Sensitivity to Nuclear Data in a Lead-Cooled Fast Reactor

Starting from code validation in thermal reactors and other applications

2017 September 26

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

SCALE at Canadian Nuclear Laboratories

An expanding role in safety and licensing analysis

SCALE has been used for several CNL applications:

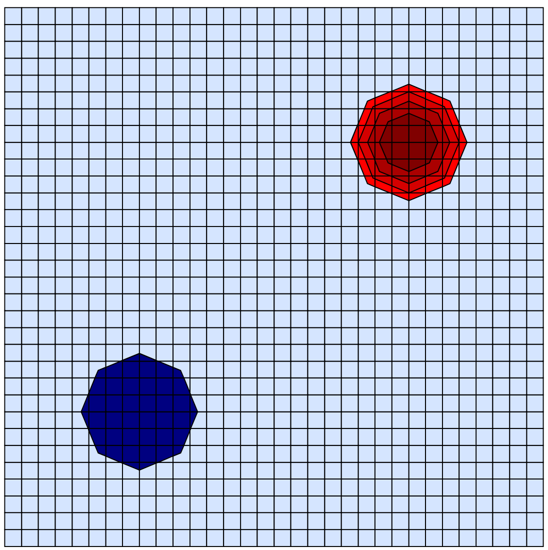
- ORIGEN for fuel source terms and material activation
- KENO V.a for criticality safety analysis (since long ago)
- TSUNAMI for nuclear data sensitivity and uncertainty now
- Others are used case-by-case

Currently running SCALE 6.1;
still working up to SCALE 6.2…

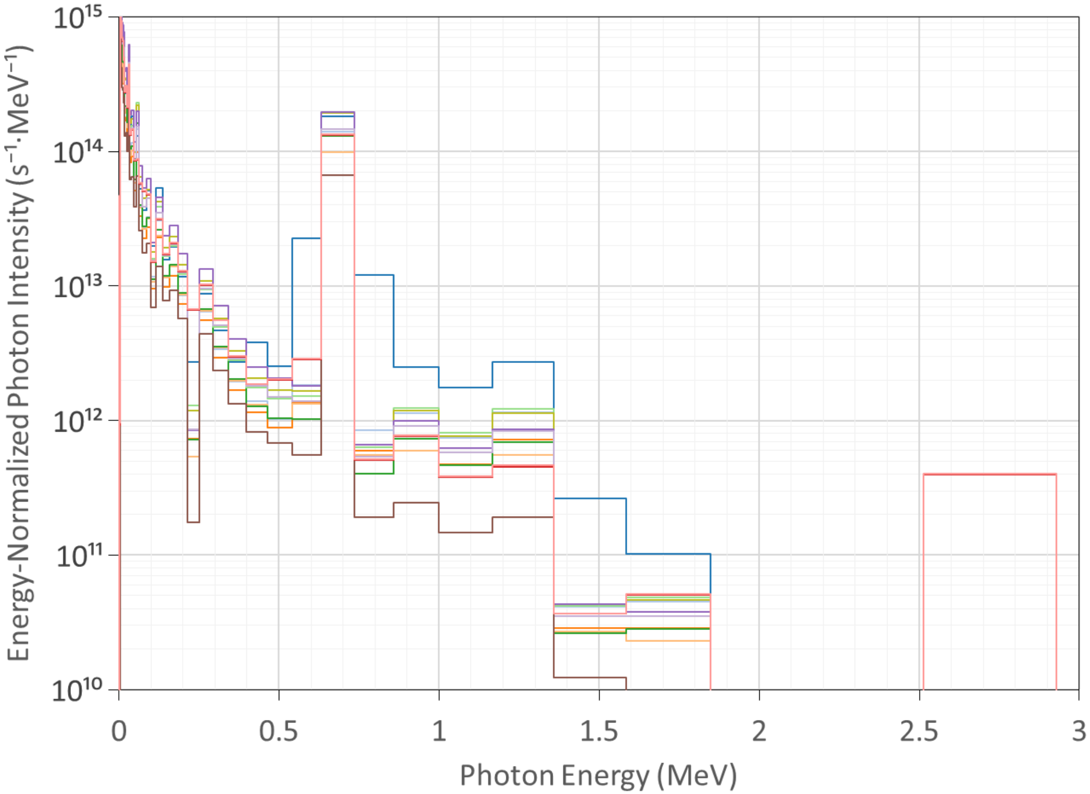
Running on CNL's "Titan" cluster ⟶
(26 nodes, 312 cores)
KENO3D, manuals etc. on PC's

