Preliminary Uncertainty Analysis at ANL

OECD/NEA WPEC Subgroup 33 Meeting

November 30, 2010

Paris, France

W. S. Yang, G. Aliberti, R. D. McKnight

Nuclear Engineering Division

Argonne National Laboratory

Methods and Data

- Experiment Analysis
  - Deterministic
    - Cross Section Generation: MC^2-3, ECCO
    - Static Analysis: DIF3D/VARIANT, TWODANT, ERANOS
    - Depletion Analysis: REBUS-3
  - Monte Carlo: MCNP5, VIM
- Sensitivity Analysis
  - Generalized Perturbation Theory: VARI3D, ERANOS
  - Depletion Perturbation Theory: DPT
- Cross Section Adjustment
  - Generalized Least Square Fitting: GMADJ
- Cross Section and Covariance Data
  - Cross Section: ENDF/B-VII
  - Covariance Data: AFCI-1.2, AFCI-1.3, AFCI-2.0

List of Parameters Analyzed

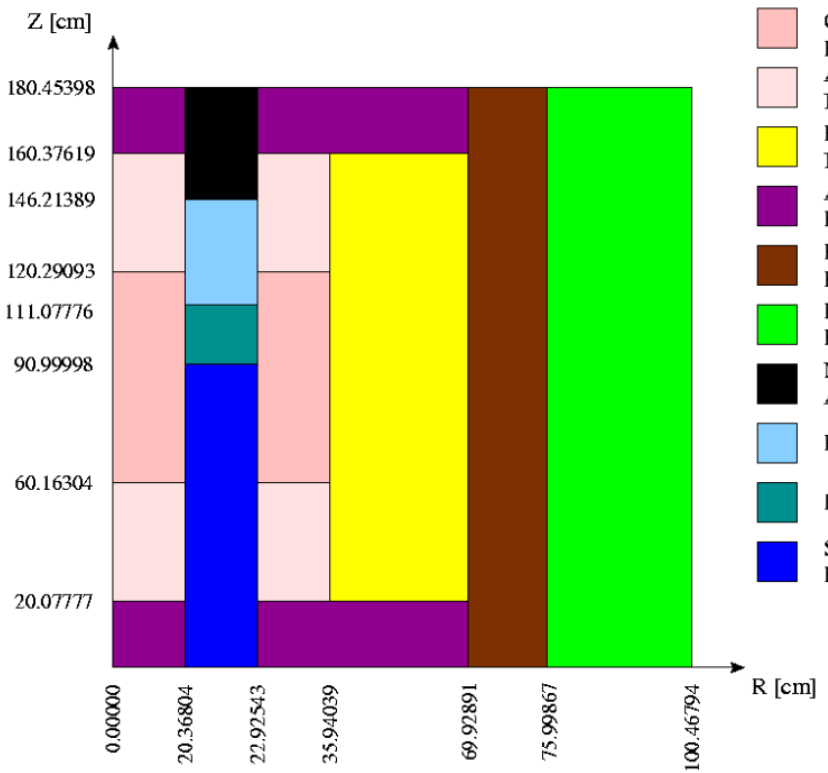
- JEZEBEL Pu239
  - Multiplication factor
  - Spectral indices at the core center: F28/F25, F37/F25 and F49/F25
- JEZEBEL Pu240
  - Multiplication factor
- FLATTOP Pu239
  - Multiplication factor
  - Spectral indices at the core center: F28/F25 and F37/F25
- JOYO
  - Multiplication factor
- ZPPR-9
  - Multiplication factor
  - Spectral indices at (R , Z) = (0 , 9.708 cm): F28/F25, F49/F25 and C28/F25
  - Sodium void worth: Step3 and Step5

