Argonne Activities within the AFCI Uncertainty Reduction Project

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Background and Objectives

- **In FY 2008, a collaborative project among INL, ANL, BNL, and LANL was initiated**
  - Selection of a set of experiments (INL, ANL)
  - Sensitivity analysis of selected configurations including reference design configurations (ANL, INL)
  - Production of science based covariance data (BNL, LANL)
  - Uncertainty evaluation and target accuracy assessment (ANL, INL)
  - Analysis of experiments using the best methodologies available (INL, ANL)
  - Statistical uncertainty evaluation and cross section adjustment using calculation/experiment discrepancies (INL, ANL)
- **The main objectives are:**
  - Reduce the uncertainty of reactor performance predictions
  - Identify the key nuclear data needs

ANL Tasks

- **Perform sensitivity analysis of the selected experiments and target systems**
  - For uncertainty and representativity analysis to identify the most relevant experiments for the target systems
  - To provide sensitivity coefficients needed for cross section adjustment
- **Investigate the accuracy of the methodologies commonly adopted for computing sensitivity coefficients with deterministic codes**
  - Relevant findings have been obtained for the sensitivity analysis of burnup dependent parameters (like burnup reactivity swing and final (EOC) nuclide number density)
  - A detailed study has been performed on the impact on parameter sensitivities due to the most common approximations (such as transport effects, geometry modeling, group collapsing) used in the calculations by perturbation theory with deterministic codes
- **Provide feedback on the quality of the AFCI covariance data and indications for further improvements of the matrix**
- **Analysis of experiments using the best methodologies available**
  - Generation of high-fidelity “as-built” models
- **Statistical uncertainty evaluation and cross section adjustment using calculation/experiment discrepancies**

Sensitivity Analysis of the Selected Experiments and Target Systems

List of Investigated Systems for the Sensitivity Study

ABR Metal Core	FY 2008	**CIRANO/ZONA2A**	FY 2008	**GODIVA**	FY 2008 [a]
ABR Oxide Core	FY 2008	**CIRANO/ZONA2A3**	FY 2008	**BIGTEN**	FY 2008 [a]
ZPPR-2	FY 2008	**CIRANO/ZONA2B**	FY 2008	**Pu239 JEZEBEL**	FY 2008 [a]
ZPPR-9	FY 2008	**COSMO**	FY 2008	**Pu240 JEZEBEL**	FY 2008 [a]
ZPPR-10A	FY 2009	**MUSE-4**	FY 2008	**U233 JEZEBEL**	FY 2008 [a]
ZPPR-15A	FY 2008	**PROFIL-1**	FY 2009	**FLATTOP Pu239**	FY 2008 [a]
ZPR6 Assembly 6A	FY 2008	**PROFIL-2**	FY 2009	**FLATTOP U235**	FY 2008 [a]
ZPR6 Assembly 7	FY 2008	**TRAPU**	FY 2009	**FLATTOP U233**	FY 2008 [a]
ZPR6 Ass.7 High Pu240	FY 2010	**ZEBRA Assembly 22**	FY 2010	**Np SPHERE**	FY 2009 [a]
ZPR3 Assembly 53	FY 2008	**ZEBRA Assembly 23**	FY 2010		
ZPR3 Assembly 54	FY 2008	**ZEBRA Assembly 24**	FY 2010		
		ZEBRA Assembly 25	FY 2010		

[a] All small size assemblies have been re-analyzed in FY 2010

Parameters Included in the Sensitivity Analysis of the Selected Experiments and Target Systems

- Four response parameters, **k_{eff}, $^{28}f/^{49}f$** and **$^{28}c/^{49}f$** at core center and **coolant void reactivit**y (where applicable) were evaluated for all critical experiments and target systems
  - For the spectral indices, the total sensitivity coefficients (i.e., the sum of direct and indirect effects) are dominated by the direct effect, and thus the indirect effects on the spectral index sensitivities have been considered separately.
  - Sensitivity coefficients have also been produced for a number of additional integral parameters of interest, including various spectral indices at the core center and reaction rate ratios at the interface between the core and reflector/blanket (specifically to improve the agreement between calculation and measurements on transitional flux effects at the core boundary).
- For the irradiation experiments (PROFIL-1, PROFIL-2 and TRAPU), the sensitivity analysis was performed for 14 integral parameters:
  - ^{240}Pu final densities of two ^{239}Pu samples and ^{242m}Am, ^{238}Pu, and ^{242}Cm final densities of two ^{241}Am samples for PROFIL-1;
  - 238Pu final densities of two 237Np samples and ^{239}Pu final densities of two ^{238}Pu samples for PROFIL-2;
  - and ^{237}Np and ^{243}Am final densities of the TRAPU pin.

Computational Tools in the Sensitivity Analysis of the Selected Experiments and Target Systems

- For all critical assemblies:
  - Cross-sections were generated in 33 energy groups using the MC^2-2 code and ENDF/B-VII.0 nuclear data.
  - Sensitivity coefficient calculations were performed in diffusion theory using the VARI3D code.
  - Flux, adjoint flux, and generalized adjoint flux were calculated with the finite difference diffusion theory option of the DIF3D code.
- For the small size assemblies (FLATTOP, JEZEBEL, GODIVA, BIGTEN, and NP SPHERE), sensitivity analysis was performed in transport theory with the BISTRO code of ERANOS (cross sections are generated with ECCO and ENDF/B-VII.0 nuclear data).
- For the irradiation experiments, the sensitivity coefficient calculations were performed using the depletion perturbation theory code DPT.
  - Which is based on the non-equilibrium and equilibrium fuel cycle analysis methodologies of REBUS-3 in diffusion theory and RZ geometry.
  - The generalized adjoint flux equations are solved using DIF3D.
  - Cross sections are processed with the MC^2-2 code using ENDF/B-VII.0 nuclear data.

Approach and Theoretical Background in the Sensitivity Analysis of the Selected Experiments and Target Systems

- Sensitivity studies using Generalized Perturbation Theory (GPT)
  - Uncertainty assessment
  - Representativity analysis
- Using the sensitivity coefficients, S_R, for each integral parameter P of the reactor R under study and the covariance matrix D, the uncertainty on the integral parameter P can be evaluated:

$$I_R^2 = S_R^+ D S_R$$

- An integral experiment can be conceived in order to reduce the uncertainty
  - If S_E is the sensitivity matrix associated with this experiment for the same parameter P, a “representativity factor” defined as:

$$r_{RE} = \frac{\left(S_R^+ D S_E\right)}{\left[\left(S_R^+ D S_R\right)\left(S_E^+ D S_E\right)\right]^{1/2}}$$

    can be introduced to quantify the similarity between the reactor and the selected experiment.
  - It can be shown that the uncertainty on the reference parameter P is reduced by:

$$I_R'^{\,2} = I_R^2 \cdot \left(1 - r_{RE}^2\right)$$

Integral Parameter Calculated Values and Uncertainties (Uncertainty Values in %)

Systems	Multiplication Factor		f^{28}/f^{49}		c^{28}/f^{49}		Coolant Void Worth	
	Value	AFCI-1.3 Uncertainty	Value	AFCI-1.3 Uncertainty	Value	AFCI-1.3 Uncertainty	Value [pcm]	AFCI-1.3 Uncertainty
ABR Metal	0.97233	1.34	0.022	6.23	0.133	1.98	1402	13.07
ABR Oxide	0.98823	1.19	0.021	5.04	0.168	1.74	2443	6.17
ZPPR-2	0.98818	0.86	0.024	5.72	0.151	1.69	-74	197.11
ZPPR-9	0.98959	1.19	0.022	7.10	0.150	1.72	1413	12.08
ZPPR-10A	1.00264	1.11	0.019	6.69	0.152	1.69	1305	11.45
ZPPR-15A	0.98726	0.96	0.019	5.89	0.138	1.77	1508	8.94
ZPR-6 Assembly 6A	0.99704	1.57	0.025	5.55	0.146	1.76	-1855	11.94
ZPR-6 Assembly 7	0.99217	0.97	0.024	5.65	0.151	1.67	200	98.33
ZPR-6/7 High Pu240	0.99088	0.97	0.025	5.44	0.149	1.66	308	61.08
ZPR-3 Assembly 53	0.96875	0.74	0.039	2.56	0.166	1.73		
ZPR-3 Assembly 54	0.88874	1.61	0.041	2.78	0.162	1.79		
ZEBRA Assembly 22	0.99001	0.91	0.035	4.73	0.127	1.74	-1032	16.55
ZEBRA Assembly 23	1.00293	0.86	0.034	4.67	0.133	1.73	-1138	14.98
ZEBRA Assembly 24	0.99391	1.00	0.039	5.06	0.116	1.82		
ZEBRA Assembly 25	1.00539	0.95	0.038	5.02	0.122	1.82		
CIRANO/ZONA2A	0.99372	0.70	0.041	4.92	0.123	1.87	-1642	6.70
CIRANO/ZONA2A3	0.98585	0.81	0.041	4.91	0.123	1.90	-1678	8.08
CIRANO/ZONA2B	0.98189	0.94	0.042	4.88	0.122	1.93	-1776	8.84
COSMO	0.98199	0.93	0.042	4.93	0.122	1.93	-1818	9.12
MUSE-4	0.97313	0.96	0.033	4.98	0.130	1.85	-1582	10.35

