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Recent R&D Activities at NCSU using SCALE Tools

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Overview

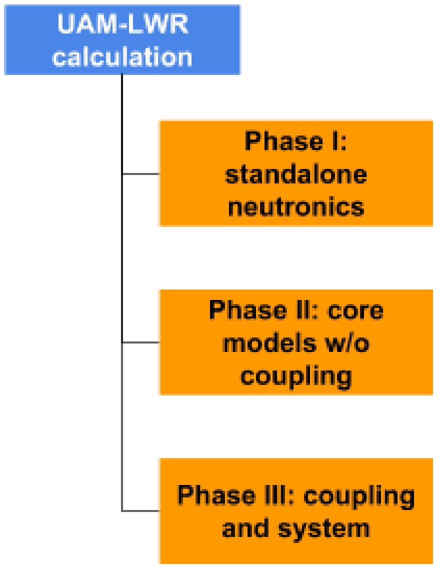
- The SCALE package has been extensively used in the Nuclear Engineering Department (NED) at North Carolina State University (NCSU)

- Research activities:
  - Sensitivity analysis (SA) and uncertainty quantification (UQ) in modeling and simulation of reactors
  - Development of multi-physics and multi-scale reactor analysis platform
- Curriculum activities:
  - Senior design projects
  - Course projects in graduate classes

- This presentation intends to give an overview of various activities since last workshop:
  - Primarily focusing on activities in the Reactor Dynamics and Fuel Modeling Group (RDFMG), which is part of NED, NCSU

OECD/NEA LWR Uncertainty Analysis in Modeling (UAM) Benchmark

- Overview:
  - Aims to test consistently uncertainty propagation from basic data and engineering uncertainties across different scales (multi-scale) and physics phenomena (multi-physics)
  - In three phases consisting of ten benchmark exercises
  - On a number of numerical and experimental test cases
- Phase I (Neutronics Phase) – completed:
  - Exercise I-1: Cell Physics
  - Exercise I-2: Lattice Physics
  - Exercise I-3: Core Physics
- Phase II (Core Phase) – ongoing:
  - Exercise II-1: Fuel Physics
  - Exercise II-2: Time Dependent Neutronics
  - Exercise II-3: Bundle Thermal-Hydraulics
- Phase III (System Phase) – ongoing:
  - Exercise III-1: Core Multi-Physics
  - Exercise III-2: System Thermal-Hydraulics
  - Exercise III-3: Coupled Core-System
  - Exercise III-4: Comparison of BEPU vs. Conservative Calculations



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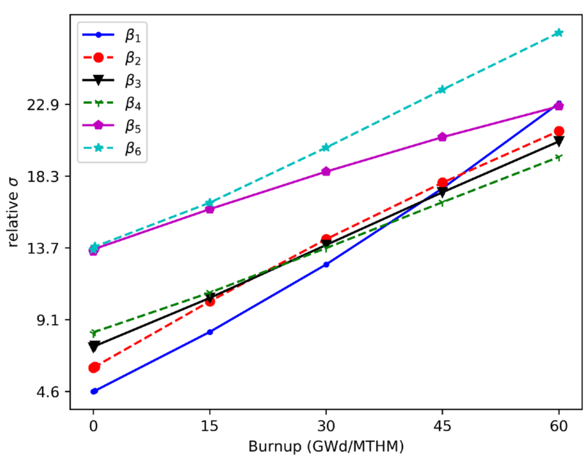
SCALE tools and data used in Phase I

- SCALE lattice physics codes and nuclear data covariance libraries are widely adopted by the participants of LWR UAM benchmark:
  - 19 results (~ 39%) used SCALE solvers, i.e., Polaris & NEWT
  - 36 results (~75%) used SCALE covariance libraries provided in various versions (5.1, 6.0, 6.1 or 6.2)
  - Both SAMPLER (sampling approach) and TSUNAMI (deterministic approach) are widely used for uncertainty propagation
- SCALE covariance libraries
  - A range of different tests (e.g., critical benchmark experiments) are performed to investigate and adjust the new covariance data from evaluated nuclear data libraries
  - Produces more realistic estimate of the uncertainty of integral parameters due to nuclear data uncertainty