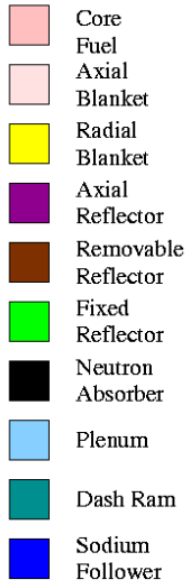
Preliminary Analysis of Experiments

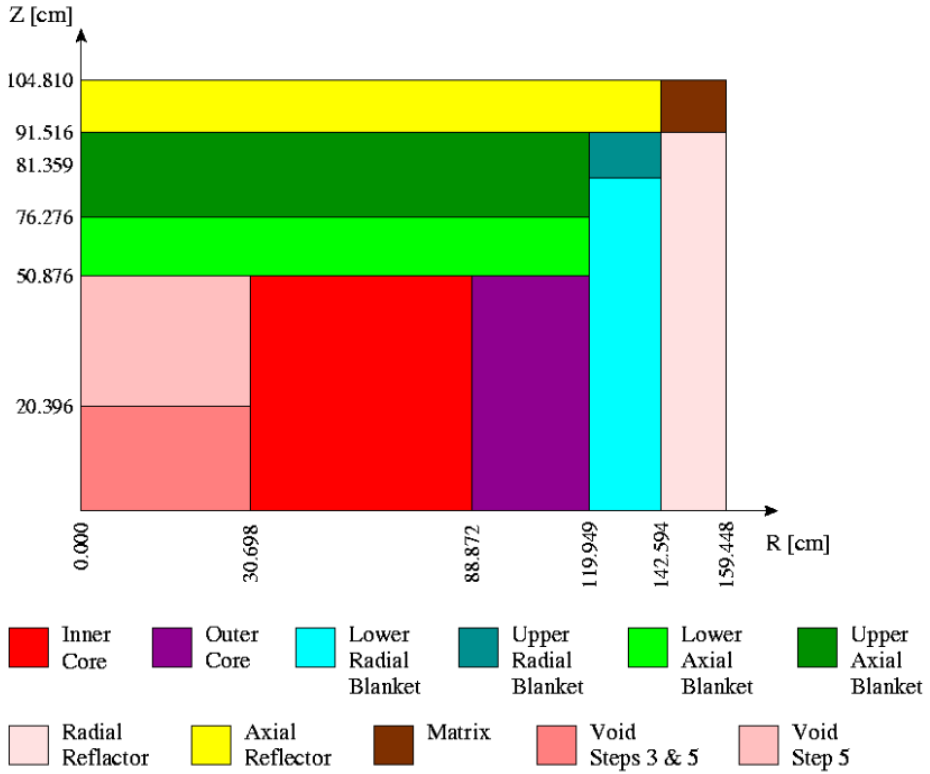
- JEZEBEL and FLATTOP
  - Base calculations
    - 33-group cross section generation with ECCO
    - ERANOS with S16 angular and P1 scattering approximations
  - Parametric studies with MC^2-3/TWODANT and VIM

- JOYO and ZPPR-9
  - Base calculation
    - 33-group cross section generations using MC^2-3
    - Finite difference diffusion theory option of DIF3D
  - Parametric studies with ECCO/ERANOS
  - Finer meshes than those suggested by JAEA
    - Suggested meshes are too coarse (up to ~6 cm)
    - ZPPR-9 mesh is not suitable for the analysis of spectral indices at (R , Z) = (0 , 9.708) cm

