Analysis of Reaction Rate Distribution Measurements in ZPR-6 Assembly 7 Cores with MC^2-3/UNIC Code System

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International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C 2011)

May 9, 2011

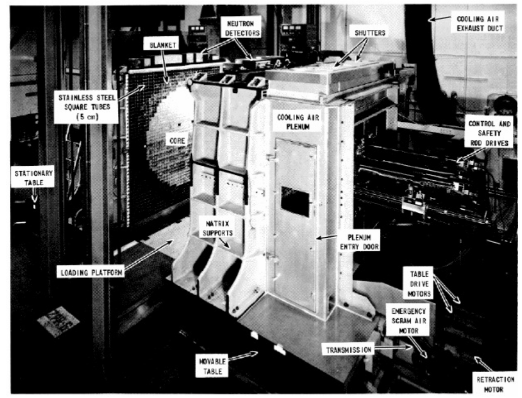
Objective

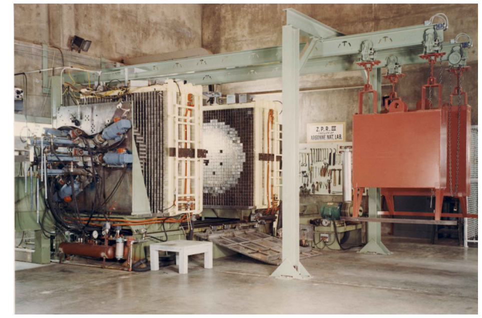
Under the DOE's NEAMS program, the high-fidelity deterministic neutron transport code UNIC and the fast spectrum cross section generation code MC^2-3 are being developed.

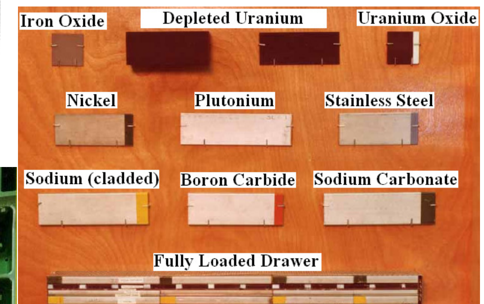
As part of the verification and validation efforts, radial traverses of ^{235}U fission, ^{238}U capture, ^{238}U fission, and ^{239}Pu fission reaction rates measured with activation foils in Loadings 104, 106, 120 and 132 of the ZPR-6 Assembly 7 (ZPR-6/7) high ^{240}Pu core are analyzed.

Description of Experiment: ZPR-6 Facility

The ZPR-6 fast critical facility was a horizontal split-table type machine consisting of a large, cast-steel bed supporting two tables, one stationary (S) and the other movable (M).







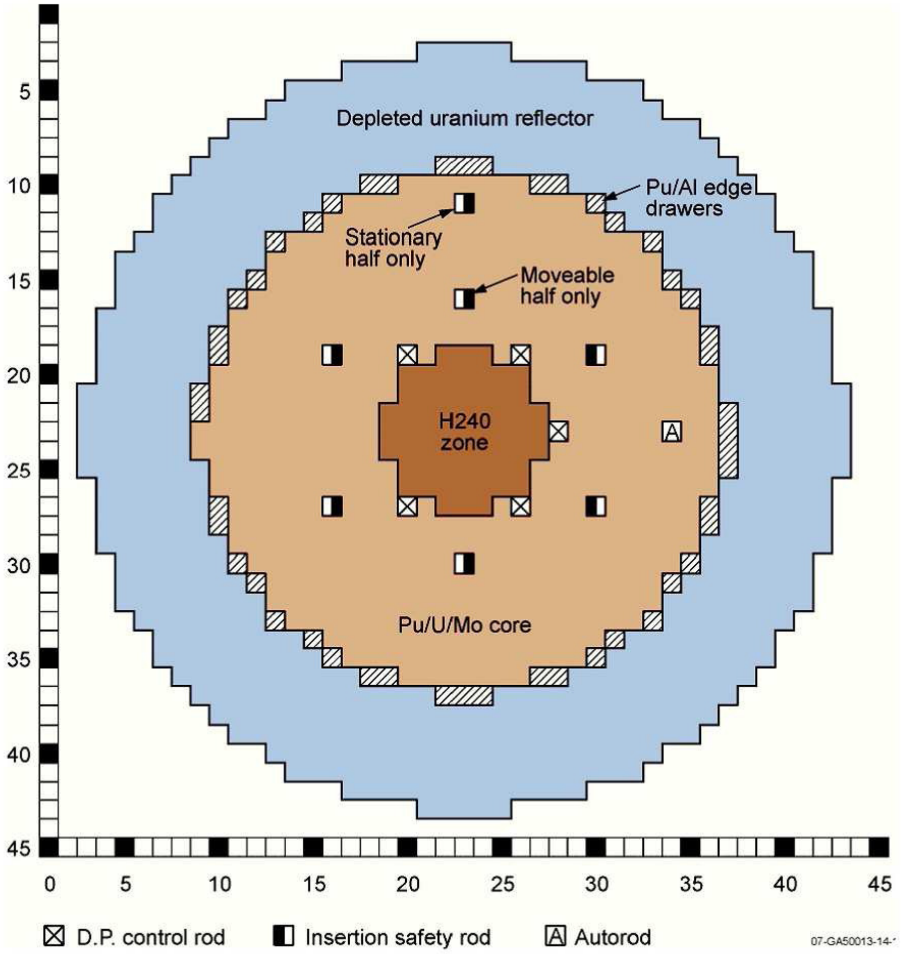
Stainless steel square tubes were stacked horizontally on both tables to form a 45-row and 45-column square matrix.

The desired average composition in a region was achieved by loading the matrix with drawers containing rectangular plates of different materials. In ZPR 6-7, the focus was on using depleted uranium, plutonium, stainless steel, and sodium to simulate a typical SFBR.

Description of Experiment: ZPR-6 Assembly 7

ZPR-6 Assembly 7 (ZPR-6/7) encompassed a series of experiments performed at the ZPR-6 facility at Argonne National Laboratory in 1970 and 1971 to test fast reactor physics data and methods as part of the Demonstration Reactor Benchmark Program.