Example: Source Term Calculation

Parametric study of different lattices of different fuels to find maxima



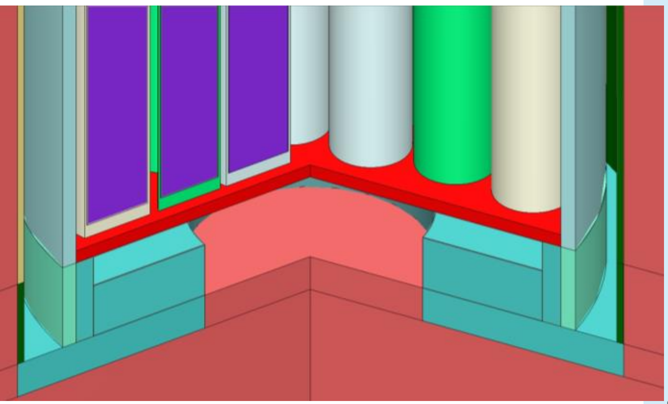
Geometry in NEWT



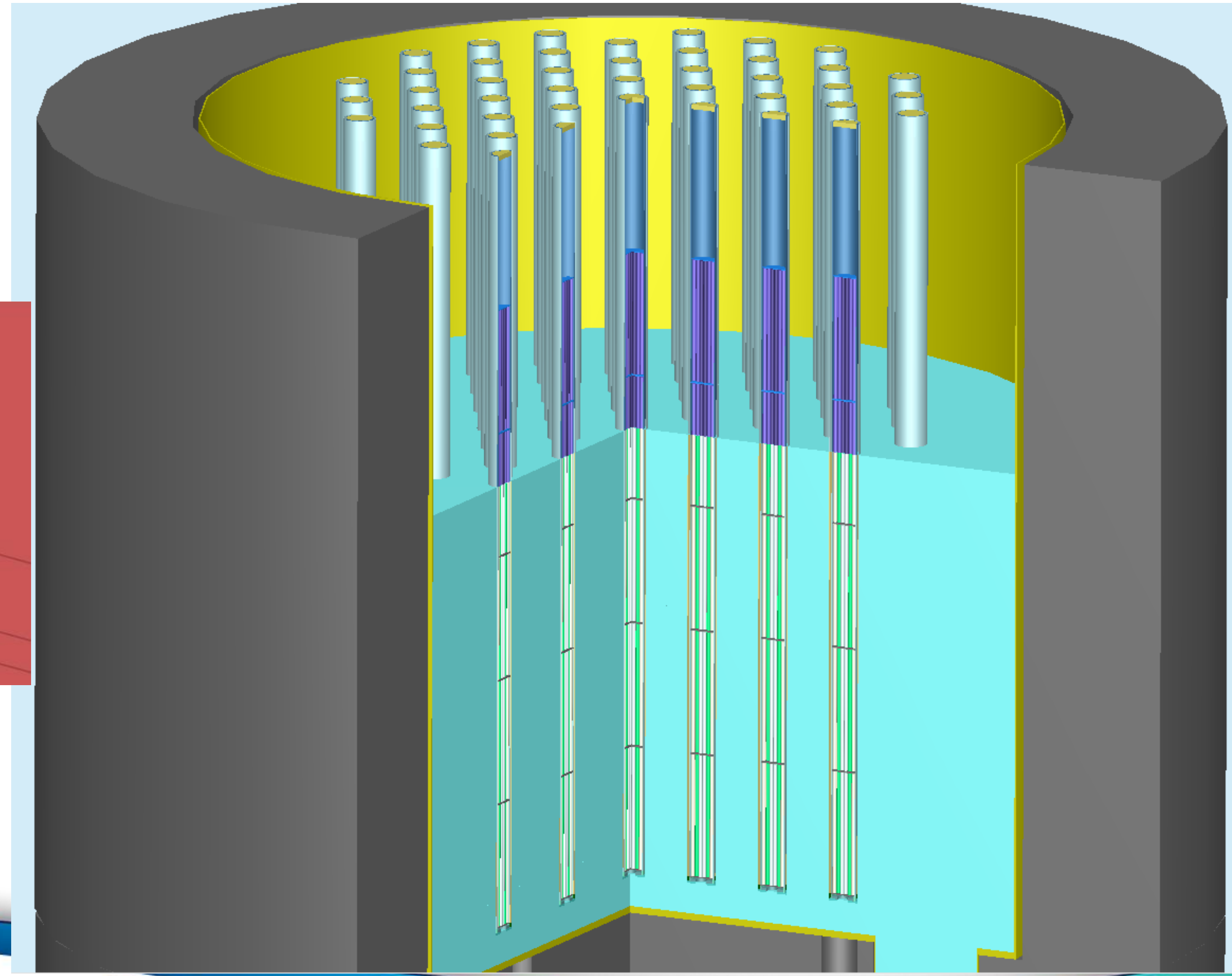
Spectra in ORIGEN-S

KENO Model of ZED-2 Reactor Experiment

For Coolant Voiding Reactivity Validation

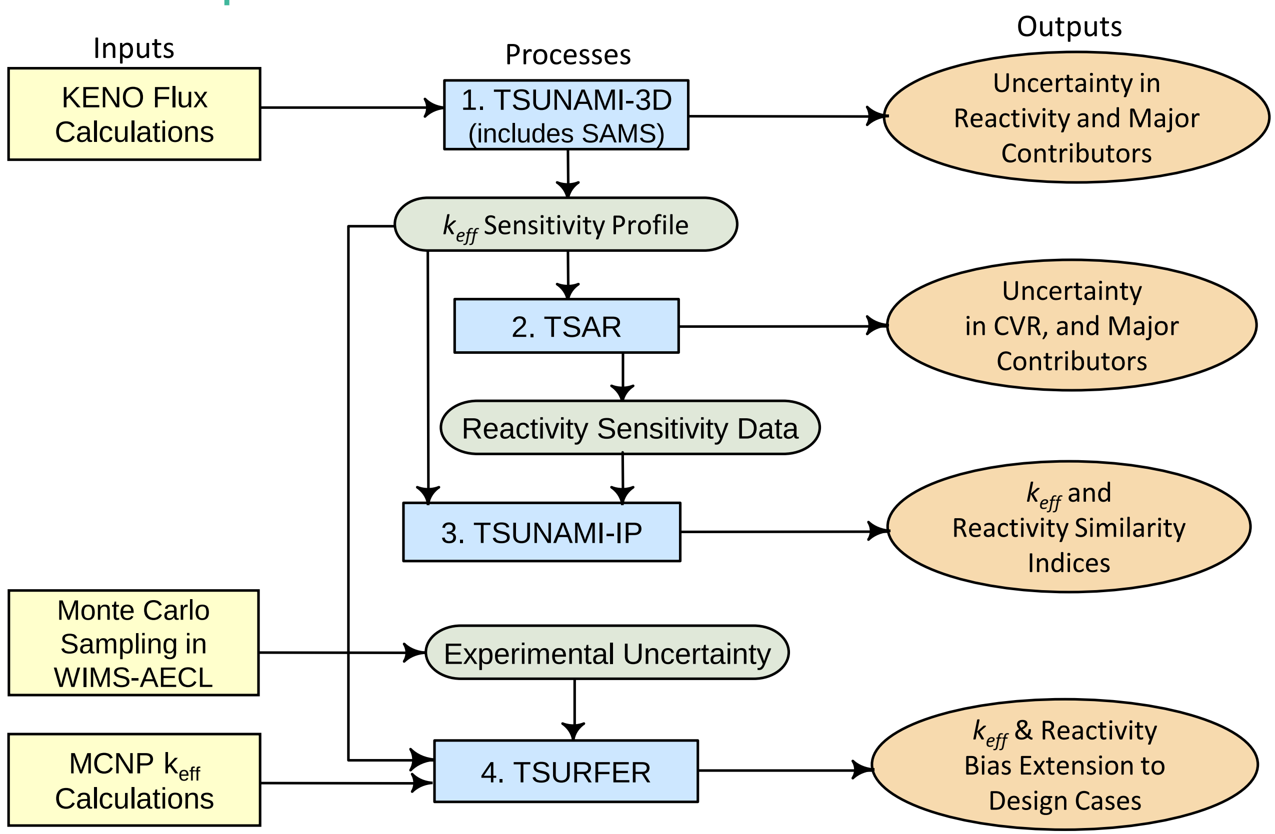


↑ KENO model of NU 28-element fuel in a channel of ZED-2 →



Validation Workflow with TSUNAMI

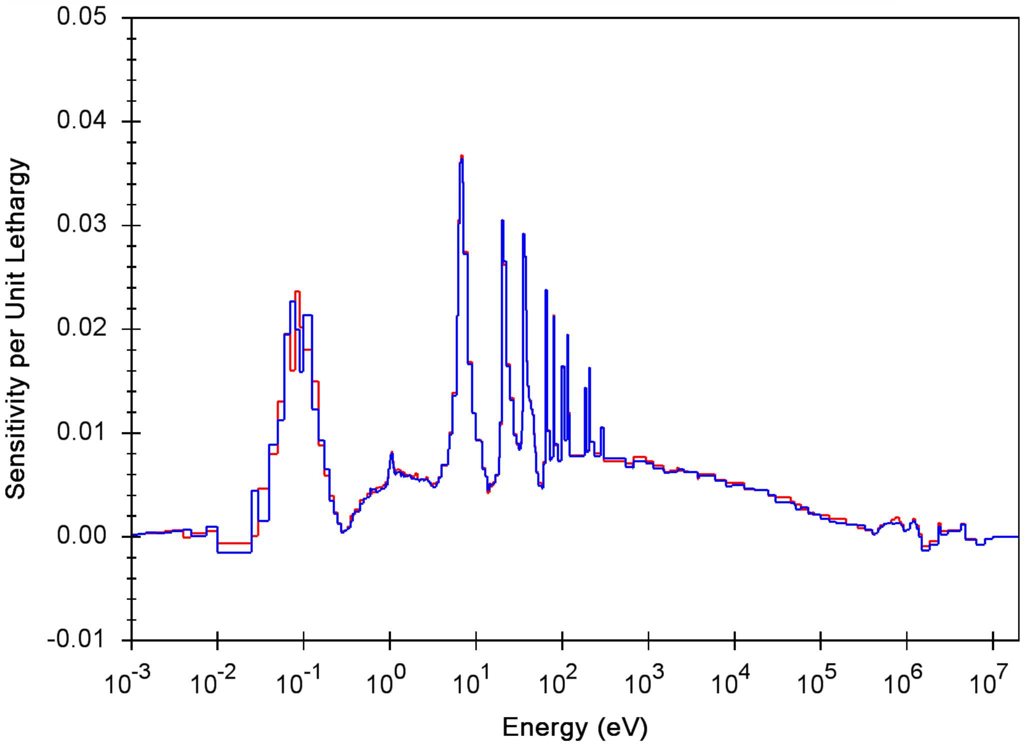
Approach as developed for use at CNL



$$\sigma_{CVR} = \sqrt{\sigma_C{}^2 + \sigma_V{}^2 - 2\sigma_C\sigma_V C_{C,V}}$$

Sensitivity to Nuclear Data in TSUNAMI