Joyo and ZPPR-9 Meshes

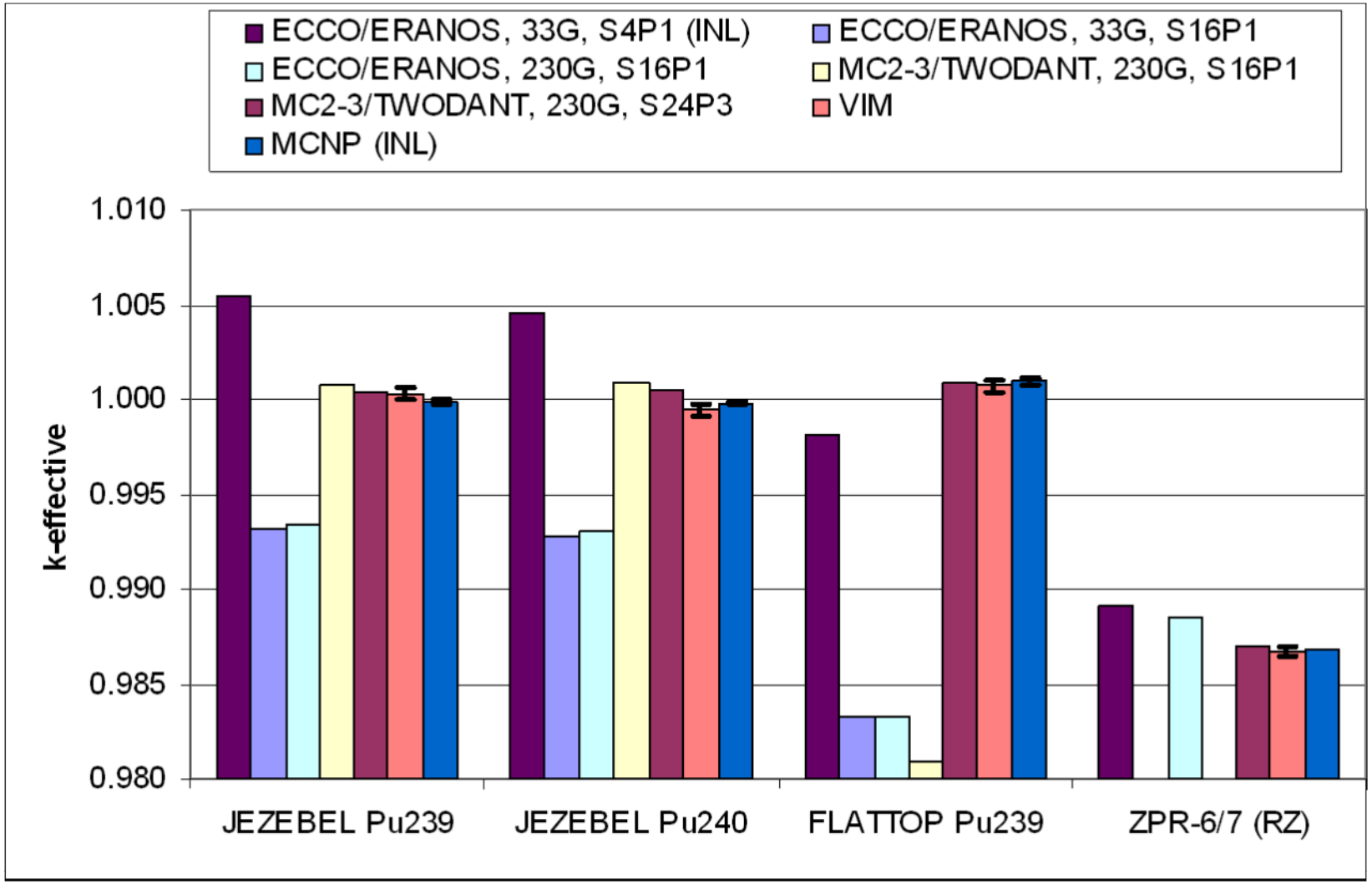






Joyo	R	Node	1	11	13	20	37	40	53		
		Coordinate	0.0	20.36804	22.92543	35.94039	69.92891	75.99867	100.46794		
	Z	Node	1	11	31	46	57	62	75	82	92
		Coordinate	0.0	20.07777	60.16304	90.99998	111.07776	120.29093	146.21389	160.37619	180.45398
ZPPR-9	R	Node	1	2	17	46	62	73	82		
		Coordinate	0.0	0.5	30.698	88.872	119.949	142.594	159.448		
	Z	Node	1	6	7	12	27	40	43	48	55
		Coordinate	0.0	9.208	10.208	20.396	50.876	76.276	81.359	91.516	104.810

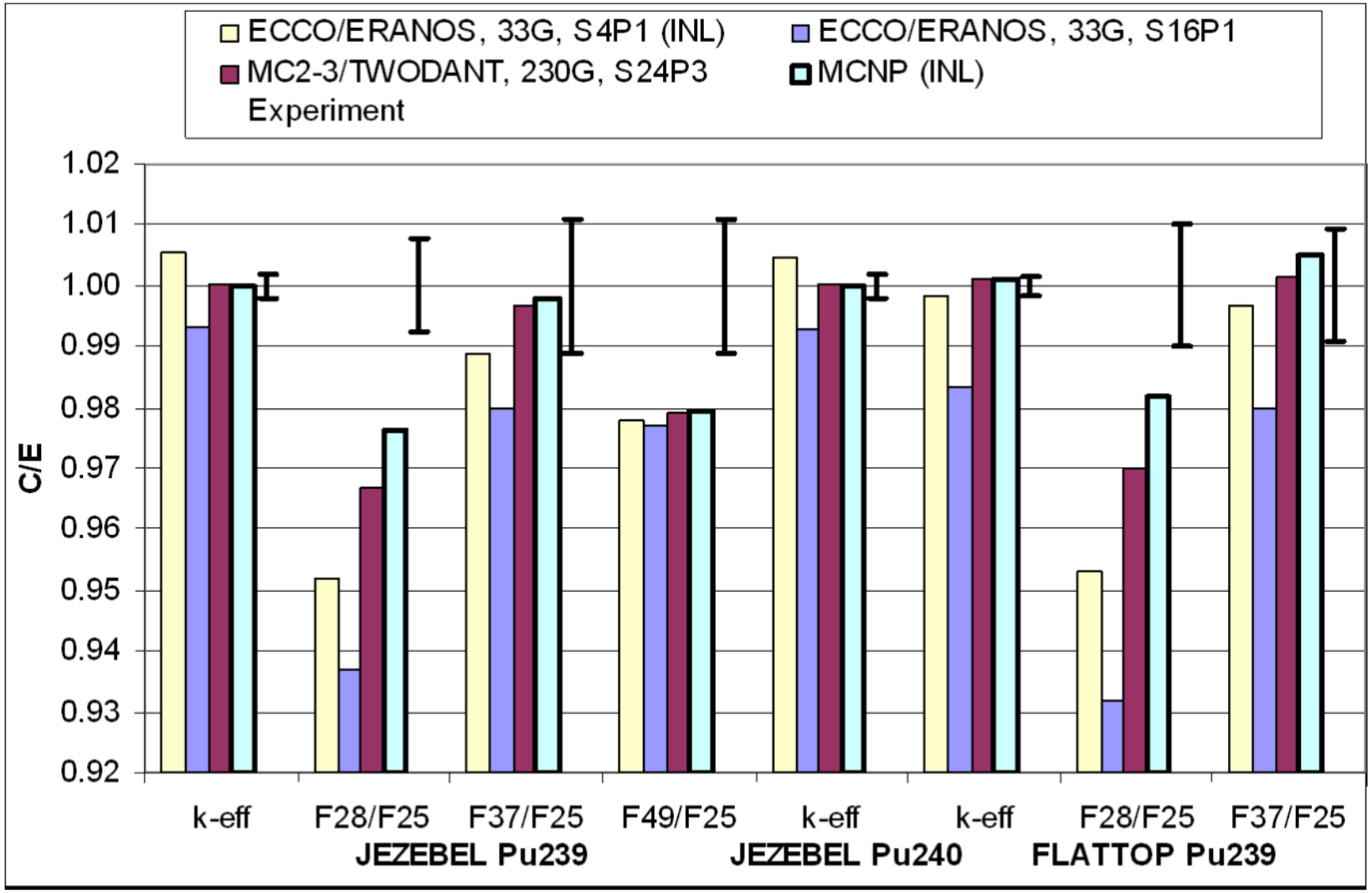
Calculated k-effectives of JEZEBEL, FLATTOP and ZPR-6/7