Plutonium in Pu-U-Mo fuel plates in the core contained 11% ^{240}Pu. In the high ^{240}Pu core, all Pu-U-Mo plates in the inner core region were replaced by Pu-U-Mo plates containing 27% ^{240}Pu in the plutonium component in order to construct a central core zone with a composition closer to that in a Liquid Metal Fast Breeder Reactor (LMFBR) core with high burnup.



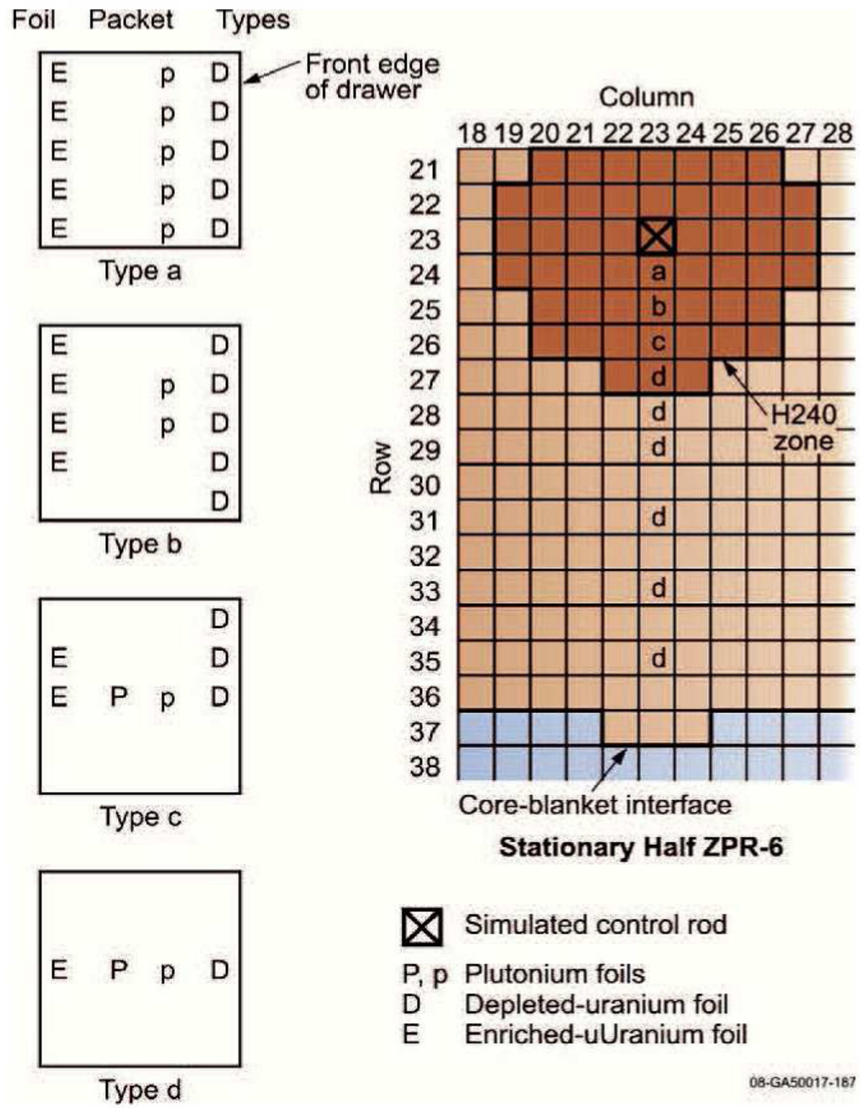
Reference ZPR-6/7 High ^{240}Pu Configuration

Description of Experiment: Foils

Foils were placed in column 23 below the central position and irradiated in order to measure radial traverses of specific reaction rates.

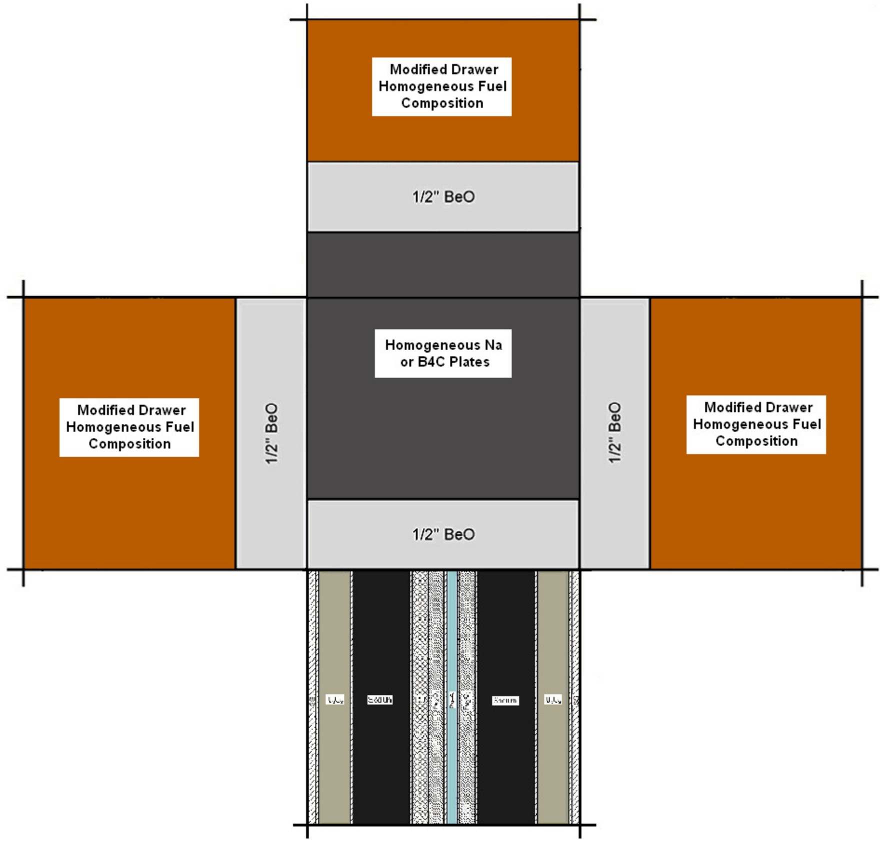
Four types of foils (designated as E, D, p, P) were used to measure relative reaction rates of Enriched Uranium fission (EU f) using E-type foils; Depleted Uranium capture (DU c) and fission (DU f) using D type foils, and ^{239}Pu fission (Pu49 f) using p- and P-type foils.

