KAERI Results for BN600 full MOX Benchmark (Phase 4)

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1. Introduction

The prupose of this document is to report the results of KAERI's calculation for the Phase-4 of BN-600 full MOX fueled core benchmark analyses according to the RCM report of IAEA CRP Action item 3.12 on "Updated Codes and Methods to Reduce the Calculational Uncertainties of the LMFR Reactivity Effects." The BN-600 full MOX core model is based on the specification in the document, "Full MOX Model (Rev. 3.1)(Phase4)(ACTION3.11).doc". This document addresses the calculational methods employed in the benchmark analyses and benchmark results carried out by KAERI.

2. Calculational methods

All the calculation procedure and evaluation were performed by using the K-CORE System of KAERI. Based on the self-shielding f-factor approach, the microscopic cross sections for the benchmark model were generated. An 80-group neutron cross section library, KAFAX(KAERI FAst XS)/F22 [1] was prepared in the MATXS library format based on the JEF-2.2 nuclear data. This version contains infinite dilute cross sections for various temperatures and Bondarenko self-shielding f-factors. The composition-dependent, 9-group microscopic cross section sets for all reactor constituent materials were generated from KAFAX/F22 at the specified temperatures (1500 K and 2100 K for fuel isotopes including fission product and oxygen, 600 K and 900 K for structural and coolant isotopes) by utilizing the effective cross section generation module composed of TRANSX [2] and TWODANT [3] codes. The data processing in this module includes resonance and spatial self-shielding corrections, reactor and cell flux solutions and cross section group collapsing. Neutron spectra necessary for group collapsing were obtained from the P_3S_8 transport theory calculations for the

two dimensional, coarse meshed RZ model for the reference configuration with the TWODANT code. The TWODANT code employing discrete ordinates approximation was used for two-dimensional (RZ) model calculations. The 9-group structure has 1.2 and 1.5 lethargies for the first two energy groups, and a 1.0 lethargy for the remaining 7 energy groups, with the highest energy boundary of 20.0 MeV. Group structures for the 80- and 9-group cross section sets are compared in Appendix . The 9-group cross section set is used for all neutronics calculations.

The lumped Pu239 fission product cross sections was generated by collapsing into 9 groups from the cross section library for 172 fission product isotopes of Pu239, fission yields, and a typical neutron spectrum of fuel region of BN-600 full MOX core from TWODANT result as a weighting spectrum.

The neutron multiplication factor k_{eff} and basic neutronics parameters such as forward and adjoint neutron flux distribution, power distribution were calculated by using DIF3D [4] associated with the 9-group cross section set. The DIF3D code employs the coarse-mesh nodal diffusion approximation to the Hex-Z geometry model.

Various reactivity parameters such as fuel density coefficients and sodium density coefficients, were calculated by using the PERT-K code [5]. The PERT-K code solves the first order perturbation theory equations based on diffusion theory nodal expansion method using the forward and adjoint flux solutions obtained from DIF3D calculations.

The power distribution for fuel and non-fuelled regions is determined by the energy deposition of fission and capture reactions including the energy deposition of structure and coolant materials capture reactions. These energy deposition values implicitly assumed that the energy generated by fission and capture reactions is deposited at the site of the reaction. However, assuming all core power comes from the fission energy deposition, the powers for non-fuelled region is completely ingored and the core power is normalized for fuel regions only.

The effective delayed neutron fraction, β_{eff} and the prompt neutron life time were calculated by using the BETA-K code [6]. The BETA-K code can generates several kinetic parameters such as the effective delayed neutron fraction, prompt neutron lifetime, fission spectrum and fission yield data for each fissionable isotope, fuel compositions and the whole core, utilizing the DIF3D forward and adjoint flux solutions. For this calculation, the delayed neutron data such as yield numbers for 6 delayed neutron groups were prepared from the ENDF/B-VI file.

3. Benchmark results

Benchmark results for Phase-4 are shown below and also in the attached Microsoft Excel file, 'KAERI-Phase4-Results.xls'.

Parameters for the benchmark calculation in Phase 4 are as follows:

- Fuel and steel Doppler coefficients and their distributions;
- Fuel density coefficient and its distribution;
- Sodium density coefficient and its distribution;
- Power distribution for fuel and non-fuelled regions;
- Beta-effective and prompt neutron lifetime.

The definition of the above coefficients conforms to those in previous phases of CRP.

3.1 Eigenvalues and Whole Core Coefficients by Diffusion Theory Calculation

Table 1 Eigenvalues and Whole Core Coefficients

In table 1, the fuel and sodium density coefficients for whole core are calculated by homogeneous diffusion model with constant cross sections. Please note it is not by the first order perturbation theory. The cross sections for the state of changed density are not prepared additionaly. With the reference state cross sections, the densities only of all fuel materials and sodium are respectively changed 1% increasing each for fuel and sodium density coefficients of whole core.

3.2 Fuel Doppler Coefficients

Table 2 Fuel Doppler Coefficients

3.3 Steel Doppler Coefficients

Table 3 Steel Doppler Coefficients

3.4 Fuel Density Coefficients by the First Order Perturbation Theory

Table 4 Fuel Density Coefficients

3.5 Sodium Density Coefficients by the First Order Perturbation Theory

Table 5 Sodium Density Coefficients

3.6 Power Distribution for Fuel and Non-Fuelled Regions

Table 6-1 Power Distribution for Fuel and Non-Fuelled Regions

Table 6-2 Power Distribution for Fuel Regions only

3.7 Beta-effective and Prompt Neutron Lifetime

Table 7 Beta-effective and Prompt Neutron Lifetime

References

[1] J. D. Kim and C. S. Gil, "KAFAX-F22: Development and Benchmark of Multi-group Library for Fast Reactor Using JEF-2.2," KAERI/TR-842/97, KAERI (1997).

[2] R. E. MacFarlane, "TRANSX 2: A Code for Interfacing MATXS Cross-Section Libraries to Nuclear Transport Codes," LA-12312-MS, LANL (Dec. 1993).

[3] R. E. Alcouffe, et al., "User's Guide for TWODANT: A Code Package for Two-Dimensional, Diffusion-Accelerated, Neutron Transport," LA-10049-M, LANL.(Feb. 1990).

[4] K. L. Derstine, "DIF3D: A Code to Solve One-, Two-, and Three-Dimensional Finite-Difference Difference Diffusion Theory Problems," ANL-82-64, ANL (April 1984).

[5] T. K. Kim, et al., "Development of A Perturbation Code, PERT-K, for Hexagonal Core Geometry," KAERI/TR-1194/98, KAERI (1998).

[6] T. K. Kim, et al., "Development of An Effective Delayed Neutron Fraction Calculation Code, BETA-K," KAERI/TR-1120/98, KAERI (1998).

Appendix. Neutron Energy Group Structures for Cross Section Data

80 Groups				9 Groups	
Group No.	Upper E. Boundary (MeV)	Group No	Upper E. Boundary (MeV)	Group No	Upper E. Boundary (MeV)
1	2.0000+1**	41	1.5034-2	1	2.0000+1
2	1.6905+1	42	1.3268-2		
3	1.4918+1	43	1.1709-2	2	6.0653+0
4	1.3499+1	44	1.0333-2		
5	1.1912+1	45	9.1188-3	3	1.3534+1
6	1.0000+1	46	8.0473-3		
7	7.7880+0	47	7.1017-3	4	4.9787-1
8	6.0653+0	48	6.2673-3		
9	4.7237+0	49	5.5308-3	5	1.8316-1
10	3.6788+0	50	4.8810-3		
11	2.8650+0	51	4.3074-3	6	6.7379-2
12	2.2313+0	52	3.8013-3		
13	1.7377+0	53	3.3546-3	7	2.4788-2
14	1.3534+0	54	2.9604-3		
15	1.1943+0	55	2.6126-3	8	9.1188-3
16	1.0540+0	56	2.3056-3		
17	9.3014-1	57	2.0347-3	9	3.3546-3
18	8.2085-1	58	1.7956-3		
19	7.2440-1	59	1.5846-3		1.3888-10*
20	6.3928-1	60	1.3984-3		
21	5.6416-1	61	1.2341-3		
22	4.9787-1	62	1.0891-3		
23	4.3937-1	63	9.6112-4		
24	3.8774-1	64	7.4852-4		
25	3.0197-1	65	5.8295-4		
26	2.3518-1	66	4.5400-4		
27	1.8316-1	67	3.5358-4		
28	1.4264-1	68	2.7536-4		
29	1.1109-1	69	1.6702-4		
30	8.6517-2	70	1.0130-4		
31	6.7379-2	71	6.1442-5		
32	5.2475-2	72	3.7267-5		
33	4.0868-2	73	2.2603-5		
34	3.1828-2	74	1.3710-5		
35	2.8088-2	75	8.3153-6		
36	2.6058-2	76	5.0435-6		
37	2.4788-2	77	3.0590-6		
38	2.1875-2	78	1.1254-6		
39	1.9305-2	79	4.1399-7		
40	1.7036-2	80	1.5230-7		
			1.3888-10*		