Integral Parameter Calculated Values and Uncertainties (Uncertainty Values in %)

Systems	Multiplication Factor		f^{28}/f^{49}		c^{28}/f^{49}	
	Value	AFCI-1.3 Uncertainty	Value	AFCI-1.3 Uncertainty	Value	AFCI-1.3 Uncertainty
FLATTOP Pu239	0.98331	0.81	0.122	1.92	0.055	2.21
FLATTOP U235	0.99229	1.08	0.103	1.71	0.059	1.99
FLATTOP U233	0.98654	0.87	0.140	1.90	0.048	2.42
Pu239 JEZEBEL	0.99315	0.63	0.141	2.56	0.047	2.90
Pu240 JEZEBEL	0.99277	0.49	0.137	2.38	0.048	2.65
U233 JEZEBEL	0.99503	0.88	0.144	2.01	0.046	2.52
GODIVA	0.99586	0.90	0.112	1.85	0.055	2.12
NP SPHERE	1.02554	0.98	0.107	3.39	0.059	3.15
BIGTEN	0.99456	2.34	0.030	12.41	0.096	2.60

Uncertainty Breakdown with AFCI-13 Data

- The U238 inelastic scattering data is consistently one of the larger uncertainties on k_{eff} for most of the systems (exceptions generally not containing significant U238). In the case of ZPR-6 Assembly 6A, FLATTOP U235 and GODIVA, most of the k_{eff} uncertainty is due to U235 capture. Pu239 capture is the dominant contributor for ZPR-3 Assembly 53 and plays a significant role in all other Pu systems, except ABR Metal and all small size assemblies. U233 fission and inelastic are the dominant uncertainty contributions for the k_{eff} of the two assemblies with U233 loadings, FLATTOP U233 and U233 JEZEBEL. For Pu239 and Pu240 JEZEBEL the k_{eff} uncertainty is practically completely due to Pu239 inelastic. The Np cross sections are relevant for the Np SPHERE. Among structural isotopes, Fe56 elastic is the largest contributor for ZPR-3 Assembly 54, CIRANO ZONA2A3, CIRANO ZONA2B, MUSE-4 and COSMO.

- The uncertainty profiles for the spectral index f^{28}/f^{49} of all regular size experiments are dominated by the contribution of U238 inelastic. In the case of small size assemblies, the dominant effects are from U233 inelastic (FLATTOP U233 and U233 JEZEBEL), U235 inelastic and capture (FLATTOP U235 and GODIVA), U238 inelastic (FLATTOP U235 and BIGTEN), Np237 inelastic and elastic (Np SPHERE) and Pu239 inelastic (FLATTOP Pu239, Pu239 JEZEBEL and Pu240 JEZEBEL).

Uncertainty Breakdown with AFCI-13 Data

- Concerning the spectral index c^{28}/f^{49}, U238 capture is a dominant contributor for all systems. For the regular size assemblies there are also significant effects from U238 inelastic. Finally, for the small size assemblies depending on the fuel compositions important contributions are also due to U233, U235, Np237, and Pu239 reactions.

- For the coolant void worth, the major components are U238 and Na23 inelastic for ZPPR-2, ZPPR-9, ZPPR-10A, ZPR-6/7, ZPR-6/7 High Pu240, Na23 inelastic and U238 capture for ZPPR-15A, U235 capture and Na23 elastic for ZPR-6/6A, U238 inelastic and elastic for ZEBRA Assemblies 23 and 24, Na23 elastic for CIRANO ZONA2A, Fe56 and Na23 elastic for CIRANO ZONA2A3, CIRANO ZONA2B, COSMO and MUSE-4, Fe56 elastic and Na23 inelastic for ABR Metal and Na23 inelastic for ABR Oxide.

Sensitivity analysis of the selected experiments and target systems

Representativities between System Pairs with Respect to Multiplication Factor using AFCI-1.3 Data

System	ZPPR-2	ZPPR-9	ZPPR-10A	ZPPR-15A	ZPR-6 6A	ZPR-6 7	ZPR-6/7 Pu40	ZPR-3 53	ZPR-3 54	ZEBRA 22	ZEBRA 23	ZEBRA 24	ZEBRA 25	CIRANO Z2A	CIRANO Z2A3
ZPPR-2	1.000	0.960	0.970	0.961	0.353	0.991	0.990	0.821	0.377	0.963	0.976	0.935	0.950	0.958	0.867
ZPPR-9		1.000	0.999	0.963	0.348	0.986	0.988	0.738	0.172	0.964	0.962	0.958	0.961	0.877	0.743
ZPPR-10A			1.000	0.967	0.349	0.991	0.992	0.753	0.196	0.966	0.967	0.957	0.962	0.889	0.759
ZPPR-15A				1.000	0.344	0.971	0.973	0.705	0.244	0.975	0.972	0.969	0.972	0.907	0.807
ZPR-6/6A					1.000	0.352	0.352	0.228	0.130	0.377	0.379	0.369	0.372	0.341	0.316
ZPR-6/7						1.000	1.000	0.802	0.281	0.970	0.977	0.950	0.960	0.924	0.807
ZPR-6/7 Pu40							1.000	0.794	0.278	0.974	0.980	0.955	0.965	0.926	0.809
ZPR-3/53								1.000	0.429	0.733	0.767	0.685	0.719	0.791	0.680
ZPR-3/54									1.000	0.298	0.331	0.257	0.287	0.472	0.684
ZEBRA/22										1.000	0.998	0.993	0.996	0.941	0.845
ZEBRA/23											1.000	0.984	0.992	0.956	0.862
ZEBRA/24												1.000	0.998	0.908	0.814
ZEBRA/25													1.000	0.925	0.832
CIRANO Z2A														1.000	0.942
CIRANO Z2A3															1.000
CIRANO Z2B															
COSMO															
MUSE4															
Flattop Pu239															
Flattop U235															
Flattop U233															
Pu239 Jezebel															
Pu240 Jezebel															
U233 Jezebel															
GODIVA															
Np SPHERE															
BIGTEN															
ABR Metal															
ABR Oxide															

Sensitivity analysis of the selected experiments and target systems

Representativities between System Pairs with Respect to Multiplication Factor using AFCI-1.3 Data