Sensitivity for ZED-2 experiment with seven channels of "test fuel" substituted into a lattice of natural-uranium 28-element fuel



Sensitivity profiles of k_{eff} for $^{2}H(n,n)$ reaction in ZED-2

Blue: fully cooled lattice

Red: seven voided channels

The small difference is the coolant voiding reactivity sensitivity, which can be extracted using TSAR

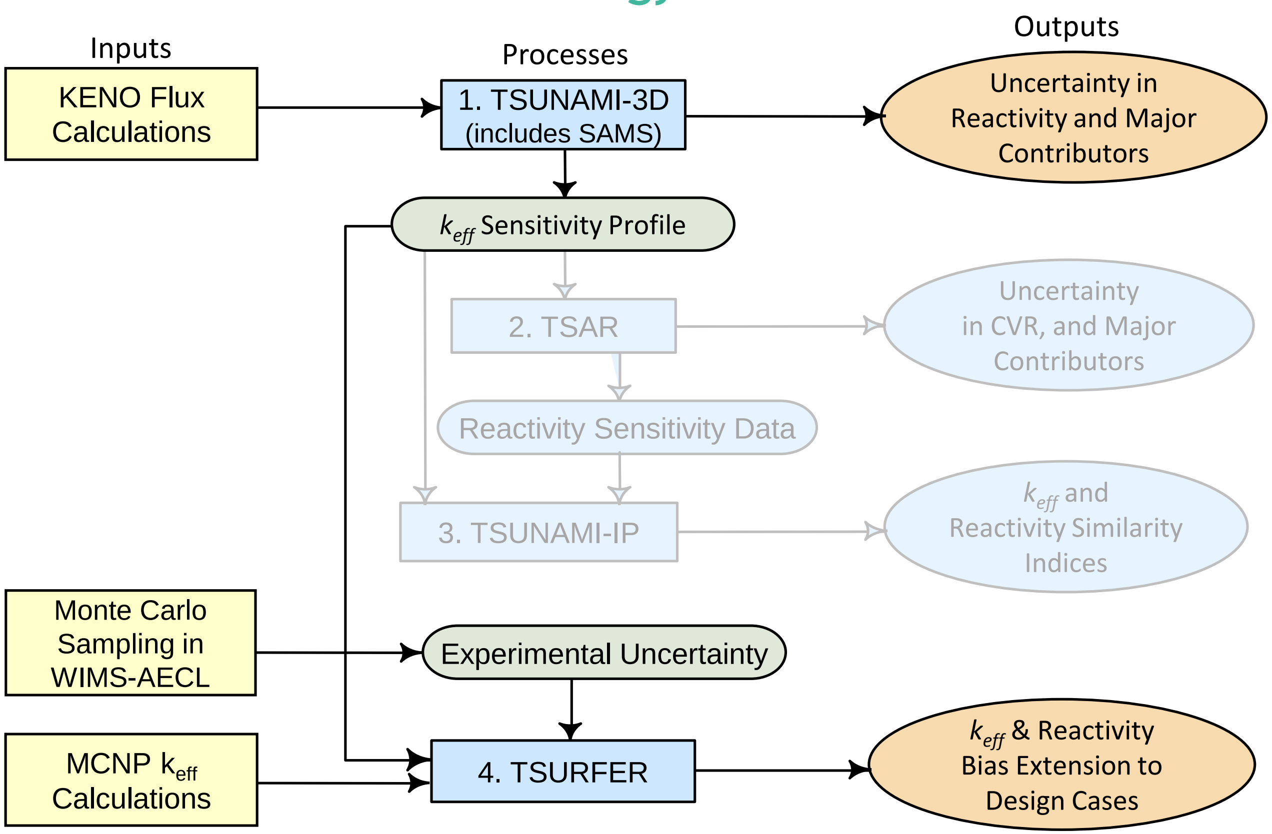
TSURFER Extension of Bias and Uncertainty

Based on ZED-2 Experiments, and selected plutonium benchmarks

Nuclide	Reaction	Adjustment Fraction
H-2	n,2n	38.1%
	elastic	**58.0%**
U-238	n,n'	68.0%
O-16	elastic	74.8%
U-238	n,gamma	80.9%
Pu-239	nubar	84.5%
Zr-92	n,gamma	87.3%
Pu-239	n,gamma	89.4%
U-238	nubar	91.5%
Pu-239	fission	93.5%