* Lower Energy Boundary ** read as 2.0000×10^{11}

Table 1 Eigenvalues and Whole Core Coefficients

Case.	Item	Keff	Coefficients
1	Reference Value (Fuel: 1500K, Steel: 600K)	1.0097619	
2	Fuel Doppler (Fuel: 2100K, Steel: 600K)	1.0067262	-8.875E-03 (Δk/kk'/ΔlnK)
3	Steel Doppler (Fuel: 1500K, Steel: 900K)	1.0093455	-1.008E-03 (Δk/kk'/ΔlnK)
4	Fuel Density 1.01 Change (Fuel Density*1.01)	1.0135709	3.722E-01 (Δk/kk'/Δρ/ρ)
5	Sodium Density 1.01 Change (Sodium Density*1.01)	1.0097847	2.234E-03 (Δk/kk'/Δρ/ρ)

Table 2 Fuel Doppler Coefficients

[Unit: (Δk/kk')/(ln(T2/T1))]

	Height (cm)	dZ (cm)	LEZ 1	MEZ 2	HEZ 3	SHR 4	SCR 5	SSA1 6	SSA2,3 7	R. Refletor 8
Reflector	234.90	30.00								
Cones	204.90	4.50								
Upper Boron Shield	200.40	5.00								
	195.40	5.00								
	190.40	5.00								
(sum of UBS)										
Cones	185.40	4.50								
Sodium Plenum	180.90	8.00								
	172.90	8.00								
	164.90	7.00								
(sum of SP)										
Plugs	157.90	5.30								
Core	152.60	8.23	-1.516E-04	-4.428E-05	-1.650E-04					
	144.37	8.23	-1.983E-04	-5.714E-05	-1.986E-04					
	136.14	8.23	-2.721E-04	-7.886E-05	-2.646E-04					
	127.91	8.23	-3.539E-04	-1.027E-04	-3.340E-04					
	119.68	8.23	-4.373E-04	-1.279E-04	-3.889E-04					
Internal Breeding Zone	111.45	5.10	-3.804E-04	-9.394E-05	-2.574E-04					
Core	106.35	8.23	-5.558E-04	-1.633E-04	-4.157E-04					
	98.12	8.23	-5.520E-04	-1.580E-04	-3.852E-04					
	89.89	8.23	-4.863E-04	-1.359E-04	-3.240E-04					
	81.66	8.23	-3.839E-04	-1.049E-04	-2.461E-04					
	73.43	8.23	-2.684E-04	-7.181E-05	-1.672E-04					
(sum of Core)			-4.040E-03	-1.139E-03	-3.147E-03					
Axial Blanket 1	65.20	5.50	-1.420E-04	-3.882E-05	-8.907E-05					
Axial Blanket 2	59.70	9.70	-1.290E-04	-3.369E-05	-7.332E-05					
	50.00	10.00	-4.906E-05	-1.188E-05	-2.440E-05					
	40.00	10.00	-1.878E-05	-4.245E-06	-8.446E-06					
(sum of AB2)			-1.968E-04	-4.981E-05	-1.062E-04					
Reflector	30.00	30.00								
(sum)			-4.379E-03	-1.227E-03	-3.342E-03					
Total Sum			-8.948E-03							

Table 3 Steel Doppler Coefficients

[Unit: (Δk/kk')/(ln(T2/T1))]

	Height (cm)	dZ (cm)	LEZ 1	MEZ 2	HEZ 3	SHR 4	SCR 5	SSA1 6	SSA2,3 7	R. Refletor 8
Reflector	234.90	30.00	2.419E-11	-2.419E-11	-2.177E-10	0.000E+00	0.000E+00	-2.419E-11	-4.838E-11	3.386E-10
Cones	204.90	4.50	2.419E-11	0.000E+00	0.000E+00	4.838E-11	0.000E+00	0.000E+00	-1.088E-09	3.145E-10
Upper Boron Shield	200.40	5.00	1.209E-10	2.419E-11	9.675E-11	5.080E-10	1.451E-10	-1.669E-09	-5.225E-09	7.498E-10
	195.40	5.00	1.911E-09	6.047E-10	1.596E-09	2.999E-09	1.161E-09	-9.167E-09	-1.553E-08	1.330E-09
	190.40	5.00	1.538E-08	3.919E-09	3.120E-09	9.288E-09	6.192E-09	-4.932E-08	-3.943E-08	2.080E-09
(sum of UBS)			1.742E-08	4.547E-09	4.814E-09	1.280E-08	7.498E-09	-6.016E-08	-6.018E-08	4.160E-09
Cones	185.40	4.50	-3.312E-07	-1.263E-07	-6.254E-07	-1.500E-09	-3.145E-10	-1.734E-07	-7.230E-08	2.806E-09
Sodium Plenum	180.90	8.00	-6.095E-07	-2.238E-07	-1.051E-06	-5.191E-08	-3.011E-08	-8.517E-07	-2.775E-07	8.006E-09
	172.90	8.00	-1.237E-06	-4.330E-07	-1.960E-06	-1.074E-07	-6.845E-08	-1.694E-06	-5.748E-07	1.439E-08
	164.90	7.00	-1.783E-06	-5.939E-07	-2.573E-06	-1.430E-07	-9.782E-08	-2.344E-06	-8.601E-07	2.182E-08
(sum of SP)			-3.629E-06	-1.251E-06	-5.583E-06	-3.023E-07	-1.964E-07	-4.890E-06	-1.712E-06	4.422E-08
Plugs	157.90	5.30	-1.567E-05	-4.970E-06	-1.897E-05	-1.238E-07	-1.048E-07	-2.444E-06	-9.526E-07	2.542E-08
Core	152.60	8.23	-1.196E-05	-3.689E-06	-1.213E-05	-3.541E-07	-2.478E-07	-5.238E-06	-2.143E-06	6.170E-08
	144.37	8.23	-1.736E-05	-5.404E-06	-1.641E-05	-6.693E-07	-3.956E-07	-7.520E-06	-3.126E-06	9.576E-08
	136.14	8.23	-2.469E-05	-7.793E-06	-2.284E-05	-1.042E-06	-5.910E-07	-1.017E-05	-4.206E-06	1.327E-07
	127.91	8.23	-3.240E-05	-1.029E-05	-2.929E-05	-1.416E-06	-7.925E-07	-1.265E-05	-5.196E-06	1.654E-07
	119.68	8.23	-3.967E-05	-1.275E-05	-3.430E-05	-2.025E-06	-9.532E-07	-1.442E-05	-5.897E-06	1.877E-07
Internal Breeding Zone	111.45	5.10	-2.760E-05	-9.179E-06	-2.269E-05	-1.425E-06	-4.403E-07	-9.362E-06	-3.818E-06	1.212E-07
Core	106.35	8.23	-4.963E-05	-1.584E-05	-3.667E-05	-3.114E-06	-7.492E-07	-1.489E-05	-6.057E-06	1.924E-07
	98.12	8.23	-4.943E-05	-1.524E-05	-3.379E-05	-3.224E-06	-7.300E-07	-1.353E-05	-5.494E-06	1.748E-07
	89.89	8.23	-4.326E-05	-1.296E-05	-2.804E-05	-2.757E-06	-6.204E-07	-1.115E-05	-4.519E-06	1.450E-07
	81.66	8.23	-3.338E-05	-9.724E-06	-2.064E-05	-1.987E-06	-4.487E-07	-8.175E-06	-3.312E-06	1.091E-07
	73.43	8.23	-2.198E-05	-6.220E-06	-1.301E-05	-1.135E-06	-2.572E-07	-5.096E-06	-2.109E-06	7.397E-08
(sum of Core)			-3.514E-04	-1.091E-04	-2.698E-04	-1.915E-05	-6.226E-06	-1.122E-04	-4.588E-05	1.460E-06
Axial Blanket 1	65.20	5.50	-7.801E-06	-2.145E-06	-4.380E-06	-3.516E-07	-7.943E-08	-1.929E-06	-8.504E-07	3.287E-08
Axial Blanket 2	59.70	9.70	-5.956E-06	-1.558E-06	-3.065E-06	-2.249E-07	-5.002E-08	-1.593E-06	-7.660E-07	3.444E-08
	50.00	10.00	-2.109E-06	-5.103E-07	-9.667E-07	-5.738E-08	-1.226E-08	-5.313E-07	-2.767E-07	1.553E-08
	40.00	10.00	-7.425E-07	-1.667E-07	-3.105E-07	-2.107E-08	-4.668E-09	-1.540E-07	-8.360E-08	4.789E-09
(sum of AB2)			-8.808E-06	-2.235E-06	-4.342E-06	-3.033E-07	-6.695E-08	-2.279E-06	-1.126E-06	5.476E-08
Reflector	30.00	30.00	-3.928E-07	-8.212E-08	-1.714E-07	-3.253E-08	-1.192E-08	-2.269E-08	-1.422E-08	1.088E-09
(sum)			-3.880E-04	-1.199E-04	-3.039E-04	-2.025E-05	-6.678E-06	-1.240E-04	-5.066E-05	1.626E-06
Total Sum			-1.012E-03							