Calculated Multiplication Factors

System	MC2-3/TWODANT		ECCO/ERANOS			VIM	MCNP
	230G	230G	230G	33G	33G		
	S24P3	S16P1	S16P1	S16P1	S4P1		
JEZEBEL Pu239	1.00036	1.00078	0.99341	0.99313	1.00538	1.00028 ±0.00030	0.99986 ±0.00009
JEZEBEL Pu240	1.00049	1.00089	0.99310	0.99275	1.00459	0.99944 ±0.00031	0.99981 ±0.00009
FLATTOP Pu239	1.00092	0.98092	0.98331	0.98330	0.99815	1.00072 ±0.00034	1.00097 ±0.00018
ZPR-6/7 (RZ)	0.98700		0.98847		0.98915	0.98671 ±0.00022	0.98680

C/E Values for Integral Parameters of JEZEBEL and FLATTOP



Integral Parameters of Joyo and ZPPR-9

Integral Parameter		ANL		JAEA		Experiment
		DIF3D	ERANOS	Most Detailed	33G, S4P1	
		33G, Diff	33G, S4P1			
JOYO	k-eff	0.98660	0.99910	0.99923	1.01373	1.00105 ± 0.00180
ZPPR-9	k-eff	0.98879	0.98733	1.00237	0.99436	1.00080 ± 0.00154
	F28/F25	0.0203	0.0198	0.0212	0.0200	0.0221 ± 0.0006
	F49/F25	0.9102	0.9142	0.9172	0.9239	0.9295 ± 0.0185
	C28/F25	0.1368	0.1371	0.1411	0.1387	0.1379 ± 0.0026
	Na void (Step 3)	0.00107	0.00106	0.00117	0.00115	0.00104 ± 0.00001
	Na void (Step 5)	0.00141	0.00140	0.00118	0.00158	0.00112 ± 0.00001

Sensitivity and Uncertainty Analysis

- Sensitivity Analysis
  - 33-group sensitivity coefficients were calculated for fission, nu, capture, elastic scattering, inelastic scattering and n,2n reactions.
    - Sensitivity coefficients for fission spectra were also obtained from direct perturbation calculations with ERANOS
  - JEZEBEL and FLATTOP
    - ERANOS with S16 angular and P1 scattering approximation
  - JOYO and ZPPR-9
    - VARI3D with diffusion approximation
    - ERANOS with S4 angular and P1 scattering approximation
- Uncertainty Analysis
  - AFCI-1.2, AFCI-1.3 and AFCI-2.0 covariance data

Estimated Overall Uncertainties (%) of Integral Parameters of JEZEBEL and FLATTOP

Integral Parameter		ERANOS 33G, S16P1		
		AFCI-1.2	AFCI-1.3	AFCI-2.0
JEZEBEL Pu239	k-eff	0.65	0.65	0.67
	F28/F25	2.97	3.56	3.49
	F37/F25	8.49	3.56	3.55
	F49/F25	0.80	0.82	0.81
JEZEBEL Pu240	k-eff	0.76	0.53	0.79
FLATTOP Pu239	k-eff	0.83	0.83	0.85
	F28/F25	2.25	2.94	2.88
	F37/F25	8.33	3.38	3.38

* Including the effect of fission spectrum uncertainties

Estimated Overall Uncertainties (%) of Integral Parameters of JOYO and ZPPR-9

Integral Parameter		VARI3D, Diffusion			ERANOS
		AFCI-1.2	AFCI-1.3	AFCI-2.0	AFCI-2.0
JOYO	k-eff	0.89	0.95	0.97	0.91
ZPPR-9	k-eff	1.25	1.25	1.24	1.19
	F28/F25	7.55	7.60	7.59	7.85
	F49/F25	0.87	0.88	0.88	0.88
	C28/F25	1.55	1.55	1.54	1.55
	Na void (Step 3)	7.04	7.38	7.36	13.8
	Na void (Step 5)	11.3	11.5	11.4	16.4

* The effect of fission spectrum uncertainties are included only in ERANOS results

Sample Isotopic Contributions to Uncertainty of FLATTOP k-effective

U238	ν	σ_f	σ_{inel}	σ_{el}	σ_c	$\sigma_{n,2n}$	sum
ν	9.39E-07						9.39E-07
σ_f		1.08E-07		1.24E-10	1.35E-13		1.08E-07
σ_{inel}			9.93E-05	-3.05E-05			6.88E-05
σ_{el}		1.24E-10	-3.05E-05	1.47E-05	3.77E-09	2.59E-09	-1.58E-05
σ_c		1.35E-13		3.77E-09	2.83E-07		2.87E-07
$\sigma_{n,2n}$				2.59E-09		3.38E-08	3.64E-08
sum	9.39E-07	1.08E-07	6.88E-05	-1.58E-05	2.87E-07	3.64E-08	5.43E-05

Pu239	ν	σ_f	σ_{inel}	σ_{el}	σ_c	$\sigma_{n,2n}$	sum
ν	5.03E-07						5.03E-07
σ_f		8.34E-06		-6.68E-08	-1.18E-13		8.28E-06
σ_{inel}			1.22E-05	-5.85E-06			6.39E-06
σ_{el}		-6.68E-08	-5.85E-06	3.05E-06	1.95E-08	-9.04E-11	-2.85E-06
σ_c		-1.18E-13		1.95E-08	1.28E-06		1.30E-06
$\sigma_{n,2n}$				-9.04E-11		2.71E-09	2.62E-09
sum	5.03E-07	8.28E-06	6.39E-06	-2.85E-06	1.30E-06	2.62E-09	1.36E-05

Major Standard Deviations and Correlation Coefficients (%) of ZPPR-9 Na Void Worth (Step 3)