Validation Workflow with TSUNAMI

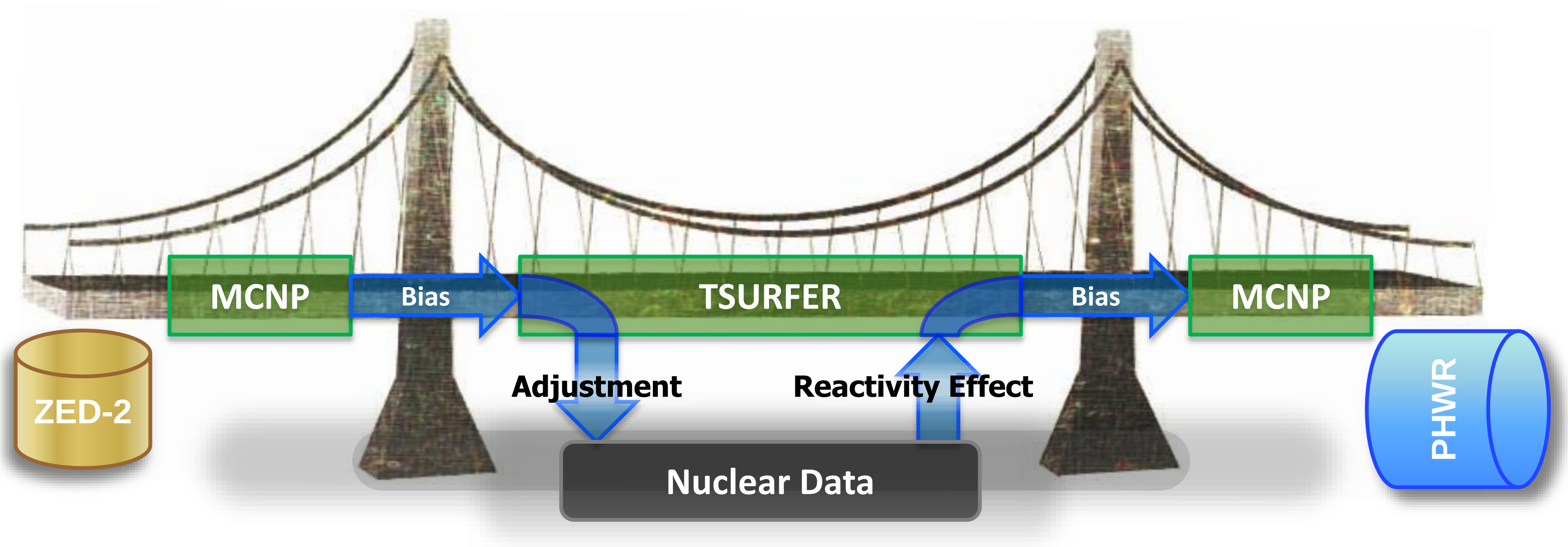
The core of the effective methodology



$$\sigma_{CVR} = \sqrt{\sigma_C{}^2 + \sigma_V{}^2 - 2\sigma_C\sigma_V C_{C,V}}$$

Validation Extension via TSUNAMI

TSUNAMI bridged the gap between ZED-2 experiments and applications for pressurized-channel heavy water power reactors (PHWRs)



And then we moved on from PHWRs…

Application to a Lead-Cooled Fast Reactor

Nuclear data for lead was expected to be important

- Nuclear data effects on k_{eff} and coefficients examined:
  - Coolant voiding reactivity (-20% density in fuel region)
  - Fuel temperature reactivity (700 K – 900 K – 1100 K)
- Sensitivity analysis models in various codes were compared.

Lead-Cooled Fast Reactor Modelling

Quarter-core region in MCNP (VisEd): fresh UO_2 fuel, control rods fully in

Steel core wall →

Shield with B_4C pins →

Zirconium reflector pins →

Lead-filled site for shutoff rod →

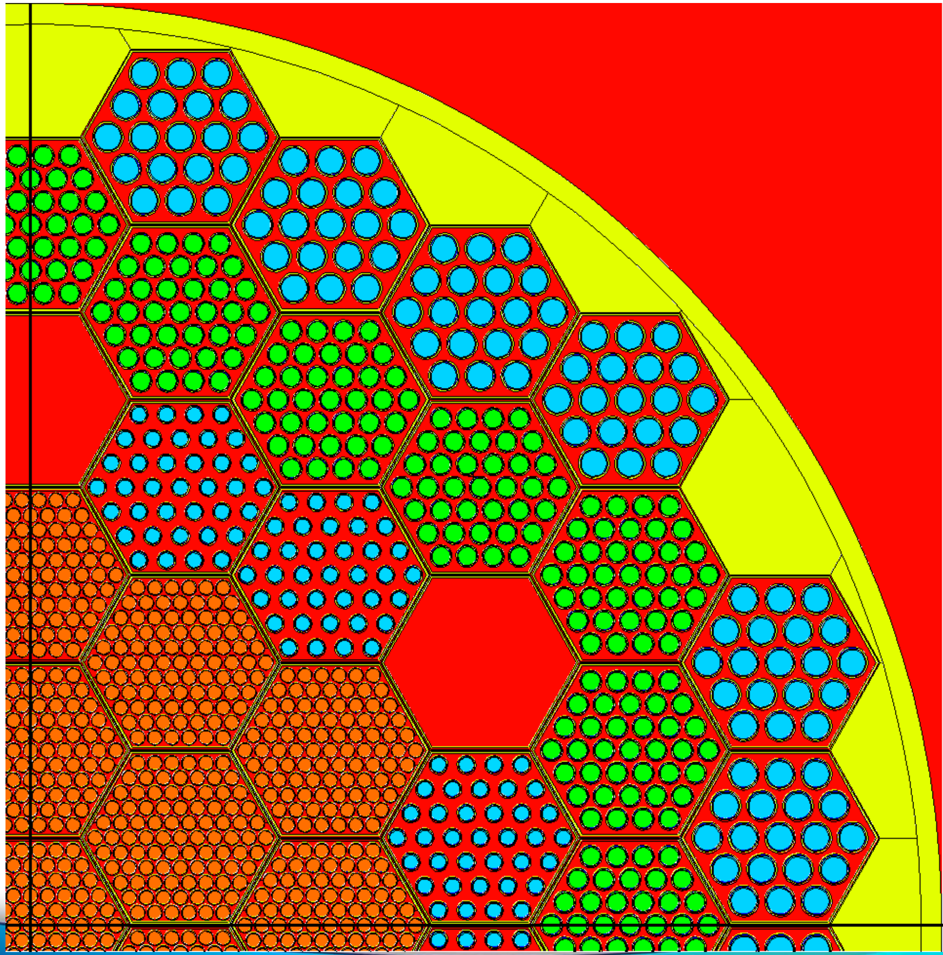
Control rod with B_4C pins →

UO_2 fuel pins (orange) →

(20% enriched)