These foils were placed in 2-inch square packets and the packets were placed in the fronts of the drawers of the stationary half to form a continuous radial traverse of each foil type.



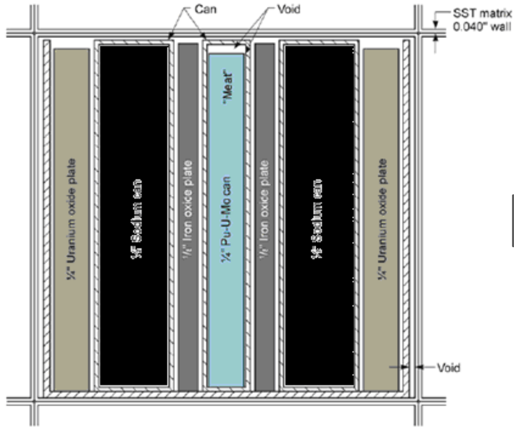
Description of Experiment: ZPR-6/7 Loadings for Foil Irradiation Measurements

Loading 104 – Drawers containing only sodium plates were loaded into S/M-23/23 of the reference high ^{240}Pu loading to simulate a withdrawn control rod.
Loading 106 – Same as Loading 104 except that 0.5-inch-thick BeO plates were placed at the bottom of the central sodium drawer and in all adjacent drawers to the central sodium channel.
Loading 120 – Same as Loading 104 except that the sodium channel was removed from S/M-23/23 and was replaced by drawers simulating a mockup B_4C control rod.
Loading 132 – The central sodium channel of Loading 106 was removed and the mockup B_4C simulated control rod used in Loading 120 was reinserted in the S/M-23/23 central position. The drawers containing BeO plates remained the same.

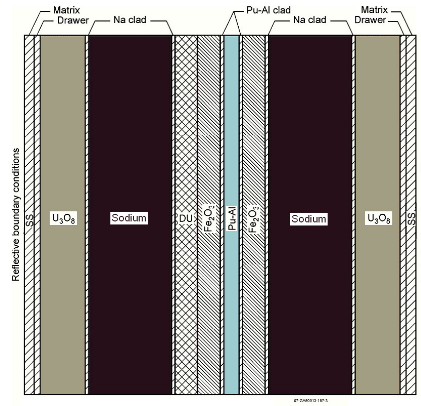


Modifications to S/M-23/23 and the Four Adjacent Drawers with Heterogeneous BeO Ring Present

Solution Methodology



Exact Drawer Geometry



One Dimensional MC^2-3 Model

(1) MC^2-3 was used to generate effective, homogenized-drawer, 70-group microscopic cross sections using “equivalent” one-dimensional plate geometries.

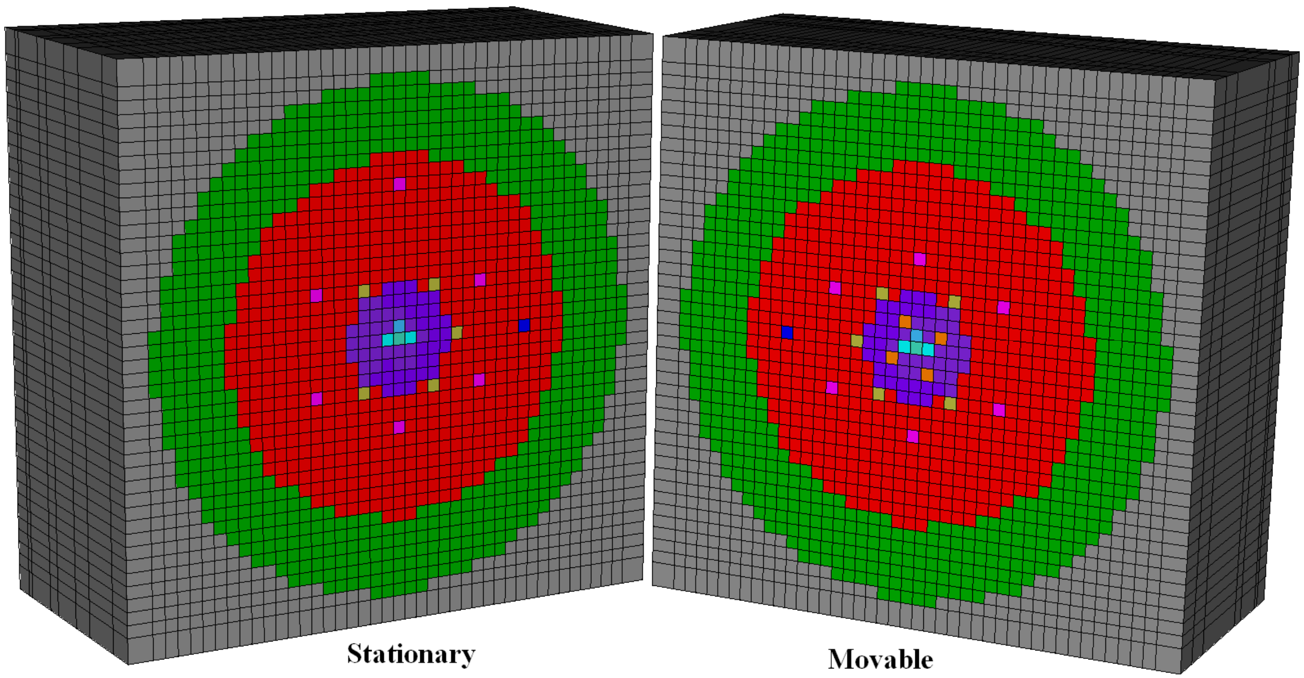
(2) These cross sections were then used in full-core UNIC calculations with the SN2ND discrete ordinates solver.

