Multigroup Cross Section Processing Capability of the SCALE-6.3 XSProc for Non-LWR analysis

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What is Multigroup Resonance Self-Shielding Effect?

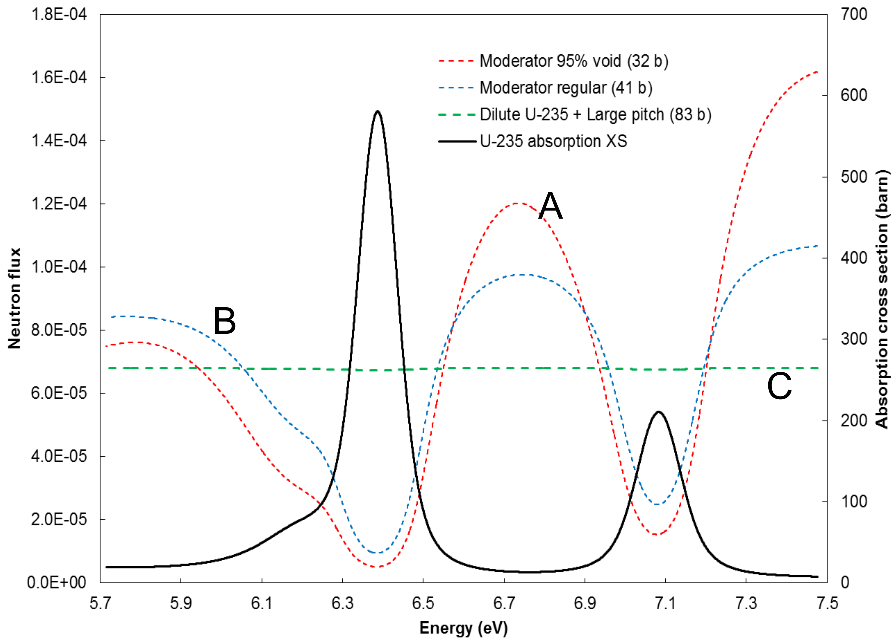
- **Boltzmann neutron transport equation**
  - Continuous energy

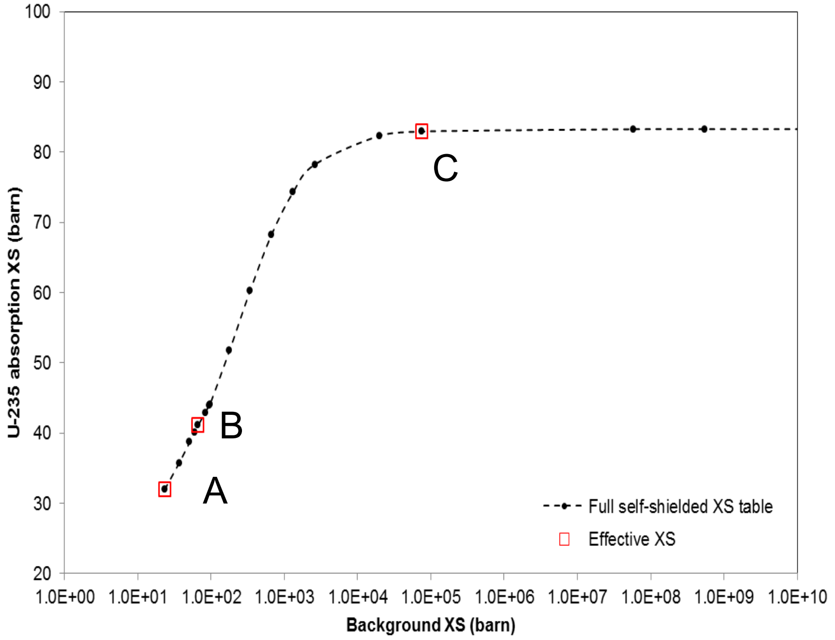
$$\hat{\Omega}\cdot\nabla\psi+\Sigma_t(\vec{r},E)\psi(\vec{r},E,\hat{\Omega}) = \int_{4\pi} d\Omega' \int_0^{\infty} dE' \Sigma_s(\vec{r},E'\rightarrow E,\hat{\Omega}'\cdot\hat{\Omega})\psi(\vec{r},E',\hat{\Omega}')+q(\vec{r},E,\hat{\Omega})$$

  - Multigroup

$$\hat{\Omega}\cdot\nabla\psi_g+\Sigma_{t,g}(\vec{r})\psi_g(\vec{r},\hat{\Omega})=\sum_{g'}\int_{4\pi}\sum_{l}\frac{2l+1}{4\pi}P_l(\hat{\Omega}\cdot\hat{\Omega}')\Sigma^{l}_{s,g'g}\psi_{g'}(\vec{r},\hat{\Omega}')d\hat{\Omega}'+\frac{1}{k_{eff}}\chi_g\sum_{g'}\nu_g\Sigma_{f,g'}\phi_{0,g'}$$

  - Multigroup resonance self-shielding effect
    - ➢ Somewhat different from physical resonance, but mostly from it.
    - ➢ Composition
    - ➢ Geometry





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Representative Resonance Self-Shielding Methods

Bondarenko approach

- Procedure
  - Prepare resonance cross section tables
    - $\sigma_{x,g}$ vs. background cross sections (XS)
    - High order calculation for flux weighting
      - Narrow resonance approximation
      - Homogeneous slowing down calculation
      - Heterogeneous slowing down calculation
      - Continuous energy Monte Carlo calculation
    - Estimate background XS
      - Dancoff factor, fixed source calculation …
    - Read/interpolate self-shielded XS tables
  - Calculate resonance interference effect
    - Bondarenko iteration, Resonance interference table
- Application
  - Methods
    - **Embedding Self-Shielding method: Polaris, MPACT**
    - Subgroup method: MPACT, HELIOS, DeCART
    - Dancoff method: SCALE-BONAMI, CASMO
  - Drawbacks
    - Fast but less accurate
    - Fine energy groups
    - Reactor specific XS libraries

PW Slowing down calculation

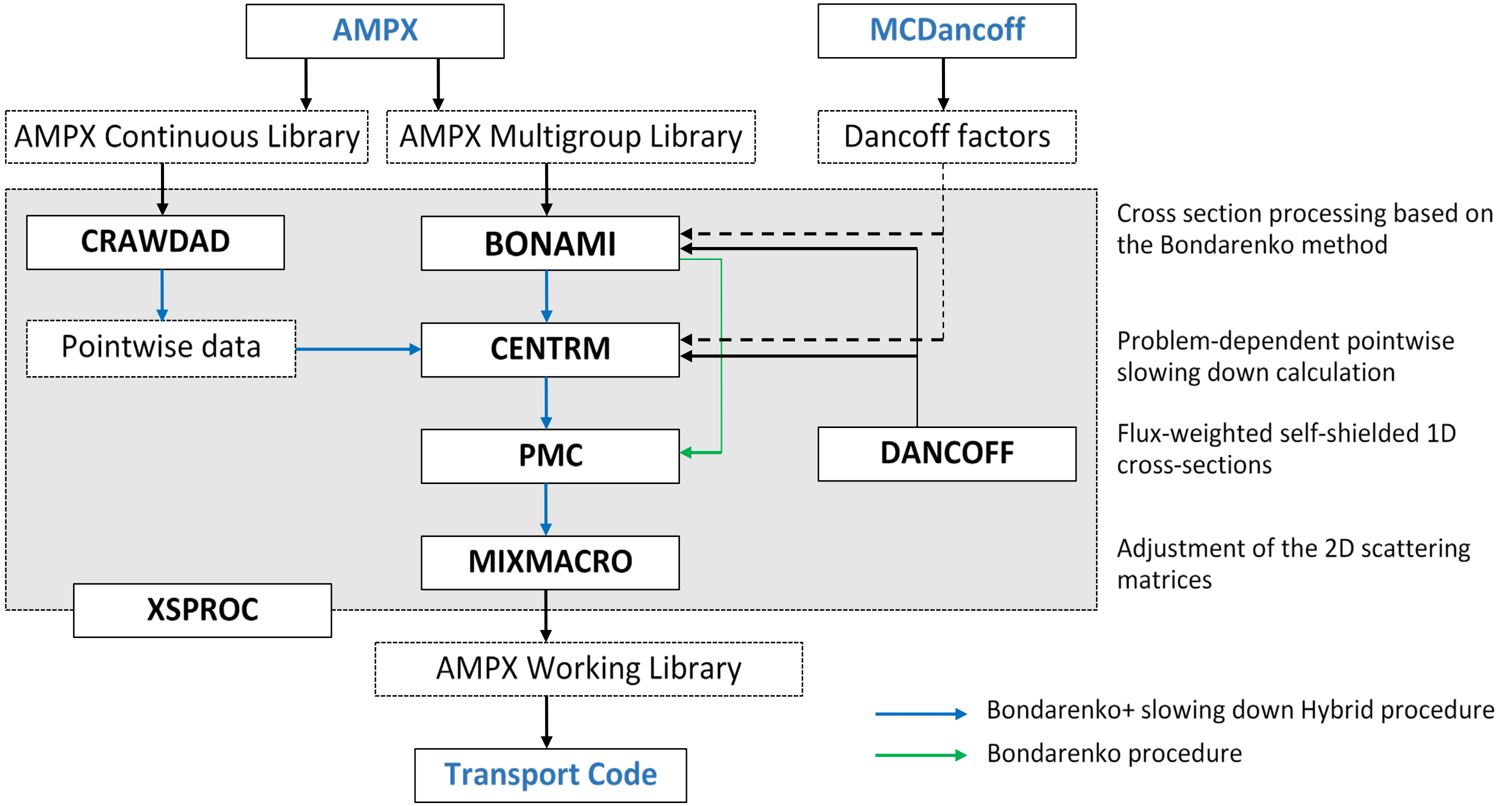
- Procedure
  - Divide whole domain into constituent cells
  - Global Dancoff factor
    - MCDancoff in SCALE
  - Adjust cell pitch for each cell
    - Global Dancoff factors
  - Perform pointwise slowing down calculations
    - Heterogeneous cells
  - Obtain self-shielded MG XSs & scatt. matrices
    - Flux weighting
- Application
  - **SCALE-XSProc**, MC^2-3
  - Drawbacks
    - Accurate but very time consuming
    - Poor global effect

Hybrid method

- Bondarenko + Slowing down methods
  - SCALE-BONAMI+CENTRM
  - MPACT ESSM-X

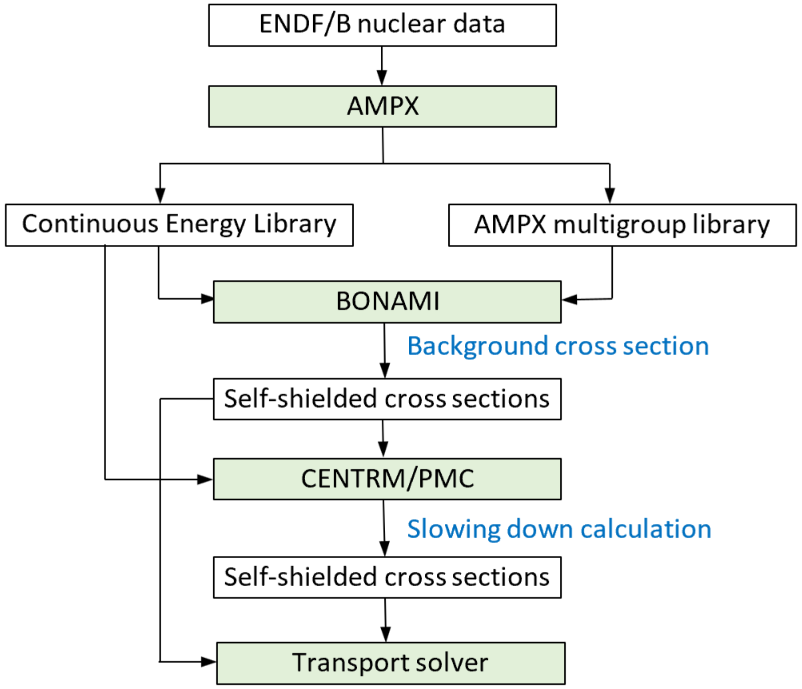
SCALE Cross Section Processing Procedure