Case	NDL	Transport Code	VCM	UQ Method
1	ENDF/B-VI	SERPENT 2	SCALE 6.0	Deterministic
2	ENDF/B-V	SCALE 6.0	SCALE 6.0	Deterministic
3	ENDF/B-VI	MULTICELL	SCALE 5.1	Sampling
4	ENDF/B-VI	MULTICELL	SCALE 5.1	Sampling
5	ENDF/B-VI	KIKO3D	SCALE 5.1	Sampling
6	ENDF/B-VII.0	XSDRNPM	SCALE 6.1	Deterministic
7	ENDF/B-VI	CASMO-4	SCALE 6.0	Deterministic
8	ENDF/B-VII.RO	CASMO-5MX	SCALE 6.0	Sampling
9	ENDF/B-VII.0	NEWT	SCALE 6.1	Deterministic
10	ENDF/B-VI	MGRAC	SCALE 6.1	Sampling
11	ENDF/B-VII	MCNP5	SCALE 6.0	Deterministic
12	ENDF/B-VII.0	NEWT	SCALE 6.1	Deterministic
13	ENDF/B-VII.0	NEWT	SCALE 6.2	Sampling
14	ENDF/B-VII.1	COBAYA	SCALE 6.2	Sampling
15	ENDF/B-VII.1	COBAYA	SCALE 6.2	Sampling
16	ENDF/B-VII.1	COBAYA	SCALE 6.2	Sampling
17	ENDF/B-VII.1	COBAYA	SCALE 6.2	Sampling
18	ENDF/B-VII.1	POLARIS	SCALE 6.2	Sampling
19	ENDF/B-VII.1	NEWT	SCALE 6.2	Sampling
20	ENDF/B-VII.0	NEWT	SCALE 6.2	Sampling
21	JENDL-4.0	CASMO5	JENDL-4.0	Sampling
22	ENDF/B-VII.0	NEWT	SCALE 6.2	Deterministic
23	ENDF/B-VII.0	NEWT	SCALE 6.2	Deterministic
24	ENDF/B-VII.0	NEWT	SCALE 6.2	Deterministic
25	ENDF/B-VII.1	McCARD	ENDF/B-VII.1	Deterministic
26	ENDF/B-VII.1	MCS	ENDF/B-VII.1	Deterministic
27	ENDF/B-VII.1	MCS	SCALE 6.1	Deterministic
28	ENDF/B-VII.1	MCS	ENDF/B-VII.1	Deterministic
29	ENDF/B-VII.1	MCS	SCALE 6.1	Deterministic
30	ENDF/B-VII.1	STREAM	SCALE 6.2	Deterministic
31	ENDF/B-VII.1	STREAM	ENDF/B-VII.1	Deterministic
32	ENDF/B-VII.1	STREAM	ENDF/B-VII.1	Sampling
33	ENDF/B-VII.0	NEWT	SCALE 6.1	Deterministic
34	ENDF/B-VII.1	NEWT	SCALE 6.2	Deterministic
35	ENDF/B-VII.1	HELIOS2	SCALE 6.1	Sampling
36	ENDF/B-VII.0	NEWT	SCALE 6.1	Sampling
37	ENDF/B-VII.1	NEWT	SCALE 6.2	Sampling
38	ENDF/B-VI	NEWT	SCALE 6.1	Deterministic
39	JEFF-3.1.2	WIMS	WIMS[1]	Sampling
40	ENDF/B-VII.0	NEWT	SCALE 6.2	Sampling
41	ENDF/B-VII.0	NEWT	SCALE 6.2	Sampling
42	JEFF-3.1.2	WIMS	WIMS[1]	Sampling
43	JEFF-3.1.2	WIMS	WIMS[1]	Sampling
44	JEFF-3.1.2	WIMS	WIMS[1]	Sampling
45	ENDF/B VII.0	RMC	SCALE 6.0	Sampling
46	ENDF/B-VII.1	PARCS	SCALE 6.2	Sampling
47	ENDF/B-VII R1	MPACT	ENDF/B-VII.1	Sampling
48	ENDF/B-VII.1	SCALE 6.0	ENDF/B-VII.1	Sampling