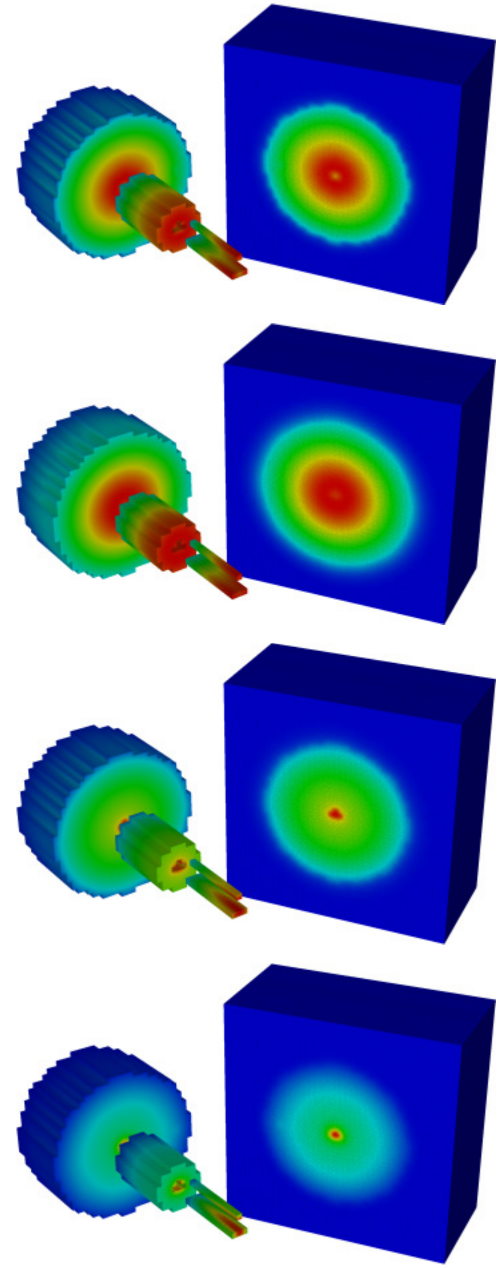
(3) The SN2ND fluxes from step 2 were superimposed with foil cross sections calculated in step 1 to reconstruct foil reaction rates according to the equation

$$RR_{\alpha}(\vec{r}_0) = \sum_{g=1}^{70} \overline{\sigma}_{\alpha,g}^{lattice}(\vec{r}_0)\,\varphi_g^{core}(\vec{r}_0)$$

for a type α reaction of a foil located at $\vec{r}_0$.

MC²-3+SN2ND Modeling; Global Gradients





- Typical Homogenized Drawer Model of ZPR-6/7 **L106**
  - 10-14.2 MeV, 0.39-0.50 MeV, 7.1-9.1 keV, 214-275 eV
  - High energy flux depression visible
  - Low energy flux peak visible
  - Strong axial dependence associated with BeO

Numerical Results: Homogeneous Drawer Models

BeO ring was homogenized with the material at the central position, i.e., with sodium in Loading106 and with B_4C in Loading 132

Eigenvalues

ZPR6-7 Loadings 104, 106, 120, and 132 Measured and Calculated Eigenvalues

Loading #	UNIC	MCNP	Experimental†
104	1.00147	1.00016 ± 0.00007	1.00072 ± 0.00002
106	1.00134	1.00049 ± 0.00007	1.00091 ± 0.00003
120	1.00127	0.99967 ± 0.00007	1.00099 ± 0.00003
132	1.00016	1.00040 ± 0.00007	1.00040 ± 0.00002

† Measurement uncertainty only, excluding composition and geometry uncertainties

Numerical Results: Homogeneous Drawer Models

Reaction Rates

C/E Values in % Error for Normalized Foil Reaction Rates for the First 5 Foil Locations

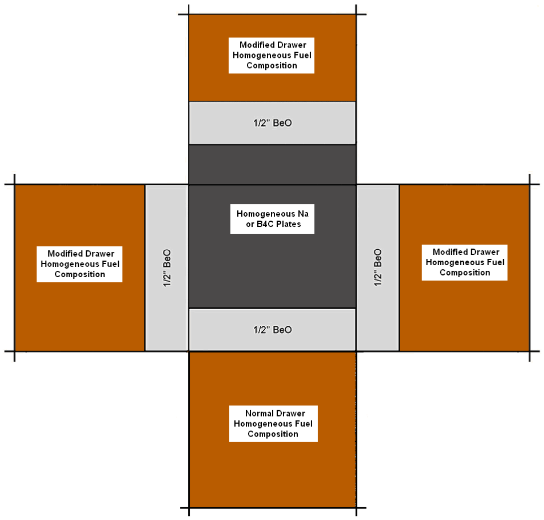
Foil location (cm)	Loading 104				Loading 106			
	EU f	DU c	DU f	Pu49 f	EU f	DU c	DU f	Pu49 f
3.53	2.60	-0.82	1.25	2.92	-4.83	-16.77	1.69	-5.50
4.55	2.62	0.58	-0.18	3.39	-2.70	-11.05	-1.09	-2.71
5.56	2.73	1.65	-0.34	3.03	-1.29	-6.53	-0.98	-1.01
6.58	2.84	1.79	0.42	3.01	-0.42	-4.64	-0.68	-0.01
7.60	2.61	0.48	1.33	2.40	-0.94	-4.61	0.23	-0.77
Foil location (cm)	Loading 120				Loading 132			
	EU f	DU c	DU f	Pu49 f	EU f	DU c	DU f	Pu49 f
3.53	0.25	0.39	1.18	2.64	-6.35	-13.16	1.84	-4.83
4.55	1.53	2.19	0.20	3.05	-3.81	-8.44	-0.53	-2.13
5.56	1.54	2.29	-0.05	2.91	-1.69	-4.50	-1.09	-1.01
6.58	1.85	1.85	0.11	2.23	-1.10	-3.37	-0.16	-0.79
7.60	1.81	1.27	1.86	2.79	-0.82	-3.68	0.86	-0.46

C/E % error values for All other foil locations are small (< 2%).

Numerical Results: Heterogeneous BeO Plate Models

Explicit modeling of the BeO ring using UNIC's unstructured mesh capability to capture the spectral shift effect induced by the plates on the reaction rates of the foils.

Fuel drawers and sodium or B_4C control rod central region still homogeneous.