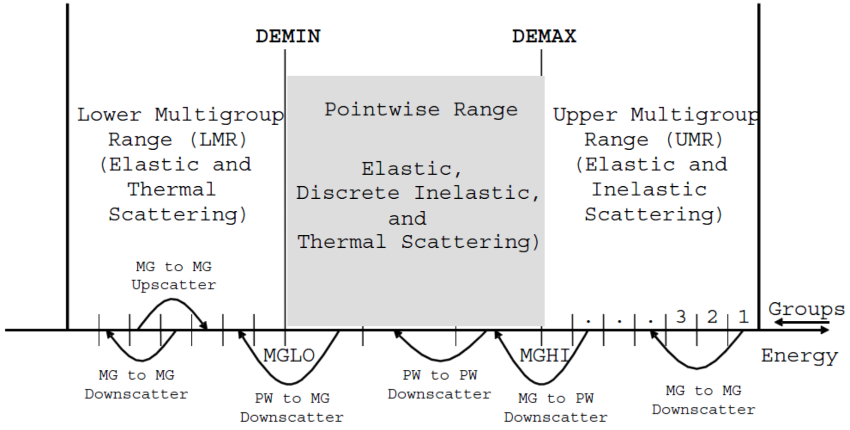
- **XS processing for transport calculations and resonance data**
  - Responsible for accuracy of SCALE MG transport calculations
  - XSPROC: XSDRN, NEWT, KENO, Shift
  - ESSM: Polaris
  - ROUX (Irffactor): resonance data generation vs. ESSM
- **Collaboration**
  - AMPX and nuclear data team: Improve AMPX MG library
  - Polaris team: Improve self-shielding method (ESSM)



SCALE MG Cross Section Processing Procedure

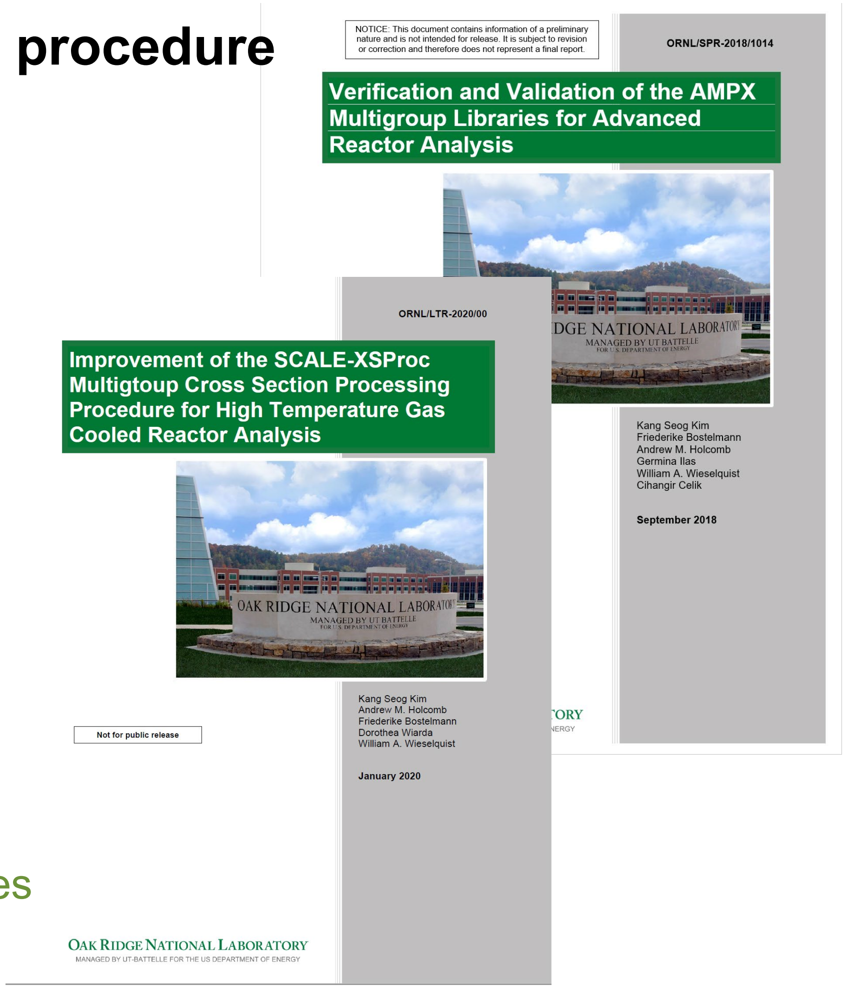
- **Standard procedure**
  - BONAMI based self-shielding calculation
    - Bondarenko approach using Dancoff factor
    - For all nuclides, all reactions and all energy groups
  - CENTRM
    - UMR (20 keV) + PW + LMR (0.001 eV)
    - Scattering kernels: internal and outside
    - Infinite medium, 1-D slab, cylinder and spherical, 2D MOC
    - Double heterogeneity treatment
    - Multiple cells based on Dancoff factors (McDancoff)
    - Compatible to MC except for spatial discretization and UMR
  - PMC
    - Explicit group collapsing for MG cross sections
    - Implicit group collapsing for scattering matrices
  - Follow-up transport calculations
    - XSDRN: 0D and 1D
    - MG-KENO: 0D, 1D, 2D and 3D
    - NEWT: 2D
    - Applications
      - AMPX MG library dependent
      - 1597-group library for any advanced reactor analysis





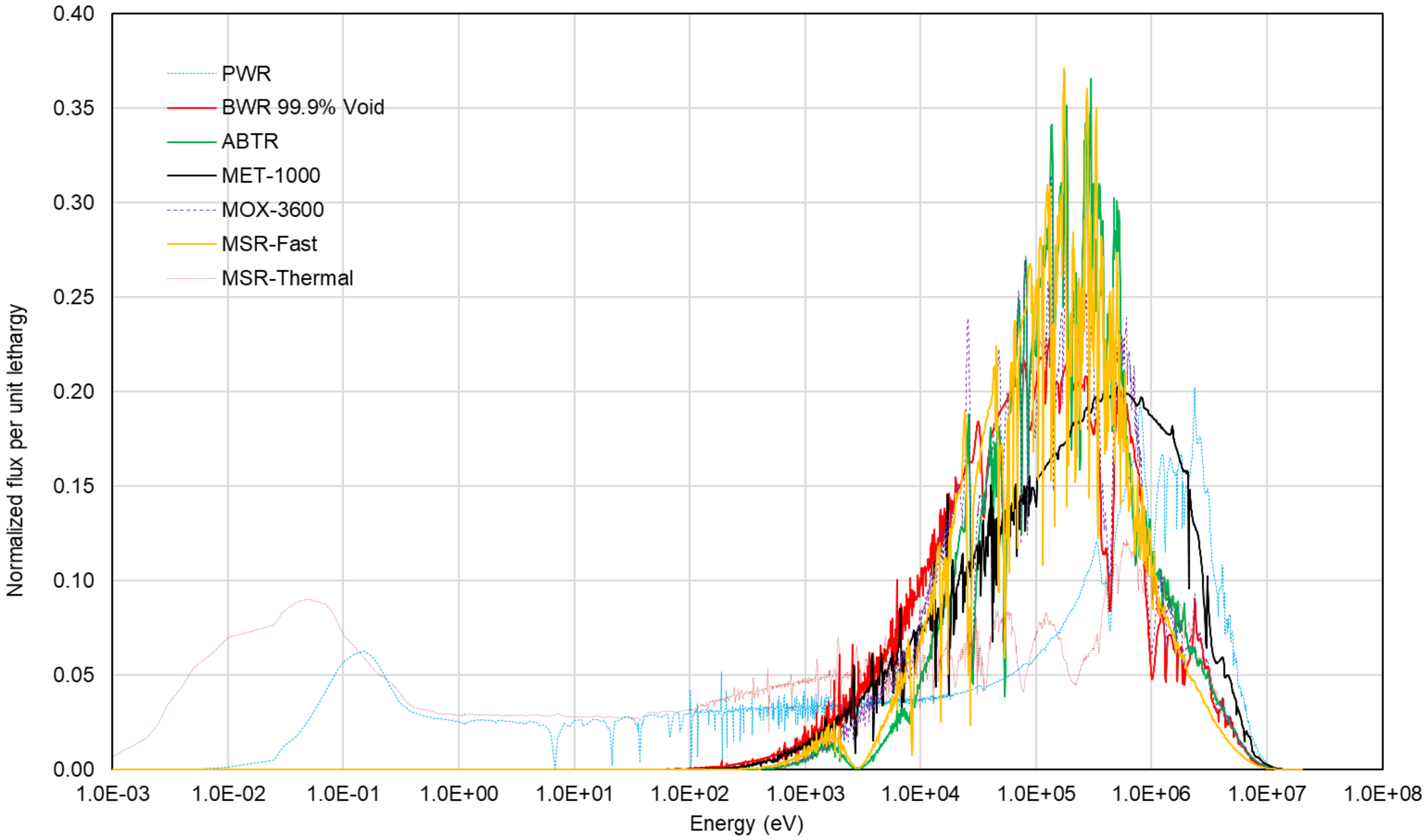
MG Cross Section Capability for Advanced Reactors

- **Benchmark suite for verification for library processing procedure**
  - Various advanced reactors: MADRE benchmark suite
    - Light water reactor (LWR) benchmarks
      - Pressurized water reactor (PWR)
      - Boiling water reactor (BWR)
    - Fast reactor benchmarks
      - Advanced burner test reactor (ABTR)
      - EBR-II fast reactor
      - OECD-NEA MET-1000 benchmarks
      - OECD-NEA MOX-3600 benchmarks
    - Molten salt reactor benchmarks
      - Thermal spectrum molten salt reactor
      - Fast spectrum molten salt reactor
    - High temperature gas-cooled reactor benchmarks
      - Prismatic HTGR
      - Pebble-bed HTGR
  - AMPX MG libraries
    - ENDF/B-VII.1 and VIII.0 AMPX 252-, 302- and 1597-group libraries
      - AMPX 1597-group library: General purpose, multi-spectra
      - AMPX 252-group library: Thermal systems
      - AMPX 302-group library: Fast systems
    - Standard SCALE procedure using XSProc based on BONAMI and CENTRM
    - Reference solution: CE-KENO
    - Verification: eigenvalue comparison & reaction rate analysis



Neutronic Characteristic

- **Comparison of neutron spectra**
  - Significantly reactor specific

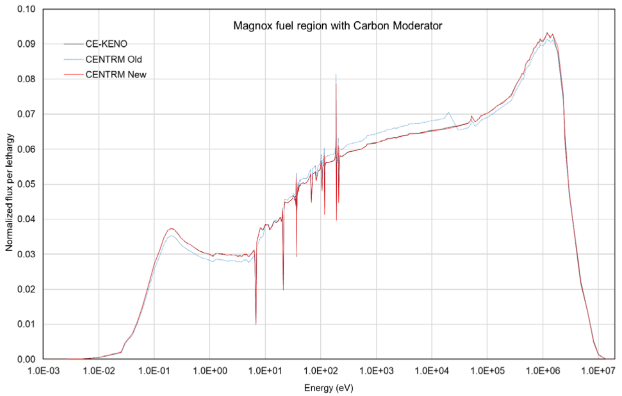


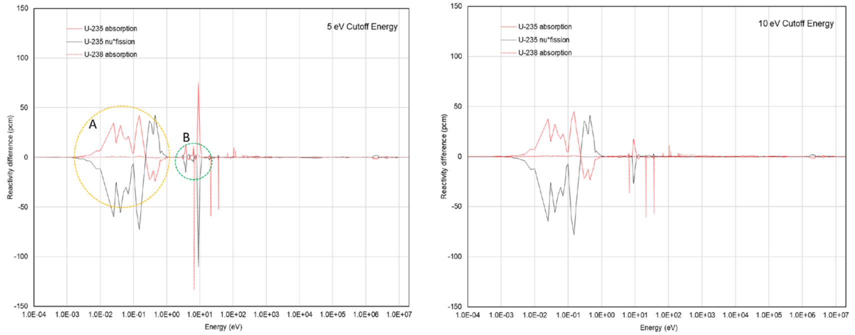
XSProc Improvement for Advanced Reactor Analysis

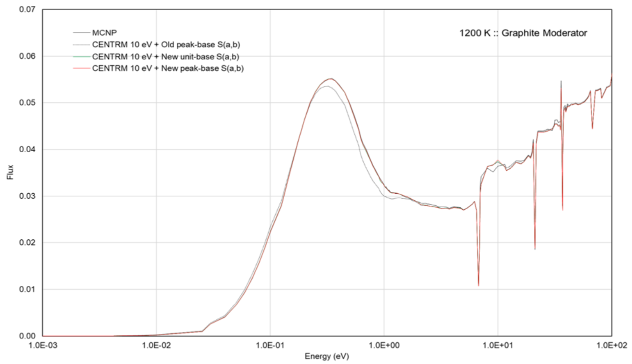
- **Benchmark suite for verification for library processing procedure**
  - Unresolved resonance self-shielding
    - Analytic probability table method with narrow resonance

$$\sigma_{x,g,i} = \frac{\int_g \sum_m p_i^m \sigma_{x,i}^m(E)\phi^m(E)dE}{\int_g \sum_m p_i^m \phi^m(E)dE}$$