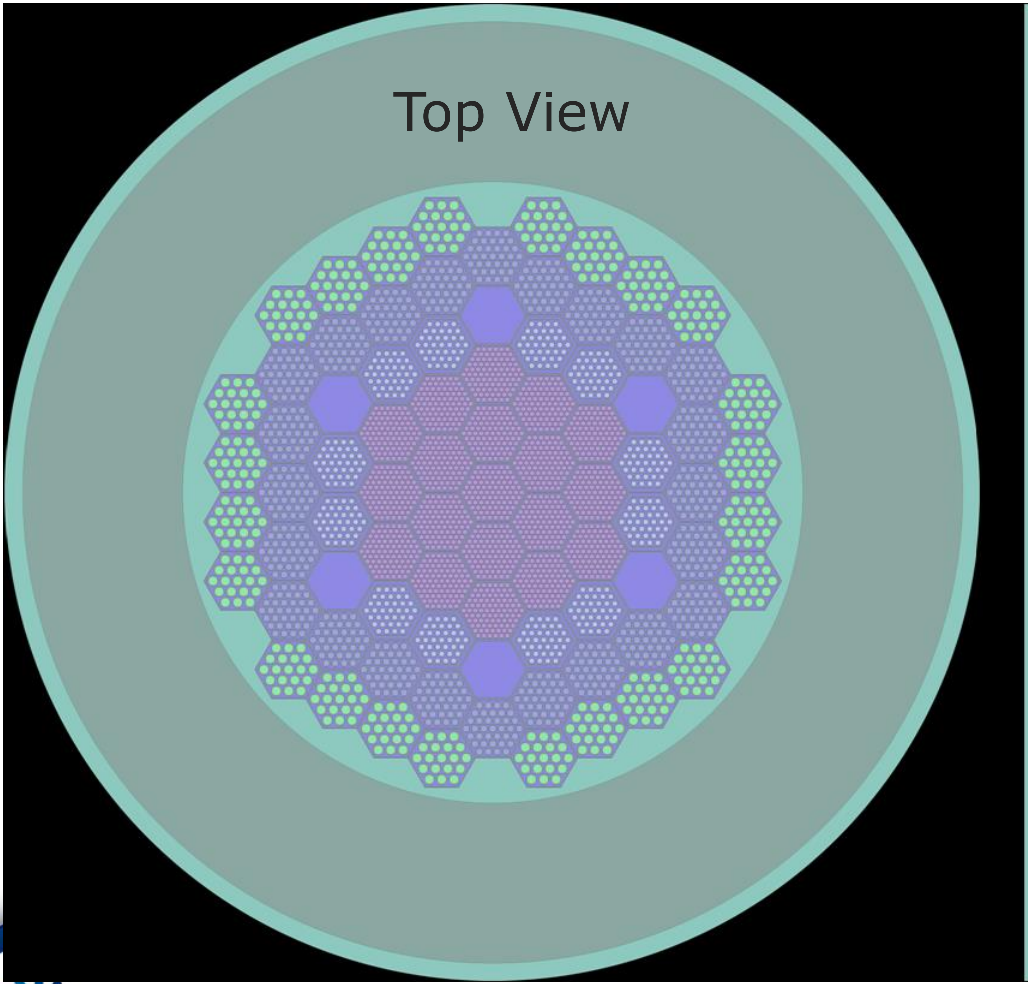
UO_2 fuel pins (orange) →

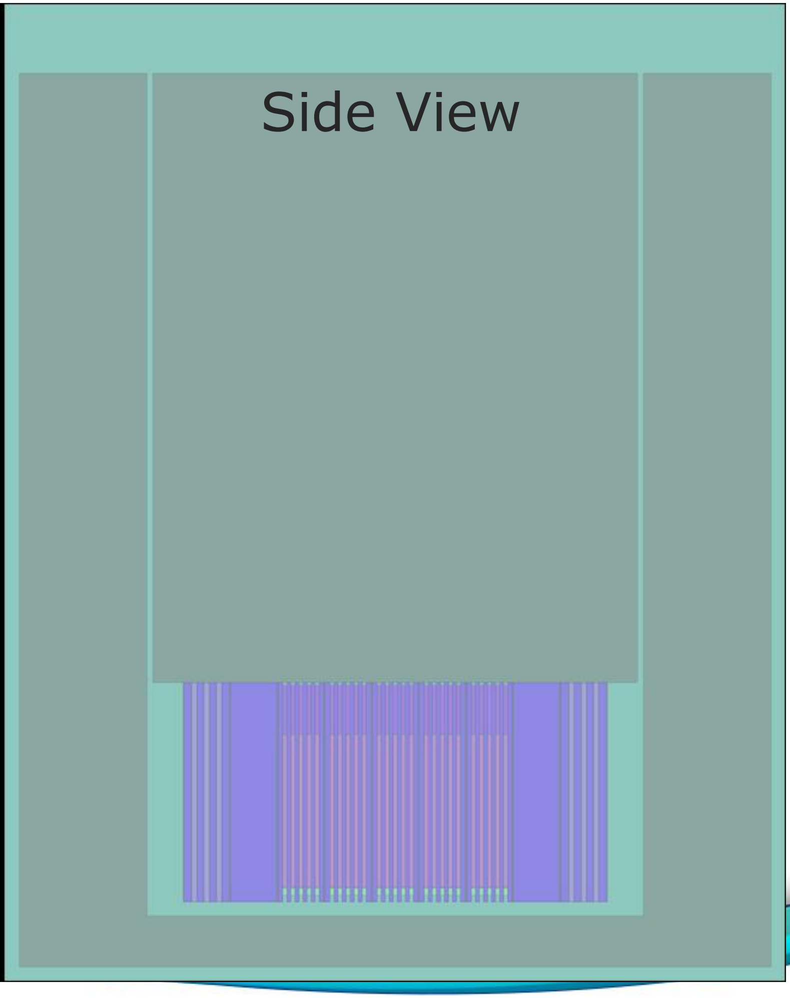
Density (colour) spectrum high (red) to low (blue)