System	CIRANO Z2B	COSMO	MUSE 4	Flattop Pu239	Flattop U235	Flattop U233	Pu239 Jezebel	Pu240 Jezebel	U233 Jezebel	GODIVA	Np SPHERE	BIGTEN	ABR Metal	ABR Oxide
ZPPR-2	0.754	0.768	0.757	-0.437	-0.272	-0.006	0.095	0.128	-0.005	-0.024	-0.001	0.685	0.799	0.765
ZPPR-9	0.608	0.626	0.613	-0.611	-0.350	-0.008	0.051	0.075	-0.007	-0.035	-0.004	0.813	0.828	0.782
ZPPR-10A	0.626	0.643	0.631	-0.591	-0.341	-0.008	0.054	0.080	-0.007	-0.033	-0.004	0.798	0.828	0.786
ZPPR-15A	0.691	0.707	0.695	-0.503	-0.305	-0.007	0.070	0.103	-0.006	-0.028	-0.002	0.744	0.848	0.787
ZPR-6/6A	0.279	0.283	0.279	-0.185	0.642	-0.001	0.000	0.000	0.000	0.780	0.478	0.624	0.290	0.264
ZPR-6/7	0.681	0.696	0.684	-0.511	-0.304	-0.007	0.076	0.105	-0.006	-0.028	-0.002	0.741	0.813	0.778
ZPR-6/7 Pu40	0.684	0.699	0.687	-0.519	-0.308	-0.007	0.074	0.106	-0.006	-0.029	-0.002	0.748	0.821	0.785
ZPR-3/53	0.572	0.581	0.573	-0.143	-0.132	-0.004	0.209	0.232	-0.003	-0.008	0.003	0.426	0.508	0.536
ZPR-3/54	0.777	0.767	0.777	0.154	0.042	0.001	0.143	0.151	0.001	0.007	0.002	-0.048	0.204	0.181
ZEBRA/22	0.730	0.745	0.733	-0.516	-0.285	-0.007	0.093	0.130	-0.006	-0.002	0.015	0.791	0.849	0.780
ZEBRA/23	0.747	0.762	0.750	-0.487	-0.270	-0.007	0.100	0.137	-0.006	0.001	0.016	0.766	0.840	0.779
ZEBRA/24	0.701	0.717	0.704	-0.562	-0.308	-0.008	0.079	0.113	-0.007	-0.008	0.012	0.823	0.858	0.776
ZEBRA/25	0.719	0.734	0.722	-0.540	-0.296	-0.007	0.085	0.120	-0.006	-0.005	0.014	0.806	0.854	0.780
CIRANO Z2A	0.849	0.860	0.848	-0.317	-0.216	-0.005	0.140	0.187	-0.005	-0.012	0.004	0.612	0.759	0.706
CIRANO Z2A3	0.977	0.981	0.976	-0.247	-0.179	-0.004	0.128	0.170	-0.004	-0.011	0.002	0.490	0.699	0.632
CIRANO Z2B	1.000	0.999	0.998	-0.178	-0.140	-0.003	0.117	0.154	-0.003	-0.010	0.000	0.375	0.614	0.543
COSMO		1.000	0.999	-0.194	-0.149	-0.003	0.115	0.152	-0.003	-0.011	0.000	0.393	0.640	0.569
MUSE4			1.000	-0.187	-0.144	-0.003	0.112	0.148	-0.003	-0.011	0.000	0.380	0.632	0.564
Flattop Pu239				1.000	0.452	0.008	0.414	0.417	0.007	0.067	0.023	-0.725	-0.564	-0.489
Flattop U235					1.000	0.013	0.000	0.000	0.014	0.869	0.512	-0.065	-0.325	-0.284
Flattop U233						1.000	0.000	0.000	0.979	0.013	0.008	-0.007	-0.007	-0.006
Pu239 Jezebel							1.000	0.951	0.000	0.000	0.000	0.000	0.018	0.023
Pu240 Jezebel								1.000	0.000	0.000	0.000	0.000	0.050	0.060
U233 Jezebel									1.000	0.016	0.010	-0.005	-0.006	-0.005
GODIVA										1.000	0.577	0.283	-0.038	-0.033
Np SPHERE											1.000	0.197	-0.002	-0.002
BIGTEN												1.000	0.709	0.623
ABR Metal													1.000	0.970
ABR Oxide														1.000

Due to the limitations of the computational tools in use or to the difficulties in the system modeling, sensitivity coefficients are often obtained via simplifications or approximations whose impact is not exactly known.

A specific study was been performed to address the impact on parameter sensitivities due to the most common approximations (such as transport effects, geometry modeling, group collapsing and the change in the flux distribution during depletion in the case of the burnup reactivity swing) used in the calculations by perturbation theory with deterministic codes. The nature of these effects was analyzed in connection with the features of the investigated systems.

Computational Tools

- For the analysis of the effects on parameter sensitivities due to transport theory, geometry modeling and group collapsing, the ERANOS code system was used. Cross sections were processed in 33 and 299 groups with the ECCO code using ENDF\B-VII nuclear data. Flux and importance functions were obtained with BISTRO.

- The analysis of burnup dependent parameters was performed with the depletion perturbation theory code DPT, based on the non-equilibrium and equilibrium fuel cycle analysis methodologies of REBUS-3 in diffusion theory and RZ geometry. The generalized adjoint flux equations were solved using DIF3D. Cross sections were processed with the MC^2-2 code using ENDF/B-VII nuclear data.

Investigation of Transport Effects

For the investigation of the transport effects on sensitivity coefficients, a small size assembly (FLATTOP Pu239), a standard size experimental core (CIRANO ZONA2B) and a large size sodium-cooled European Fast Reactor (EFR) have been analyzed. Since the goal of the present study is to investigate the impact on sensitivity coefficients, the analysis of CIRANO and EFR use simplified models in RZ geometry with homogenized compositions.

The FLATTOP Pu239 experiment consists of a spherical delta-phase plutonium core (4.5332 cm radius) reflected by normal uranium (24.142 cm radius). The Pu239 content in the Pu vector is about 95%.

In the CIRANO ZONA2B configuration, a PuO_2-UO_2 oxide core was cooled by sodium and surrounded by axial and radial reflector (core radius 45cm, Pu/(U+Pu) ~ 25%, Pu239 fraction in Pu ~ 77%, MA < 1%).

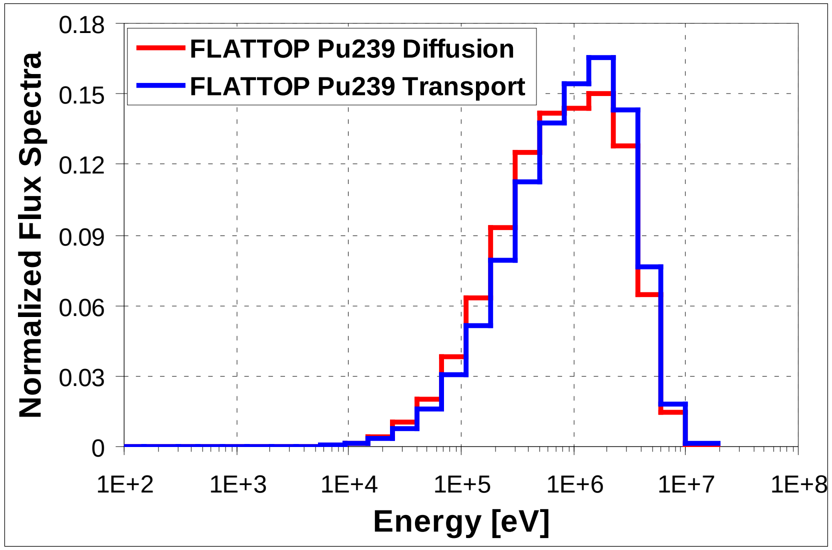
The large size sodium-cooled reactor considered in this study refers to the design of an EFR of 3600 MWth. The core is loaded with U-TRU fuel and is surrounded by axial and radial UO_2 blankets (core radius 2 m, Pu/(U+Pu) ~ 23%, Pu239 fraction in Pu ~ 57%, MA = 1.2%).

Transport effects on sensitivity coefficients have been investigated for the following integral parameters: multiplication factor and spectral index of U238 fission to Pu239 fission (f^{28}/f^{49}) at core center for the FLATTOP Pu239 experiment; and multiplication factor, spectral index f^{28}/f^{49} at core center and coolant void reactivity worth for CIRANO ZONA2B and EFR.