  - Pointwise neutron flux normalization
    - Improve an interpolation scheme for thermal scattering data
  - Increase thermal cutoff energy for HTGR
    - 5 eV → 10 eV
  - Explicit on-the-fly thermal scattering matrices
    - Adjust the AMPX MG scattering matrices
  - Dancoff adjustment for leakage in Double-het
    - CPM based Dancoff capability
  - Explicit treatment of nonuniform temperature
    - Keep nuclidewise temperature with homogenization
  - New ultra-fine energy group structure
    - 1597-group structure
    - 302-group structure
    - 258-group structure for S-wave approximation







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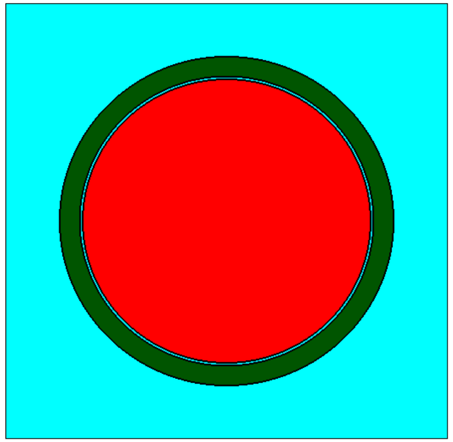
PWR Benchmarks

- **Benchmark problems**
  - Single pins and assemblies
    - Mostly covered by other benchmarks

No	Problem ID	Description	Temperature (K)			Moderator density (g/cm³)	^{235}U wt %
			Mod.	Clad	Fuel		
PWR-01	pwr-pin-**-6k	Pin	600	600	600	0.661	3.1
PWR-02	pwr-pin-**-9k	Pin	600	600	900	0.661	3.1
PWR-03	pwr-pin-**-12k	Pin	600	600	1200	0.661	3.1
PWR-04	pwr-fa-**-6k	Fuel assembly	600	600	600	0.661	3.1
PWR-05	pwr-fa-**-9k	Fuel assembly	600	600	900	0.661	3.1
PWR-06	pwr-fa-**-12k	Fuel assembly	600	600	1200	0.661	3.1

* Can be "ce," "mg252," "mg302," and "mg1597."

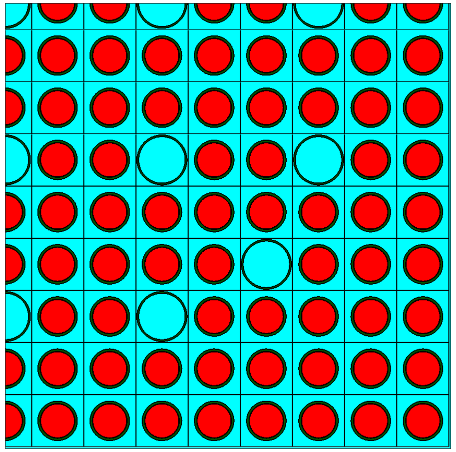


- **Benchmark results**
  - SCALE-MG vs. CE-KENO

No	Problem ID	ENDF/B-VII.1				ENDF/B-VIII.0			
		CE, k_{eff}	$\Delta\rho^a$ (pcm)			CE, k_{eff}	$\Delta\rho$ (pcm)		
			1597-g	252-g	302-g		1597-g	252-g	302-g
PWR-01	pwr-pin-**-6k	1.18194	-106	-117	-790	1.18126	-132	-112	-811
PWR-02	pwr-pin-**-9k	1.17163	-115	-139	-845	1.17066	-118	-99	-861
PWR-03	pwr-pin-**-12k	1.16255	-117	-126	-878	1.16215	-125	-138	-927
PWR-04	pwr-fa-**-6k	1.18318	-53	-38	-476	1.18310	-76	-66	-513
PWR-05	pwr-fa-**-9k	1.17337	-30	-17	-475	1.17352	-68	-58	-537
PWR-06	pwr-fa-**-12k	1.16556	-49	-54	-509	1.16519	-76	-53	-560

*Standard deviations are less than 20 pcm for all cases.

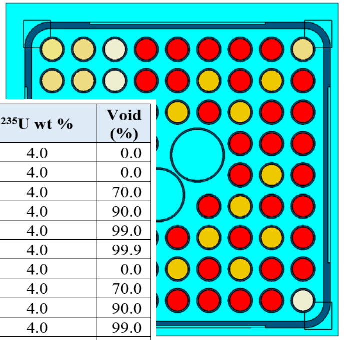
[a]Reactivity difference ($\Delta\rho$) is obtained by $(1/k_{eff}^{CE}-1/k_{eff}^{MG})\cdot 10^5$



BWR Benchmarks

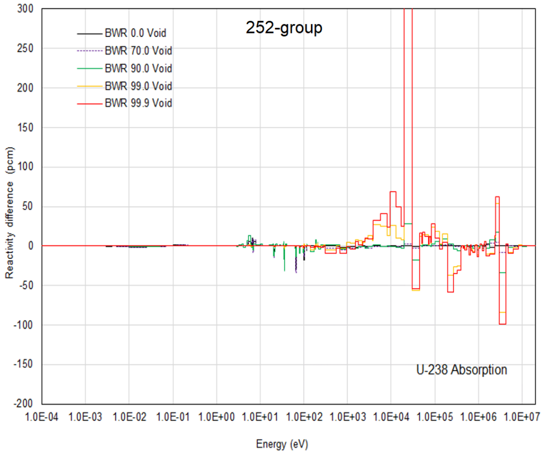
▪ Benchmark problems

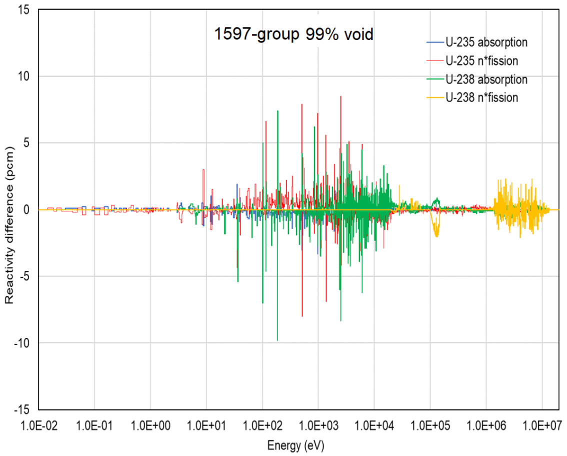
- Single pins and assemblies



No	Problem ID	Description	Temperature (K)			Mod. density (g/cm³)	^{235}U wt %	Void (%)
			Mod.	Clad	Fuel			
BWR-01	bwr-pin0-**-3k0v	Pin	293.6	293.6	293.6	1.005112	4.0	0.0
BWR-02	bwr-pin0-**-6k0v	Pin	600	600	600	0.660151	4.0	0.0
BWR-03	bwr-pin0-**-6k70v	Pin	600	600	600	0.198045	4.0	70.0
BWR-04	bwr-pin0-**-6k90v	Pin	600	600	600	0.066015	4.0	90.0
BWR-05	bwr-pin0-**-6k99v	Pin	600	600	600	0.006602	4.0	99.0
BWR-06	bwr-pin0-**-6k999v	Pin	600	600	600	0.000660	4.0	99.9
BWR-07	bwr-pin0-**-9k0v	Pin	600	600	900	0.660151	4.0	0.0
BWR-08	bwr-pin0-**-9k70v	Pin	600	600	900	0.198045	4.0	70.0
BWR-09	bwr-pin0-**-9k90v	Pin	600	600	900	0.066015	4.0	90.0
BWR-10	bwr-pin0-**-9k99v	Pin	600	600	900	0.006602	4.0	99.0
BWR-11	bwr-pin0-**-9k999v	Pin	600	600	900	0.000660	4.0	99.9
BWR-12	bwr-pin0-**-12k0v	Pin	600	600	1200	0.660151	4.0	0.0
BWR-13	bwr-pin0-**-12k70v	Pin	600	600	1200	0.198045	4.0	70.0
BWR-14	bwr-pin0-**-12k90v	Pin	600	600	1200	0.066015	4.0	90.0
BWR-15	bwr-pin0-**-12k99v	Pin	600	600	1200	0.006602	4.0	99.0
BWR-16	bwr-pin0-**-12k999v	Pin	600	600	1200	0.000660	4.0	99.9
BWR-17	bwr-fa1-**-6k0v	Fuel assembly	600	600	600	0.660151	3.2	0.0
BWR-18	bwr-fa1-**-6k40v	Fuel assembly	600	600	600	0.396090	3.2	40.0
BWR-19	bwr-fa1-**-6k90v	Fuel assembly	600	600	600	0.066015	3.2	90.0
BWR-20	bwr-fa1-**-9k0v	Fuel assembly	600	600	900	0.660151	3.2	0.0
BWR-21	bwr-fa1-**-9k40v	Fuel assembly	600	600	900	0.396090	3.2	40.0
BWR-22	bwr-fa1-**-9k90v	Fuel assembly	600	600	900	0.066015	3.2	90.0
BWR-23	bwr-fa1-**-12k0v	Fuel assembly	600	600	1200	0.660151	3.2	0.0
BWR-24	bwr-fa1-**-12k40v	Fuel assembly	600	600	1200	0.396090	3.2	40.0
BWR-25	bwr-fa1-**-12k90v	Fuel assembly	600	600	1200	0.066015	3.2	90.0

** Can be "ce," "mg252," "mg302," and "mg1597."





▪ Benchmark results

- SCALE-MG vs. CE-KENO

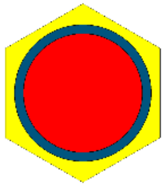
ID	Input file name	ENDF/B-VII.1				ENDF/B-VIII.0			
		CE, k_{eff}	Δρ[a] (pcm)			CE, k_{eff}	Δρ (pcm)		
			1597-g	252-g	302-g		1597-g	252-g	302-g
BWR-01	bwr-pin0-**-3k0v	1.49082	-75	-60	-39	1.48616	-95	-70	-17
BWR-02	bwr-pin0-**-6k0v	1.43265	-73	-84	-394	1.42800	-95	-89	-413
BWR-03	bwr-pin0-**-6k70v	1.15497	-119	-147	-608	1.15173	-166	-174	-665
BWR-04	bwr-pin0-**-6k90v	0.92504	-112	-95	-380	0.92556	-206	-196	-487
BWR-05	bwr-pin0-**-6k99v	0.75968	64	320	30	0.76314	-282	-20	-370
BWR-06	bwr-pin0-**-6k999v	0.72997	-2	385	-19	0.73212	-362	56	-389
BWR-07	bwr-pin0-**-9k0v	1.42295	-104	-101	-449	1.41800	-91	-104	-474
BWR-08	bwr-pin0-**-9k70v	1.14011	-150	-152	-691	1.13692	-180	-188	-762
BWR-09	bwr-pin0-**-9k90v	0.91000	-145	-109	-432	0.91063	-294	-264	-591
BWR-10	bwr-pin0-**-9k99v	0.74922	12	264	-29	0.75275	-342	-54	-441
BWR-11	bwr-pin0-**-9k999v	0.72201	47	400	-5	0.72448	-388	35	-427
BWR-12	bwr-pin0-**-12k0v	1.41419	-94	-107	-469	1.40981	211	227	1037
BWR-13	bwr-pin0-**-12k70v	1.12788	-176	-153	-756	1.12513	-237	-254	-837
BWR-14	bwr-pin0-**-12k90v	0.89791	-155	-125	-451	0.89894	-335	-282	-626
BWR-15	bwr-pin0-**-12k99v	0.74209	-2	250	-100	0.74525	-365	-76	-446
BWR-16	bwr-pin0-**-12k999v	0.71686	24	454	-3	0.71942	-429	18	-439
BWR-17	bwr-fa1-**-6k0v	1.37798	180	260	1005	1.37625	187	263	947
BWR-18	bwr-fa1-**-6k40v	1.34983	225	307	871	1.34817	200	299	802
BWR-19	bwr-fa1-**-6k90v	1.27163	42	77	-287	1.26947	58	95	-308
BWR-20	bwr-fa1-**-9k0v	1.37008	201	275	1019	1.36816	187	277	983
BWR-21	bwr-fa1-**-9k40v	1.34035	238	332	918	1.33893	198	313	836
BWR-22	bwr-fa1-**-9k90v	1.26107	43	60	-320	1.25922	52	88	-343
BWR-23	bwr-fa1-**-12k0v	1.36285	200	289	1079	1.36172	182	266	997
BWR-24	bwr-fa1-**-12k40v	1.33267	225	325	929	1.33121	186	301	868
BWR-25	bwr-fa1-**-12k90v	1.25241	36	77	-336	1.25081	36	63	-401

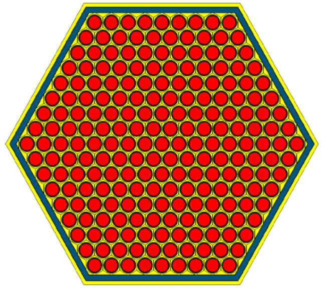
*Standard deviations are less than 20 pcm for all cases.