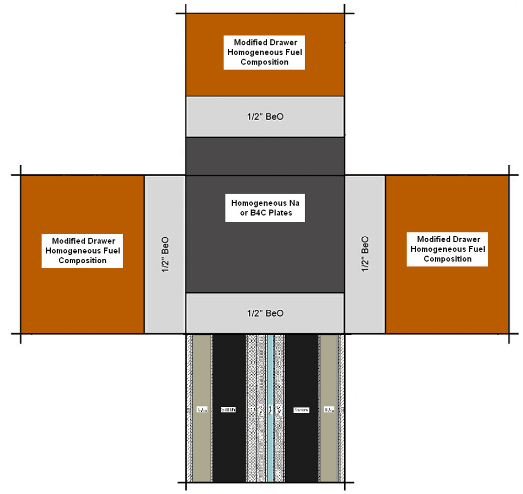
C/E Values in % Error for Normalized Foil Reaction Rates with Explicit BeO Ring for the First 5 Foil Locations

Foil location (cm)	Loading 106				Loading 132			
	EU f	DU c	DU f	Pu49 f	EU f	DU c	DU f	Pu49 f
3.53	3.75	-10.78	0.84	-0.31	3.19	-5.67	1.40	1.33
4.55	3.80	-6.51	-1.31	1.25	2.86	-3.18	-0.55	2.17
5.56	3.98	-2.80	-1.12	2.21	3.24	-0.57	-1.16	2.10
6.58	3.82	-1.65	-0.79	2.56	2.82	-0.26	-0.24	1.66
7.60	2.41	-2.28	0.12	1.23	2.29	-1.25	0.78	1.47

Numerical Results: Heterogeneous BeO Plate Models

MCNP model of the central drawers containing BeO plates was built with the first fuel drawer represented explicitly.

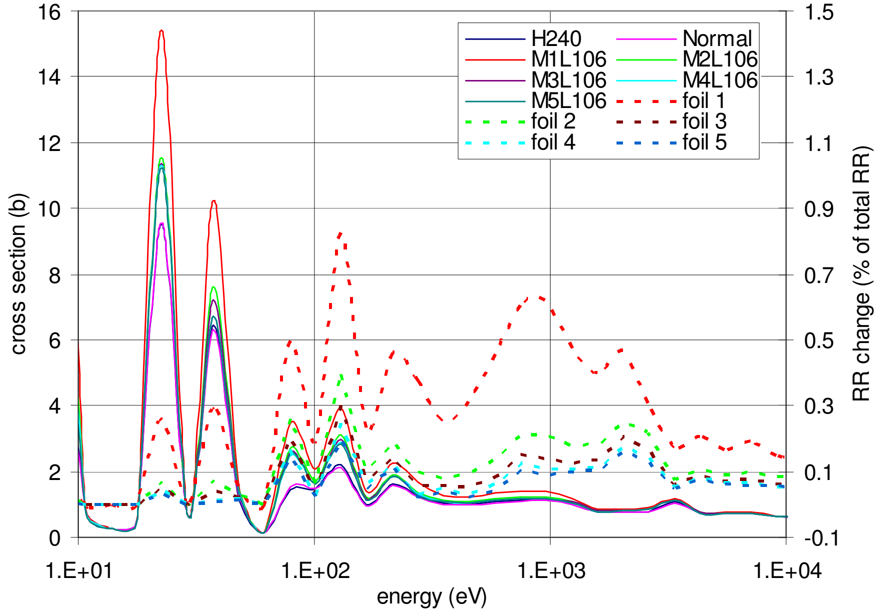
70-group homogenized cross sections for ^{238}U capture and ^{235}U fission were tallied over five different Y sections of the heterogeneous fuel drawer corresponding to the first five foil locations.



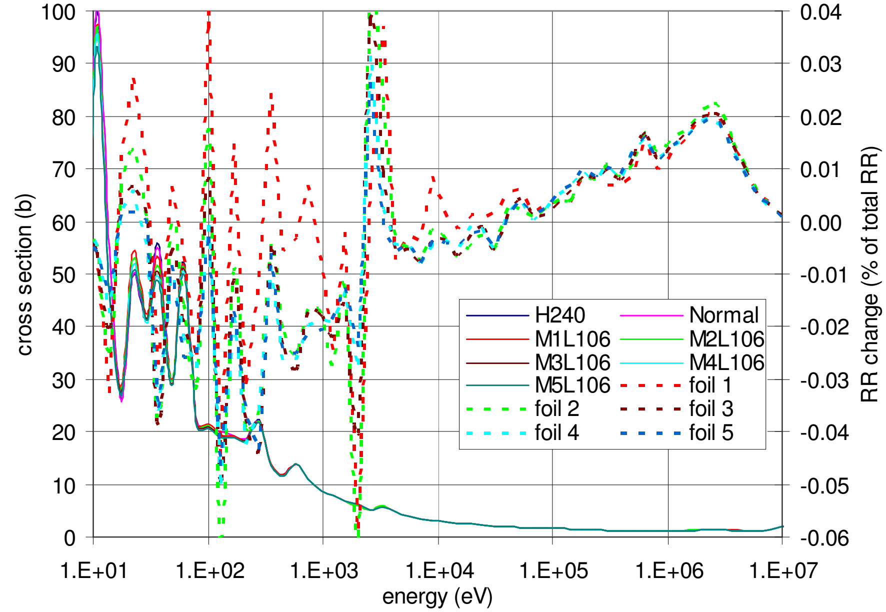
C/E Values (% Error) for Normalized Foil Reaction Rates Determined with Cross Sections from One-Dimensional MC^2-3 and Two-Dimensional MCNP Calculations

Foil location (cm)	Loading 106				Loading 132			
	EU f		DU c		EU f		DU c	
	MC^2-3	MCNP	MC^2-3	MCNP	MC^2-3	MCNP	MC^2-3	MCNP
3.53	3.75	3.90	-10.78	-2.11	3.19	3.38	-5.67	1.42
4.55	3.80	3.67	-6.51	-2.79	2.86	2.86	-3.18	-0.06
5.56	3.98	3.81	-2.80	0.02	3.24	3.21	-0.57	1.84
6.58	3.82	3.62	-1.65	0.68	2.82	2.76	-0.26	1.76
7.60	2.41	2.21	-2.28	-0.24	2.29	2.21	-1.25	0.54