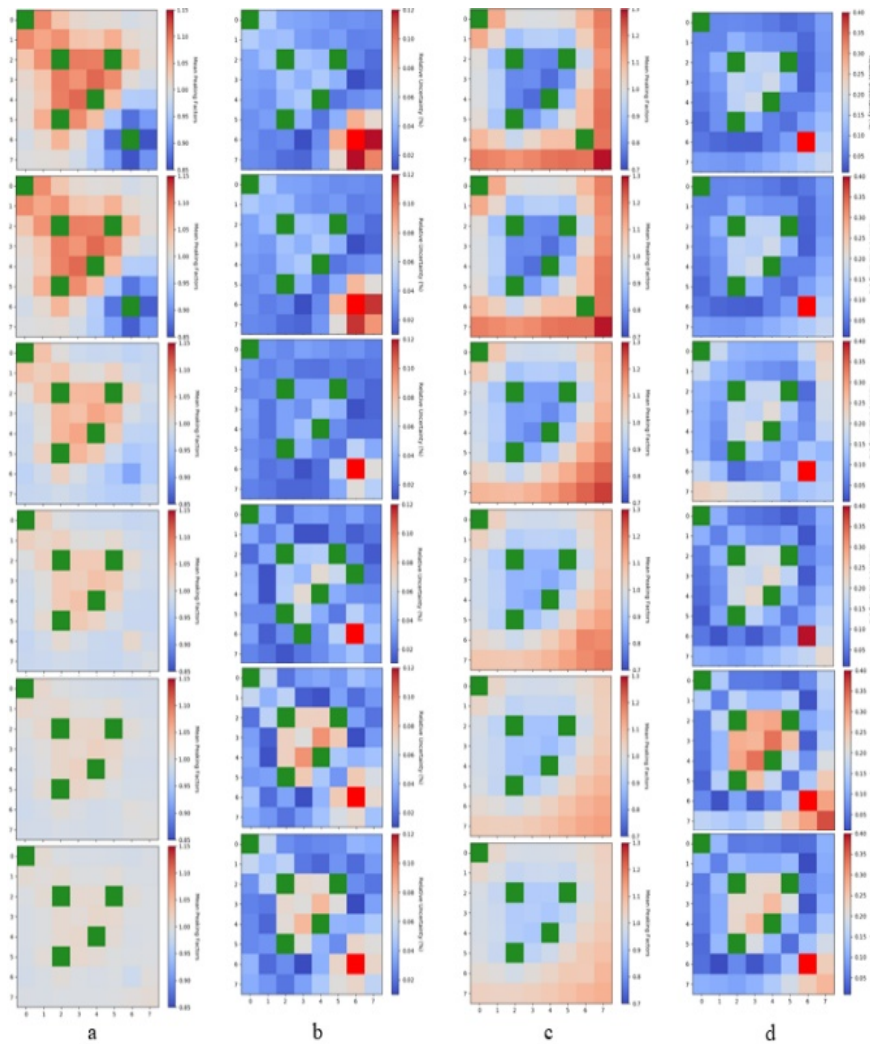
Phase II, Exercise II-2a: TMI-I PWR assembly depletion

- Output uncertainties targeted
  - Fission product concentrations
  - Actinide concentrations
  - Two-group cross sections
  - Delayed neutron data
  - Peaking factors
- POLARIS: lattice physics calculation
- ORIGEN: depletion calculation
- SAMPLER: cross section, fission yield, manufacturing data perturbation



Delayed neutron fraction

Pin-wise power distribution



Nominal | Rel. Uncer. | Nominal | Rel. Uncer.