[a]Reactivity difference (Δρ) is obtained by $(1/k_{eff}^{CE}-1/k_{eff}^{MG})\cdot 10^5$

ABTR Benchmarks

- **Benchmark problems**
  - Single pins and assemblies





No	Problem ID	Description	Temperature (K)				Mod. density (g/cm^3)	Sodium void (%)
			Mod.	Clad	Gap	Fuel		
ABTR-01	abtr-pin0-**-3k0v	Pin type-0	293.6	293.6	293.6	293.6	0.8502	0.0
ABTR-02	abtr-pin0-**-6k0v	Pin type-0	600	600	600	600	0.8502	0.0
ABTR-03	abtr-pin0-**-9k0v	Pin type-0	900	900	900	900	0.8502	0.0
ABTR-04	abtr-pin0-**-12k0v	Pin type-0	1200	1200	1200	1200	0.8502	0.0
ABTR-05	abtr-pin1-**-8k0v	Pin type-1	700	700	–	800	0.8502	0.0
ABTR-06	abtr-pin1-**-15k0v	Pin type-1	700	700	–	1500	0.8502	0.0
ABTR-07	abtr-pin2-**-8k0v	Pin type-2	700	700	–	800	0.8502	0.0
ABTR-08	abtr-pin2-**-15k0v	Pin type-2	700	700	–	1500	0.8502	0.0
ABTR-09	abtr-pin3-**-8k0v	Pin type-3	700	700	–	800	0.8502	0.0
ABTR-10	abtr-pin3-**-15k0v	Pin type-3	700	700	–	1500	0.8502	0.0
ABTR-11	abtr-fa1-**-8k0v	Assembly type-1	700	700	–	800	0.8502	0.0
ABTR-12	abtr-fa1-**-15k0v	Assembly type-1	700	700	–	1500	0.8502	0.0
ABTR-13	abtr-fa2-**-8k0v	Assembly type-2	700	700	–	800	0.8502	0.0
ABTR-14	abtr-fa2-**-15k0v	Assembly type-2	700	700	–	1500	0.8502	0.0
ABTR-15	abtr-fa3-**-8k0v	Assembly type-3	700	700	–	800	0.8502	0.0
ABTR-16	abtr-fa3-**-15k0v	Assembly type-3	700	700	–	1500	0.8502	0.0

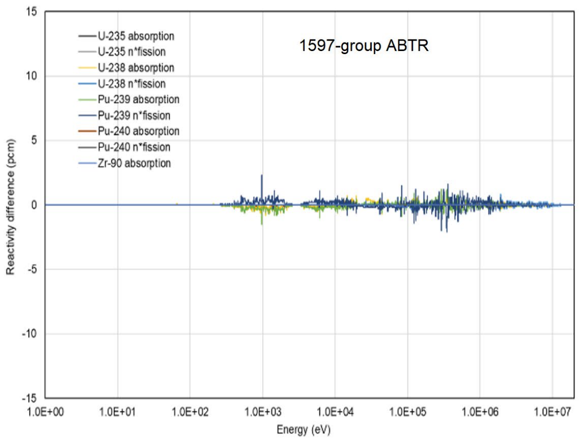
* Can be “ce,” “mg252,” “mg302,” and “mg1597.”

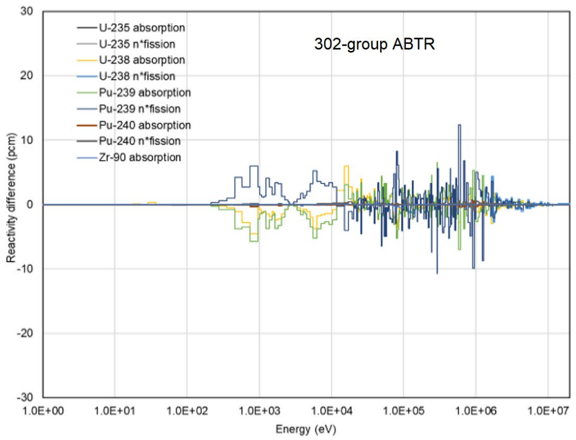
- **Benchmark results**
  - SCALE-MG vs. CE-KENO

ID	Input file name	ENDF/B-VII.1				ENDF/B-VIII.0			
		CE, k_{eff}	$\Delta\rho^a$ (pcm)			CE, k_{eff}	$\Delta\rho$ (pcm)		
			1597-g	252-g	302-g		1597-g	252-g	302-g
ABTR-01	abtr-pin0-ce1597-3k0v	1.60110	-15	[redacted]	4	1.60779	-51	-220	[redacted]
ABTR-02	abtr-pin0-ce1597-6k0v	1.59466	-8	[redacted]	9	1.60186	-54	-239	[redacted]
ABTR-03	abtr-pin0-ce1597-9k0v	1.59194	-37	[redacted]	-16	1.59897	-58	-248	[redacted]
ABTR-04	abtr-pin0-ce1597-12k0v	1.58972	-24	[redacted]	-1	1.59707	-70	-255	[redacted]
ABTR-05	abtr-pin1-ce-8k0v	1.62967	-51	[redacted]	-3	1.63782	-75	-365	[redacted]
ABTR-06	abtr-pin1-ce-15k0v	1.62688	-39	[redacted]	7	1.63535	-78	-362	[redacted]
ABTR-07	abtr-pin2-ce-8k0v	1.46696	-62	[redacted]	-8	1.47688	-139	-401	[redacted]
ABTR-08	abtr-pin2-ce-15k0v	1.46466	-59	[redacted]	-2	1.47474	-128	-404	[redacted]
ABTR-09	abtr-pin3-ce-8k0v	1.79577	-43	[redacted]	7	1.80334	-64	-312	[redacted]
ABTR-10	abtr-pin3-ce-15k0v	1.79367	-35	[redacted]	2	1.80115	-56	-305	[redacted]
ABTR-11	abtr-fa1-ce-8k0v	1.55855	21	[redacted]	129	1.56477	-19	-259	[redacted]
ABTR-12	abtr-fa1-ce-15k0v	1.55546	21	[redacted]	129	1.56164	-23	-253	[redacted]
ABTR-13	abtr-fa2-ce-8k0v	1.39788	12	[redacted]	130	1.40530	-79	-290	[redacted]
ABTR-14	abtr-fa2-ce-15k0v	1.39512	5	[redacted]	127	1.40244	-72	-300	[redacted]
ABTR-15	abtr-fa3-ce-8k0v	1.72492	13	[redacted]	100	1.73057	-25	-226	[redacted]
ABTR-16	abtr-fa3-ce-15k0v	1.72257	-1	[redacted]	80	1.72794	-19	-231	[redacted]

*Standard deviations are less than 20 pcm for all cases.

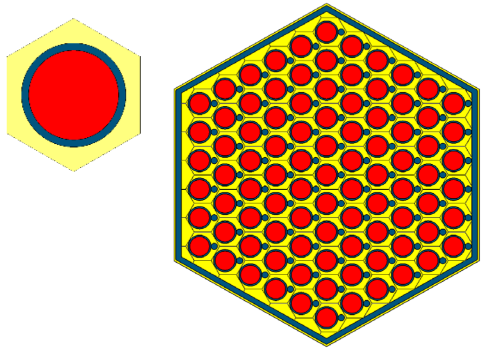
[a]Reactivity difference ($\Delta\rho$) is obtained by $(1/k_{eff}^{CE} - 1/k_{eff}^{MG}) \cdot 10^5$





EBR-II Reactor Benchmarks

- **Benchmark problems**
  - Single pins and assemblies



No	Problem ID	Description	Temperature (K)			Mod. density (g/cm^3)	Sodium void (%)
			Mod.	Clad	Fuel		
EBR2-01	ebr2-pin1-**-7k0v	pin type-1	700	700	700	0.8502	0.0
EBR2-02	ebr2-pin1-**-15k0v	pin type-1	700	700	1500	0.8502	0.0
EBR2-03	ebr2-pin2-**-7k0v	pin type-2	700	700	700	0.8502	0.0
EBR2-04	ebr2-pin2-**-15k0v	pin type-2	700	700	1500	0.8502	0.0
EBR2-05	ebr2-pin3-**-7k0v	pin type-3	700	700	700	0.8502	0.0
EBR2-06	ebr2-pin3-**-15k0v	pin type-3	700	700	1500	0.8502	0.0
EBR2-07	ebr2-fa1-**-7k0v	assembly type-1	700	700	700	0.8502	0.0
EBR2-08	ebr2-fa1-**-15k0v	assembly type-1	700	700	1500	0.8502	0.0
EBR2-09	ebr2-fa2-**-7k0v	assembly type-2	700	700	700	0.8502	0.0
EBR2-10	ebr2-fa2-**-15k0v	assembly type-2	700	700	1500	0.8502	0.0
EBR2-11	ebr2-fa3-**-7k0v	assembly type-3	700	700	700	0.8502	0.0
EBR2-12	ebr2-fa3-**-15k0v	assembly type-3	700	700	1500	0.8502	0.0

- **Benchmark results**
  - SCALE-MG vs. CE-KENO

No	Problem ID	ENDF/B-VII.1				ENDF/B-VIII.0			
		CE, k_{eff}	$\Delta\rho^a$ (pcm)			CE, k_{eff}	$\Delta\rho$ (pcm)		
			1597-g	252-g	302-g		1597-g	252-g	302-g
EBR2-01	ebr2-pin1-**-7k0v	1.96763	-7	-51	-2	1.96407	-40	-78	-30
EBR2-02	ebr2-pin1-**-15k0v	1.96784	-12	-61	-8	1.96385	-31	-80	-29
EBR2-03	ebr2-pin2-**-7k0v	1.97328	-8	-60	-4	1.96931	-31	-72	-24
EBR2-04	ebr2-pin2-**-15k0v	1.97309	-10	-53	-5	1.96959	-41	-82	-33
EBR2-05	ebr2-pin3-**-7k0v	1.97309	-5	-53	5	1.96950	-40	-77	-30
EBR2-06	ebr2-pin3-**-15k0v	1.97294	-9	-54	-3	1.96939	-43	-81	-31
EBR2-07	ebr2-fa1-**-7k0v	1.92622	-30	-111	-25	1.92130	-58	-134	-42
EBR2-08	ebr2-fa1-**-15k0v	1.92630	-32	-112	-25	1.92111	-49	-132	-40
EBR2-09	ebr2-fa2-**-7k0v	1.93177	-31	-109	-29	1.92709	-58	-139	-50
EBR2-10	ebr2-fa2-**-15k0v	1.93186	-39	-116	-26	1.92682	-57	-132	-53
EBR2-11	ebr2-fa3-**-7k0v	1.93177	-28	-109	-19	1.92693	-60	-136	-47
EBR2-12	ebr2-fa3-**-15k0v	1.93155	-34	-111	-20	1.92667	-52	-129	-50