Cross Section		VARI3D			ERANOS	Cross Section		VARI3D			ERANOS
		AFCI-1.2	AFCI-1.3	AFCI-2.0	AFCI-2.0			AFCI-1.2	AFCI-1.3	AFCI-2.0	AFCI-2.0
U238	σ_c	2.17	2.17	2.16	2.13	Pu240	χ				11.4
	σ_{el}	0.58	0.58	0.58	0.17	Fe56	σ_c	0.48	0.38	0.38	0.37
	σ_{inel}	5.90	5.89	5.88	5.77		σ_{el}	0.45	1.03	1.03	0.95
	σ_{inel} σ_{el}	-93.7	-93.7	-93.5	-49.7		σ_{inel}	0.20	0.53	0.53	0.52
Pu238	χ				1.00	Na23	σ_{el}	2.27	1.80	2.10	2.14
Pu239	σ_f	1.53	1.53	1.52	1.52		σ_{inel}	2.16	3.27	3.26	3.24
	χ				1.28	O16	σ_c	0.00	0.00	0.00	0.56
	ν	1.19	1.19	0.41	0.42		σ_{el}	1.14	1.14	1.14	1.08
	σ_c	0.60	0.60	0.60	0.59						
	σ_{inel}	0.70	0.69	0.69	0.67	Total	w/o χ	7.04	7.38	7.36	7.61
	σ_c σ_f	-22.2	-22.1	-22.0	-22.2		w/ χ				13.8

Major Standard Deviations and Correlation Coefficients (%) of ZPPR-9 Na Void Worth (Step 3)

Cross Section		VARI3D			ERANOS	Cross Section		VARI3D			ERANOS
		AFCI-1.2	AFCI-1.3	AFCI-2.0	AFCI-2.0			AFCI-1.2	AFCI-1.3	AFCI-2.0	AFCI-2.0
U238	σ_c	2.17	2.17	2.16	2.13	Pu240	χ				11.4
	σ_{el}	0.58	0.58	0.58	0.17	Fe56	σ_c	0.48	0.38	0.38	0.37
	σ_{inel}	5.90	5.89	5.88	5.77		σ_{el}	0.45	1.03	1.03	0.95
	σ_{inel} σ_{el}	-93.7	-93.7	-93.5	-49.7		σ_{inel}	0.20	0.53	0.53	0.52
Pu238	χ				1.00	Na23	σ_{el}	2.27	1.80	2.10	2.14
Pu239	σ_f	1.53	1.53	1.52	1.52		σ_{inel}	2.16	3.27	3.26	3.24
	χ				1.28	O16	σ_c	0.00	0.00	0.00	0.56
	ν	1.19	1.19	0.41	0.42		σ_{el}	1.14	1.14	1.14	1.08
	σ_c	0.60	0.60	0.60	0.59						
	σ_{inel}	0.70	0.69	0.69	0.67	Total	w/o χ	7.04	7.38	7.36	7.61
	σ_c σ_f	-22.2	-22.1	-22.0	-22.2		w/ χ				13.8

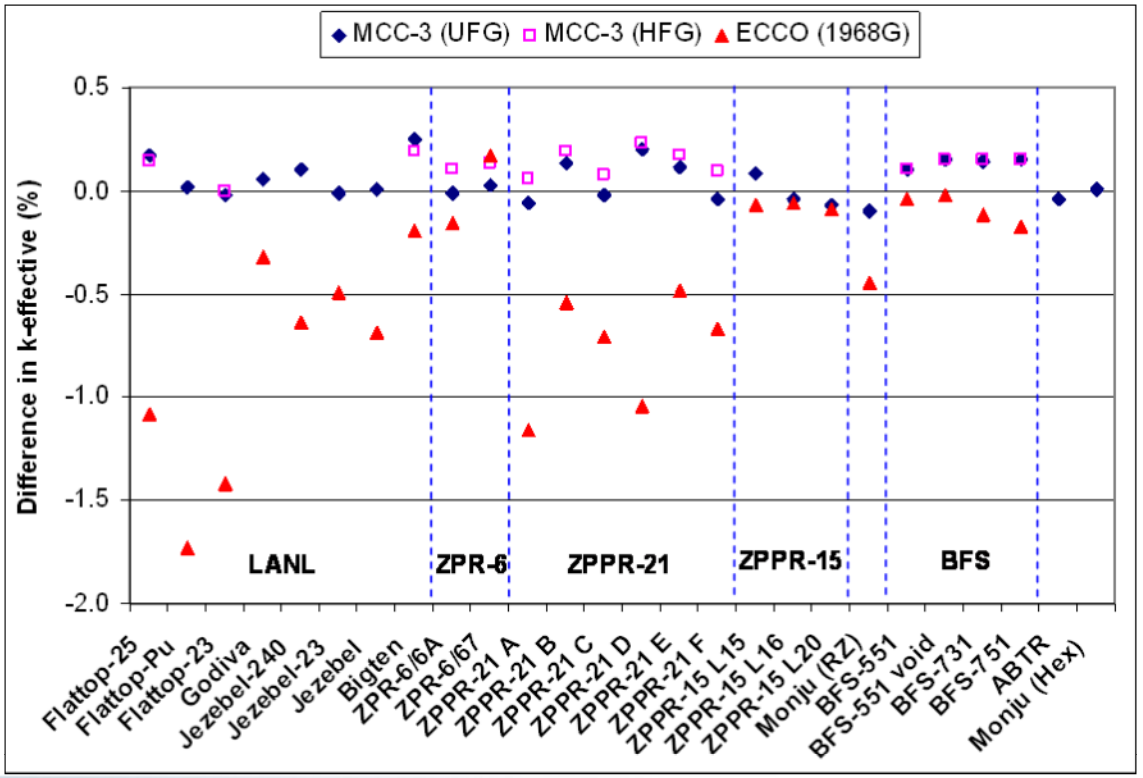
Major Standard Deviations and Correlation Coefficients (%) of ZPPR-9 Na Void Worth (Step 5)