Unrodded | Rodded

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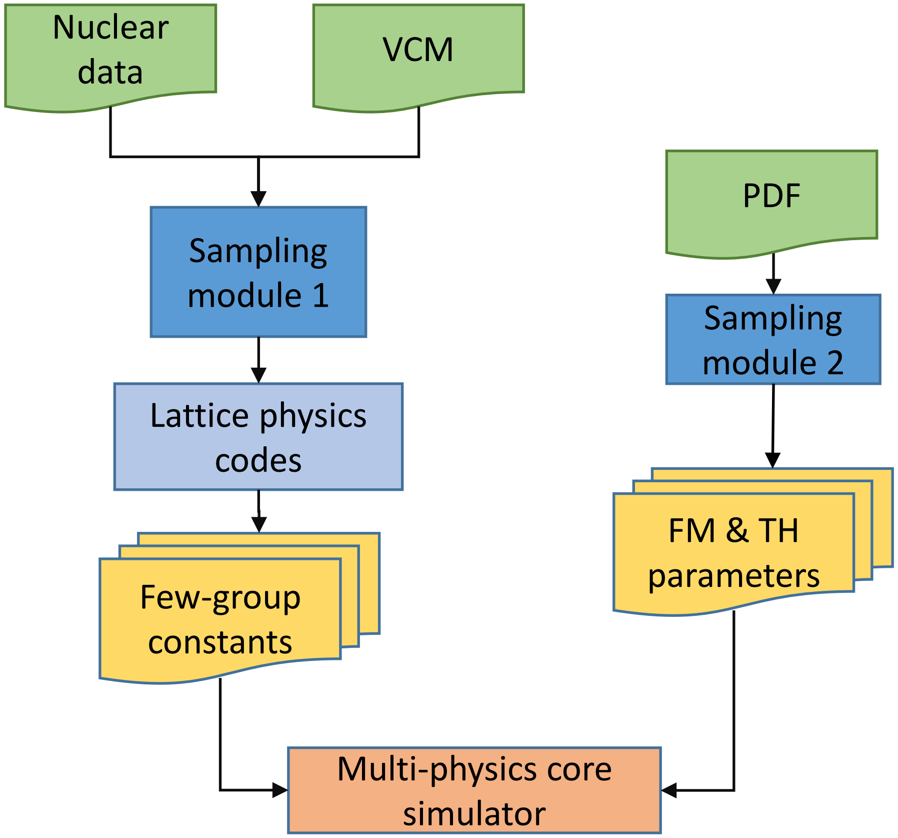
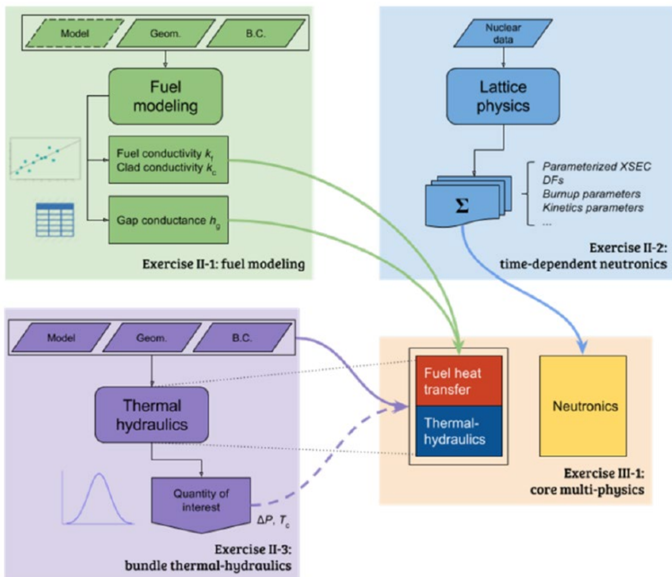
Contribution to Exercise III-1: core multi-physics

- Uncertainty propagation approach for multi-physics core simulation:
  - Compatible with two-step core simulation method
  - Uncertainties from different physics domains (neutronics, thermal-hydraulics, fuel performance) are considered to be *uncorrelated*
- SCALE 6.2 tools were used to prepare perturbed cross section libraries:
  - Sampler: general stochastic sampling method for uncertainty propagation
  - Polaris: new LWR lattice physics neutron transport code

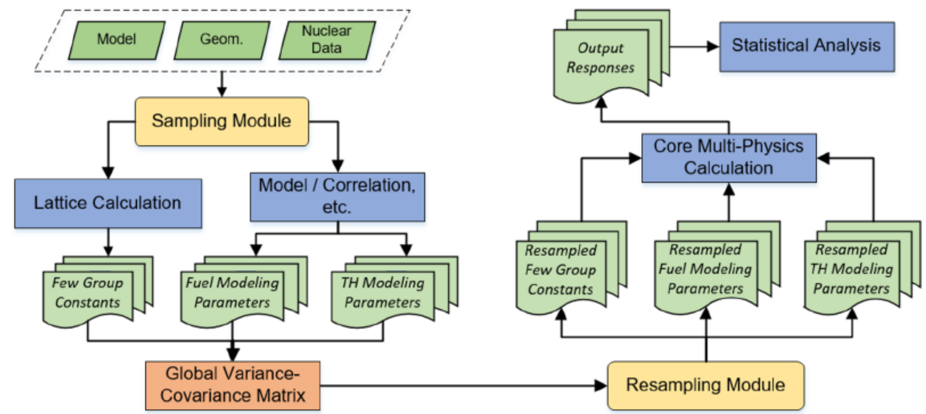


Contribution to Exercise III-1: core multi-physics (cont.)