OECD-NEA MET-1000 Benchmarks

▪ Benchmark problems

- Single pins and assemblies

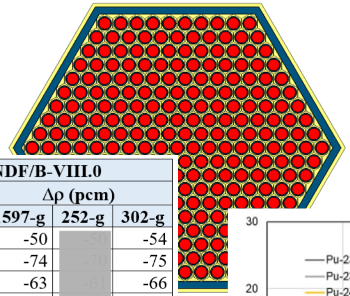
No	Problem ID	Description	Temperature (K)			Cool density (g/cm³)	Sodium Void (%)
			Cool	Clad	Fuel		
MET-01	met1000-pin0-**-3k0v	Homog.[a]	293.6				
MET-02	met1000-pin0-**-6k0v	Homog.	600				
MET-03	met1000-pin0-**-9k0v	Homog.	900				
MET-04	met1000-pin0-**-12k0v	Homog.	1200				
MET-05	met1000-pin1-**-8k0v	Pin-1	700	700	800	0.8502	0.0
MET-06	met1000-pin1-**-8k10v	Pin-1	700	700	800	0.7652	10.0
MET-07	met1000-pin1-**-8k100v	Pin-1	700	700	800	0.0000	100.0
MET-08	met1000-pin1-**-12k0v	Pin-1	700	700	1200	0.8502	0.0
MET-09	met1000-pin1-**-12k10v	Pin-1	700	700	1200	0.7652	10.0
MET-10	met1000-pin1-**-12k100v	Pin-1	700	700	1200	0.0000	100.0
MET-11	met1000-pin1-**-16k0v	Pin-1	700	700	1600	0.8502	0.0
MET-12	met1000-pin1-**-16k10v	Pin-1	700	700	1600	0.7652	10.0
MET-13	met1000-pin1-**-16k100v	Pin-1	700	700	1600	0.0000	100.0
MET-14	met1000-pin1hom-**-8k0v	Homog. Pin-1	800			0.8502	0.0
MET-15	met1000-pin1hom -**-8k10v	Homog. Pin-1	800			0.7652	10.0
MET-16	met1000-pin1hom -**-8k100v	Homog. Pin-1	800			0.0000	100.0
MET-17	met1000-pin1hom -**-12k0v	Homog. Pin-1	1200			0.8502	0.0
MET-18	met1000-pin1hom -**-12k10v	Homog. Pin-1	1200			0.7652	10.0
MET-19	met1000-pin1hom -**-12k100v	Homog. Pin-1	1200			0.0000	100.0
MET-20	met1000-pin1hom -**-16k0v	Homog. Pin-1	1600			0.8502	0.0
MET-21	met1000-pin1hom -**-16k10v	Homog. Pin-1	1600			0.7652	10.0
MET-22	met1000-pin1hom -**-16k100v	Homog. Pin-1	1600			0.0000	100.0
MET-23	met1000-fa-**-8k0v	Assembly-1	700	700	800	0.8502	0.0
MET-24	met1000-fa-**-8k10v	Assembly-1	700	700	800	0.7652	10.0
MET-25	met1000-fa-**-8k100v	Assembly-1	700	700	800	0.0000	100.0
MET-26	met1000-fa-**-12k0v	Assembly-1	700	700	1200	0.8502	0.0
MET-27	met1000-fa-**-12k10v	Assembly-1	700	700	1200	0.7652	10.0
MET-28	met1000-fa-**-12k100v	Assembly-1	700	700	1200	0.0000	100.0
MET-29	met1000-fa-**-16k0v	Assembly-1	700	700	1600	0.8502	0.0
MET-30	met1000-fa-**-16k10v	Assembly-1	700	700	1600	0.7652	10.0
MET-31	met1000-fa-**-16k100v	Assembly-1	700	700	1600	0.0000	100.0
MET-32	met1000-fahom-**-8k0v	Homog. assembly-1	800			0.8502	0.0
MET-33	met1000-fahom-**-8k10v	Homog. assembly-1	800			0.7652	10.0
MET-34	met1000-fahom-**-8k100v	Homog. assembly-1	800			0.0000	100.0
MET-35	met1000-fahom-**-12k0v	Homog. assembly-1	1200			0.8502	0.0
MET-36	met1000-fahom-**-12k10v	Homog. assembly-1	1200			0.7652	10.0
MET-37	met1000-fahom-**-12k100v	Homog. assembly-1	1200			0.0000	100.0
MET-38	met1000-fahom-**-16k0v	Homog. assembly-1	1600			0.8502	0.0
MET-39	met1000-fahom-**-16k10v	Homog. assembly-1	1600			0.7652	10.0
MET-40	met1000-fahom-**-16k100v	Homog. assembly-1	1600			0.0000	100.0

** Can be "ce," "mg252," "mg302," and "mg1597."

[a] Homog. = Homogenized with fuel, clad, coolant and structure material

▪ Benchmark results

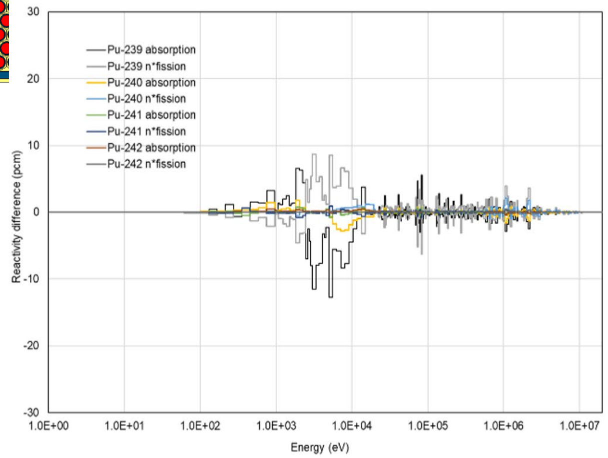
- SCALE-MG vs. CE-KENO

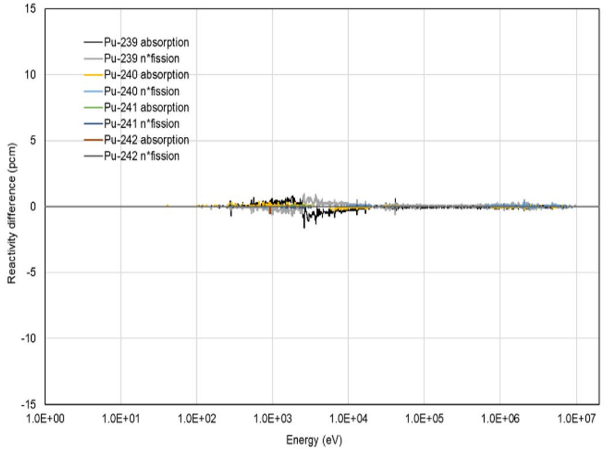


No	Problem ID	ENDF/B-VII.1				ENDF/B-VIII.0			
		CE, k_{eff}	Δρ[a] (pcm)			CE, k_{eff}	Δρ (pcm)		
			1597-g	252-g	302-g		1597-g	252-g	302-g
MET-01	met1000-pin0-**-3k0v	2.22275	-24	-22	-20	2.22580	-50	-50	-54
MET-02	met1000-pin0-**-6k0v	2.21833	-11	-10	-11	2.22286	-74	-70	-75
MET-03	met1000-pin0-**-9k0v	2.21614	-7	-7	-10	2.22057	-63	-61	-66
MET-04	met1000-pin0-**-12k0v	2.21483	-8	-4	-5	2.21952	-64	-64	-68
MET-05	met1000-pin1-**-8k0v	1.35885	-72	-450	-1	1.36764	-161	-493	-77
MET-06	met1000-pin1-**-8k10v	1.36680	-68	-437	5	1.37625	-161	-525	-88
MET-07	met1000-pin1-**-8k100v	1.45334	-70	-477	-11	1.46514	-131	-491	-71
MET-08	met1000-pin1-**-12k0v	1.35700	-73	-443	11	1.36606	-161	-504	-83
MET-09	met1000-pin1-**-12k10v	1.36533	-77	-461	2	1.37446	-157	-500	-85
MET-10	met1000-pin1-**-12k100v	1.45230	-73	-479	-20	1.46418	-142	-502	-84
MET-11	met1000-pin1-**-16k0v	1.35578	-63	-436	16	1.36503	-168	-508	-92
MET-12	met1000-pin1-**-16k10v	1.36427	-72	-455	3	1.37365	-163	-505	-88
MET-13	met1000-pin1-**-16k100v	1.45147	-72	-480	-16	1.46377	-143	-515	-83
MET-14	met1000-pin1hom-**-8k0v	1.35764	-53	-431	38	1.36648	-135	-477	-51
MET-15	met1000-pin1hom -**-8k10v	1.36566	-40	-409	38	1.37483	-129	-460	-46
MET-16	met1000-pin1hom -**-8k100v	1.45239	-34	-432	33	1.46436	-98	-449	-26
MET-17	met1000-pin1hom -**-12k0v	1.35561	-44	-414	33	1.36439	-121	-468	-41
MET-18	met1000-pin1hom -**-12k10v	1.36365	-30	-409	47	1.37305	-129	-463	-47
MET-19	met1000-pin1hom -**-12k100v	1.45116	-34	-442	20	1.46310	-109	-455	-41
MET-20	met1000-pin1hom -**-16k0v	1.35436	-43	-419	30	1.36300	-110	-456	-28
MET-21	met1000-pin1hom -**-16k10v	1.36273	-46	-422	20	1.37199	-120	-472	-54
MET-22	met1000-pin1hom -**-16k100v	1.45021	-45	-441	21	1.46200	-96	-449	-18
MET-23	met1000-fa-**-8k0v	1.27991	45	-245	194	1.28572	-86	-346	57
MET-24	met1000-fa-**-8k10v	1.28873	29	-264	175	1.29450	-77	-351	59
MET-25	met1000-fa-**-8k100v	1.38473	-25	-420	93	1.39422	-109	-464	2
MET-26	met1000-fa-**-12k0v	1.27767	35	-258	185	1.28350	-96	-357	56
MET-27	met1000-fa-**-12k10v	1.28629	33	-266	203	1.29268	-100	-372	53
MET-28	met1000-fa-**-12k100v	1.38327	-21	-420	108	1.39262	-92	-453	19
MET-29	met1000-fa-**-16k0v	1.27621	32	-266	185	1.28243	-110	-385	40
MET-30	met1000-fa-**-16k10v	1.28526	22	-297	167	1.29128	-96	-379	49
MET-31	met1000-fa-**-16k100v	1.38225	-16	-419	111	1.39210	-115	-473	0
MET-32	met1000-fahom-**-8k0v	1.27523	-65	-579	36	1.28084	-192	-676	-85
MET-33	met1000-fahom-**-8k10v	1.28404	-61	-579	44	1.28977	-169	-668	-72
MET-34	met1000-fahom-**-8k100v	1.38089	-63	-674	25	1.39027	-150	-723	-72
MET-35	met1000-fahom-**-12k0v	1.27261	-53	-574	44	1.27828	-185	-668	-82
MET-36	met1000-fahom-**-12k10v	1.28167	-57	-590	34	1.28750	-173	-674	-79
MET-37	met1000-fahom-**-12k100v	1.37916	-53	-673	24	1.38862	-150	-729	-65
MET-38	met1000-fahom-**-16k0v	1.27118	-65	-578	21	1.27670	-177	-671	-82
MET-39	met1000-fahom-**-16k10v	1.28014	-64	-593	24	1.28610	-174	-690	-80
MET-40	met1000-fahom-**-16k100v	1.37817	-70	-683	10	1.38776	-157	-735	-91

*Standard deviations are less than 15 pcm for all cases.

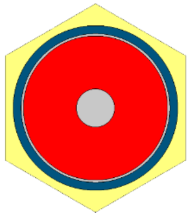
[a] Reactivity difference (Δρ) is obtained by $(1/k_{eff}^{CE}-1/k_{eff}^{MG})\cdot 10^5$