Lead-Cooled Fast Reactor: Serpent

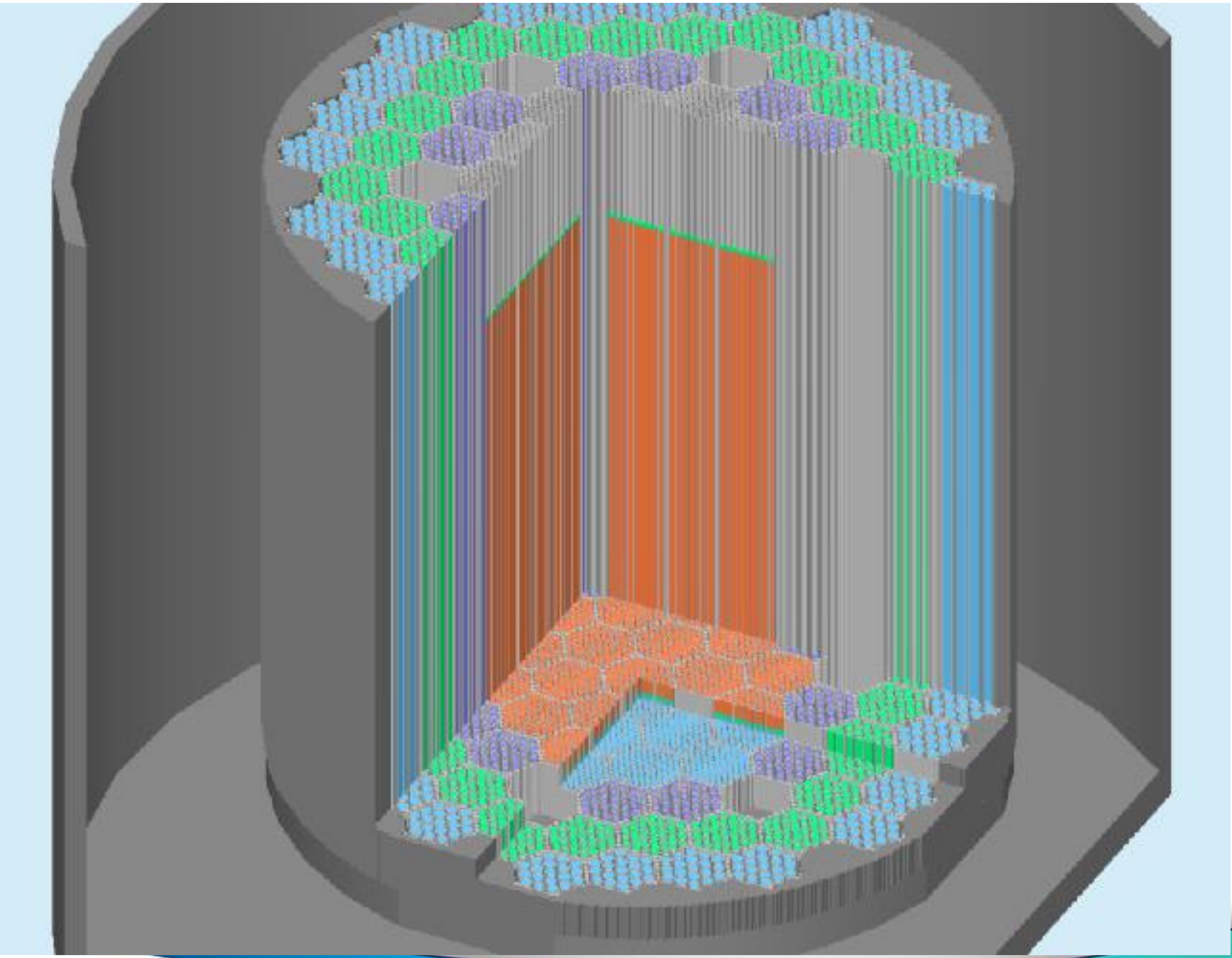
A Serpent model was the basis for the MCNP model





Lead-Cooled Fast Reactor: KENO V.a

KENO cutaway model



Uses 6012 holes in KENO instead of hexagonal arrays

Based on the MCNP model, which was based on the Serpent model

The colours match the MCNP model (in VisEd) as well

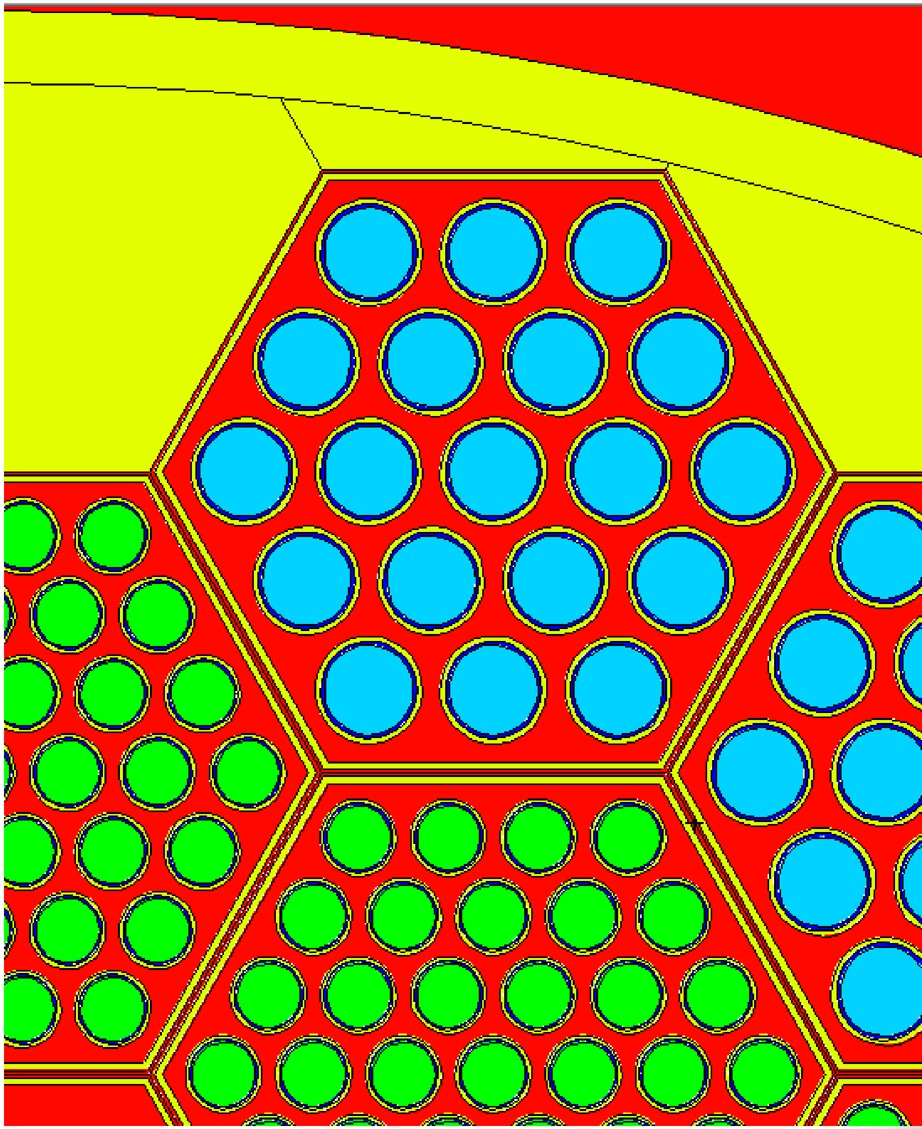
LCFR Model Detail

MCNP model (in VisEd)

Each hexagonal site has a steel wrapper, with angled walls, and a gap between walls.