Table 4 Fuel Density Coefficients

[Unit: (Δk/kk')/(Δρ/ρ)]

	Height (cm)	dZ (cm)	LEZ 1	MEZ 2	HEZ 3	SHR 4	SCR 5	SSA1 6	SSA2,3 7	R. Refletor 8
Reflector	234.90	30.00								
Cones	204.90	4.50								
Upper Boron Shield	200.40	5.00								
	195.40	5.00								
	190.40	5.00								
(sum of UBS)										
Cones	185.40	4.50								
Sodium Plenum	180.90	8.00								
	172.90	8.00								
	164.90	7.00								
(sum of SP)										
Plugs	157.90	5.30								
Core	**152.60**	**8.23**	5.780E-03	2.235E-03	7.763E-03					
	144.37	8.23	8.502E-03	3.406E-03	1.237E-02					
	136.14	8.23	1.157E-02	4.725E-03	1.744E-02					
	127.91	8.23	1.442E-02	5.966E-03	2.209E-02					
	119.68	8.23	1.653E-02	6.908E-03	2.557E-02					
Internal Breeding Zone	111.45	5.10	-3.727E-03	4.527E-03	1.679E-02					
Core	106.35	8.23	1.825E-02	7.419E-03	2.721E-02					
	98.12	8.23	1.776E-02	7.033E-03	2.529E-02					
	89.89	8.23	1.582E-02	6.082E-03	2.136E-02					
	81.66	8.23	1.276E-02	4.752E-03	1.613E-02					
	73.43	8.23	9.462E-03	3.379E-03	1.081E-02					
(sum of Core)			1.271E-01	5.643E-02	2.028E-01					
Axial Blanket 1	65.20	5.50	-1.640E-03	-4.136E-04	-4.062E-04					
Axial Blanket 2	59.70	9.70	-1.807E-03	-4.411E-04	-6.678E-04					
	50.00	10.00	-6.218E-04	-1.389E-04	-2.462E-04					
	40.00	10.00	-1.583E-04	-3.047E-05	-6.190E-05					
(sum of AB2)			-2.587E-03	-6.104E-04	-9.759E-04					
Reflector	30.00	30.00								
(sum)			1.229E-01	5.541E-02	2.014E-01					
Total Sum			3.798E-01							

Table 5 Sodium Density Coefficients

[Unit: (Δk/kk')/(Δρ/ρ)]

	Height (cm)	dZ (cm)	LEZ 1	MEZ 2	HEZ 3	SHR 4	SCR 5	SSA1 6	SSA2,3 7	R. Refletor 8
Reflector	234.90	30.00	-4.923E-08	-1.557E-08	2.423E-07	-3.135E-09	-1.076E-09	1.661E-07	3.851E-07	7.851E-08
Cones	204.90	4.50	-1.167E-08	-1.191E-09	1.753E-07	1.107E-08	4.111E-09	8.676E-08	8.168E-08	6.703E-08
Upper Boron Shield	200.40	5.00	-5.662E-08	-1.575E-08	-3.863E-08	9.254E-08	4.228E-08	1.869E-07	2.185E-07	1.656E-07
	195.40	5.00	-4.337E-07	-1.286E-07	-3.285E-07	4.832E-07	2.716E-07	4.591E-07	5.800E-07	3.407E-07
	190.40	5.00	-9.413E-07	-1.342E-07	8.820E-07	1.402E-06	1.509E-06	1.312E-06	1.410E-06	6.469E-07
(sum of UBS)			-1.432E-06	-2.785E-07	5.148E-07	1.978E-06	1.823E-06	1.958E-06	2.209E-06	1.153E-06
Cones	185.40	4.50	1.849E-05	7.665E-06	3.919E-05	8.179E-07	5.544E-06	3.866E-06	2.400E-06	1.003E-06
Sodium Plenum	180.90	8.00	5.782E-05	2.889E-05	1.966E-04	-2.532E-06	3.902E-06	1.048E-05	8.940E-06	3.381E-06
	172.90	8.00	6.355E-05	4.054E-05	3.100E-04	-6.064E-06	3.225E-06	1.522E-05	1.755E-05	6.754E-06
	164.90	7.00	6.487E-05	4.990E-05	4.495E-04	-7.576E-06	1.416E-05	1.914E-05	2.722E-05	1.041E-05
(sum of SP)			1.862E-04	1.193E-04	9.561E-04	-1.617E-05	2.128E-05	4.483E-05	5.371E-05	2.054E-05
Plugs	157.90	5.30	-6.141E-06	1.073E-05	9.897E-05	-1.373E-05	3.718E-05	2.369E-05	3.364E-05	1.191E-05
Core	152.60	8.23	-4.732E-05	7.852E-06	2.933E-04	-4.560E-05	6.529E-05	9.512E-05	8.570E-05	2.787E-05
	144.37	8.23	-2.938E-04	-7.544E-05	3.534E-04	-1.134E-04	3.387E-05	1.761E-04	1.405E-04	4.195E-05
	136.14	8.23	-5.910E-04	-1.746E-04	3.938E-04	-1.881E-04	-1.307E-05	2.568E-04	1.992E-04	5.724E-05
	127.91	8.23	-8.761E-04	-2.664E-04	4.329E-04	-2.568E-04	-6.079E-05	3.273E-04	2.510E-04	7.102E-05
	119.68	8.23	-1.172E-03	-3.426E-04	4.745E-04	-3.000E-04	-1.001E-04	3.775E-04	2.872E-04	8.061E-05
Internal Breeding Zone	111.45	5.10	-9.380E-04	-2.426E-04	3.091E-04	-2.503E-04	-7.404E-05	2.473E-04	1.869E-04	5.215E-05
Core	106.35	8.23	-1.273E-03	-3.686E-04	5.362E-04	-4.051E-04	-1.228E-04	3.959E-04	2.975E-04	8.267E-05
	98.12	8.23	-1.107E-03	-3.154E-04	5.526E-04	-3.320E-04	-1.066E-04	3.636E-04	2.710E-04	7.491E-05
	89.89	8.23	-8.656E-04	-2.313E-04	5.404E-04	-1.785E-04	-5.779E-05	3.012E-04	2.229E-04	6.163E-05
	81.66	8.23	-5.364E-04	-1.262E-04	4.968E-04	3.336E-05	1.498E-05	2.179E-04	1.613E-04	4.542E-05
	73.43	8.23	-2.226E-04	-3.116E-05	4.005E-04	2.309E-04	8.461E-05	1.264E-04	9.832E-05	2.953E-05
(sum of Core)			-7.923E-03	-2.166E-03	4.783E-03	-1.805E-03	-3.364E-04	2.885E-03	2.202E-03	6.250E-04
Axial Blanket 1	65.20	5.50	-1.216E-04	-1.674E-05	9.039E-05	1.939E-04	7.036E-05	3.654E-05	3.708E-05	1.237E-05
Axial Blanket 2	59.70	9.70	-1.872E-04	-3.557E-05	-1.083E-05	2.239E-04	8.259E-05	2.015E-05	3.026E-05	1.188E-05
	50.00	10.00	-8.065E-05	-1.510E-05	-2.136E-05	9.362E-05	3.583E-05	3.494E-06	9.435E-06	4.723E-06
	40.00	10.00	-2.186E-05	-3.352E-06	-6.512E-06	3.123E-05	1.234E-05	5.561E-07	2.411E-06	1.534E-06
(sum of AB2)			-2.897E-04	-5.402E-05	-3.871E-05	3.488E-04	1.308E-04	2.420E-05	4.211E-05	1.814E-05
Reflector	30.00	30.00	1.134E-05	7.756E-06	1.708E-05	5.377E-06	1.850E-06	4.641E-06	8.285E-06	8.730E-07
(sum)			-8.126E-03	-2.092E-03	5.947E-03	-1.285E-03	-6.763E-05	3.025E-03	2.381E-03	6.911E-04
Total Sum			4.747E-04							

Table 6-1 Power Distribution for Fuel and Non-fuelled Regions

[Unit: watts]