Numerical Results: Heterogeneous BeO Plate Models



Loading 106 ^{238}U Capture Cross Sections (Solid Lines) and Reaction Rate Changes (Dotted Lines)



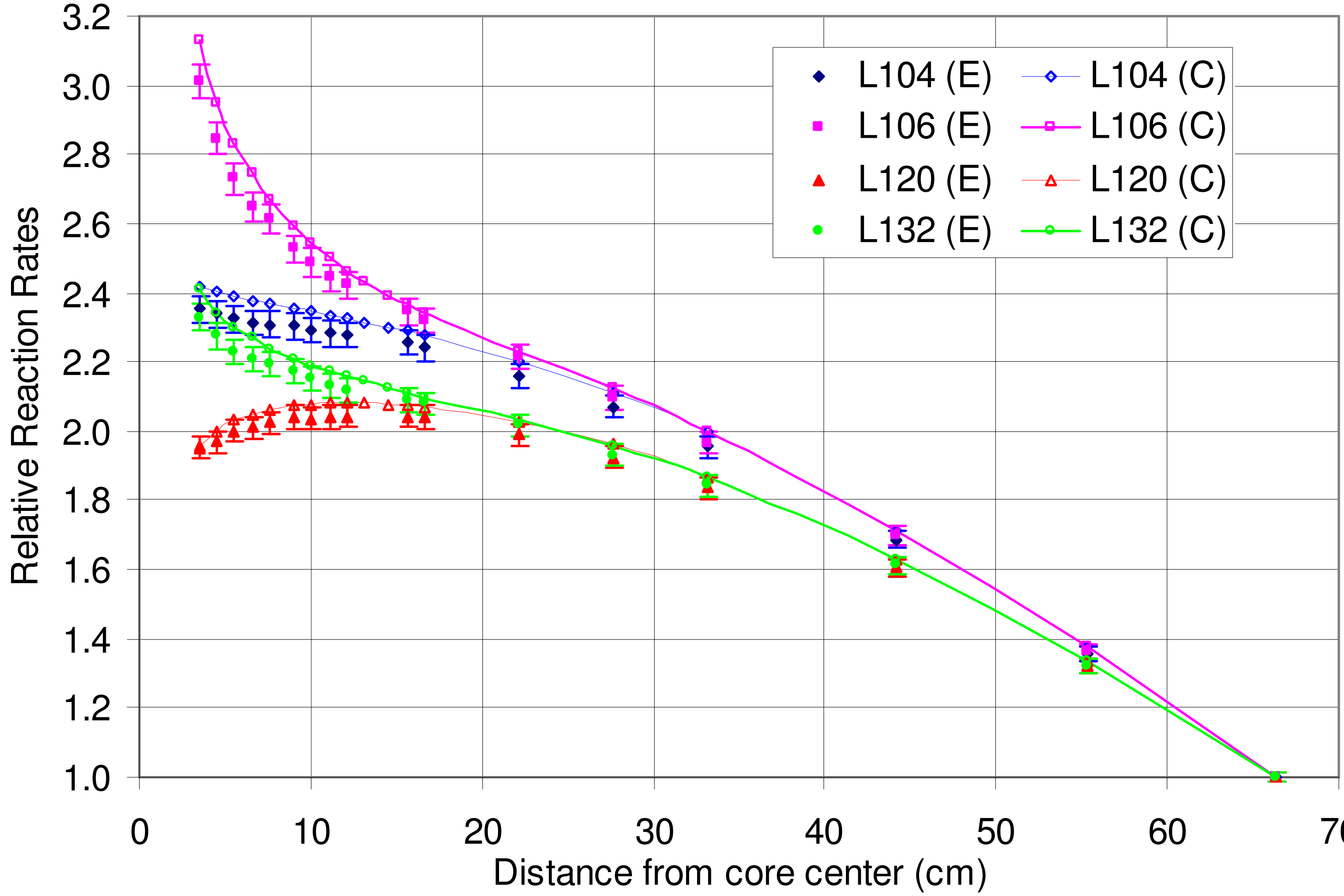
Loading 106 ^{235}U Fission Cross Sections (Solid Lines) and Reaction Rate Changes (Dotted Lines)

The main improvement in C/E values by the use of MCNP foil cross sections comes from the improved foil cross sections in the energy range between 100 eV to 3 keV, i.e., below the ^{23}Na resonance at 2.83 keV.

In this energy range, the incoming neutrons to the fuel drawer from the BeO plate effectively increase the background cross section and thus reduce the self-shielding of ^{238}U capture cross section.