Cross Section		VARI3D			ERANOS	Cross Section		VARI3D			ERANOS
		AFCI-1.2	AFCI-1.3	AFCI-2.0	AFCI-2.0			AFCI-1.2	AFCI-1.3	AFCI-2.0	AFCI-2.0
U238	ν	0.51	0.51	0.51	0.50	Pu240	χ				13.1
	σ_c	2.89	2.88	2.87	2.83		σ_f	0.39	0.04	0.16	0.16
	σ_{el}	2.25	2.25	2.24	0.19		σ_c	0.33	0.31	0.33	0.32
	σ_{inel}	7.43	7.42	7.40	7.35	Pu241	σ_f	0.34	0.12	0.34	0.35
	σ_{inel} σ_{el}	97.4	97.4	97.1	75.5	Fe56	σ_c	0.64	0.51	0.51	0.50
Pu238	χ				1.32		σ_{el}	0.40	0.48	0.48	0.76
Pu239	σ_f	2.07	2.07	2.06	2.05		σ_{inel}	0.26	0.69	0.69	0.69
	χ				1.30	Ni60	σ_{el}	0.57	0.57	0.32	0.03
	ν	1.60	1.60	0.56	0.57	Na23	σ_{el}	2.60	1.72	2.03	1.95
	σ_c	0.80	0.80	0.80	0.79		σ_{inel}	2.77	4.19	4.18	4.16
	σ_{inel}	0.85	0.85	0.85	0.82	O16	σ_c	0.00	0.00	0.00	0.76
	σ_c σ_f	-22.1	-22.0	-21.9	-22.0		σ_{el}	1.08	1.08	1.08	1.20
	σ_{inel} σ_{el}	92.6	92.6	92.5	96.3	Total	w/o χ	11.3	11.5	11.4	9.72
							w/o χ				16.4

Backup Slides

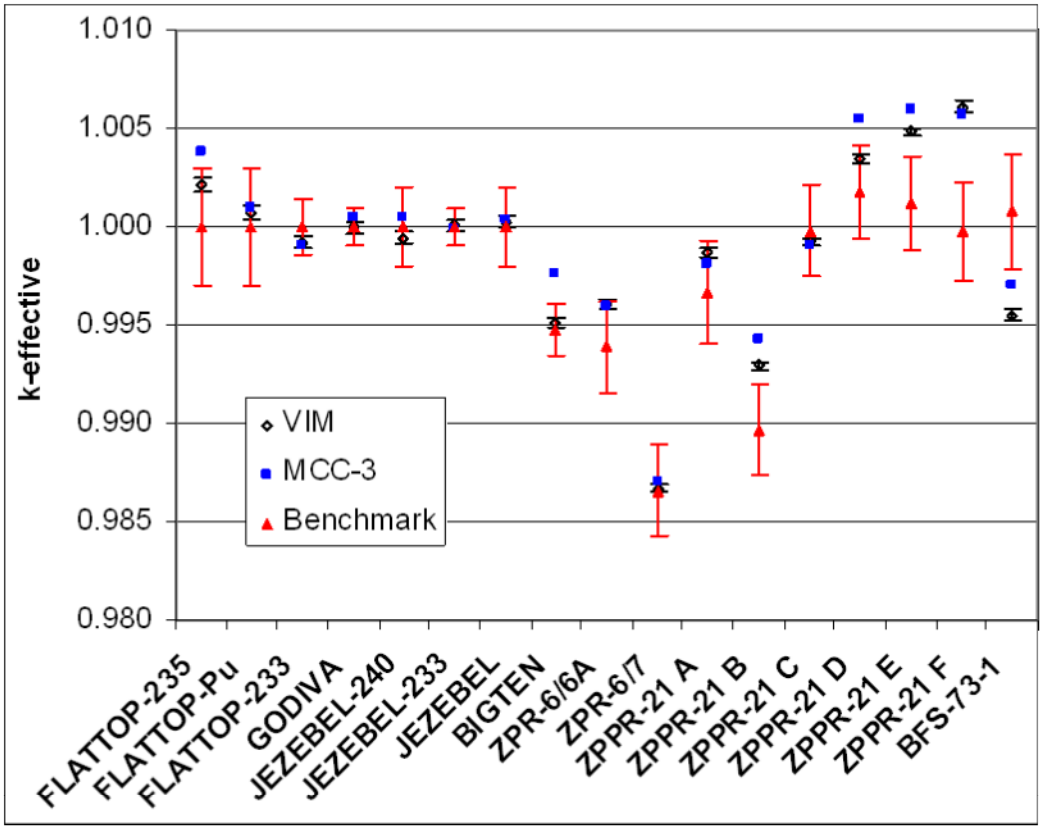
Additional Criticality Benchmarks

- Region-dependent cross sections were generated in a 230-group structure using ENDF/B-VII data
- Whole core calculations were carried out with TWODANT and ERANOS
  - TWODANT $S_{24}P_3$ and VARIANT P_5P_1 with MC^2-3 cross sections
  - ERANOS $S_{16}P_3$ with ECCO cross sections (1968 group slowing-down calculation)
- Deterministic results compared with VIM and MCNP5 Monte Carlo solutions
- RMS difference between MC^2-3/TWODANT and Monte Carlo solutions is 0.14%
- Relatively large differences in ECCO/ERANOS results
  - LANL small critical assemblies with large leakage
  - ZPPR-21 assemblies with no blankets and thick graphite reflector around core