	Height (cm)	dZ (cm)	LEZ 1	MEZ 2	HEZ 3	SHR 4	SCR 5	SSA1 6	SSA2,3 7	R. Refletor 8
Reflector	234.90	30.00	3.956E+03	1.538E+03	9.442E+03	4.398E+02	1.248E+02	5.173E+03	8.205E+03	1.010E+04
Cones	204.90	4.50	1.275E+03	4.511E+02	2.676E+03	2.603E+03	1.453E+03	5.351E+03	9.917E+03	3.622E+03
Upper Boron Shield	200.40	5.00	5.189E+04	1.713E+04	7.795E+04	5.021E+03	2.770E+03	8.943E+03	1.622E+04	5.450E+03
	195.40	5.00	1.501E+05	4.862E+04	1.809E+05	1.236E+04	7.938E+03	1.401E+04	2.308E+04	7.376E+03
	190.40	5.00	5.249E+05	1.708E+05	6.424E+05	3.030E+04	3.028E+04	2.260E+04	3.148E+04	9.669E+03
(sum of UBS)			7.270E+05	2.366E+05	9.013E+05	4.769E+04	4.099E+04	4.555E+04	7.078E+04	2.250E+04
Cones	185.40	4.50	4.198E+04	1.379E+04	5.401E+04	5.356E+04	5.894E+02	3.073E+04	3.634E+04	1.089E+04
Sodium Plenum	180.90	8.00	4.127E+04	1.369E+04	5.595E+04	1.429E+05	1.640E+03	7.636E+04	8.448E+04	2.493E+04
	172.90	8.00	5.086E+04	1.678E+04	6.829E+04	1.793E+05	2.096E+03	9.678E+04	1.089E+05	3.238E+04
	164.90	7.00	5.033E+04	1.646E+04	6.593E+04	1.783E+05	2.107E+03	9.615E+04	1.133E+05	3.456E+04
(sum of SP)			1.425E+05	4.692E+04	1.902E+05	5.005E+05	5.844E+03	2.693E+05	3.067E+05	9.186E+04
Plugs	157.90	5.30	2.547E+05	8.243E+04	3.067E+05	1.372E+05	1.720E+03	7.654E+04	9.632E+04	3.009E+04
Core	152.60	8.23	3.154E+07	1.137E+07	4.285E+07	2.401E+05	2.778E+03	1.236E+05	1.676E+05	5.354E+04
	144.37	8.23	3.958E+07	1.448E+07	5.291E+07	2.904E+05	3.105E+03	1.366E+05	1.906E+05	6.183E+04
	136.14	8.23	4.740E+07	1.747E+07	6.300E+07	3.457E+05	3.580E+03	1.535E+05	2.134E+05	6.956E+04
	127.91	8.23	5.397E+07	1.996E+07	7.122E+07	3.973E+05	4.057E+03	1.687E+05	2.329E+05	7.593E+04
	119.68	8.23	5.902E+07	2.190E+07	7.683E+07	4.665E+05	4.470E+03	1.789E+05	2.460E+05	8.013E+04
Internal Breeding Zone	111.45	5.10	1.796E+07	1.428E+07	4.909E+07	8.202E+03	2.407E+03	1.133E+05	1.554E+05	5.059E+04
Core	106.35	8.23	6.402E+07	2.344E+07	7.919E+07	1.432E+04	3.911E+03	1.817E+05	2.490E+05	8.104E+04
	98.12	8.23	6.346E+07	2.285E+07	7.604E+07	1.426E+04	3.803E+03	1.742E+05	2.390E+05	7.774E+04
	89.89	8.23	5.939E+07	2.106E+07	6.936E+07	1.338E+04	3.560E+03	1.605E+05	2.208E+05	7.178E+04
	81.66	8.23	5.220E+07	1.825E+07	5.960E+07	1.201E+04	3.209E+03	1.421E+05	1.964E+05	6.372E+04
	73.43	8.23	4.277E+07	1.470E+07	4.773E+07	1.046E+04	2.820E+03	1.220E+05	1.683E+05	5.432E+04
(sum of Core)			5.313E+08	1.998E+08	6.878E+08	1.813E+06	3.770E+04	1.655E+06	2.279E+06	7.402E+05
Axial Blanket 1	65.20	5.50	6.045E+06	1.821E+06	5.040E+06	6.147E+03	1.673E+03	7.045E+04	9.592E+04	3.078E+04
Axial Blanket 2	59.70	9.70	6.201E+06	1.817E+06	5.012E+06	8.955E+03	2.466E+03	1.013E+05	1.371E+05	4.370E+04
	50.00	10.00	3.840E+06	1.076E+06	2.921E+06	6.651E+03	1.860E+03	7.429E+04	1.014E+05	3.222E+04
	40.00	10.00	2.345E+06	6.320E+05	1.721E+06	4.658E+03	1.325E+03	4.914E+04	6.758E+04	2.211E+04
(sum of AB2)			1.239E+07	3.525E+06	9.654E+06	2.026E+04	5.651E+03	2.247E+05	3.061E+05	9.802E+04
Reflector	30.00	30.00	1.073E+05	3.007E+04	8.983E+04	1.125E+04	3.818E+03	2.343E+04	2.903E+04	3.274E+04
(sum)			5.510E+08	2.055E+08	7.041E+08	2.592E+06	9.956E+04	2.406E+06	3.239E+06	1.071E+06
Total Power			1.470E+09							

Table 6-2 Power Distribution for Fuel Regions (Fission Power only)

[Unit: watts]

	Height (cm)	dZ (cm)	LEZ 1	MEZ 2	HEZ 3	SHR 4	SCR 5	SSA1 6	SSA2,3 7	R. Refletor 8
Reflector	234.90	30.00								
Cones	204.90	4.50								
Upper Boron Shield	200.40	5.00								
	195.40	5.00								
	190.40	5.00								
(sum of UBS)										
Cones	185.40	4.50								
Sodium Plenum	180.90	8.00								
	172.90	8.00								
	164.90	7.00								
(sum of SP)										
Plugs	157.90	5.30								
Core	152.60	8.23	3.181E+07	1.147E+07	4.322E+07					
	144.37	8.23	3.992E+07	1.461E+07	5.337E+07					
	136.14	8.23	4.781E+07	1.762E+07	6.354E+07					
	127.91	8.23	5.443E+07	2.014E+07	7.184E+07					
	119.68	8.23	5.953E+07	2.209E+07	7.750E+07					
Internal Breeding Zone	111.45	5.10	1.812E+07	1.440E+07	4.951E+07					
Core	106.35	8.23	6.458E+07	2.365E+07	7.988E+07					
	98.12	8.23	6.401E+07	2.305E+07	7.670E+07					
	89.89	8.23	5.990E+07	2.125E+07	6.997E+07					
	81.66	8.23	5.266E+07	1.840E+07	6.011E+07					
	73.43	8.23	4.314E+07	1.483E+07	4.815E+07					
(sum of Core)			5.359E+08	2.015E+08	6.938E+08					
Axial Blanket 1	65.20	5.50	6.097E+06	1.836E+06	5.084E+06					
Axial Blanket 2	59.70	9.70	6.255E+06	1.833E+06	5.056E+06					
	50.00	10.00	3.873E+06	1.085E+06	2.947E+06					
	40.00	10.00	2.365E+06	6.375E+05	1.736E+06					
(sum of AB2)			1.249E+07	3.556E+06	9.738E+06					
Reflector	30.00	30.00								
(sum)			5.545E+08	2.069E+08	7.086E+08					
Total Power			1.470E+09							

Table 7 Beta-effective and Prompt Neutron Lifetime

Item	value
Effective Delayed Neutron Fraction	3.4196E-03
Neutron Lifetime (sec)	4.2570E-07

Fraction of Delayed Neutron Groups

delayed neutron group	1	2	3	4	5	6
B_k/B_eff (%)	2.485	17.614	15.306	35.818	21.054	7.724

Mean Velocity of Neutron Energy Groups

neutron energy group	1	2	3	4	5	6	7	8	9
mean velocity(m/sec)	3.800E+07	2.092E+07	1.185E+07	7.432E+06	4.579E+06	2.796E+06	1.726E+06	1.060E+06	4.460E+05

KAERI Results on BN-600 Fully MOX Fueled Core Benchmark Analyses (Phase 4)

The 4th RCM on "Updated Codes and Methods to Reduce the Calculational Uncertainties of the LMFR Reactivity Effects"

Obninsk, Russia

2003. 5

Ki Bog Lee

Korea Atomic Energy Research Institute

Contents

- Introduction
- Computing System and Methods
- Benchmark Calculations
- Benchmark Results
  - k_{eff} and Whole Core Coefficients by Direct Calculation
  - Fuel Doppler Coefficients
  - Steel Doppler Coefficients
  - Fuel Density Coefficients
  - Sodium Density Coefficients
  - Power Distribution
  - Beta-effective and Prompt Neutron Lifetime

Introduction

- **Purpose**
  - To report the results of KAERI's calculation on the BN-600 fully MOX fueled core benchmark analyses (Phase-4)
- **Phase-4 Model**
  - A 60° sector of homogeneous full MOX core model
    - The same configuration as that of the hybrid core of BN-600
    - A sodium plenum to reduce the sodium void effect
    - Internal Breeding Zone is inserted in the core middle-plane
- **Action Item 3.12**
  - KAERI performs the homogeneous diffusion calculation only.