Problem: Usually multi-physics correlations are not considered



Idea: Estimate a Global Covariance Matrix by propagating common sources uncertainty



PhD dissertation: Development of the consistent uncertainty propagation methodology (K. Zeng)

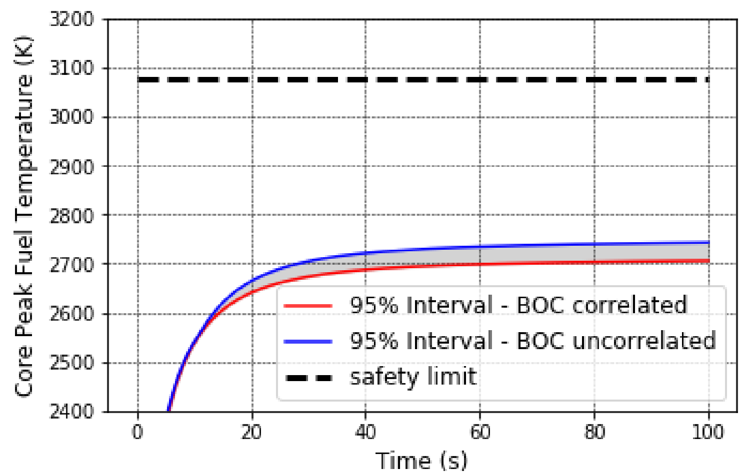
Consistent uncertainty propagation methodology

- Global Covariance Matrix construction
- Application to Exercise III-1 for steady state, depletion and Rod Ejection Accident (REA) in TM-1 core
- Significance: taking into account multi-physics correlations reduces uncertainties and creates larger design margins

Input parameters	Impact			Uncertainty
	NK	TH	FM	
Fuel rod radius R_{fuel}	√	√	√	0.99% (normal)
Gap thickness T_{gap}	√	√	√	5.25% (normal)
Cladding thickness T_{clad}	√	√	√	0.89% (normal)
Fuel rod density ρ_{fuel}	√		√	1.65% (normal)
Gadolinia enrichment f_{Gd}	√		√	5.43% (normal)
Nuclear cross-sections	√			SCALE 56-g VCM
System pressure $P_{sys.}$		√	√	±1.0% (normal)
Flow rate $\dot{m}$		√	√	±1.5% (normal)
Inlet temperature $\bar{R}_{cool,in}$		√	√	±1.0% (uniform)
Total power P		√	√	±1.0% (normal)
Power distribution f_{power}	√	√	√	±3.0% (normal)

REA results

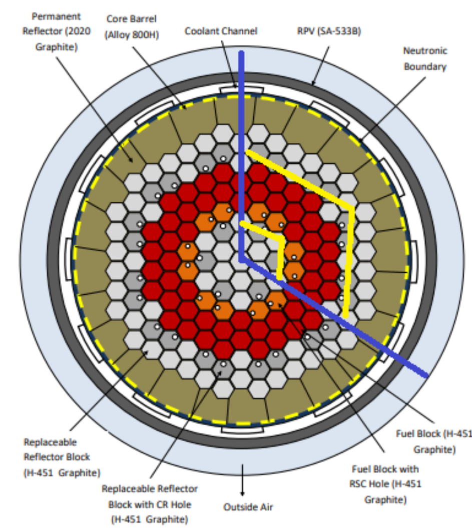
State	Peak core total power	Peak Fuel Temperature (K)
Uncorrelated BOC	1.71 + 16.3%	2593 + 148
Correlated BOC	1.69 + 17.1%	2598 + 106
Uncorrelated EOC	1.63 + 25.5%	1815 + 95
Correlated EOC	1.65 + 24.3%	1810 + 89

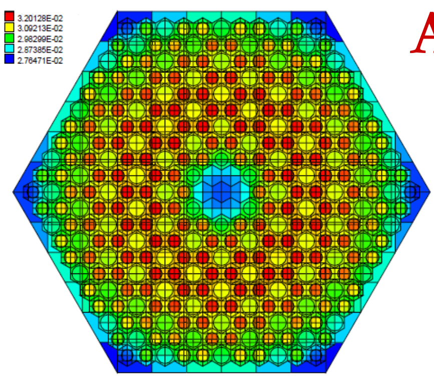


IAEA CRP on HTGR UAM: modeling uncertainty

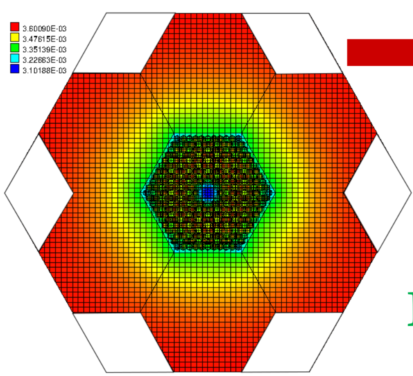
- To support IAEA CRP High Temperature Gas-cooled Reactor (HTGR) UAM
  - Improve uncertainty modeling in HTGR systems
- Objective: evaluate the cross section sensitivity to the topology of lattice cells after energy collapsing

