel elements are inserted into the 7-1 and 8-1 positions.

3. COMPARISON OF TWO METHODS

Reactivity Effects

Several of the key neutronic parameters have been calculated with both the present methodology, using MCNPX and 60 materials, and the previous methodology, using MONTEBURNS and 30 materials.

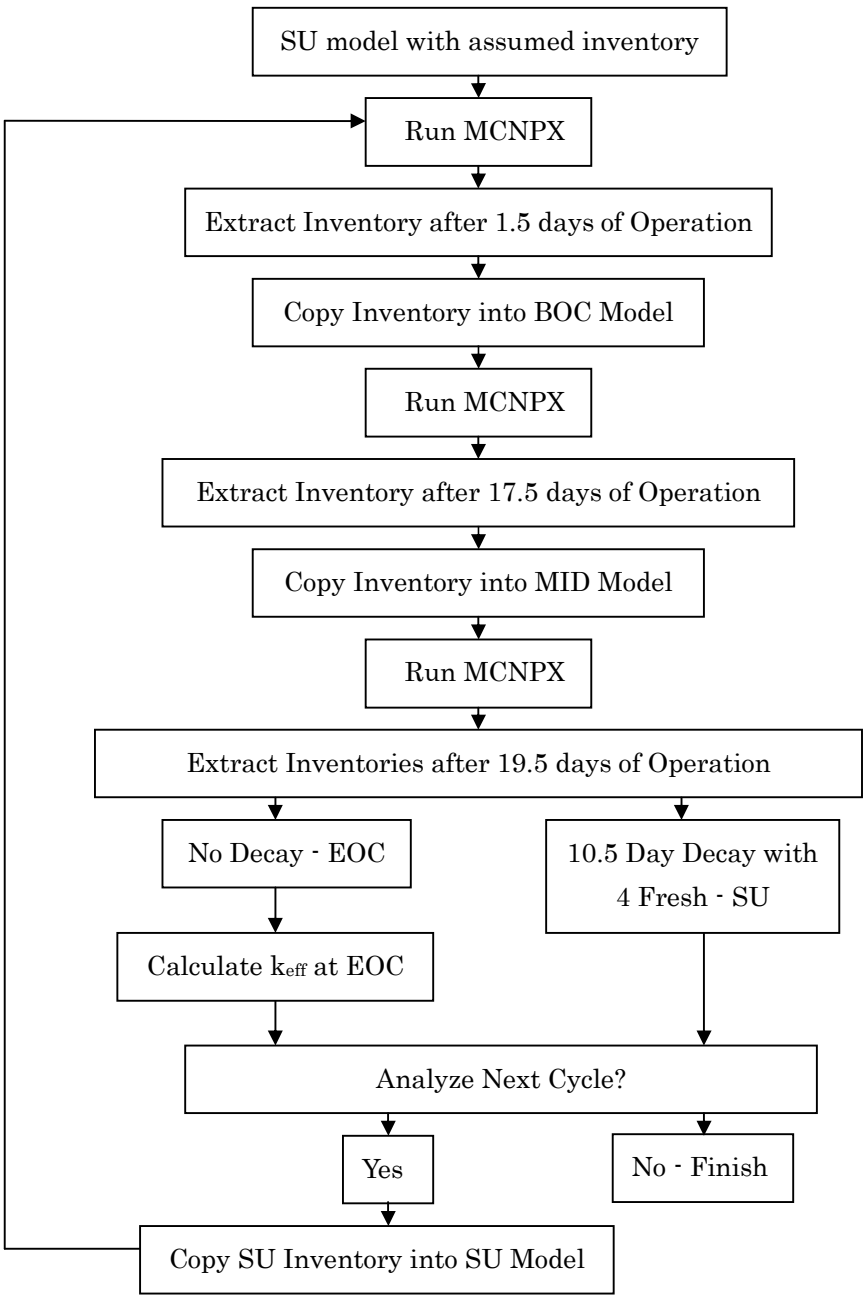
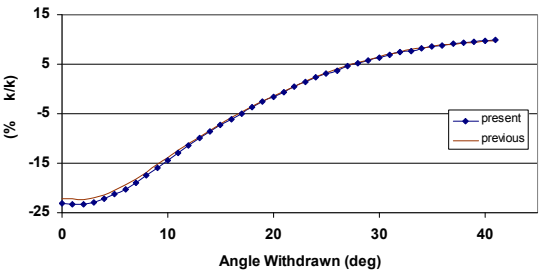
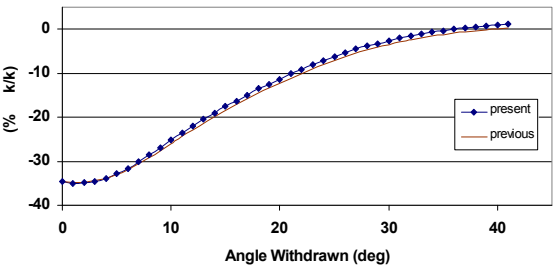