Computing System and Methods(I)

- **Cross Section Library KAFAX**
  - Based on the nuclear data file : JEF-2.2, ENDF-B/VI
  - Prepared in MATXS format with multi-groups (neutron: 80 G, gamma 24 G)
- **Effective Cross Section(XS) Generation**
  - Cell XS calculation: infinite dilute XS
    - Resonance/spatial self-shielding corrections : Bondarenko f-factor method
    - 1500/2100 K for fuel isotopes including FP and oxygen
    - 600/900 K for structural and Na isotopes
  - Group collapsing from 80 G to 9 G
    - Weighting spectra(RZFLUX) generation: TWODANT(P_3S_8)

Computing System and Methods(II)

Neutron Energy Group Structures for Cross Section Data

80 Groups				9 Groups	
Group No	Upper E Boundary (MeV)	Group No	Upper E Boundary (MeV)	Group No	Upper E Boundary (MeV)
1	2.0000+1**	41	1.5034-2	1	2.0000+1
2	1.6905+1	42	1.3268-2		
3	1.4918+1	43	1.1709-2	2	6.0653+0
4	1.3499+1	44	1.0333-2		
5	1.1912+1	45	9.1188-3	3	1.3534+1
6	1.0000+1	46	8.0473-3		
7	7.7880+0	47	7.1017-3	4	4.9787-1
8	6.0653+0	48	6.2673-3		
9	4.7237+0	49	5.5304-3	5	1.8316-1
10	3.6788+0	50	4.8810-3		
11	2.8650+0	51	4.3074-3	6	6.7379-2
12	2.2313+0	52	3.8013-3		
13	1.7377+0	53	3.3546-3	7	2.4788-2
14	1.3534+0	54	2.9604-3		
15	1.1943+0	55	2.6125-3	8	9.1188-3
16	1.0540+0	56	2.3054-3		
17	9.3014-1	57	2.0347-3	9	3.3546-3
18	8.2085-1	58	1.7956-3		
19	7.2440-1	59	1.5846-3		1.3888-10*
20	6.3928-1	60	1.3984-3		
21	5.8416-1	61	1.2341-3		
22	4.9787-1	62	1.0891-3		
23	4.3937-1	63	9.8112-4		
24	3.8774-1	64	7.4852-4		
25	3.0197-1	65	5.8295-4		
26	2.3518-1	66	4.5400-4		
27	1.8316-1	67	3.5358-4		
28	1.4264-1	68	2.7536-4		
29	1.1109-1	69	1.6702-4		
30	8.6517-2	70	1.0130-4		
31	6.7379-2	71	6.1442-5		
32	5.2475-2	72	3.7267-5		
33	4.0868-2	73	2.2603-5		
34	3.1828-2	74	1.3710-5		
35	2.8088-2	75	8.3153-6		
36	2.6058-2	76	5.0435-6		
37	2.4788-2	77	3.0590-6		
38	2.1875-2	78	1.1254-6		
39	1.9305-2	79	4.1399-		
40	1.7036-2	80	1.5230-		
			1.3884-		

* Lower Energy Boundary

** read as 2.0000 x 10^1

Computing System and Methods(III)

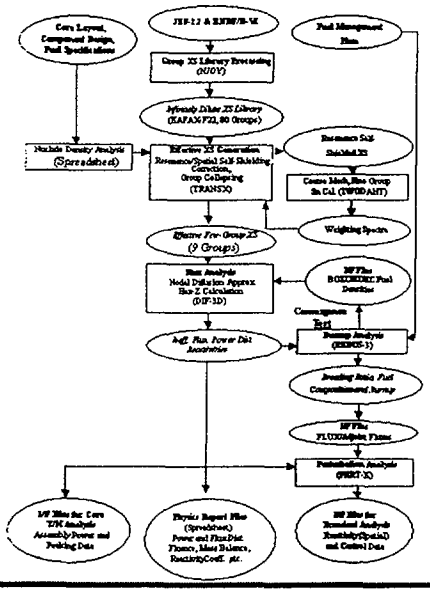
- The lumped Pu239 fission product XS was generated by collapsing into 9G from the 80G XS library for 172 fission product isotopes of Pu239, fission yields and a typical neutron spectrum of BN-600 full MOX core from TWODANT result as a weighting spectrum
  - It is proposed to use Pu239 FP for all compositions.
  - The effect by using the different isotope FP is negligible.
- The spatial dependent power distribution assuming the local deposition at the site of reaction, is determined with only an energy of 200 Mev/fission and no gamma energy by capture reactions
- And normalized with the total power of 1470 MW.

Computing System and Methods(IV)

- **Core Physics Parameter Calculation**
  - **For k_{eff}, neutron flux and power distribution**
    - DIF3D : Hex-Z model, coarse-mesh nodal diffusion approximation
  - **For fuel and steel Doppler reactivity coefficients**
    - DIF3D
  - **For fuel and sodium density reactivity coefficients**
    - PERT-K : First order perturbation theory solver
  - **For beta-effective and prompt neutron lifetime**
    - BETA-K : Kinetics parameter calculation code utilizing the DIF3D forward and adjoint flux solutions

Computing System and Methods(V)

K-CORE System of KAERI



Benchmark Calculations

- **Parameters for the benchmark calculations in Phase-4 are as follows:**
  - k_{eff} and Whole Core Coefficients by Direct Calculation
  - Fuel Doppler Coefficients
    - Increasing the fuel temperature to 2100 K from 1500 K
  - Steel Doppler Coefficients
    - Increasing the steel temperature to 900 K from 600 K
  - Fuel Density Coefficients
    - Increasing the fuel isotopes number density by 1%
  - Sodium Density Coefficients
    - Increasing the sodium number density by 1%
  - Power Distribution
  - Beta-effective and Prompt Neutron Lifetime

Benchmark Results

- k_{eff} and Whole Core Coefficients
  - Table 1
- Fuel Doppler Coefficients
  - Table 2
- Steel Doppler Coefficients
  - Table 3
- Fuel Density Coefficients
  - Table 4
- Sodium Density Coefficients
  - Table 5
- Power Distribution
  - Table 6-1 for Fuel and Non-Fueled Regions
  - Table 6-2 for Fuel Regions only
- Beta-effective and Prompt Neutron Lifetime
  - Table 7

Benchmark Results : Table 1

- k_{eff} and Whole Core Coefficients
  - **Direct calculation for a whole core is performed without using the first order perturbation theory. The direct calculation means that the reactivity coefficient is computed with the constant XS corresponding to the whole core conditions.**
  - **Vacuum boundary conditions are used.**
    - If the flux zero boundary conditions are used, then k_{eff} shows lower values by about 170 pcm but the reactivity coefficients are not changed so much.
    - refer to the Appendix Slide Page 20

Table 1

Case.	Item	Keff	Coefficients	unit
1	Reference Value (Fuel: 1500K, Steel: 600K)	1.009762		
2	Fuel Doppler (Fuel: 2100K, Steel: 600K)	1.006726	- 3.875E- 03	(Δk/kk'/ΔlnK)
3	Steel Doppler (Fuel: 1500K, Steel: 900K)	1.009346	- 1.008E- 03	(Δk/kk'/ΔlnK)
4	Fuel Density 1.01 Change (Fuel Density* 1.01)	1.013571	3.722E- 01	(Δk/kk'/Δρ/ρ)
5	Sodium Density 1.01 Change (Sodium Density* 1.01)	1.009785	2.234E- 03	(Δk/kk'/Δρ/ρ)

Benchmark Results : Table 2

Table 2 Fuel Doppler Coefficients

[Unit: (Δk/kk')/(ln(T2/T1))]

	Height (cm)	dZ (cm)	LEZ 1	MEZ 2	HEZ 3	SHR 4	SCR 5	SSA1 6	SSA2,3 7	R Reflector 8
Reflector	234.90	30.00								
Cones	204.90	4.50								
Upper Boron Shield	200.40	5.00								
	195.40	5.00								
	190.40	5.00								
(sum of UBS)										
Cones	185.40	4.50								
Sodium Plenum	180.90	8.00								
	172.90	8.00								
	164.90	7.00								
(sum of SP)										
Plugs	157.90	5.30								
Core	152.60	8.23	-1.516E-04	-4.428E-05	-1.650E-04					
	144.37	8.23	-1.983E-04	-5.714E-05	-1.966E-04					
	136.14	8.23	-2.721E-04	-7.886E-05	-2.646E-04					
	127.91	8.23	-3.539E-04	-1.027E-04	-3.340E-04					
	119.68	8.23	-4.373E-04	-1.279E-04	-3.889E-04					
Internal Breeding Zone	111.45	5.10	-3.804E-04	-9.394E-05	-2.574E-04					
Core	106.35	8.23	-5.558E-04	-1.633E-04	-4.157E-04					
	98.12	8.23	-5.520E-04	-1.580E-04	-3.852E-04					
	89.89	8.23	-4.863E-04	-1.359E-04	-3.240E-04					
	81.66	8.23	-3.839E-04	-1.049E-04	-2.461E-04					
	73.43	8.23	-2.684E-04	-7.181E-05	-1.672E-04					
(sum of Core)			-4.040E-03	-1.139E-03	-3.147E-03					
Axial Blanket 1	65.20	9.50	-1.420E-04	-3.882E-05	-8.907E-05					
Axial Blanket 2	59.70	9.70	-1.290E-04	-3.369E-05	-7.332E-05					
	50.00	10.00	-4.906E-05	-1.188E-05	-2.440E-05					
	40.00	10.00	-1.878E-05	-4.245E-06	-8.446E-06					
(sum of AB2)			-1.968E-04	-4.981E-05	-1.062E-04					
Reflector	30.00	30.00								
(sum)			-4.376E-03	-1.227E-03	-3.342E-03					
Total Sum			-8.948E-05							