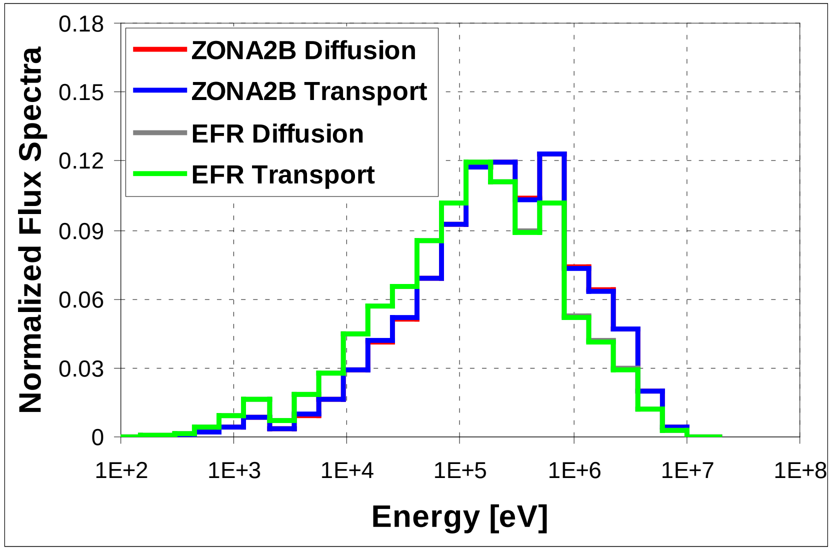
Investigation of Transport Effects

Calculated values for using diffusion and transport theory

Parameter	FLATTOP Pu239		CIRANO ZONA2B		EFR	
	Diffusion	Transport	Diffusion	Transport	Diffusion	Transport
k_{eff}	0.83811	0.98135	0.97349	0.98596	1.10398	1.10927
f^{28}/f^{49}	0.109	0.122	0.040	0.040	0.025	0.025
Na Void Worth	-	-	-1992 pcm	-1603 pcm	1962 pcm	1977pcm



Direct flux spectra at the core center of FLATTOP Pu239



Direct flux spectra at the core of CIRANO ZONA2B and EFR

Transport Effects [(a)] on Parameter Sensitivities

FLATTOP Pu239

Reaction	k_{eff}	f^{28}/f^{49}
U238 σ_c	-25.4%	-29.2%
U238 σ_f	-44.6%	0.8%
U238 ν	-40.1%	-31.3%
U238 σ_{el}	-42.0%	-17.7%
U238 σ_{inel}	-43.1%	1.2%
Pu239 σ_f	-0.2%	9.4%
Pu239 ν	7.3%	-16.5%
Pu239 σ_{el}	-16.9%	2988.9%
Pu239 σ_{inel}	-45.0%	347.6%
Overall [(b)]	-10.2%	-340.1%

CIRANO ZONA2B

Reaction	k_{eff}	f^{28}/f^{49}	Na Void Worth
U238 σ_c	0.1%	1.3%	27.7%
U238 σ_f	-0.3%	-0.1%	18.6%
U238 ν	0.9%		23.5%
U238 σ_{el}		-7.7%	-3.8%
U238 σ_{inel}		2.9%	419.6%
Pu239 σ_c	-0.3%	1.6%	27.3%
Pu239 σ_f	-0.4%	-0.9%	-14.5%
Pu239 ν	-0.1%		-80.5%
Pu240 σ_f	-0.4%		17.9%
Pu240 ν	0.3%		20.6%
Fe56 σ_{el}	-9.3%	-3.5%	2.5%
Fe56 σ_{inel}		3.9%	-45.6%
Cr52 σ_{el}			6.5%
Na23 σ_{el}		-3.3%	13.4%
Na23 σ_{inel}		5.6%	81.9%
O16 σ_{el}		-0.7%	-12.5%
Overall [(b)]	-1.7%	-2.0%	4.3%

EFR

Reaction	k_{eff}	f^{28}/f^{49}	Na Void Worth
U238 σ_c	-0.2%	-0.1%	0.1%
U238 σ_f	-0.7%	0.0%	
U238 ν	-0.4%		-2.2%
U238 σ_{inel}	0.7%	0.3%	0.5%
Pu239 σ_c	0.2%	0.3%	-0.5%
Pu239 σ_f	-0.1%	-0.2%	0.0%
Pu239 ν	0.0%		-0.2%
Pu240 σ_c	0.2%		-0.4%
Pu240 σ_f	-0.1%		
Pu240 ν	0.1%		0.4%
Pu241 σ_f	-0.1%		-0.1%
Pu241 ν	0.0%		-0.2%
Fe56 σ_{inel}		0.3%	1.2%
Na23 σ_{el}			1.4%
Na23 σ_{inel}		-0.7%	0.9%
O16 σ_{el}	-0.1%	0.3%	-0.6%
Overall [(b)]	-0.6%	-3.7%	-0.1%

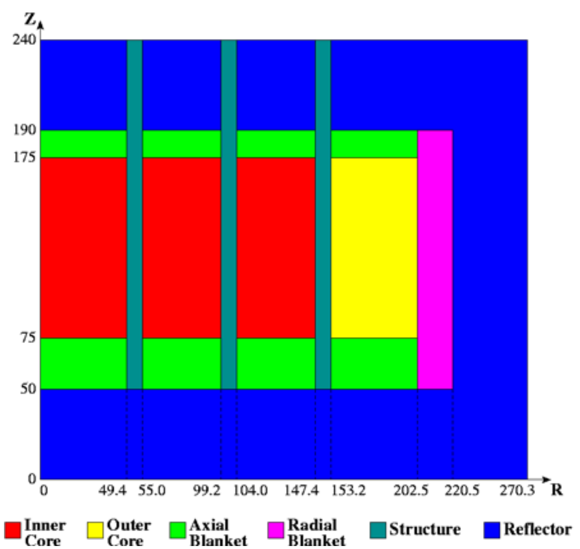
[(a)] with S = Sensitivity Value: $(S_{transport} - S_{diffusion}) / S_{diffusion}$

[(b)] Effect on overall (total) sensitivity due to all cross sections

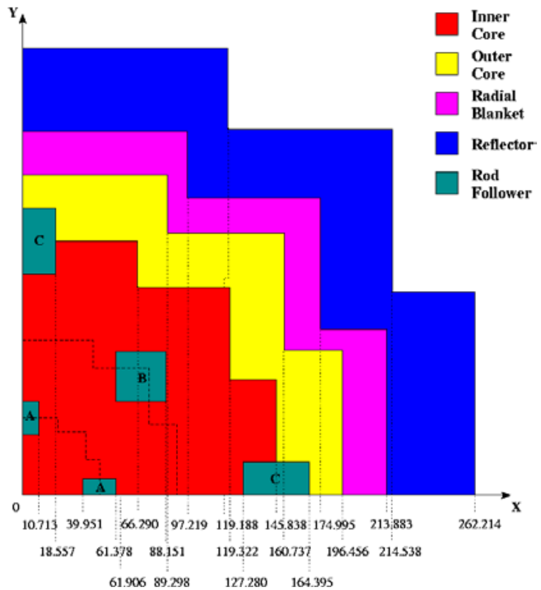
Effects of Geometry Modeling on Sensitivity Coefficients

Due to the limitations imposed by the codes in use or by the computational cost, or just for user's choice, sensitivity coefficients are often calculated using simplified models in RZ geometry.

We investigated the impact on sensitivity coefficients of selected parameters when a RZ model is adopted instead of an original 3D model. For this purpose, an XYZ geometry model has been opportunely built for the EFR reactor. *Note that the purpose of this analysis is only to investigate the dependence of sensitivity coefficients on the adopted geometry model. As consequence, the adopted XYZ configuration has been derived from the RZ model only by preserving the volumes and without any correlation with the real reactor design.*



RZ Configuration of EFR



XYZ model of EFR

Effects on Sensitivities due to Geometry Modeling

Nominal Values of EFR Parameters Using Diffusion Theory

k_{eff}		Control Rod Worth [a] [pcm]	
RZ	XYZ	RZ	XYZ
1.10398	1.10828	-3485	-1241

Geometry Modeling Effects [b] on Sensitivity Coefficients of EFR Parameters

Reaction	k_{eff}	Control Rod Worth	Reaction	k_{eff}	Control Rod Worth
U238 σ_c	-0.1%	157.1%	Pu241 ν	-0.4%	-45.2%
U238 σ_f	0.7%	2.8%	Fe56 σ_c		296.1%
U238 ν	1.0%	-3.1%	Fe56 σ_{el}		471.3%
U238 σ_{el}		221.8%	Fe56 σ_{inel}		-85.1%
U238 σ_{inel}	1.4%	-164.7%	Cr52 σ_{el}		535.6%
Pu239 σ_c	-0.9%	58.9%	Ni58 σ_{el}		218.9%
Pu239 σ_f	-0.2%	-15.1%	Na23 σ_{el}		-1067.9%
Pu239 ν	-0.2%	-6.3%	C σ_{el}		-51.3%
Pu240 σ_c	-0.6%	36.8%	O16 σ_{el}	0.6%	511.4%
Pu240 σ_f	0.1%	32.4%	B10 σ_c		-44.0%
Pu240 ν	0.2%	44.7%	B11 σ_{el}		-49.4%
Pu241 σ_f	-0.4%	-42.4%	Overall [c]	-0.1%	95.9%

[a] First and third rings of B_4C rods inserted up to core midplane

[b] With S = Sensitivity Value: $(S_{xyz} - S_{rz}) / S_{rz}$

[c] Effect on overall (total) sensitivity due to all cross sections

Effects of Group Collapsing on Sensitivity Coefficients

The existence of spectral effects at core-reflector interfaces is a well-known phenomenon which affects calculations of fast reactors when using a deterministic code system. In fact, the neutrons escaping from the core at high energies enter the reflector where they are slowed down by scattering. Some of these neutrons escape capture and return to the core with lower energies. As consequence, important transients arise at the interface of the two regions.