Figure 4. Methodology Flow Chart





	Previous Method	Present Method
SU Core		
Change kernel only	-9.1	-7.9
Change density only	-22.2	-25.0
Total	-31.3	-32.9
EOC Core		
Change kernel only	-6.9	-8.5
Change density only	-18.3	-23.6
Total	-25.2	-32.1

	Previous Method	Present Method
All Shim Arms In	-17.1	-17.4
Shim Arm 1 out	-11.4	-11.3
Shim Arm 2 out	-9.4	-9.9
Shim Arm 3 out	-9.7	-9.4
Shim Arm 4 out	-11.1	-11.0
All Shim Arms Out	6.6	7.2

multiplied by the relative value in each cell of the figure. These figures demonstrate that when the shim arms are partially inserted in the core at SU, the power is dominantly in the lower half of the core. As the shim arms are withdrawn, the power shifts to the upper half. The maximum power peaking factor in the SU core is 1.29 and in the EOC core it is 1.15. The differences between the calculations using inventories generated with previous and present methodologies are shown in Figure 8 for the SU core.

4. CONCLUSIONS

A methodology for analyzing the NBSR was developed using MCNPX and replaces the previous approach using MCNP5. The BURN/CINDER90 module used with MCNPX is similar to the MONTEBURNS/ORIGEN2 module used with MCNP5, and the inventories generated using both codes are similar. However, MCNPX allows for more materials to be analyzed so that the thirty fuel elements, which previously were represented using thirty compositions (an upper fuel element section and a lower fuel element section in 15 elements), can now be represented with sixty different materials. This eliminates the need to assume half-core symmetry in the planar direction. New libraries also reduce the amount of mass unaccounted for after doing the depletion; the relative value goes from ~1.2% with MCNP5 to ~0.02% with MCNPX. Although the new model has increased rigor, a comparison of key parameters using both methods shows that the changes did not invalidate the previous analysis, i.e., the earlier simplifications were acceptable.

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	A	B	C	D	E	F	G	H	I	J	K	L	M
				COLD									
				SOURCE									
1				0.97		1.06		1.11		1.01			
2			0.96		1.02		<>		0.94		0.82		
3		0.75		<>		0.93		0.90		<>		0.71	
4	0.65		0.72		0.83		<>		0.82		0.71		0.64
5		0.67		<>		0.74		0.75		<>		0.69	
6			0.72		0.80		<RR>		0.86		0.85		
7				0.88		0.88		0.90		0.95			

SU

Lower core

	A	B	C	D	E	F	G	H	I	J	K	L	M
				COLD									
				SOURCE									
1				1.05		1.16		1.20		1.14			
2			1.23		1.28		<>		1.29		1.26		
3		1.23		<>		1.29		1.29		<>		1.23	
4	1.24		1.21		1.24		<>		1.22		1.17		1.19
5		1.21		<>		1.06		1.05		<>		1.15	
6			1.12		1.08		<RR>		1.07		1.09		
7				1.03		0.97		0.98		1.04			

Figure 7. Radial Power Distribution at SU Using the Present Methodology.

	A	B	C	D	E	F	G	H	I	J	K	L	M
				COLD SOURCE									
1				5.1		6.5		6.4		8.6			
2			8.8		4.8		<>		4.6		8.8		
3		9.0		<>		7.7		4.4		<>		7.9	
4	7.6		8.6		5.5		<>		4.1		4.4		5.1
5		6.2		<>		-2.0		-2.6		<>		1.0	
6			-1.4		-7.4		<RR>		-9.6		-6.8		
7				-10.6		-14.5		-15.2		-11.1			

	A	B	C	D	E	F	G	H	I	J	K	L	M
				COLD SOURCE									
1				1.4		2.8		1.1		1.5			
2			3.7		5.5		<>		4.3		3.2		
3		0.6		<>		7.1		5.5		<>		1.9	
4	1.0		5.5		5.6		<>		3.6		4.8		-1.5
5		0.9		<>		-0.5		-2.2		<>		-1.2	
6			-3.7		-6.6		<RR>		-7.5		-5.6		
7				-10.5		-13.9		-14.1		-10.6			

Figure 8. Difference (%) in the Radial Power Distribution at SU Using the Previous and Present Methodologies