Benchmark Results : Table 3

Table 3 Steel Doppler Coefficients

[Unit: (Δk/kk')/(ln(T2/T1))]

	Height (cm)	dZ (cm)	LEZ 1	MEZ 2	HEZ 3	SFR 4	SCR 5	SSA1 6	SSA2,3 7	R. Reflector 8
Reflector	234.90	30.00	2.419E-11	-2.419E-11	-2.177E-10	0.000E+00	0.000E+00	-2.419E-11	-4.838E-11	3.386E-10
Cones	204.90	4.50	2.419E-11	0.000E+00	0.000E+00	-4.838E-11	0.000E+00	0.000E+00	-1.088E-09	3.145E-10
Upper Boron Shield	200.40	5.00	1.209E-10	2.419E-11	9.675E-11	5.080E-10	1.451E-10	-1.669E-09	-5.225E-09	7.498E-10
	195.40	5.00	1.911E-09	6.047E-10	1.596E-09	2.999E-09	1.161E-09	-9.167E-09	-1.553E-08	1.330E-09
	190.40	5.00	1.538E-08	3.919E-09	3.120E-09	9.255E-09	6.192E-09	-4.932E-08	-3.943E-08	2.080E-09
(sum of UBS)			1.742E-08	4.547E-09	4.814E-09	1.286E-08	7.498E-09	-6.016E-08	-6.018E-08	4.160E-09
Cones	185.40	4.50	-3.312E-07	-1.263E-07	-6.254E-07	-1.530E-09	-3.145E-10	-1.734E-07	-7.230E-08	2.806E-09
Sodium Plenum	180.90	8.00	-6.095E-07	-2.238E-07	-1.051E-06	-5.195E-08	-3.511E-08	-8.517E-07	-2.775E-07	8.006E-09
	172.90	8.00	-1.237E-06	-4.330E-07	-1.960E-06	-1.074E-07	-6.545E-08	-1.694E-06	-5.748E-07	1.439E-08
	164.90	7.00	-1.783E-06	-5.939E-07	-2.573E-06	-1.430E-07	-7.752E-08	-2.344E-06	-8.601E-07	2.182E-08
(sum of SP)			-3.629E-06	-1.251E-06	-5.583E-06	-3.023E-07	-1.964E-07	-4.890E-06	-1.712E-06	4.422E-08
Plugs	157.90	5.30	-1.567E-05	-4.970E-06	-1.897E-05	-1.238E-07	-1.048E-07	-2.444E-06	-9.526E-07	2.542E-08
Core	152.60	8.23	-1.196E-05	-3.689E-06	-1.213E-05	-3.541E-07	-2.478E-07	-5.238E-06	-2.143E-06	6.170E-08
	144.37	8.23	-1.736E-05	-5.404E-06	-1.641E-05	-6.695E-07	-3.956E-07	-7.520E-06	-3.126E-06	9.576E-08
	136.14	8.23	-2.469E-05	-7.793E-06	-2.284E-05	-1.045E-06	-5.910E-07	-1.017E-05	-4.206E-06	1.327E-07
	127.91	8.23	-3.240E-05	-1.029E-05	-2.929E-05	-1.416E-06	-7.925E-07	-1.265E-05	-5.196E-06	1.654E-07
	119.68	8.23	-3.967E-05	-1.275E-05	-3.430E-05	-2.025E-06	-9.532E-07	-1.442E-05	-5.897E-06	1.877E-07
Internal Breeding Zone	111.45	5.10	-2.760E-05	-9.179E-06	-2.269E-05	-1.425E-06	-4.403E-07	-9.362E-06	-3.818E-06	1.212E-07
Core	106.35	8.23	-4.963E-05	-1.584E-05	-3.667E-05	-3.114E-06	-7.492E-07	-1.489E-05	-6.057E-06	1.924E-07
	98.12	8.23	-4.943E-05	-1.524E-05	-3.579E-05	-3.227E-06	-7.300E-07	-1.353E-05	-5.494E-06	1.748E-07
	89.89	8.23	-4.326E-05	-1.296E-05	-2.804E-05	-2.755E-06	-6.204E-07	-1.115E-05	-4.519E-06	1.450E-07
	81.66	8.23	-3.338E-05	-9.724E-06	-2.064E-05	-1.996E-06	-4.487E-07	-8.175E-06	-3.312E-06	1.091E-07
	73.43	8.23	-2.198E-05	-6.220E-06	-1.301E-05	-1.135E-06	-2.572E-07	-5.096E-06	-2.109E-06	7.397E-08
(sum of Core)			-3.514E-04	-1.091E-04	-2.698E-04	-1.915E-05	-6.226E-06	-1.122E-04	-4.588E-05	1.460E-06
Axial Blanket 1	65.20	5.50	-7.801E-06	-2.145E-06	-4.380E-06	-3.515E-07	-7.543E-08	-1.929E-06	-8.504E-07	3.287E-08
Axial Blanket 2	59.70	9.70	-5.956E-06	-1.558E-06	-3.065E-06	-2.249E-07	-5.302E-08	-1.593E-06	-7.660E-07	3.444E-08
	50.00	10.00	-2.109E-06	-5.103E-07	-9.667E-07	-5.735E-08	-1.226E-08	-5.313E-07	-2.767E-07	1.553E-08
	40.00	10.00	-7.425E-07	-1.667E-07	-3.105E-07	-2.107E-08	-4.668E-09	-1.540E-07	-8.360E-08	4.789E-09
(sum of AB2)			-8.808E-06	-2.235E-06	-4.342E-06	-3.033E-07	-6.695E-08	-2.279E-06	-1.126E-06	5.476E-08
Reflector	30.00	30.00	-3.928E-07	-8.212E-08	-1.714E-07	-3.255E-08	-1.192E-08	-2.269E-08	-1.422E-08	1.088E-09
(sum)			-3.880E-04	-1.199E-04	-3.039E-04	-2.025E-05	-6.678E-06	-1.240E-04	-5.066E-05	1.626E-06
Total Sum						-1.012E-05				

Benchmark Results : Table 4

Table 4 Fuel Density Coefficients

[Unit: (Δk/kk')/(Δρ/ρ)]

	Height (cm)	dZ (cm)	LEZ 1	MEZ 2	HEZ 3	SFR 4	SCR 5	SSA1 6	SSA2,3 7	R. Reflector 8
Reflector	234.90	30.00								
Cones	204.90	4.50								
Upper Boron Shield	200.40	5.00								
	195.40	5.00								
	190.40	5.00								
(sum of UBS)										
Cones	185.40	4.50								
Sodium Plenum	180.90	8.00								
	172.90	8.00								
	164.90	7.00								
(sum of SP)										
Plugs	157.90	5.30								
Core	152.60	8.23	5.780E-03	2.235E-03	7.761E-03					
	144.37	8.23	8.502E-03	3.405E-03	1.237E-02					
	136.14	8.23	1.157E-02	4.725E-03	1.744E-02					
	127.91	8.23	1.442E-02	5.965E-03	2.209E-02					
	119.68	8.23	1.653E-02	6.908E-03	2.557E-02					
Internal Breeding Zone	111.45	5.10	3.727E-03	4.527E-03	1.679E-02					
Core	106.35	8.23	1.825E-02	7.419E-03	2.721E-02					
	98.12	8.23	1.776E-02	7.033E-03	2.529E-02					
	89.89	8.23	1.582E-02	6.082E-03	2.136E-02					
	81.66	8.23	1.276E-02	4.752E-03	1.613E-02					
	73.43	8.23	9.462E-03	3.379E-03	1.081E-02					
(sum of Core)			1.271E-01	5.641E-02	2.028E-01					
Axial Blanket 1	65.20	5.50	-1.640E-03	-4.136E-04	-4.062E-04					
Axial Blanket 2	59.70	9.70	-1.807E-03	-4.411E-04	-6.678E-04					
	50.00	10.00	-6.218E-04	-1.389E-04	-2.462E-04					
	40.00	10.00	-1.583E-04	-3.047E-05	-6.190E-05					
(sum of AB2)			-4.587E-03	-1.034E-03	-1.759E-03					
Reflector	30.00	30.00								
(sum)			1.229E-01	5.541E-02	2.014E-01					
Total Sum						3.796E-01				