Criticality Benchmarks

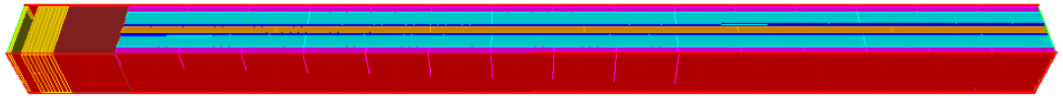
- Comparison with the specified benchmark k-effective values with 1-σ uncertainties

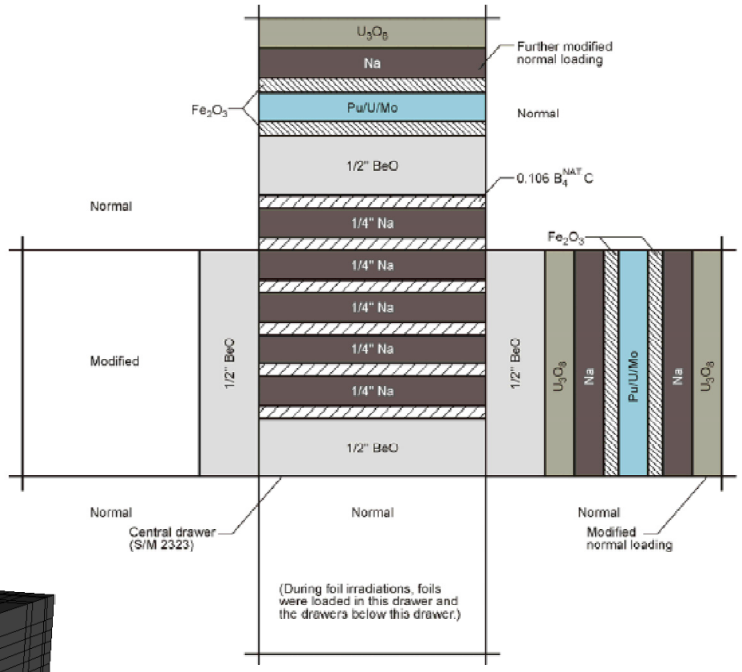


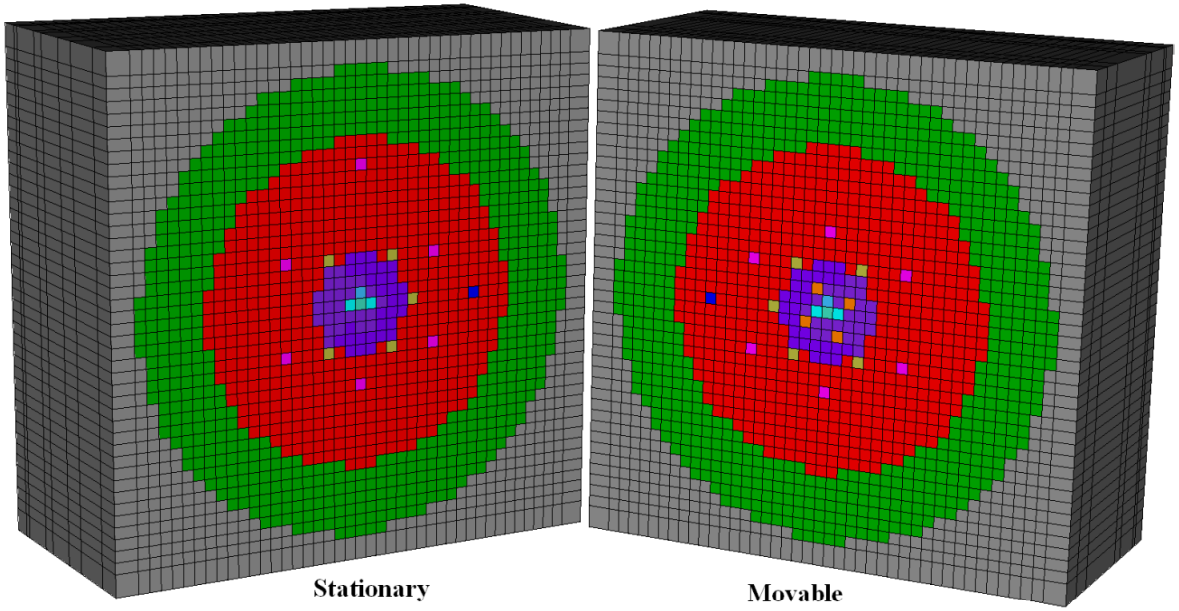
	VIM	MC^2-3
< 1σ	13	10
1σ - 2σ	3	5
2σ - 3σ	1	2
Total	17	17