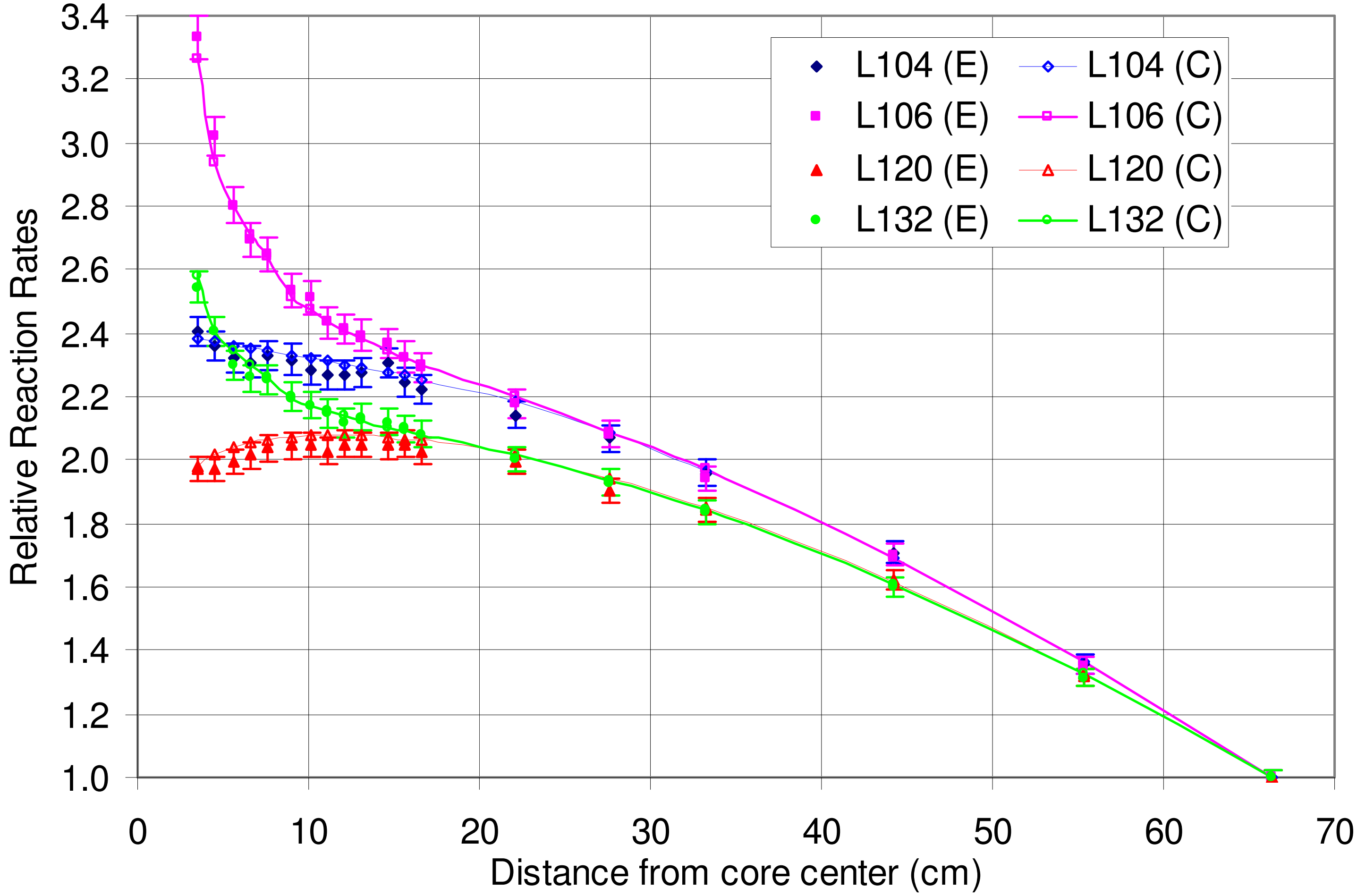
Since the incoming neutrons are attenuated by the fuel plates, this effect is monotonically decreasing with the increase in the distance between the foil position and the BeO plates

Numerical Results: EU Fission



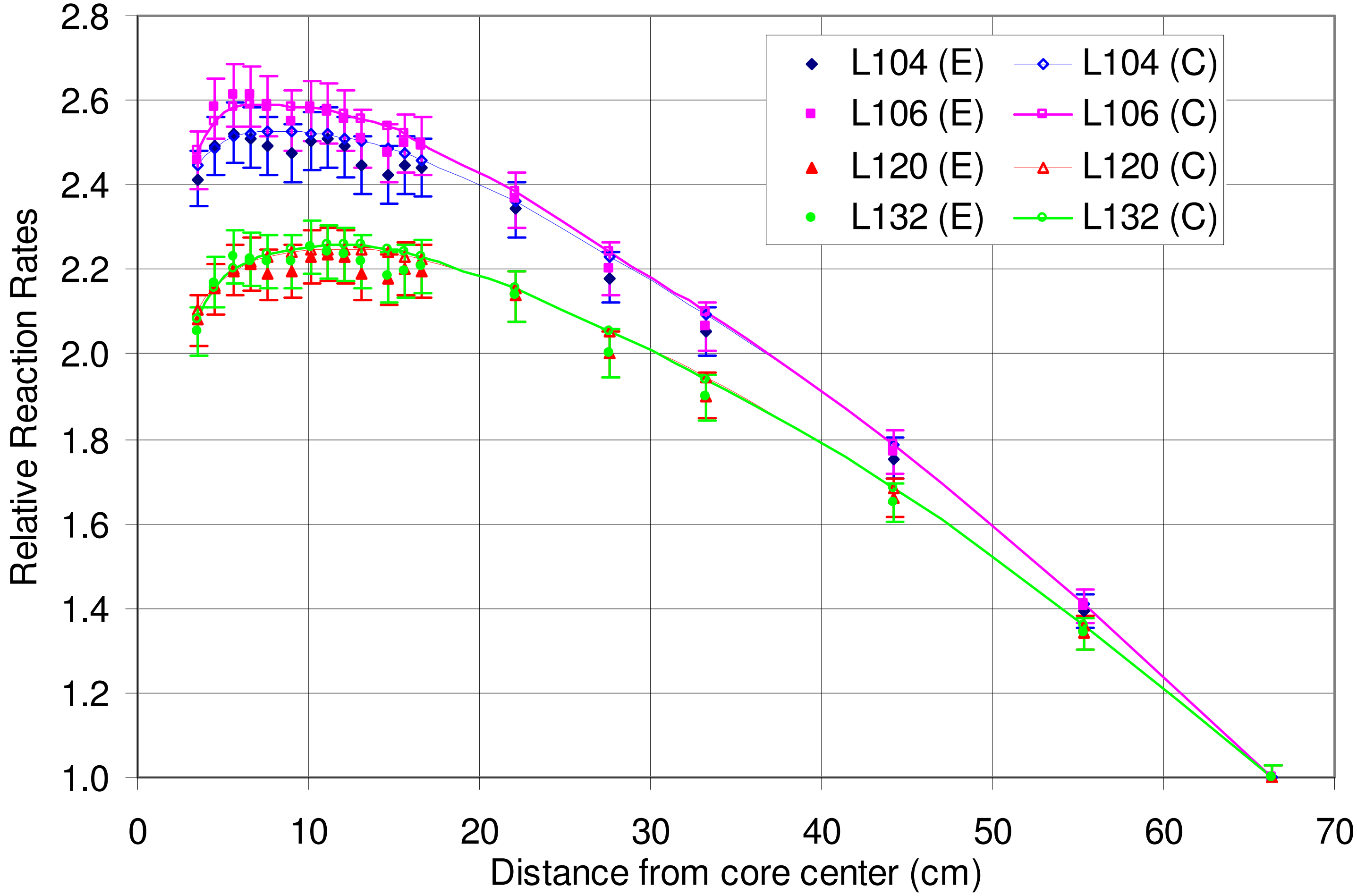
Experimental (E) and Calculated (C) EU Radial Fission Rate Distribution