The core wall has a cylindrical exterior, and conforms to the outline of the hexagonal sites.

The pins within the sites are arranged in regular hexagonal lattices.



LCFR Model Detail

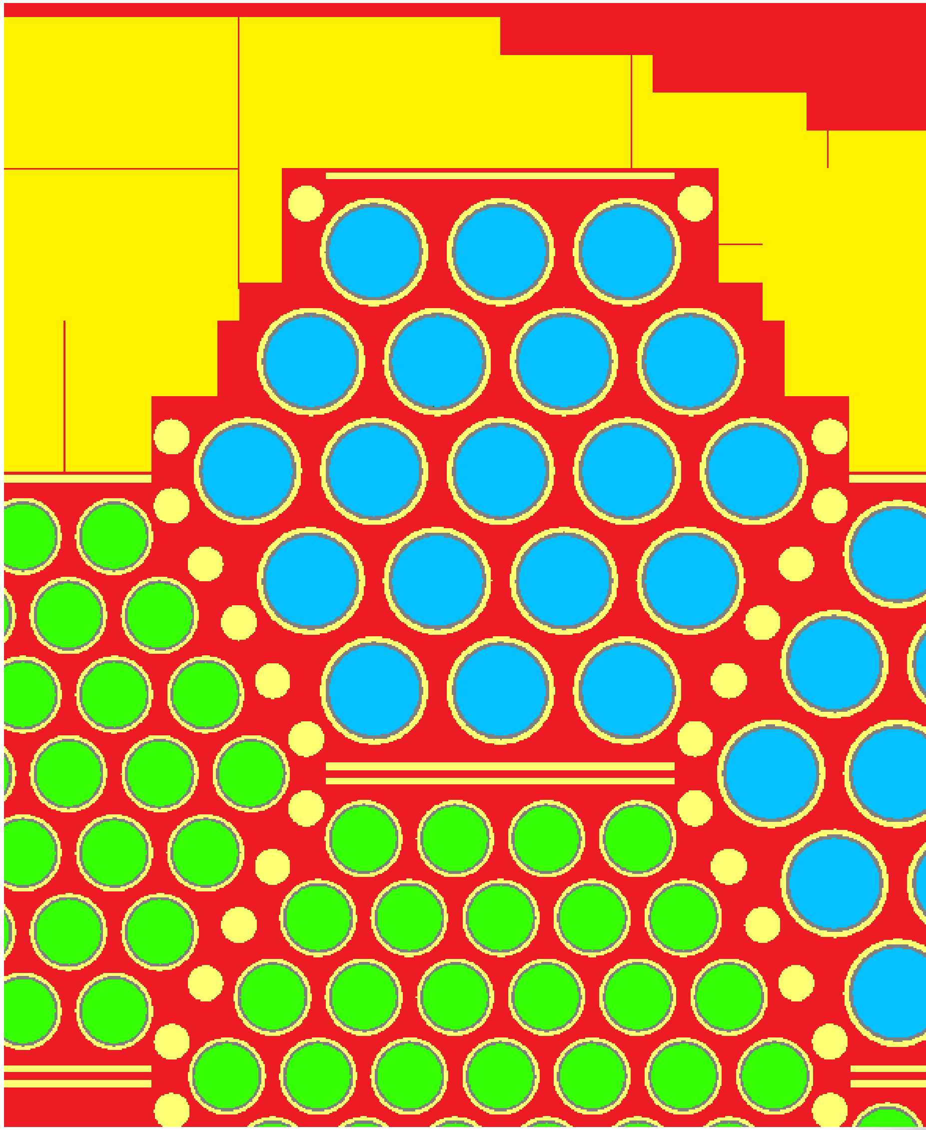
KENO model (in KENO3D)

The angled walls of the steel wrappers are represented by rows of pins.

An array of square steel blocks was used to approximate the core wall's complex shape.

An Excel spreadsheet was used to generate thousands of holes.

Most importantly, masses are conserved.



MCNP6 and KENO Sensitivity Cases

Running KENO in TSUNAMI-3D sequence, and MCNP6 with KSEN card for lead and for uranium in fresh fuel

- KENO forward k_{eff} = 0.99769 ±0.00019
  - 15 million neutron histories
  - 27 hours for forward calculation in a single process
  - 38 hours for the full sensitivity calculation
- MCNP6 k_{eff} = 0.99046±0.00002
  - 870 million neutron histories
  - 1100 cpu-hours in six computer processes

    (Only 4.2 cpu-hours for ±0.00030 k_{eff} uncertainty)
- +7.2 mk k_{eff} discrepancy for KENO with respect to MCNP6
  (greater than our previous experience in thermal reactors)

MCNP6 and KENO ^{235}U Sensitivity Results

Running KENO in TSUNAMI-3D sequence, and MCNP6 with KSEN card

Nuclear Data	MCNP6		TSUNAMI		
^{235}U(n,γ) Cross-Section	-0.0803	±0.04%	-0.0806	±0.01%	**±22.1 mk**
^{238}U(n,n') Cross-Section	-0.0095	±4.2%	-0.0076	±0.87%	±2.91 mk
^{235}U(n,f) Cross-Section	+0.538	±0.07%	+0.5370	±0.01%	±2.20 mk
^{238}U(n,γ) Cross-Section	-0.173	±0.04%	-0.171	±0.01%	±2.12 mk
^{235}U χ ("chi")	—		—		±1.89 mk
^{238}U $\bar{\nu}$ ("nu-bar")	—		+0.130	±0.01%	±1.55 mk
^{235}U $\bar{\nu}$ ("nu-bar")	—		+0.870	±0.01%	±1.34 mk
^{208}Pb(n,n) Cross-Section	+0.0389	±3.0%	+0.0395	±0.08%	±0.95 mk
^{16}O(n,n) Cross-Section	+0.0553	±2.0%	+0.0500	±0.67%	±0.94 mk
			Total All Data		**±22.9 mk**