Recent studies showed that the conventional procedures for cross sections condensation over a small number of energy groups (as the standard 33 group structure) are not suitable for accurately describing the slowing-down of the neutrons reflected in the core and a poor agreement with reference continuous energy (Monte Carlo) solutions is generally found for parameters like reactivity and reaction rate distributions. On the contrary, satisfactory results can be achieved if the cross sections are collapsed over higher numbers (at the least 300) of energy groups.

We investigated the impact of the group collapsing on sensitivity coefficients rather than nominal values of integral parameters.

The analysis is performed for the multiplication factor and the ratio of Pu239 fission rates (f^{49}) at the locations (r,z) = (37.5 cm, 100.5 cm) and (r,z) = (52.5 cm, 100.5 cm) of CIRANO ZONA2B.

Effects on Parameter Sensitivities due to Group Collapsing

Nominal Values of CIRANO ZONA2B Parameters Using Diffusion Theory

k_{eff}		f^{49} (37.5cm/52.5cm)	
33 Gr.	299 Gr.	33 Gr.	299 Gr.
0.98596	0.99957	0.356	0.375

Effects of Group Collapsing [a] on Sensitivity Coefficients of CIRANO ZONA2B Parameters

Reaction	k_{eff}	f^{49} (37.5/52.5cm)	Reaction	k_{eff}	f^{49} (37.5/52.5cm)
U238 σ_c	1.8%		Fe56 σ_{el}	-10.2%	-6.9%
U238 σ_f	-2.3%		Fe57 σ_{el}		7.0%
U238 ν	-1.4%		Cr52 σ_c		-1.9%
U238 σ_{el}		-5.2%	Cr52 σ_{el}		10.4%
Pu239 σ_c	2.7%		Ni58 σ_c		-8.1%
Pu239 σ_f	-0.5%		Ni58 σ_{el}		-24.6%
Pu239 ν	0.2%		Na23 σ_{el}		19.9%
Pu240 σ_f	-1.6%		O16 σ_{el}		-1.8%
Pu240 ν	-1.0%		Mo95 σ_c		-14.8%
Fe54 σ_{el}		4.1%	Mn55 σ_c		2.7%
Fe56 σ_c		-7.7%	Mn55 σ_{el}		19.4%
			Overall [b]	-1.2%	-2.7%

[a] With S = Sensitivity Value: $(S_{collapsed\_33gr} - S_{standard\_33gr}) / S_{standard\_33gr}$

[b] Effect on overall (total) sensitivity due to all cross sections

Investigation of the accuracy of the methodologies for computing sensitivity coefficients – Sensitivity of Burnup Dependent Parameters

By depletion perturbation theory the sensitivity coefficients for a multiplication factor, k, are obtained according to the general formulation:

$$S_k = \left(\frac{\delta k}{\delta \sigma} \cdot \frac{\sigma}{k}\right) = \frac{\sigma}{k}\left(\overset{\substack{\text{Direct “Static” Term} \\ \Downarrow}}{\frac{\partial k}{\partial \sigma}} + \underset{\substack{\Uparrow \\ \text{Density Term}}}{\frac{\partial k}{\partial N}\frac{\partial N}{\partial \sigma}} + \overbrace{\frac{\partial k}{\partial \Phi}\frac{\partial \Phi}{\partial \sigma} + \frac{\partial k}{\partial \Phi^*}\frac{\partial \Phi^*}{\partial \sigma}}^{\text{Flux Term}} + \underset{\substack{\Uparrow \\ \text{Power Term}}}{\frac{\partial k}{\partial P}\frac{\partial P}{\partial \sigma}}\right)$$

- Direct term, $\frac{\sigma}{k} \cdot \frac{\partial k}{\partial \sigma}$: explicit derivative of the response parameter with respect to cross sections;
- Nuclide density term, $\frac{\sigma}{k}\left(\frac{\partial k}{\partial N}\frac{\partial N}{\partial \sigma}\right)$: variation of the response through the nuclide transmutation rate changes;
- Flux term, $\frac{\sigma}{k}\left(\frac{\partial k}{\partial \Phi}\frac{\partial \Phi}{\partial \sigma} + \frac{\partial k}{\partial \Phi^*}\frac{\partial \Phi^*}{\partial \sigma}\right)$: variation of the response during burnup through the changes in flux distribution in space and energy for fixed flux level;
- Power terms, $\frac{\sigma}{k}\left(\frac{\partial k}{\partial P}\frac{\partial P}{\partial \sigma}\right)$: variation of the response during burnup through the changes in flux level for given power level.

Investigation of the accuracy of the methodologies for computing sensitivity coefficients – Sensitivity of Burnup Dependent Parameters

In the case of the BOC multiplication factor, only the direct ("static") term is to be determined.

The sensitivity coefficients for a burnup reactivity swing, $\Delta\rho = -\frac{1}{k_{EOC}} + \frac{1}{k_{BOC}}$, are obtained as:

$$S_{\Delta\rho} = \frac{\partial(\Delta\rho)}{\partial\sigma}\cdot\frac{\sigma}{\Delta\rho} \quad = \quad \frac{1}{\Delta\rho}\left(\frac{1}{k_{EOC}}S_{k_{EOC}} - \frac{1}{k_{BOC}}S_{k_{BOC}}\right)$$

Breakdown of DPT Sensitivities for the Burnup Reactivity Swing of EFR ($\Delta\rho_{1700\ days}$ = -9621 pcm)

Reaction	Direct Term	Density Term	Flux Terms	Power Term	Overall
U238 σ_c		-3.056	0.391	-0.026	-2.666
U238 σ_f	-0.081	0.081		-0.118	-0.130
U238 ν	-0.072				-0.084
U238 σ_{el}	0.058				0.051
U238 σ_{inel}	0.058		-0.184		-0.125
Pu239 σ_c		0.522	0.066		0.554
Pu239 σ_f	-0.534	3.234	0.175	-0.685	2.191
Pu239 ν	-0.382				-0.394
Pu240 σ_c		-0.415	0.039		-0.372
Pu240 σ_f	-0.110	0.195		-0.090	0.006
Pu240 ν	-0.115				-0.109
Pu241 σ_f	-0.320	0.439		-0.071	0.080
Pu241 ν	-0.393				-0.380
Na23 σ_{el}	0.095		-0.054		0.041
O16 σ_{el}	0.250		-0.280		-0.031
Overall	-1.351	1.054	0.104	-1.049	-1.242

Transport Effects on Uncertainty Components (%) of some of Most Relevant Reaction

Reaction	k_{eff} FLATTOP Pu239		Reaction	f^{28}/f^{49} FLATTOP Pu239		Reaction	Coolant Void Worth CIRANO ZONA2B	
	Diffusion	Transport		Diffusion	Transport		Diffusion	Transport
U238 σ_{el}	0.88i	0.42i	U238 σ_{el}	0.15	0.32i	U238 σ_{inel}	1.95	3.43
U238 σ_{inel}	1.28	0.82	Pu239 σ_{inel}	0.83	1.79	Fe56 σ_{el}	5.42	5.78
Overall	1.08	0.81	Overall	1.15	1.93	Overall	8.09	9.48

Geometry Modeling Effects on Uncertainty Components (%) of some of Most Relevant Reaction

Reaction	Control Rod Worth EFR	
	RZ Diffusion	XYZ Diffusion
U238 σ_{inel}	1.64	0.25
Fe56 σ_{el}	0.29	1.28
O16 σ_{el}	0.12	0.72
Overall	1.93	2.01

Group Collapsing Effects on Uncertainty Components (%) of some of Most Relevant Reaction

Reactions	f^{49} 37.5 cm to 52.5 cm CIRANO ZONA2B	
	33Gr. Stand.	33Gr. Collap.
Fe56 σ_c	1.17	1.09
Fe56 σ_{el}	3.49	3.39
Ni58 σ_{el}	0.50	0.35
Overall	3.99	3.90

AFCI-1.3 data are used for all parameters.