Numerical Results: DU Capture



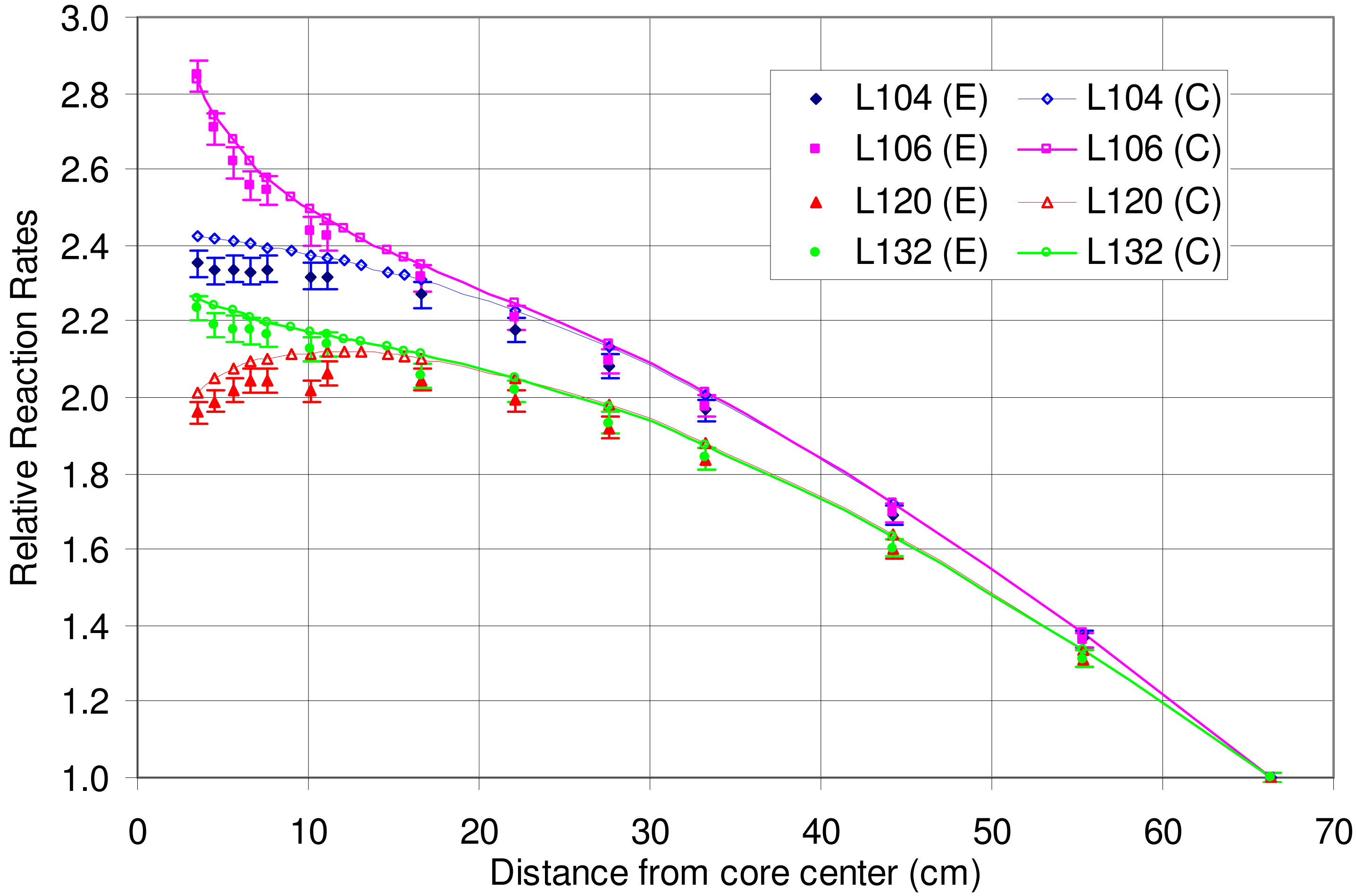
Experimental (E) and Calculated (C) DU Radial Capture Rate Distribution

Numerical Results: DU Fission



Experimental (E) and Calculated (C) DU Radial Fission Rate Distribution

Numerical Results: Pu49 Fission



Experimental (E) and Calculated (C) Pu49 Radial Fission Rate Distribution

Conclusions

Focus of work was to verify PROTEUS=MC^2-3+SN2ND module

Foil activation measurements of radial traverses of ^{235}U fission, ^{238}U capture, ^{238}U fission, and ^{239}Pu fission reaction rates were compared against PROTEUS results for four core loadings of the ZPR-6 Assembly 7 High ^{240}Pu configuration

- For Loadings 104 and 120, the calculated results agreed well with experiment
  - Used isotopic multigroup cross sections for foils obtained with MC^2-3
  - Indicates validity of using PROTEUS on typical SFR problems was verified
- For Loadings 106 and 132 the accuracy of the calculated results were diminished
  - BeO plates loaded near the core center caused problems
  - The one-dimensional single drawer MC^2-3 approach is inadequate for foil XS
  - MCNP based foil cross section data proved to eliminate the residual errors
  - Indicates that PROTEUS provides acceptable results on exotic FR concepts, but further development is needed

Future Work

- Improve the solutions on all loadings 104, 106, 120, and 132
  - Implement a 2D lattice option using MOC in MC^2-3.
  - Determine a more efficient energy structure than 230 groups for fast reactors
- Cross section generation procedure for heterogeneous geometries
  - Heterogeneous models in SN2ND are postulated to be needed for safety related accident modeling with thermal-mechanical feedback.
  - Paper to be presented in Summer ANS meeting in Hollywood Florida