Figure I.3.MHTGR Reactor Unit Layout – Plane



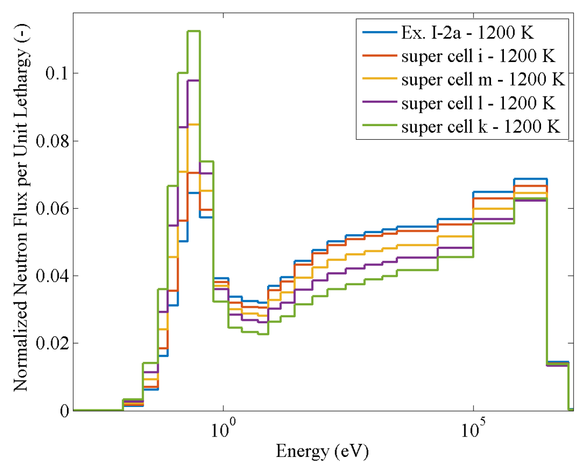


A

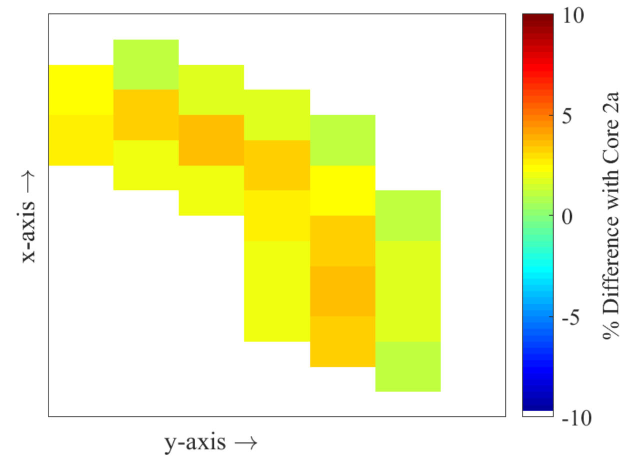


B

HTGR super cell



Effect of lattice surroundings on the spectrum (NEWT)