DPT Uncertainty Components (%) for the Burnup Reactivity Swing of EFR

Reactions	Direct Term	Density Term	Flux Terms	Power Term	Overall
U238 σ_c		4.38	0.61		3.78
U238 σ_{inel}	0.69		2.14		1.45
Pu238 σ_f	0.49			0.41	0.22
Pu239 σ_c		2.71			2.91
Pu239 σ_f				0.27	0.89
Pu240 σ_c		1.73			1.60
Overall	1.42	5.74	2.56	0.52	5.52

Testing of AFCI Covariance Data

AFCI Covariance Matrix

Versions	AFCI-1.0	AFCI-1.1	AFCI-1.2	AFCI-1.3
Release Date	November 2008	May 2009	August 2009	April 2010
Isotope/Reaction updated with respect to the previous version	-	Pu239 (only ν), Fe56, Cr50, Ni58, C, O, Na23, B10, Zr90 and Mn55	U235 capture, Pu239 ν and structural materials (Cr, Fe, Ni, Pb, Bi); 14 MAs were updated by Maslov review; Missing correlation matrices were recovered.	U233, U234, U235, U236, U238, Np237, Pu238, Pu239, Pu240, Pu241, Pu242, Am243, Cm242, Cm244, Fe54, Fe56, Cr52, Ni58, Na23, Mn55

All AFCI matrices have been tested by performing the uncertainty estimation of the main integral parameters (multiplication factor, power peaking factor, Doppler reactivity coefficient, coolant void reactivity worth and burnup reactivity swing) of a series of fast reactors (ABR metal core, ABR oxide core, SFR, EFR, GFR, LFR, ADMAB).

Features of the Investigated Systems

System	Coolant	Fuel Type	%TRU in (U+TRU)	% MA[a] in (U+TRU)	Power [MW_{th}]
ABR Metal Core	Na	Metal	18.5 – 24.2 [b]	1.5 – 2.2 [b]	1000
ABR Oxide Core	Na	MOX	23.2 – 37.1[b]	2.2 – 4.1 [b]	1000
SFR	Na	Metal	60.5	10.6	840
EFR	Na	MOX	23.7	1.2	3600
GFR	He	Carbide	21.7	5.0	2400
LFR	Pb	Metal	23.3	2.4	900
ADMAB	LBE	Nitride	100	68.0	380

[a] MA: Minor Actinides;

[b] Inner Core – Outer Core.

Total Nuclear Data Uncertainties (%) for Sodium Cooled Fast Neutron Systems

Reactor		Multiplication Factor	Power Peaking Factor	Doppler Coefficient	Coolant Void Worth	Burnup Reactivity Swing [a]
ABR Metal [b]	BOLNA	1.47			13.10	
	AFCI1.2	1.54			10.32	
	AFCI1.3	1.34			13.07	
ABR Oxide [b]	BOLNA	1.44			7.82	
	AFCI1.2	1.49			5.60	
	AFCI1.3	1.19			6.17	
SFR	BOLNA	1.86	0.45	5.57	17.11	4.59
	AFCI1.2	2.16	0.22	6.88	14.02	5.11
	AFCI1.3	1.81	0.30	6.62	14.29	4.38
EFR	BOLNA	1.27	1.18	3.80	7.83	7.29
	AFCI1.2	1.29	1.01	4.03	5.40	6.36
	AFCI1.3	1.14	1.09	3.84	5.97	5.52

[a] Sensitivity coefficients calculated with the Depletion Perturbation Theory implemented in the ANL code REBUS3-DPT;
[b] Sensitivity coefficients determined with DIF3D/VARI3D code;
Sensitivity coefficients of all other parameters were determined in the Sg26 activities with the ERANOS/BISTRO code.

Total Nuclear Data Uncertainties (%) for Fast Neutron Systems

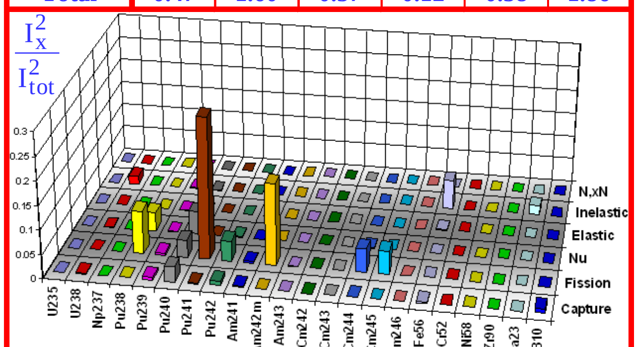
Reactor		Multiplication Factor	Power Peaking Factor	Doppler Coefficient	Coolant Void Worth	Burnup Reactivity Swing [a]
GFR	BOLNA	1.89	1.68	5.51	7.67	35.99
	AFCI1.2	1.95	1.71	5.44	6.75	35.33
	AFCI1.3	1.74	1.69	5.02	6.53	25.63
LFR	BOLNA	1.40	0.64	4.35	7.18	8.61
	AFCI1.2	1.67	0.58	6.20	9.81	9.52
	AFCI1.3	1.43	0.59	6.24	9.71	6.89
ADMAB	BOLNA	2.90	21.42	-	15.49	
	AFCI1.2	2.46	17.99	-	13.89	
	AFCI1.3	2.23	16.37		13.86	

[a] Sensitivity coefficients calculated with the Depletion Perturbation Theory implemented in the ANL code REBUS3-DPT; Sensitivity coefficients of all other parameters were determined in the Sg26 activities with the ERANOS/BISTRO code.

Uncertainty Breakdown

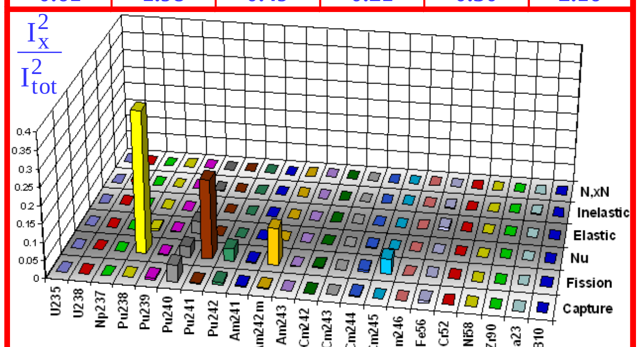
SFR k_{eff}: BOLNA Uncertainties (%) by Isotope

Isotope	σ_{capt}	σ_{fiss}	ν	σ_{el}	σ_{inel}	Total
U238	(a)				0.24	**0.26**
Pu238		0.56	0.36			**0.67**
Pu239	0.13	0.13				**0.20**
Pu240	0.33	0.35	0.41			**0.63**
Pu241	0.06	1.01				**1.01**
Pu242	0.18	0.38				**0.43**
Am241	0.07	0.09				**0.11**
Am242m	0.05	0.77				**0.77**
Cm242		0.04				**0.04**
Cm244	0.04	0.41	0.08			**0.42**
Cm245		0.41				**0.41**
Fe56	0.10			0.09	0.46	**0.48**
Cr52				0.05		**0.06**
Na23					0.26	**0.26**
B10	0.18					**0.18**
Total	**0.47**	**1.60**	**0.57**	**0.12**	**0.58**	**1.86**