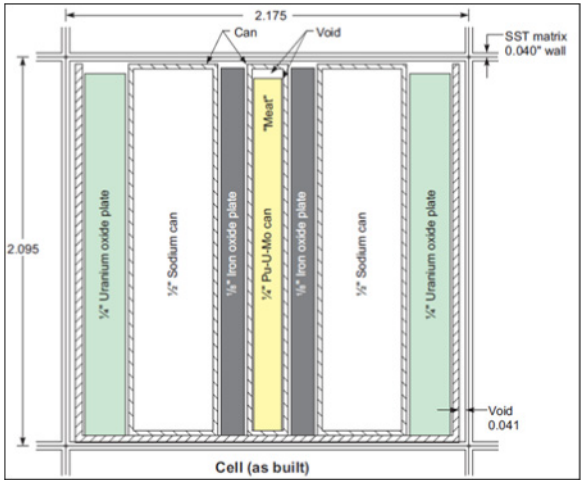
ZPR-6 Assembly 7 Critical Experiments

- Loadings 104, 106, 120, and 132 of high Pu-240 reactor physics benchmark
  - Control rod worth measurements
  - Sodium channel and BeO ring at the core center of loading 106 and 132









ZPR6 Assembly 7 High Pu240 Critical Experiments

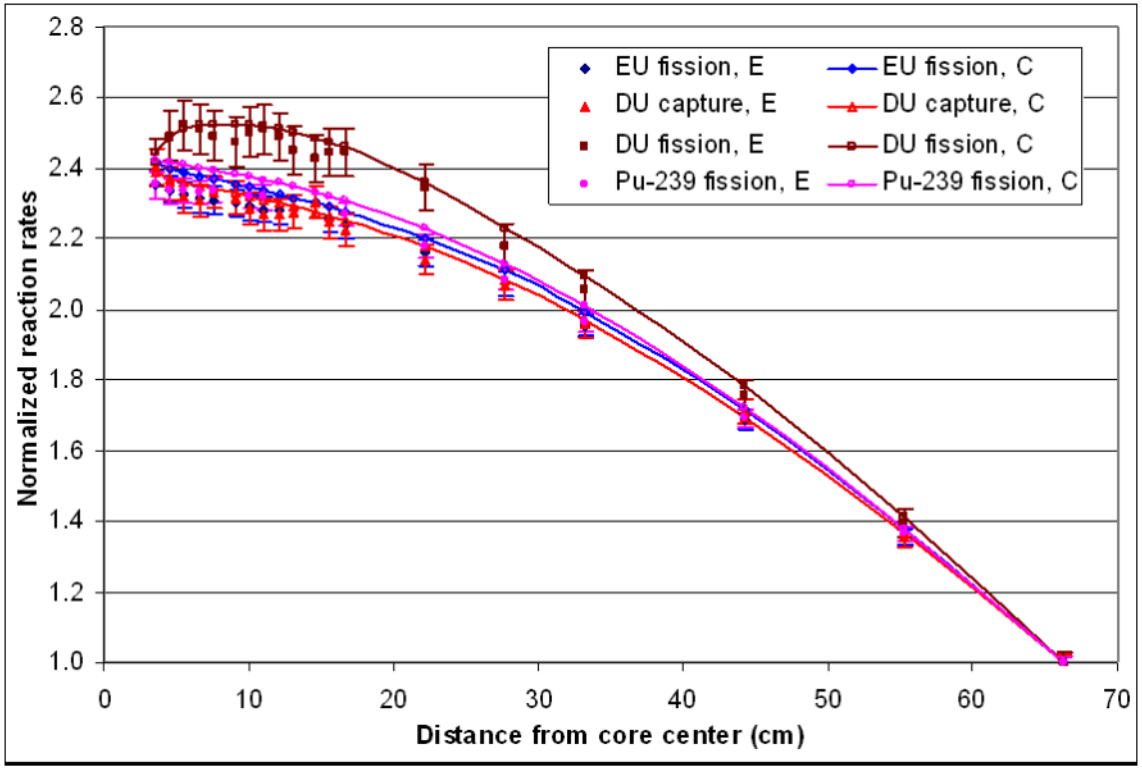
- MC^2-3/UNIC analyses
  - 70 energy groups, 1M spatial meshes, 72 angular directions, P_3 scattering order

	Loading 104	Loading 106	Loading 120	Loading 132
MC^2-3/UNIC	1.00147	1.00134	1.00127	1.00016
	0.075%	0.043%	0.028%	-0.024%
MCNP5 (as-built model)	1.00016 ±0.00007	1.00049 ±0.00007	0.99967 ±0.00007	1.00040 ±0.00007
	-0.056%	-0.042%	-0.132%	0.000%
Measurement	1.00072 ±0.00002	1.00091 ±0.00003	1.00099 ±0.00003	1.00040 ±0.00002

* Measurement uncertainty only
* Combined uncertainty due to geometry and composition uncertainties estimated for the Loading 99 is ~0.080%

ZPR6-7 Foil Measurement Comparisons

- 69 foil activation measurements were analyzed for each of four loadings
- Calculated reaction rates agreed very with the measurements except for a couple of depleted uranium capture rates near the BeO plates (in loadings 106 and 132)
  - Enhanced self-shielding of low energy resonances of U-238 (below 1 keV)
- Additional studies are ongoing to account for surface sources in MC^2-3 calculations



ZPR6-7 Foil Measurement Comparisons

- Foil reaction rates in the loading 106 with BeO plates around the central sodium drawer