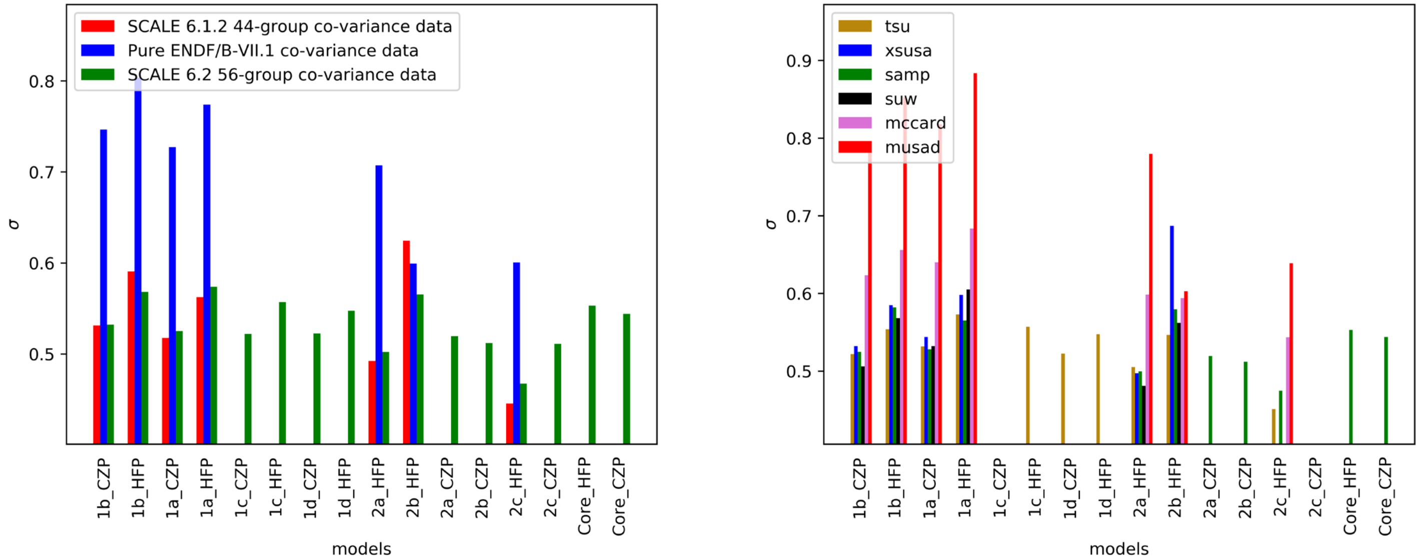


Difference of MHTGR power density between core made of **A** only and core **A**+**B**

IAEA CRP on HTGR UAM: preparation of final report

Objectives

- Collection and comparative analysis of participants' results obtained throughout the CRP
- The final TecDoc of CRP is expected at the end of the year
- SCALE codes and data were extensively used



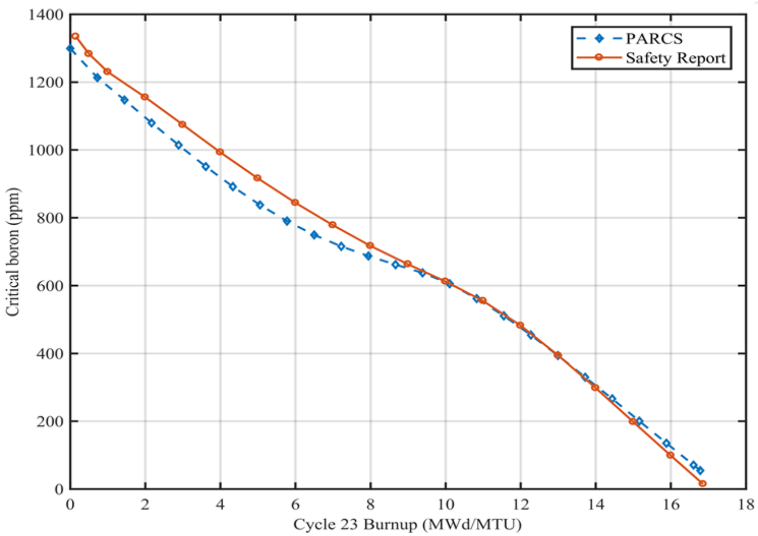
k-inf (*k*-eff) uncertainty based on covariance data

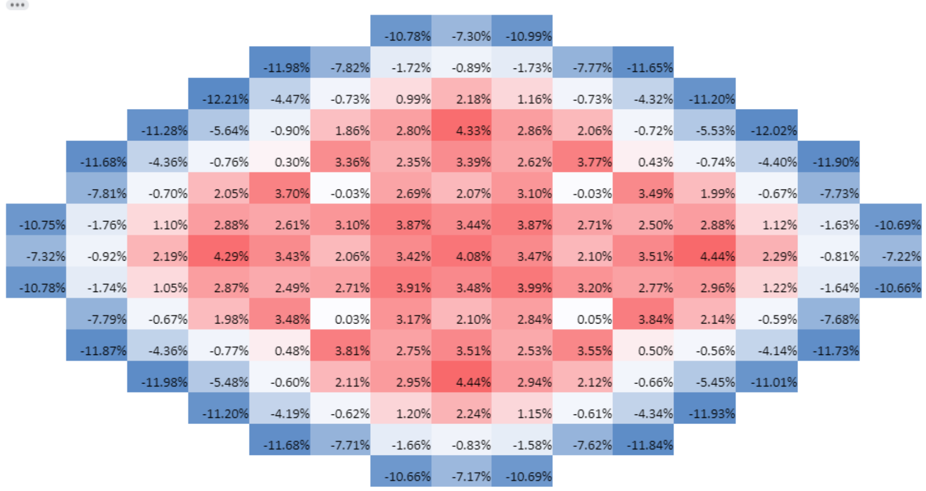
Multi-physics platform for safety analysis based on NRC codes

- Overview
  - Provide training to CNSS (Centre for Nuclear Safety and Security) partners at National Nuclear Regulator (NNR) in South Africa
  - Support Koeberg NPP M&S capability
  - Deliver advanced software capacity based on US NRC codes for safety analysis of LWRs
  - Improved estimates of local parameters
- Software involved: PARCS, CTF, POLARIS, SAMPLER, FRAPTRAN/FRAPCON, TRACE and DAKOTA
- POLARIS used to generate two-group nuclear data on assembly level:
  - Multi-histories libraries
  - Multi-branches libraries
  - Libraries also generated with Serpent for code-to-code comparison
- SAMPLER is used to generate perturbed libraries, on a mono-history, multi-branches level

Multi-physics platform for safety analysis based on NRC codes (cont.)