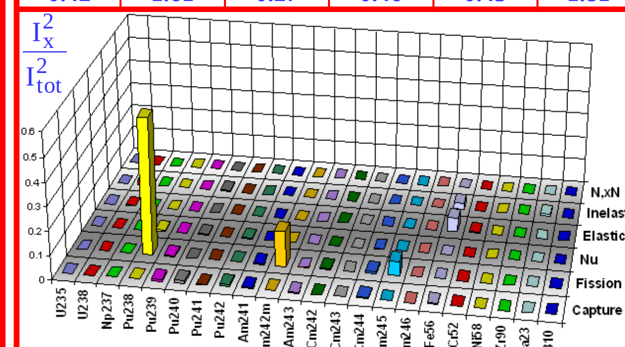
SFR k_{eff}: AFCI1.2 Uncertainties (%) by Isotope

Isotope	σ_{capt}	σ_{fiss}	ν	σ_{el}	σ_{inel}	Total
U238					0.25	**0.26**
Pu238		1.36	0.16			**1.37**
Pu239	0.13	0.13				**0.21**
Pu240	0.46	0.38	0.42			**0.73**
Pu241	0.12	1.02				**1.02**
Pu242	0.20	0.40				**0.46**
Am241	0.11	0.10				**0.16**
Am242m	0.10	0.69				**0.70**
Cm242		0.12				**0.12**
Cm244	0.13	0.15	0.12			**0.23**
Cm245		0.43				**0.44**
Fe56	0.17			0.19	0.08	**0.27**
Cr52				0.02		**0.03**
Na23					0.11	**0.12**
B10	0.02					**0.02**
Total	**0.61**	**1.98**	**0.49**	**0.21**	**0.30**	**2.16**

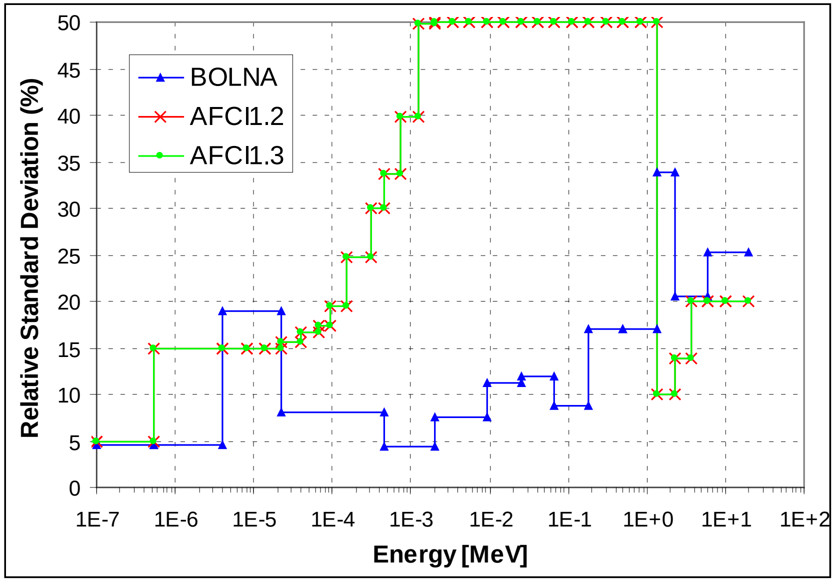


SFR k_{eff}: AFCI1.3 Uncertainties (%) by Isotope

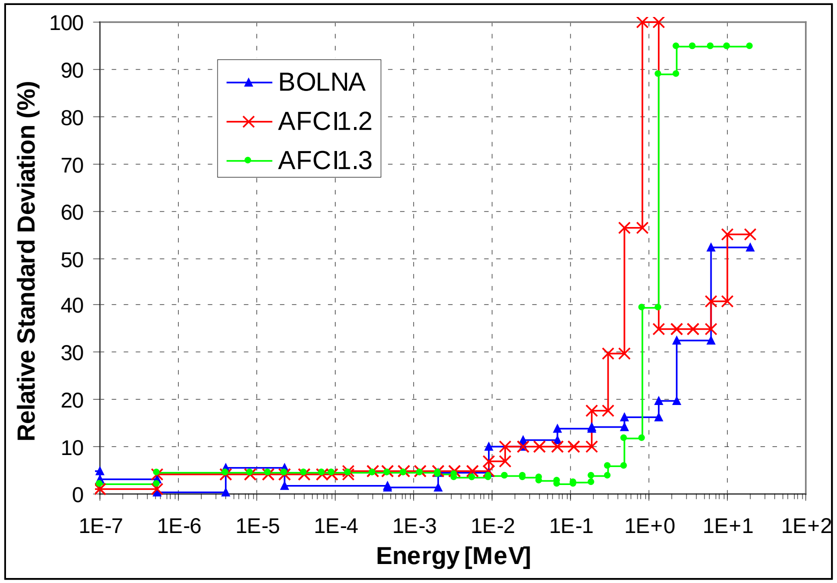
Isotope	σ_{capt}	σ_{fiss}	ν	σ_{el}	σ_{inel}	Total
U238					0.25	**0.26**
Pu238		1.36	0.16			**1.37**
Pu239	0.13	0.13				**0.21**
Pu240	0.19	0.09	0.11			**0.28**
Pu241	0.12	0.06				**0.14**
Pu242	0.19	0.08				**0.22**
Am241	0.11	0.10				**0.16**
Am242m	0.10	0.69				**0.70**
Cm242		0.12				**0.12**
Cm244	0.13	0.15	0.12			**0.23**
Cm245		0.43				**0.44**
Fe56	0.15			0.43	0.30	**0.55**
Cr52				0.12		**0.12**
Na23					0.16	**0.16**
B10	0.02					**0.02**
Total	**0.42**	**1.61**	**0.27**	**0.46**	**0.45**	**1.81**



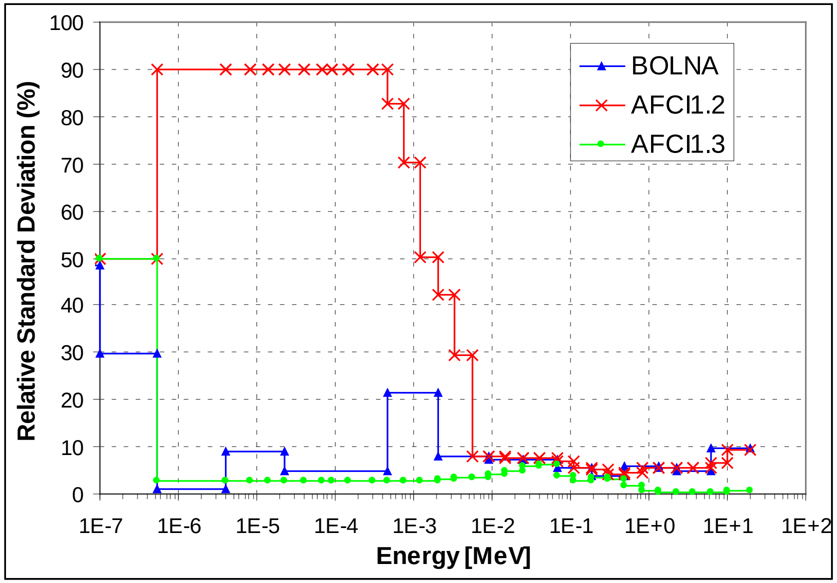
[a] **Contribution nul or less than 0.1%**