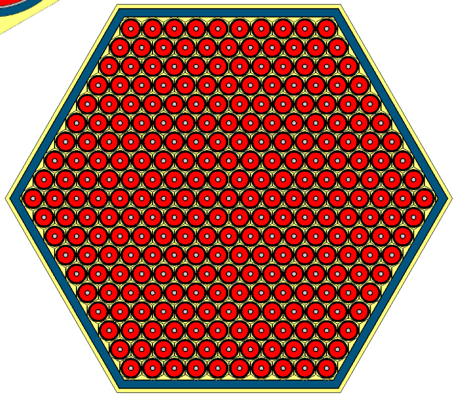




OECD-NEA MOX-3600 Benchmarks

- **Benchmark problems & Results**
  - Single pins and assemblies





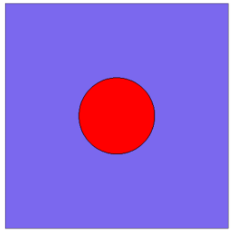
No	Problem ID	Description	Temperature (K)			Cool density (g/cm³)	Sodium void (%)	ENDF/B-VII.1				ENDF/B-VIII.0			
			Cool	Clad	Fuel			CE, k_{eff}	1597-g	252-g	302-g	CE, k_{eff}	1597-g	252-g	302-g
MOX-01	mox3600-pin-**-9k0v	Pin	740	740	900	0.83696	0.0	1.19698	-66	-46	-30	1.20189	-257	-216	-227
MOX-02	mox3600-pin-**-9k10v	Pin	740	740	900	0.75328	10.0	1.20009	-88	-44	-25	1.20495	-243	-202	-224
MOX-03	mox3600-pin-**-9k100v	Pin	740	740	900	0.00000	100.0	1.23116	-64	-25	-26	1.23750	-218	-143	-184
MOX-04	mox3600-pin-**-12k0v	Pin	740	740	1200	0.83696	0.0	1.19399	-54	-30	-18	1.19902	-249	-206	-218
MOX-05	mox3600-pin-**-12k10v	Pin	740	740	1200	0.75328	10.0	1.19720	-63	-43	-35	1.20236	-252	-202	-221
MOX-06	mox3600-pin-**-12k100v	Pin	740	740	1200	0.00000	100.0	1.22865	-47	-6	-4	1.23530	-218	-144	-176
MOX-07	mox3600-pin-**-15k0v	Pin	740	740	1500	0.83696	0.0	1.19195	-64	-49	-28	1.19689	-229	-200	-213
MOX-08	mox3600-pin-**-15k10v	Pin	740	740	1500	0.75328	10.0	1.19521	-67	-40	-21	1.20019	-240	-200	-212
MOX-09	mox3600-pin-**-15k100v	Pin	740	740	1500	0.00000	100.0	1.22692	-43	-11	-18	1.23374	-202	-145	-179
MOX-10	mox3600-pinhom-**-9k0v	Homogenized pin	900			0.83696	0.0	1.19541	9	59	61	1.20035	-188	-127	-143
MOX-11	mox3600-pinhom -**-9k10v	Homogenized pin	900			0.75328	10.0	1.19844	25	75	76	1.20338	-171	-87	-124
MOX-12	mox3600-pinhom -**-9k100v	Homogenized pin	900			0.00000	100.0	1.23054	3	74	55	1.23706	-165	-73	-121
MOX-13	mox3600-pinhom -**-12k0v	Homogenized pin	1200			0.83696	0.0	1.19279	-11	34	34	1.19738	-172	-105	-135
MOX-14	mox3600-pinhom -**-12k10v	Homogenized pin	1200			0.75328	10.0	1.19588	-6	33	39	1.20093	-189	-115	-147
MOX-15	mox3600-pinhom -**-12k100v	Homogenized pin	1200			0.00000	100.0	1.22790	5	86	60	1.23445	-129	-51	-110
MOX-16	mox3600-pinhom -**-15k0v	Homogenized pin	1500			0.83696	0.0	1.19015	26	71	68	1.19531	-184	-106	-130
MOX-17	mox3600-pinhom -**-15k10v	Homogenized pin	1500			0.75328	10.0	1.19356	-2	74	65	1.19886	-194	-121	-147
MOX-18	mox3600-pinhom -**-15k100v	Homogenized pin	1500			0.00000	100.0	1.22605	16	91	63	1.23282	-149	-55	-114
MOX-19	mox3600-fa-**-9k0v	Assembly	740	740	900	0.83696	0.0	1.15208	106	196	233	1.15436	-109	0	-5
MOX-20	mox3600-fa-**-9k10v	Assembly	740	740	900	0.75328	10.0	1.15577	83	179	212	1.15808	-129	-5	-14
MOX-21	mox3600-fa-**-9k100v	Assembly	740	740	900	0.00000	100.0	1.19119	53	183	169	1.19523	-122	4	-35
MOX-22	mox3600-fa-**-12k0v	Assembly	740	740	1200	0.83696	0.0	1.14918	77	169	197	1.15133	-108	-3	-12
MOX-23	mox3600-fa-**-12k10v	Assembly	740	740	1200	0.75328	10.0	1.15248	83	185	202	1.15506	-124	-6	-13
MOX-24	mox3600-fa-**-12k100v	Assembly	740	740	1200	0.00000	100.0	1.18855	54	167	163	1.19283	-132	1	-31
MOX-25	mox3600-fa-**-15k0v	Assembly	740	740	1500	0.83696	0.0	1.14648	93	198	218	1.14905	-126	-13	-17
MOX-26	mox3600-fa-**-15k10v	Assembly	740	740	1500	0.75328	10.0	1.15040	70	162	187	1.15277	-139	-18	-27
MOX-27	mox3600-fa-**-15k100v	Assembly	740	740	1500	0.00000	100.0	1.18684	52	151	160	1.19131	-144	-16	-50
MOX-28	mox3600-fahom-**-9k0v	Homog. assembly	900			0.83696	0.0	1.14580	6	-40	73	1.14787	-208	-228	-161
MOX-29	mox3600-fahom-**-9k10v	Homog. assembly	900			0.75328	10.0	1.14921	21	-15	90	1.15143	-199	-209	-141
MOX-30	mox3600-fahom-**-9k100v	Homog. assembly	900			0.00000	100.0	1.18665	-16	-28	63	1.19033	-175	-169	-120
MOX-31	mox3600-fahom-**-12k0v	Homog. assembly	1200			0.83696	0.0	1.14241	12	-23	73	1.14445	-191	-208	-139
MOX-32	mox3600-fahom-**-12k10v	Homog. assembly	1200			0.75328	10.0	1.14631	-10	-48	56	1.14826	-197	-205	-125
MOX-33	mox3600-fahom-**-12k100v	Homog. assembly	1200			0.00000	100.0	1.18409	14	-35	48	1.18782	-177	-174	-129
MOX-34	mox3600-fahom-**-15k0v	Homog. assembly	1500			0.83696	0.0	1.14030	-17	-51	48	1.14236	-207	-227	-157
MOX-35	mox3600-fahom-**-15k10v	Homog. assembly	1500			0.75328	10.0	1.14366	12	-26	80	1.14632	-218	-236	-165
MOX-36	mox3600-fahom-**-15k100v	Homog. assembly	1500			0.00000	100.0	1.18205	-2	-23	64	1.18592	-178	-170	-120

** Can be "ce," "mg252," "mg302," and "mg1597."

Models		Δρ (pcm)					
		ENDF/B-VII.1			ENDF/B-VIII.0		
Heterogeneous	Homogeneous	CE	1597-g	302-g	CE	1597-g	302-g
MOX-01	MOX-10	-110	-34	-19	-107	-37	-23
MOX-02	MOX-11	-115	-2	-14	-108	-37	-9
MOX-03	MOX-12	-41	27	40	-29	24	35
MOX-04	MOX-13	-84	-41	-33	-114	-37	-32
MOX-05	MOX-14	-92	-35	-18	-99	-36	-26
MOX-06	MOX-15	-50	3	15	-56	34	10
MOX-07	MOX-16	-127	-36	-31	-110	-66	-27
MOX-08	MOX-17	-116	-51	-29	-92	-46	-27
MOX-09	MOX-18	-58	1	23	-60	-8	5
MOX-19	MOX-28	-476	-576	-636	-490	-589	-646
MOX-20	MOX-29	-494	-555	-616	-499	-569	-626
MOX-21	MOX-30	-321	-391	-427	-344	-396	-430
MOX-22	MOX-31	-516	-580	-640	-522	-605	-649
MOX-23	MOX-32	-467	-559	-613	-513	-586	-625
MOX-24	MOX-33	-317	-357	-432	-354	-398	-452
MOX-25	MOX-34	-473	-583	-643	-510	-591	-650
MOX-26	MOX-35	-512	-570	-620	-488	-568	-626
MOX-27	MOX-36	-341	-395	-437	-382	-416	-452

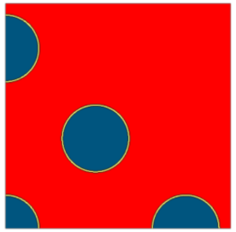
Thermal Molten Salt Reactor Benchmarks

- **Benchmark problems**
  - Single pins and assemblies



[Pin-graphite moderator]

[Pin-ZrH moderator]



[Assembly-ZrH moderator]

No	Problem ID	Description	Temperature (K)			Burnup
			Mod	Clad	Fuel	
MSRT-01	msrC-pin-**-6k0b	Pin w/ graphite moderator	600		600	0.0
MSRT-02	msrC-pin-**-6k50b	Pin w/ graphite moderator	600		600	yes
MSRT-03	msrC-pin-**-9k0b	Pin w/ graphite moderator	900		900	0.0
MSRT-04	msrC-pin-**-9k50b	Pin w/ graphite moderator	900		900	yes
MSRT-05	msrC-pin-**-12k0b	Pin w/ graphite moderator	900		1200	0.0
MSRT-06	msrC-pin-**-12k50b	Pin w/ graphite moderator	900		1200	yes
MSRT-07	msrC-pin-**-15k0b	Pin w/ graphite moderator	900		1500	0.0
MSRT-08	msrC-pin-**-15k50b	Pin w/ graphite moderator	900		1500	yes
MSRT-09	msrZr-pin-**-6k0b	Pin w/ ZrH moderator	600		600	0.0
MSRT-10	msrZr-pin-**-6k50b	Pin w/ ZrH moderator	600		600	yes
MSRT-11	msrZr-pin-**-9k0b	Pin w/ ZrH moderator	900		900	0.0
MSRT-12	msrZr-pin-**-9k50b	Pin w/ ZrH moderator	900		900	yes
MSRT-13	msrZr-pin-**-12k0b	Pin w/ ZrH moderator	900		1200	0.0
MSRT-14	msrZr-pin-**-12k50b	Pin w/ ZrH moderator	900		1200	yes
MSRT-15	msrZr-pin-**-15k0b	Pin w/ ZrH moderator	900		1500	0.0
MSRT-16	msrZr-pin-**-15k50b	Pin w/ ZrH moderator	900		1500	yes
MSRT-17	msrZr-fa-**-9k0b	Assembly w/ ZrH moderator	900	900	900	0.0
MSRT-18	msrZr-fa-**-12k0b	Assembly w/ ZrH moderator	900	900	1200	0.0
MSRT-19	msrZr-fa-**-15k0b	Assembly w/ ZrH moderator	900	900	1500	0.0

** Can be "ce," "mg252," "mg302," and "mg1597."

- **Benchmark results**
  - SCALE-MG vs. CE-KENO

No	Problem ID	ENDF/B-VII.1				ENDF/B-VIII.0			
		CE, k_{eff}	$\Delta\rho^a$ (pcm)			CE, k_{eff}	$\Delta\rho$ (pcm)		
			1597-g	252-g	302-g		1597-g	252-g	302-g
MSRT-01	msrC-pin-**-6k0b	1.49406	-103	-111	-1321	1.49272	-137	-134	-1318
MSRT-02	msrC-pin-**-6k50b	1.04586	-63	-89	-740	1.04775	-119	-140	-713
MSRT-03	msrC-pin-**-9k0b	1.47464	-82	-95	-583	1.47349	-127	-148	-609
MSRT-04	msrC-pin-**-9k50b	1.05647	-110	-110	-3078	1.05714	-139	-156	-3039
MSRT-05	msrC-pin-**-12k0b	1.46365	-92	-97	-610	1.46238	-125	-143	-643
MSRT-06	msrC-pin-**-12k50b	1.04708	-78	-117	-3427	1.04789	-172	-176	-3426
MSRT-07	msrC-pin-**-15k0b	1.45381	-80	-112	-627	1.45243	-125	-124	-657
MSRT-08	msrC-pin-**-15k50b	1.03881	-164	-177	-3891	1.03901	-181	-199	-3819
MSRT-09	msrZr-pin-**-6k0b	1.06603	-64	-107	-109	1.06678	-104	-105	-180
MSRT-10	msrZr-pin-**-6k50b	0.99945	-89	-79	3115	1.00177	-7	-32	3346
MSRT-11	msrZr-pin-**-9k0b	1.05107	-123	-93	-142	1.05191	-167	-162	-226
MSRT-12	msrZr-pin-**-9k50b	1.01604	-65	-63	53	1.01781	-69	-45	344
MSRT-13	msrZr-pin-**-12k0b	1.03876	-117	-125	-177	1.03956	-179	-171	-237
MSRT-14	msrZr-pin-**-12k50b	1.00906	-28	-24	-80	1.01024	5	6	180
MSRT-15	msrZr-pin-**-15k0b	1.02854		-151	-183	1.03002		-251	-320
MSRT-16	msrZr-pin-**-15k50b	1.00258		-2	-218	1.00430		-58	7
MSRT-17	msrZr-fa-**-9k0b	1.13517	-57	-74	460	1.13586	-106	-121	371
MSRT-18	msrZr-fa-**-12k0b	1.12591	-68	-88	474	1.12661	-140	-149	380
MSRT-19	msrZr-fa-**-15k0b	1.11837	-110	-130	473	1.11907	-174	-159	390

[a] Reactivity difference ($\Delta\rho$) is obtained by $(1/k_{eff}^{CE}-1/k_{eff}^{MG})\cdot 10^5$