Benchmark Results : Table 5

Table 5 Sodium Density Coefficients

[Unit: (Δk/kk'Y.Δρ'(ρ))

	Height (cm)	dZ (cm)	LEZ 1	MEZ 2	HEZ 3	SHR 4	SCR 5	SSA1 6	SSA2,3 7	R. Reflector 8
Reflector	254.90	30.00	-4.923E-08	-1.557E-08	2.423E-07	-3.135E-09	-1.076E-09	1.661E-07	3.551E-07	7.351E-08
Cones	204.90	4.50	-1.167E-08	-1.191E-09	1.753E-07	1.107E-08	4.111E-09	8.678E-08	8.168E-08	6.703E-08
Upper Boron Shield	200.40	5.00	-5.662E-08	-1.575E-08	5.883E-08	9.254E-08	4.228E-08	1.889E-07	2.135E-07	1.658E-07
	195.40	5.00	-4.337E-07	-1.286E-07	-3.285E-07	4.832E-07	2.716E-07	4.591E-07	5.900E-07	3.407E-07
	190.40	5.00	-9.413E-07	-1.342E-07	8.820E-07	1.402E-06	1.509E-06	1.312E-06	1.140E-06	6.469E-07
(sum of UBS)			-1.432E-06	-2.785E-07	5.148E-07	1.978E-06	1.823E-06	1.958E-06	2.209E-06	1.153E-06
Cones	185.40	4.50	1.849E-05	7.665E-06	3.919E-05	8.179E-07	5.544E-06	3.866E-06	2.430E-06	1.003E-06
Sodium Plenum	180.90	9.30	5.782E-05	2.889E-05	1.966E-04	-2.532E-06	3.902E-06	1.048E-05	8.940E-06	3.381E-06
	171.60	9.30	6.355E-05	4.054E-05	3.100E-04	-6.064E-06	3.225E-06	1.522E-05	1.785E-05	6.754E-06
	162.30	9.30	6.487E-05	4.990E-05	4.495E-04	-7.576E-06	1.416E-05	1.914E-05	2.772E-05	1.041E-05
(sum of SP)			1.862E-04	1.193E-04	9.561E-04	-1.617E-05	2.128E-05	4.483E-05	5.371E-05	2.054E-05
Plugs	157.30	5.30	-6.141E-06	1.073E-05	9.897E-05	-1.375E-05	3.718E-05	2.369E-05	3.364E-05	1.191E-05
Core	152.60	8.23	-4.732E-05	7.852E-06	2.933E-04	-4.560E-05	6.529E-05	9.512E-05	8.570E-05	2.787E-05
	144.37	8.23	-2.938E-04	-7.544E-05	3.534E-04	-1.134E-04	3.387E-05	1.761E-04	1.405E-04	4.195E-05
	136.14	8.23	-5.910E-04	-1.746E-04	3.938E-04	-1.881E-04	-1.307E-05	2.568E-04	1.992E-04	5.724E-05
	127.91	8.23	-8.761E-04	-2.664E-04	4.329E-04	-2.568E-04	-6.079E-05	3.273E-04	2.539E-04	7.102E-05
	119.68	8.23	-1.172E-03	-3.426E-04	4.745E-04	-3.000E-04	-1.001E-04	3.775E-04	2.872E-04	8.061E-05
Internal Breeding Zone	111.45	5.10	-9.380E-04	-2.126E-04	3.091E-04	-2.301E-04	-7.404E-05	2.473E-04	1.969E-04	5.215E-05
Core	106.35	8.23	-1.273E-03	-3.686E-04	5.362E-04	-4.051E-04	-1.228E-04	3.959E-04	2.975E-04	8.267E-05
	98.12	8.23	-1.107E-03	-3.154E-04	5.526E-04	-3.320E-04	-1.066E-04	3.636E-04	2.770E-04	7.491E-05
	89.89	8.23	-8.656E-04	-2.312E-04	5.404E-04	-1.785E-04	-5.779E-05	3.012E-04	2.279E-04	6.163E-05
	81.66	8.23	-5.364E-04	-1.262E-04	4.968E-04	-3.336E-05	1.498E-05	2.179E-04	1.613E-04	4.542E-05
	73.43	8.23	-2.226E-04	-3.116E-05	4.005E-04	2.309E-04	8.461E-05	1.264E-04	9.852E-05	2.953E-05
(sum of Core)			-7.973E-03	-2.166E-03	4.783E-03	1.805E-03	3.364E-04	2.858E-03	2.292E-03	6.250E-04
Axial Blanket 1	65.20	5.50	-1.216E-04	-1.674E-05	9.039E-05	1.939E-04	7.096E-05	3.654E-05	3.795E-05	1.237E-05
Axial Blanket 2	59.70	9.70	-1.872E-04	-3.557E-05	1.083E-04	2.239E-04	8.259E-05	2.015E-05	3.625E-05	1.188E-05
	50.00	10.00	-8.065E-05	-1.510E-05	2.136E-05	9.362E-05	3.583E-05	3.494E-06	9.435E-06	4.723E-06
	40.00	10.00	-2.186E-05	-3.352E-06	-6.512E-06	3.123E-05	1.234E-05	5.561E-07	2.411E-06	1.534E-06
(sum of ABZ)			-2.897E-04	-5.402E-05	3.871E-05	3.488E-04	1.300E-04	2.420E-04	4.211E-05	1.814E-05
Reflector	30.00	30.00	1.134E-05	7.756E-06	1.708E-06	5.377E-06	1.850E-06	4.641E-06	8.285E-06	8.730E-07
(sum)			-8.126E-03	-2.092E-03	5.947E-03	-1.285E-03	-6.763E-05	3.025E-03	2.361E-03	6.911E-04
Total Sum						4.747E-04				

Benchmark Results : Table 6-1

Table 6-1 Power Distribution for Fuel and Non-fuelled Regions

[Unit: watts]

	Height (cm)	dZ (cm)	LEZ 1	MEZ 2	HEZ 3	SHR 4	SCR 5	SSA1 6	SSA2,3 7	R. Reflector 8
Reflector	254.90	30.00	3.956E+03	1.538E+03	9.442E+03	4.396E+02	1.248E+02	5.173E+03	8.365E+03	1.610E+04
Cones	204.90	4.50	1.275E+03	4.511E+02	2.676E+03	2.603E+03	1.453E+03	5.351E+03	9.917E+03	3.622E+03
Upper Boron Shield	200.40	5.00	5.189E+04	1.713E+04	7.795E+04	5.021E+03	2.770E+03	8.941E+03	1.622E+04	5.450E+03
	195.40	5.00	1.501E+05	4.862E+04	1.809E+05	1.236E+04	7.930E+03	1.401E+04	2.396E+04	7.276E+03
	190.40	5.00	5.249E+05	1.708E+05	6.424E+05	3.030E+04	3.028E+04	2.260E+04	3.168E+04	9.669E+03
(sum of UBS)			7.270E+05	2.366E+05	9.013E+05	4.769E+04	4.099E+04	4.555E+04	7.078E+04	2.250E+04
Cones	185.40	4.50	4.198E+04	1.379E+04	5.401E+04	5.356E+03	5.894E+02	3.073E+04	3.634E+04	1.089E+04
Sodium Plenum	180.90	9.30	4.127E+04	1.369E+04	5.595E+04	1.429E+05	1.640E+03	7.636E+04	8.448E+04	2.493E+04
	171.60	9.30	5.086E+04	1.678E+04	6.829E+04	1.793E+05	2.096E+03	9.678E+04	1.089E+05	3.238E+04
	162.30	9.30	5.033E+04	1.646E+04	6.593E+04	1.783E+05	2.107E+03	9.615E+04	1.073E+05	3.456E+04
(sum of SP)			1.425E+05	4.692E+04	1.902E+05	5.003E+05	5.844E+03	2.693E+05	3.067E+05	9.186E+04
Plugs	157.30	5.30	2.547E+03	8.243E+04	3.067E+05	1.372E+05	1.720E+03	7.654E+04	9.622E+04	3.009E+04
Core	152.60	8.23	3.154E+07	1.137E+07	4.285E+07	2.401E+05	2.778E+03	1.236E+05	1.676E+05	5.354E+04
	144.37	8.23	3.958E+07	1.448E+07	5.291E+07	2.904E+05	3.105E+03	1.366E+05	1.906E+05	6.183E+04
	136.14	8.23	4.740E+07	1.747E+07	6.300E+07	3.457E+05	3.580E+03	1.535E+05	2.134E+05	6.956E+04
	127.91	8.23	5.397E+07	1.996E+07	7.122E+07	3.973E+05	4.057E+03	1.687E+05	2.329E+05	7.593E+04
	119.68	8.23	5.902E+07	2.190E+07	7.683E+07	4.665E+05	4.470E+03	1.789E+05	2.469E+05	8.013E+04
Internal Breeding Zone	111.45	5.10	1.796E+07	1.428E+07	4.909E+07	8.202E+03	2.407E+03	1.133E+05	1.554E+05	5.059E+04
Core	106.35	8.23	6.402E+07	2.344E+07	7.919E+07	1.432E+04	3.911E+03	1.817E+05	2.490E+05	8.104E+04
	98.12	8.23	6.346E+07	2.285E+07	7.604E+07	1.426E+04	3.803E+03	1.742E+05	2.390E+05	7.774E+04
	89.89	8.23	5.939E+07	2.106E+07	6.936E+07	1.338E+04	3.560E+03	1.605E+05	2.206E+05	7.178E+04
	81.66	8.23	5.220E+07	1.825E+07	5.960E+07	1.201E+04	3.209E+03	1.421E+05	1.964E+05	6.372E+04
	73.43	8.23	4.277E+07	1.470E+07	4.773E+07	1.046E+04	2.820E+03	1.220E+05	1.693E+05	5.432E+04
(sum of Core)			3.313E+08	1.998E+08	6.878E+08	1.813E+08	3.770E+04	1.655E+06	2.279E+06	7.402E+05
Axial Blanket 1	65.20	5.50	6.045E+06	1.821E+06	5.040E+06	6.147E+05	1.673E+03	7.045E+04	9.592E+04	3.078E+04
Axial Blanket 2	59.70	9.70	6.201E+06	1.817E+06	5.012E+06	8.955E+05	2.466E+03	1.013E+05	1.371E+05	4.370E+04
	50.00	10.00	3.840E+06	1.076E+06	2.921E+06	6.651E+05	1.860E+03	7.429E+04	1.014E+05	3.222E+04
	40.00	10.00	2.345E+06	6.320E+05	1.721E+06	4.658E+05	1.325E+03	4.914E+04	6.758E+04	2.211E+04
(sum of ABZ)			1.239E+07	3.525E+06	9.654E+06	2.026E+06	5.651E+03	2.247E+05	3.061E+05	9.802E+04
Reflector	30.00	30.00	1.073E+05	3.007E+04	8.983E+04	1.125E+04	3.818E+03	2.343E+04	2.963E+04	3.274E+04
(sum)			5.510E+08	2.055E+08	7.041E+08	2.592E+06	9.956E+04	2.406E+06	3.239E+06	1.071E+06
Total Power						1.470E+09				