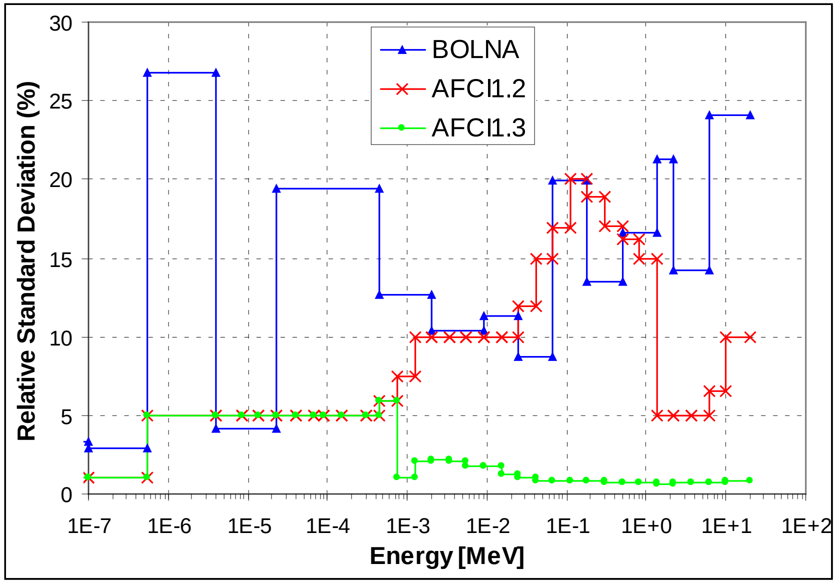
Pu238 Fission



Pu240 Capture



Pu240 Fission



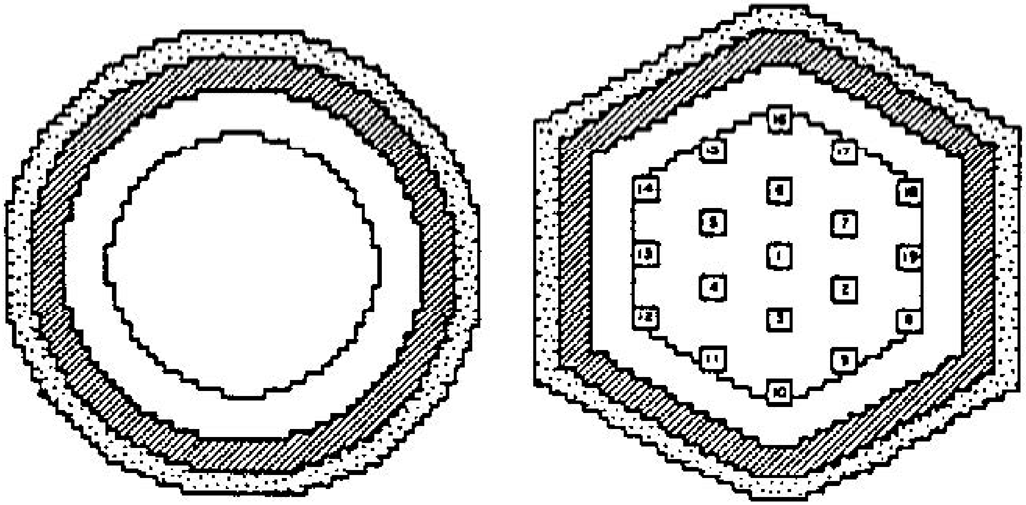
Pu241 Fission

High Fidelity "as-built" Models for ANL ZPR Experiments

- Preserve and Add Value to Legacy LMFBR Experiments
  - Experiments performed decades earlier
  - Large Engineering Benchmark Assemblies in support of LMFBR Program
  - Used to validate "legacy" methods and data, and <u>therefore</u>
  - Experiments were Modeled and reported consistent with those legacy methods, e.g.,
    - One-dimensional Unit Cells
    - Homogenized Regions
- Minimize the Introduction of Methods and Modeling Biases and Uncertainties

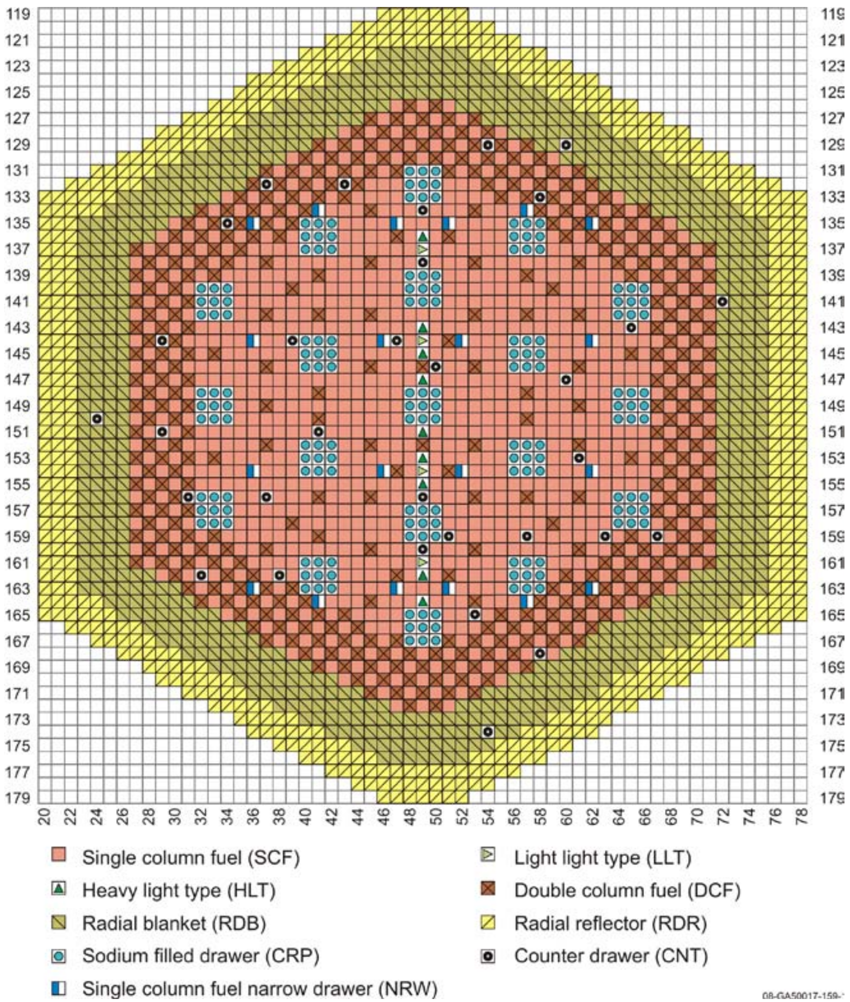
The Jupiter-I Program - Cooperative US/Japan Study of 650 MWe Conventional LMFBR Design

- ZPPR-9
  - Clean, Cylindrical Two-Zone Physics Benchmark
- ZPPR-10A
  - Hexagonal Two-Zone Engineering Assembly with 19 CRP's



ZPPR–9 ZPPR–10A

ANL ZPPR Assembly 10A



- This experiment (performed in late 1978) was a 650 MWe-class sodium-cooled MOX-fueled LMFBR core mock-up critical experiment with two homogenous zones with control rods (CRs) or control rod positions (CRPs) filled with sodium
- Detailed (i.e., exact "as-built") Monte Carlo models were generated corresponding to the subcritical reference configuration plus an extensive series of large zone sodium voided configurations plus an extensive series of control rod and control rod channel configurations of ZPPR-10A

ZPPR-10A Loading and “As-Built” Models

- For example, Loading 7 contained:
  - > 12,000 Pu-U-Mo plates
  - ~ 50,000 Na cans
  - ~ 15,000 Na_2CO_3 cans
  - > 175,000 Depl U_3O_8 plates
  - ~ 140,000 DU plates
  - ~ 45,000 Fe_2O_3 plates
  - ~12,000 SST plates

Loading	Cells/DMs	Compositions	MCNP lines
7	149	165	43623
12	149	165	43623
13	155	181	44979
15	157	181	45405
26	155	181	45047
29	157	181	45405
31	153	165	44463
33	168	174	48868
34	169	174	49289
37	169	174	49503
40	169	182	49077

Summary and Future Work - ANL

- Sensitivity/uncertainty analysis has been performed for the selected experiments
  - Static sensitivity analysis for total 128 integral parameters of 27 experiments
  - Burnup-dependent sensitivity analysis for 14 measurements in the PROFIL-1, PROFIL-2 and TRAPU irradiation experiments
  - This activity will be continued for an extended set of experiments integral measurements (reactivity coefficients, reaction rate traverses, etc.)
- A formal data adjustment procedure based on the Bayesian method will be applied to quantify the uncertainties of predicted reactor performance parameters with full application of integral experiment values
  - The cross section adjustment code GMADJ of ANL will be modified to be applicable on modern computer environments and the methods of GMADJ will be improved as needed
  - This activity will also support the participation in the cross section adjustment exercise of the OECD/NEA WPEC Subgroup 33