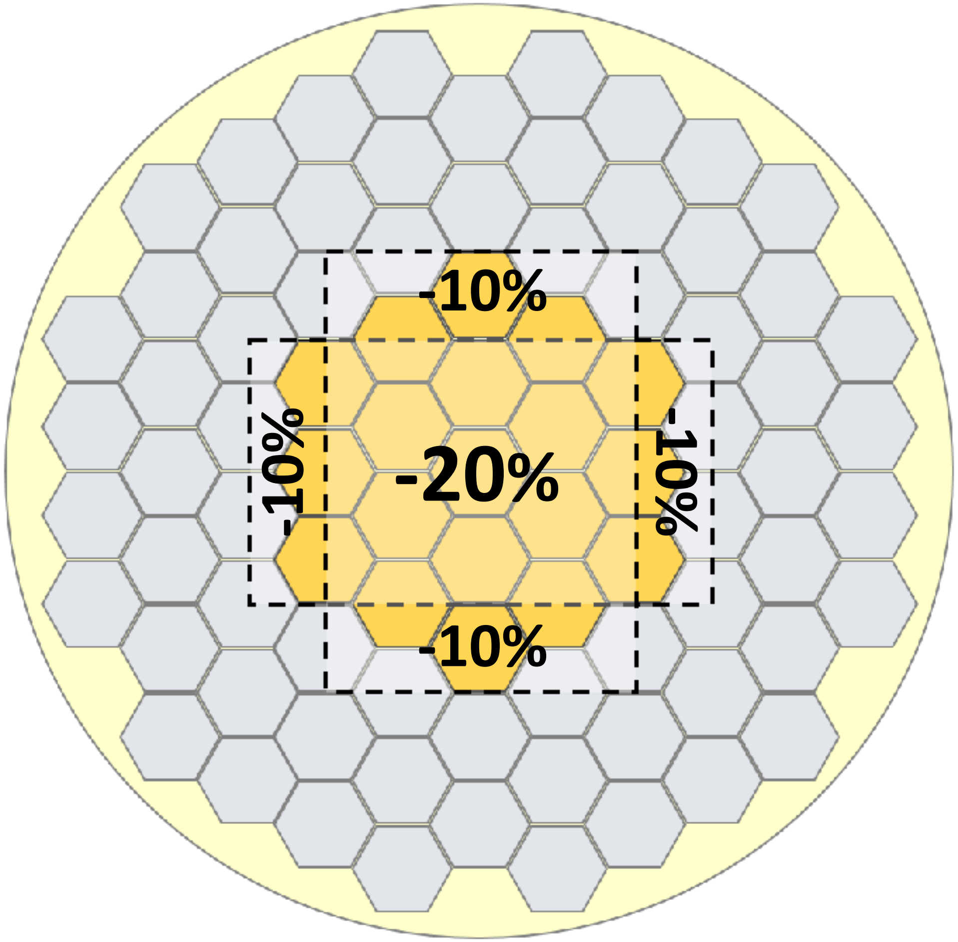
-20% Coolant Density Change in Fuel Region

Coefficients were analyzed at mid-burnup, with control rods inserted to the mid-plane of the core.

In the KENO V.a model, lead density could not be specified by site

The KENO model has 24 regions, to reduce the number of holes

As an approximation, lead density was specified by region



Coolant Density Coefficient Uncertainty

Reactivity effect of nominal 20% voiding of fuel region was -7.3 mk

Fuel Nuclear Data	TSAR Uncertainty
$^{235}U(n,\gamma)$	±0.83 mk
$^{238}U(n,n)$ and (n,n')	±0.62 mk
^{235}U χ (“chi”)	±0.41 mk
$^{16}O(n,n)$	±0.40 mk
^{238}U $\bar{\nu}$ (“nu-bar”)	±0.26 mk
$^{238}U(n,\gamma)$	±0.17 mk
$^{235}U(n,n')$	±0.15 mk

Other Nuclear Data	TSAR Uncertainty
$^{208}Pb(n,n)$	±0.20 mk
$^{90}Zr(n,n)$	±0.19 mk
$^{206}Pb(n,\gamma)$	±0.15 mk
$^{206}Pb(n,n')$	±0.12 mk
$^{206}Pb(n,n)$	±0.11 mk

Total All Data	±1.32 mk

Fuel Temperature Coefficient Uncertainty

Reactivity effect of temperature rise 700 K to 1100 K is -1.61 ±0.05 mk

The scatter in TSAR results for FTC cases was greater than the reported uncertainty.

Repeated cases at:

- 700 K
  26 days run time
- 900 K
  22 days run time
- 1100 K
  26 days run time

Nuclear Data	TSAR Uncertainty
^{235}U(n,γ)	±0.11 mk
^{238}U(n,n) and (n,n‘)	±0.02 mk
^{16}O(n,n)	±0.02 mk
^{238}U(n,γ)	±0.01 mk
^{238}U(n,n)	±0.01 mk
^{235}U(n,f)	±0.01 mk
^{52}Cr(n,n)	±0.01 mk
^{238}U(n,n) and (n,n‘)	±0.01 mk
^{238}U $\bar{\nu}$ (“nu-bar”)	±0.01 mk

Total All Data	±0.12 mk

Discussion: Fast-Reactor Results

$^{235}U(n,\gamma)$ and $^{238}U(n,n')$ cross sections stand out over data for lead

- Comparison of MCNP6 and TSUNAMI shows accuracy for both codes, with greater utility and efficiency for TSUNAMI.
- The sensitivity of fast reactors to $^{235}U(n,\gamma)$ data is not high; high uncertainty in the data makes it significant.
  - The measurement is difficult in that energy range.
  - Does JENDL data have much lower uncertainty?
  - Use TSUNAMI to find sensitivities for fast benchmarks; use TSURFER to <u>bridge</u> the gap for design cases.
- Reactivity coefficients appear to be more affected by covariance cross-terms, especially for fuel temperature.
- If a coefficient is negligible, can its uncertainty be neglected?

Conclusions

SCALE has been useful at CNL and is expanding, including TSUNAMI

- Code validation based on TSUNAMI is applicable to reactivity coefficients in nuclear reactors, as well as criticality analysis
  - Both involve k_{eff} calculations, of course
- TSUNAMI analysis is useful for fast-spectrum nuclear reactors as well as thermal reactors
- The sensitivity of fast reactors to $^{235}U(n,\gamma)$ data is not high, but the uncertainty in the data is very high.
  - TSURFER extension from benchmarks might help.

FORSS was a 1970s predecessor of TSUNAMI, for S/U analysis in fast-spectrum reactors; we have come full circle.

Thank you. Merci.

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