Benchmark Results : Table 6-2

Table 6-2 Power Distribution for Fuel Regions (Fission Power only)

(Unit: watts)

	Height (cm)	ZZ cm	LEZ 1	MEZ 2	HEZ 3	SHR 4	SCR 5	SSA1 6	SSA2,3 7	R. Reflector 8
Reflector	234.90	30.00								
Cones	204.90	4.50								
Upper Boron Shield	200.40	5.00								
	195.40	5.00								
	190.40	5.00								
(sum of UBS)										
Cones	185.40	4.50								
Sodium Plenum	180.90	5.00								
	175.90	5.00								
	170.90	6.00								
(sum of SP)										
Plugs	157.90	5.30								
Core	152.60	8.23	3.181E+07	1.147E+07	4.322E+07					
	144.37	8.23	3.992E+07	1.461E+07	5.337E+07					
	136.14	8.23	4.781E+07	1.762E+07	6.354E+07					
	127.91	8.23	5.443E+07	2.014E+07	7.184E+07					
	119.68	8.23	5.953E+07	2.209E+07	7.750E+07					
Internal Breeding Zone	111.45	5.10	1.812E+07	1.440E+07	4.951E+07					
Core	106.35	8.23	6.458E+07	2.365E+07	7.988E+07					
	98.12	8.23	6.401E+07	2.305E+07	7.670E+07					
	89.89	8.23	5.990E+07	2.125E+07	6.997E+07					
	81.66	8.23	5.266E+07	1.840E+07	6.011E+07					
	73.43	8.23	4.314E+07	1.483E+07	4.815E+07					
(sum of Core)			5.395E+08	2.015E+08	6.598E+08					
Axial Blanket 1	65.20	5.50	6.097E+06	1.836E+06	5.084E+06					
Axial Blanket 2	59.70	9.70	6.255E+06	1.833E+06	5.056E+06					
	50.00	10.00	3.873E+06	1.085E+06	2.947E+06					
	40.00	10.00	2.365E+06	6.375E+05	1.736E+06					
(sum of AB2)			1.249E+07	3.556E+06	9.738E+06					
Reflector	30.00	30.00								
(sum)			5.545E+08	2.069E+08	7.086E+08					
Total Power						1.470E+09				

Benchmark Results : Table 7

Table 7 Beta-effective and Prompt Neutron Lifetime

Item	value
Effective Delayed Neutron Fraction	3.4196E-03
Neutron Lifetime (sec)	4.2570E-07

Fraction of Delayed Neutron Groups

delayed neutron group	1	2	3	4	5	6
B_k/B_eff (%)	2.485	17.614	15.306	35.818	21.054	7.724

Mean Velocity of Neutron Energy Groups

neutron energy group	1	2	3	4	5	6	7	8	9
mean velocity(m/sec)	3.809E-07	2.092E+07	1.185E+07	7.432E+06	4.579E+06	2.796E+06	1.726E+06	1.060E+06	4.460E-05

Benchmark Results : Table 8

- Comparison of Reactivity Coefficients with the Results of Others
  - k_{eff} is higher than those of other participants but reactivity coefficients are similar except the fuel Doppler coefficient.

Table 8 Results of Reactivity Coefficients (Homogeneous Diffusion Theory)

Item	Cal. Method	(Δk/kk'/ΔlnK) or (Δk/kk')/(Δρ/ρ)							
		KAERI Korea	IPPE Russia	CIAE China	ANL USA	FZK Germany	JNC Japan	CEA/SA France/UK	IGCAR India
	XS Data	JEF2.2	ABBN-93	ENDF/B-VI CENDL-2	ENDF/B-V.2	JENDL-3.2 ENDF/B-6.7	JENDL-3.2	JEF2.2	XSET-98
	Condensed Neutron Energy Groups	9	18	12	230	11	18	33	26
Reference Value (Fuel: 1500K, Steel: 600K)	Keff	1.00976	0.99506	0.98834	1.00374	1.00254	0.99701	1.00183	1.00164
Fuel Doppler	Direct Cal.	-8.88E-03		-6.85E-03		-6.37E-03	-7.64E-03	-7.90E-03	
(Fuel: 2100K, Steel: 600K)	Sum of Locals	-8.95E-03	6.84E-03	-7.06E-03	-7.10E-03	-6.52E-03	-7.67E-03	-7.90E-03	-7.73E-03
Steel Doppler	Direct Cal.	-1.01E-03		-7.25E-04		-5.15E-04	-9.68E-04	-1.24E-03	
(Fuel: 1500K, Steel: 900K)	Sum of Locals	-1.01E-03	-1.10E-03	-1.13E-03	-7.90E-04	-5.12E-04	-9.72E-04	-1.24E-03	
Fuel Density 1% Change	Direct Cal.	3.72E-01		3.91E-01		3.88E-01	3.95E-01	3.88E-01	
(Fuel Density*1.01)	Sum of Locals *	3.80E-01	3.83E-01	3.84E-01	3.55E-01	3.89E-01	3.79E-01	3.88E-01	3.89E-01
Sodium Density 1% Change	Direct Cal.	2.23E-03		-9.87E-04		2.98E-03	3.02E-03	-1.99E-03	
(Sodium Density*1.01)	Sum of Locals *	4.75E-04	1.98E-03	-1.70E-03	1.35E-02	1.27E-03	3.40E-03	-1.77E-03	-6.55E-03

* First Order Perturbation Theory Calculation

Appendix Slide

- k_{eff} and Whole Core Coefficients
  - Direct calculation for a whole core is performed without using the first order perturbation theory.
  - Zero flux boundary conditions are used.

Case.	Item	Keff	Coefficients	unit
1	Reference Value (Fuel: 1500K, Steel: 600K)	1.008037		
2	Fuel Doppler (Fuel: 2100K, Steel: 600K)	1.005015	-8.865E-03	(Δk/kk'/ΔlnK)
3	Steel Doppler (Fuel: 1500K, Steel: 900K)	1.007632	-9.847E-04	(Δk/kk'/ΔlnK)
4	Fuel Density 1.01 Change (Fuel Density* 1.01)	1.011856	3.744E-01	(Δk/kk'/Δρ/ρ)
5	Sodium Density 1.01 Change (Sodium density* 1.01)	1.008069	3.125E-03	(Δk/kk'/Δρ/ρ)