Fast Molten Salt Reactor Benchmarks

- **Benchmark problems**
  - Single pins and assemblies

No	Problem ID	Description	Temperature (K)	Burnup
MSRF-01	msrFast-hom-**-6k0b	Homogenous	600	0.0
MSRF-02	msrFast-hom-**-6k50b	Homogenous	600	yes
MSRF-03	msrFast-hom-**-9k0b	Homogenous	900	0.0
MSRF-04	msrFast-hom-**-9k50b	Homogenous	900	yes
MSRF-05	msrFast-hom-**-12k0b	Homogenous	1200	0.0
MSRF-06	msrFast-hom-**-12k50b	Homogenous	1200	yes
MSRF-07	msrFast-hom-**-12k0b	Homogenous	1200	0.0
MSRF-08	msrFast-hom-**-12k50b	Homogenous	1200	yes

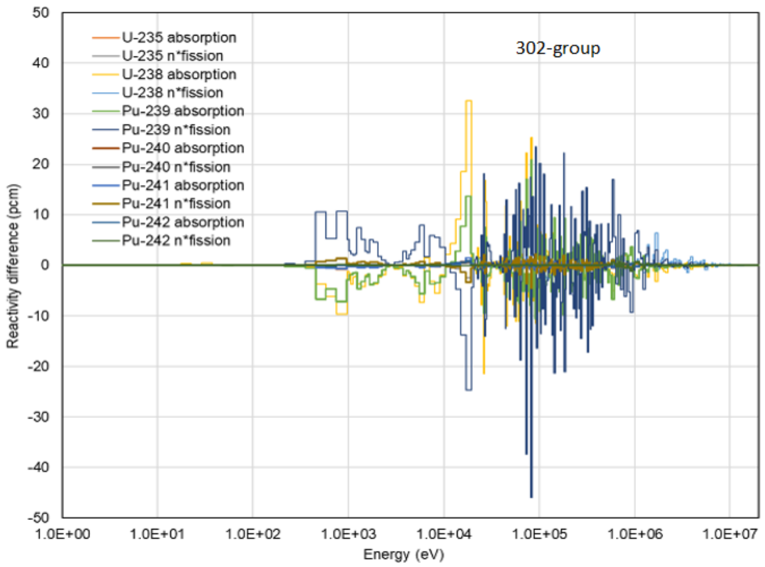
** Can be "ce," "mg252," "mg302," and "mg1597."

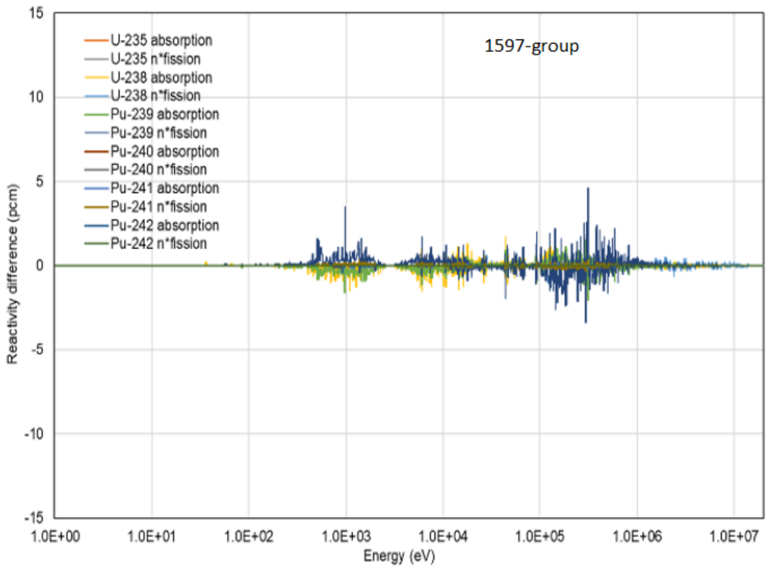
- **Benchmark results**
  - SCALE-MG vs. CE-KENO

No	Problem ID	ENDF/B-VII.1				ENDF/B-VIII.0			
		CE, k_{eff}	$\Delta\rho^a$ (pcm)			CE, k_{eff}	$\Delta\rho$ (pcm)		
			1597-g	252-g	302-g		1597-g	252-g	302-g
MSRF-01	msrFast-hom-**-6k0b	1.13229	-53	[redacted]	-46	1.13940	-150	[redacted]	-150
MSRF-02	msrFast-hom-**-6k50b	1.11051	-11	[redacted]	-67	1.11616	-172	[redacted]	-224
MSRF-03	msrFast-hom-**-9k0b	1.12813	-37	[redacted]	-42	1.13548	-147	[redacted]	-148
MSRF-04	msrFast-hom-**-9k50b	1.10442	-21	[redacted]	-75	1.11006	-162	[redacted]	-220
MSRF-05	msrFast-hom-**-12k0b	1.12572	-71	[redacted]	-68	1.13288	-148	[redacted]	-151
MSRF-06	msrFast-hom-**-12k50b	1.10035	-27	[redacted]	-78	1.10587	-159	[redacted]	-211
MSRF-07	msrFast-hom-**-15k0b	1.12386	-76	[redacted]	-76	1.13115	-167	[redacted]	-167
MSRF-08	msrFast-hom-**-15k50b	1.09744		[redacted]	-105	1.10323		[redacted]	-258

*Standard deviations are less than 15 pcm for all cases.

[a]Reactivity difference ($\Delta\rho$) is obtained by $(1/k_{eff}^{CE} - 1/k_{eff}^{MG})\cdot 10^5$





HTGR Benchmarks

- **Pebble Bed HTGR**
  - SCALE-MG vs. CE-KENO

No	Problem description					$\Delta\rho^a$ or Δk^a (pcm)			
	# of TRISOs	Temp. (K)			Burnup	CE, k_{eff}	SCALE-6.2.3		SCALE-6.3b
		Mod.	Fuel	Layers			1597-g	252-g	258-g
PEB-01	8,385	300	300	300	0.0	1.67570	-21	-41	-47
PEB-02	8,385	900	900	900	0.0	1.61492	-20	-26	-16
PEB-03	8,385	900	1200	900	0.0	1.60008	-113	-141	-35
PEB-04	8,385	900	1500	900	0.0	1.58739	-166	-184	-23
PEB-05	8,385	900	2400	900	0.0	1.55912	-303	-256	-24
PEB-06	8,385	300	300	300	yes	1.04641	-21	-56	-38
PEB-07	8,385	900	900	900	yes	1.07689	22	5	127
PEB-08	8,385	900	1200	900	yes	1.06567	359	310	130
PEB-09	8,385	900	1500	900	yes	1.05655	-108	-158	107
PEB-10	8,385	900	2400	900	yes	1.03528	-2648	-2604	125
PEB-11	15,000	300	300	300	0.0	1.51239	-114	-127	-160
PEB-12	15,000	900	900	900	0.0	1.42936	-140	-158	-123
PEB-13	15,000	900	1200	900	0.0	1.40651	-269	-286	-137
PEB-14	15,000	900	1500	900	0.0	1.38687	-347	-367	-139
PEB-15	15,000	900	2400	900	0.0	1.34303	-692	-505	-197
PEB-16	15,000	300	300	300	yes	0.99727	-150	-166	-228
PEB-17	15,000	900	900	900	yes	0.97802	-224	-257	-164
PEB-18	15,000	900	1200	900	yes	0.96124	-405	-431	-149
PEB-19	15,000	900	1500	900	yes	0.94744	-1237	-1267	-171
PEB-20	15,000	900	2400	900	yes	0.91606	-4056	-3851	-172

*Standard deviations are less than 20 pcm for all cases.

[a] $\Delta\rho$ is obtained by $(1/k_{eff}^{CE}-1/k_{eff}^{MG})\cdot10^5$ for $k_{eff} > 1.0$ and Δk is obtained by $(k_{eff}^{MG}-k_{eff}^{CE})\cdot10^5$ for $k_{eff} < 1.0$

- **Prismatic HTGR**
  - SCALE-MG vs. CE-KENO

No	Description					$\Delta\rho^a$ or Δk^a (pcm)			
	Fuel type	P.F.[b] (%)	Temp. (K)		Burnup	CE, k_{eff}	SCALE–6.2.3		SCALE–6.3b
			Mod.	Fuel			1597-g	252-g	258-g
PRM-01	Homogenous	-	-	293	0.0	1.26287	16	-19	-22
PRM-02	Homogenous	-	-	900	0.0	1.16028	-96	-123	135
PRM-03	Homogenous	-	-	1200	0.0	1.12914	-170	-214	113
PRM-04	Homogenous	-	-	2400	0.0	1.05010	-350	-384	141
PRM-05	Homogenous	-	-	293	yes[c]	0.99511	-76	-149	-47
PRM-06	Homogenous	-	-	900	yes	0.88971	-273	-346	3
PRM-07	Homogenous	-	-	1200	yes	0.85035	-165	-253	143
PRM-08	Homogenous	-	-	2400	yes	0.74210	-178	-347	250
PRM-09	Pin single-het	-	293	293	0.0	1.29662	-163	-314	-153
PRM-10	Pin single-het	-	900	900	0.0	1.20166	-285	-374	-15
PRM-11	Pin single-het	-	900	1200	0.0	1.17222	-331	-405	-25
PRM-12	Pin single-het	-	900	2400	0.0	1.09196	-389	-436	22
PRM-13	Pin single-het	-	293	293	yes	1.02216	-351	-522	-109
PRM-14	Pin single-het	-	900	900	yes	0.92145	-542	-630	-70
PRM-15	Pin single-het	-	900	1200	yes	0.89264	-511	-592	-40
PRM-16	Pin single-het	-	900	2400	yes	0.81597	-520	-526	12
PRM-17	Pin type 1	35	293	293	0.0	1.36930	-233	-276	-104
PRM-18	Pin type 1	35	900	900	0.0	1.27936	-305	-345	-16
PRM-19	Pin type 1	35	900	1200	0.0	1.25170	-387	-439	-56
PRM-20	Pin type 1	35	900	1500	0.0	1.22865	-430	-471	-30
PRM-21	Pin type 1	35	293	293	yes	1.10002	-448	-518	-195
PRM-22	Pin type 1	35	900	900	yes	0.99794	-620	-651	-151
PRM-23	Pin type 1	35	900	1200	yes	0.97364	-1201	-1222	-360
PRM-24	Pin type 1	35	900	1500	yes	0.95277	-1646	-1691	-452
PRM-25	Pin type 2	25	293	293	0.0	1.46067	-182	-215	-158
PRM-26	Pin type 2	25	900	900	0.0	1.37367	-267	-274	-104
PRM-27	Pin type 2	25	900	1200	0.0	1.34781	-315	-343	-29
PRM-28	Pin type 2	25	900	1500	0.0	1.32650	-364	-387	-65
PRM-29	Block type 1	35	293	293	0.0	1.49044	26	28	31
PRM-30	Block type 1	35	900	900	0.0	1.40838	-20	-56	106
PRM-31	Block type 1	35	900	1200	0.0	1.38363	-83	-84	107
PRM-32	Block type 1	35	900	1500	0.0	1.36359	-124	-148	91
PRM-33	Block type 1	35	293	293	yes	1.24474	-77	-55	8
PRM-34	Block type 1	35	900	900	yes	1.14232	-235	-232	-7
PRM-35	Block type 1	35	900	1200	yes	1.11989	-653	-653	-92
PRM-36	Block type 1	35	900	1500	yes	1.10137	-1049	-1068	-256
PRM-37	Block type 1 w/ BP	35	293	293	0.0	1.15295	7	8	21
PRM-38	Block type 1 w/ BP	35	900	900	0.0	1.07347	-156	-180	88
PRM-39	Block type 1 w/ BP	35	900	1200	0.0	1.05599	-489	-495	-36
PRM-40	Block type 1 w/ BP	35	900	1500	0.0	1.04089	-743	-761	-153
PRM-41	Block type 2	25	293	293	0.0	1.57019	29	29	31
PRM-42	Block type 2	25	900	900	0.0	1.49335	-10	-39	87
PRM-43	Block type 2	25	900	1200	0.0	1.47151	-65	-84	66
PRM-44	Block type 2	25	900	1500	0.0	1.45381	-111	-135	70

*Standard deviations are less than 20 pcm for all cases.

[a] $\Delta\rho$ is obtained by $(1/k_{eff}^{CE}-1/k_{eff}^{MG})\cdot10^5$ for $k_{eff} > 1.0$ and Δk is obtained by $(k_{eff}^{MG}-k_{eff}^{CE})\cdot10^5$ for $k_{eff} < 1.0$

[b] P.F. = Packing Fraction; CE = continuous energy.

[c] yes = 50 MWd/kgU.