- Core-level results compared to operational data of Koeberg NPP Cycle 23
- Good agreement with measurement data in initial agreement
  - Central assemblies provide an average RMS of 4.0 % at BOC and 2.1 % at EOC
  - Noticeable differences (~11 %) on the peripheral assemblies - work in progress
  - Perturbed libraries generated





Assembly-wise RMS

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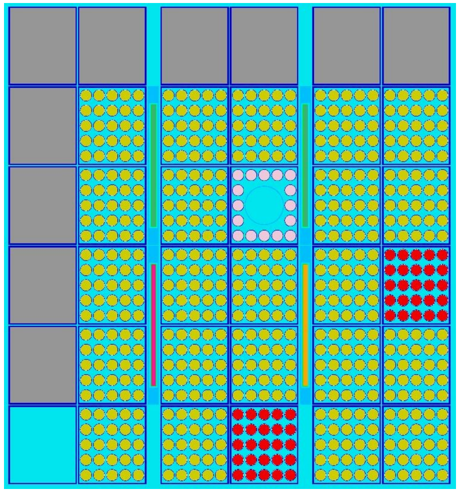
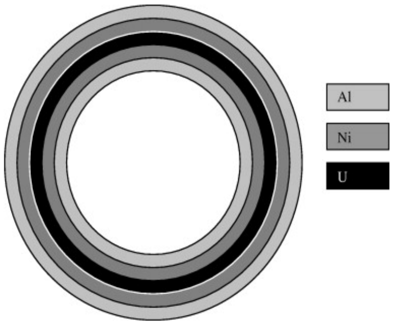
Support to senior design projects

- Molybdenum-99 production in PULSTAR reactor
  - NCSU advisor: Ayman Hawari, Jason Hou
  - ORNL advisor: Ugur Mertyurek
  - Aims to assess the feasibility of producing Mo-99 in PUSTAR reactor
  - A target containing uranium foil was designed to replace one fuel assembly
  - 3D MC code KENO was used to model reactor core
  - Target design was optimized using the calculated neutron flux and fission rate
  - Safety analysis (RIA, LOCA) was performed to ensure the modified core meets safety limits
  - Economic analysis

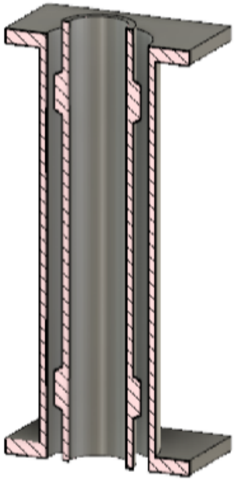
- Prepare undergraduate students for reactor modeling and criticality calculations using state-of-the-art simulation codes



PULSTAR core model (KENO)



Target design



Target holder model

Summary

- SCALE package has been extensively used in the NED at NCSU to support research and curriculum:
  - Sensitivity analysis (SA) and uncertainty quantification (UQ) in modeling and simulation of reactors
    - NEA/OECD Light Water Reactor (LWR) UAM
    - IAEA CRP High Temperature Gas-cooled Reactor (HTGR) UAM
    - SNF isotopic concentration
  - Development of reactor analysis platform
  - Support to senior design projects
  - Support to course projects in graduate classes such as NE795 “Verification and Validation in Scientific Computing”
- SCALE will be actively utilized also in the following evolving projects at NED, NCSU:
  - Phases II and III of OECD/NEA C5G7-TD benchmark;
  - NEUP project 18-15104 on multi-physics Hi2Lo model information demonstration
  - New NEUP awarded project on “Benchmark Evaluation of Transient Multi-Physics Experimental Data for Pellet Cladding Mechanical Interactions”
  - NEA/OECD Rostov-2 VVER-1000 Multi-Physics Transient Benchmark

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  - Undergraduate students: Jesse Blankenship, Graham Harger, Karthiga Jordan, Scott Burke, Matthew Filer

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