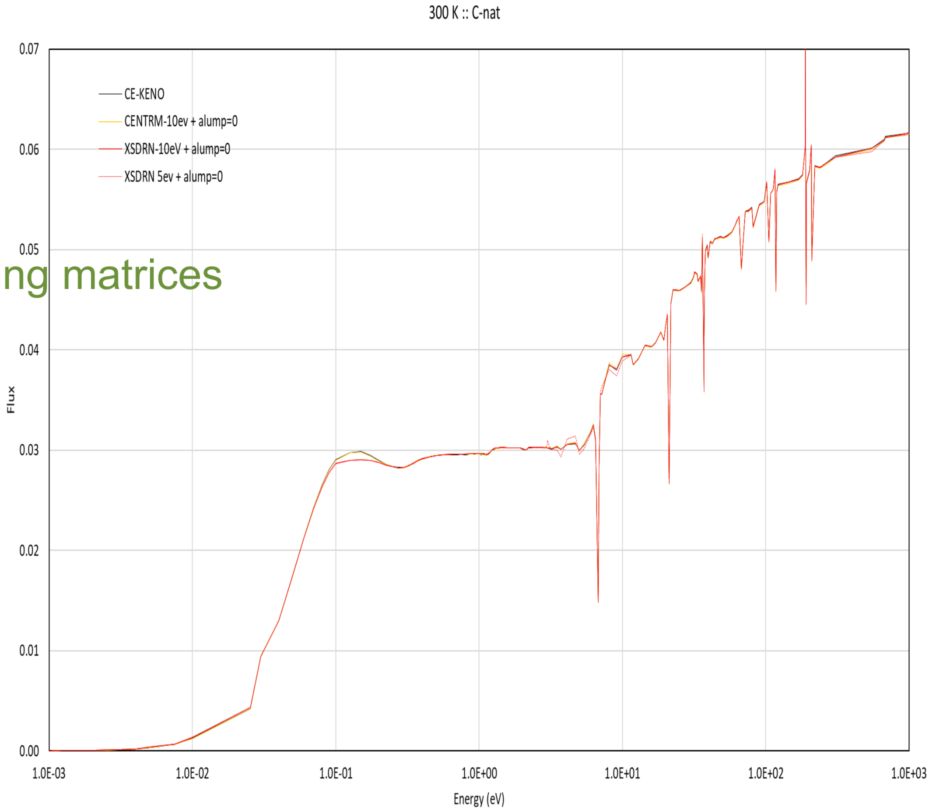
Summary of AMPX and XSProc Capability

Reactor type	Spectrum	AMPX library applicability		
		1597-group	252-group	302-group
Pressurized Water Reactor (PWR)	Thermal	yes	yes	no
Boiling Water Reactor (BWR)	Thermal - Fast	yes	yes/no[a]	no
Advanced Burner Test Reactor (ABTR)	Fast	yes	no	yes
EBR-II	Fast	yes	no	yes
OECD-NEA MET-1000	Fast	yes	no	yes
OECD-NEA MOX-3600	Fast	yes	no	yes
Thermal Molten Salt Reactor	Thermal	yes	yes	no
Fast Molten Salt Reactor	Fast	yes	no	yes[b]
Pebble Bed Gas-Cooled Reactor	Thermal	yes	yes	no
Prismatic Gas-Cooled Reactor	Thermal	yes	yes	no

[a] Large reactivity bias for very high void fraction > 99 %
[b] Reaction rate error cancellations at high energy

Challenging Issues & Pending Works

- **AMPX 1597-group library**
  - Memory burden & long computing time
    - ➢ Energy group optimization
    - ➢ Internal energy group collapsing
- **Inconsistent energy group collapsing**
  - Perfect slowing down solver CENTRM
    - ➢ PW + Scattering kernels + upscattering
    - ➢ Much faster than MC
  - No angle dependent total cross sections
    - ➢ Implicit treatment → SPH factor to conserve reaction rate
  - No explicit scattering matrix update
    - ➢ Within-group & Out-of-group corrections only for > 5eV scattering matrices
    - ➢ → Explicit correction for all energy groups and at least for P_0
- **Merits & Goal**
  - Explicit high order flux moment weighting!!!
    - ➢ MC does not support it.
  - Reference solutions without statistical error!!!
    - ➢ CENTRM slowing down solution = CE Monte Carlo solution
    - ➢ Approximation only on spatial discretization compared to MC



Conclusion

- **SCALE/XSProc module**
  - Resonance self-shielding calculation
    - Bondarenko approach: BONAMI, Polaris
    - PW slowing down calculation: XSProc-CENTRM
    - Works for any advanced reactor analysis
  - Various group structure options in SCALE-6.3
    - 1597-group: any conventional and advanced reactor analysis
    - 56- and 252(258)-group: thermal reactor analysis
    - 302-group: fast reactor analysis
  - Benchmark suite for advanced reactors in SCALE-6.3

- **Ongoing and future works**
  - Consistent energy group collapsing: equivalence theory using SPH, scattering matrix
  - Computational efficiency improvement for XSProc
    - Energy group structure optimization for memory and speed efficiency (< 1000)
    - Improve Dancoff based Wigner-Seitz approximation
    - Internal on-the-fly collapsing
    - Improve the lumping procedure for scattering source
  - Neutron leakage model for fast reactor application
  - XSProc-API development

Backup Slides

Reaction Rate Analysis for Verification

- **Reaction rate analysis procedure**
  - SCALE-MG vs. CE-KENO
    - Edit MG microscopic cross sections & scalar fluxes
  - Convert reaction rate difference into reactivity difference
    - Reactivity differences for each energy group, nuclide and reaction type
    - Identify the reactions and nuclides causing the observed reactivity difference
    - Two options:
      - [1] Only by cross section difference
      - [2] By both cross section and flux differences

$$\Delta\rho^{K}_{a,g,J} = \left(\frac{1}{k^{KENO}_{eff}} - \frac{\sum_{j}\sum_{i}\sum_{g'} N_{i,j}\sigma^{KENO}_{a,g',i,j}\varphi^{KENO}_{g',j}V_j - N_{K,J}(\sigma^{KENO}_{a,g,K,J} - \sigma^{MG}_{a,g,K,J})\hat{\varphi}_{g,J}V_J}{\sum_{j}\sum_{i}\sum_{g'} N_{i,j}\nu\sigma^{KENO}_{f,g',i,j}\varphi^{KENO}_{g',j}V_j} \right) \cdot 10^5$$

$$\Delta\rho^{K}_{\nu f,g,J} = \left(\frac{1}{k^{KENO}_{eff}} - \frac{\sum_{j}\sum_{i}\sum_{g'} N_{i,j}\sigma^{KENO}_{a,g',i,j}\varphi^{KENO}_{g',j}V_j}{\sum_{j}\sum_{i}\sum_{g'} N_{i,j}\nu\sigma^{KENO}_{f,g',i,j}\varphi^{KENO}_{g',j}V_j - N_{K,J}(\nu\sigma^{KENO}_{f,g,K,J} - \nu\sigma^{MG}_{f,g,K,J})\hat{\varphi}_{g,J}V_J} \right) \cdot 10^5$$

$$\Delta\rho_g = \sum_{j}\sum_{K}\sum_{g}(\Delta\rho^{K}_{a,g,j} + \Delta\rho^{K}_{\nu f,g,j})$$

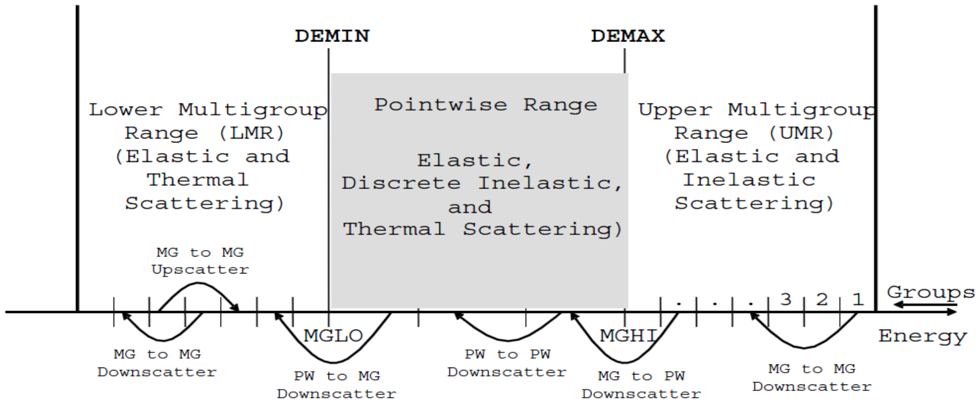
SCALE-XSPROC CENTRM Based Slowing Down Calculation I

- **Pointwise slowing down calculation (CENTRM)**
  - Nuclear data
    - CRAWDAD
      - Pointwise cross sections
      - S(α,β) thermal scattering kernel data
    - BONAMI
      - Self-shielded multigroup cross sections and scattering matrices
      - Problem dependent AMPX working library
  - Pointwise + Multigroup hybrid
    - Upper multigroup range: ≥ DEMAX (default=20 keV)
      - Multigroup cross sections are determined by BONAMI
      - Convert multigroup data into pointwise data
    - Pointwise range: DEMIN-DEMAX (default=0.001 eV - 20 keV)
      - Pure pointwise slowing down calculation

$$\hat{\Omega}\cdot\nabla\psi + \Sigma_t(\vec{r},u)\psi(\vec{r},u,\hat{\Omega}) = \int_{4\pi} d\Omega' \int_0^\infty du\, \Sigma_s(\vec{r},u'\to u,\hat{\Omega}'\cdot\hat{\Omega})\psi(\vec{r},u',\hat{\Omega}') + q(\vec{r},u,\hat{\Omega})$$

$$\int_{4\pi} d\Omega' \int_0^\infty du\, \Sigma_s(\vec{r},u'\to u,\hat{\Omega}'\cdot\hat{\Omega})\psi(\vec{r},u',\hat{\Omega}') = \sum_i \sum_{\ell=0}^{L} \sum_{k=0}^{\ell} \frac{2\ell+1}{2} Y_{\ell k}(\hat{\Omega}) \Sigma_\ell^i(u'\to u,)\Phi_{\ell k}(u')$$

    - Lower multigroup range: ≤ DEMIN (default=0.001 eV)
      - Multigroup cross sections are determined by BONAMI
      - Convert multigroup data into pointwise data



SCALE-XSPROC CENTRM Based Slowing Down Calculation II

- **Pointwise slowing down calculation (continued)**
  - Scattering physics
    - Epithermal elastic scatter
      - S-wave approximation assuming isotropic scattering in CM system
      - $\geq$ thermal cutoff energy (for example, 5 eV)
      - Discussion
        - Not true actually
        - Cause some issue at epithermal neutron spectra
        - Can be resolved by optimizing group structure
    - Epithermal inelastic scatter
      - DEMAX $\leq$ inelastic threshold
        - Multigroup inelastic scattering matrices
      - DEMAX $\geq$ inelastic threshold
        - Discrete-level inelastic reaction: two-body interaction
        - High energy: discrete → continuum
    - Thermal scatter
      - $\leq$ thermal cutoff energy (for example, 5 eV)

$$\sigma_\ell(E' \to E, T) = \frac{\sigma_b}{T}\sqrt{\frac{E}{E'}}e^{-\frac{\beta(E'\to E)}{2}}\int P_\ell(\mu_0)S(\alpha,\beta,T)d\mu_0$$

      - Free gas thermal kernel for $S(\alpha,\beta)$: internal analytic formula
    - Bound thermal scatter
      - ENDF/B data processed by AMPX
      - Prepared by CRAWDAD

SCALE-XSPROC CENTRM Based Slowing Down Calculation III

- **Pointwise slowing down calculation (continued)**
  - Slowing down transport solvers
    - 0-dimensional slowing down
    - 1-dimensional discrete ordinates (S_N)
      - Slab and Wigner-Seitz cylinder and sphere
    - 2-dimensional method of characteristics (MOC)
      - 2D square with cylindrical fuels
    - Two-region collision probability
  - Double-heterogeneity treatment
    - Consecutive two PW slowing down calculation
      - Perform the 1st slowing down calculation for infinite TRISO array
      - Homogenize TRISO and matrix using the PW flux moments
        → disadvantage factors
      - Perform the 2nd slowing down calculation
      - Collapse PW into MG
      - Slab, cylinder and sphere
    - SCALE-6.3 improvement
      - Use a Dancoff factor to adjust TRISO pitch to consider neutron leakage effect
      - Dancoff factor can be a user input and obtained using MCDancoff
      - TRISO pitch can be adjusted to have same Dancoff with input using internal 1D spherical CPM
      - Nuclide dependent temperatures and PW data can be at the 2nd slowing down calculation over the homogenized TRISO and matrix region