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SHARP Neutronics

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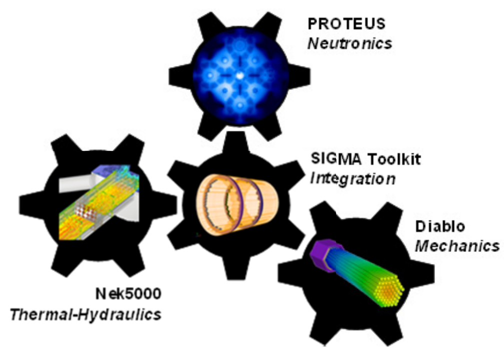
SHARP Neutronics Goal

- **Perform high-fidelity deterministic neutronics simulation for any reactor types with complex geometry and phenomena**
  - Seamless coupling with the SHARP multi-physics simulation toolkit
  - Modeling flexibility for various reactors in terms of geometry and cross sections
  - Reasonable computational performance to meet users' needs



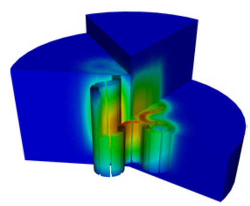
Cross section
- MC^2-3
- Cross Section Libary
- Monte Carlo Codes

Geometry + Mesh
- CUBIT
- Mesh Toolkit

PROTEUS

Transport calculation
- Unstructured mesh
- SS & TR

SN
MOC
NODAL



PERSENT	Perturbation and sensitivity
BuildBot	Nightly regression test (SQA)
VisIt	Visualization

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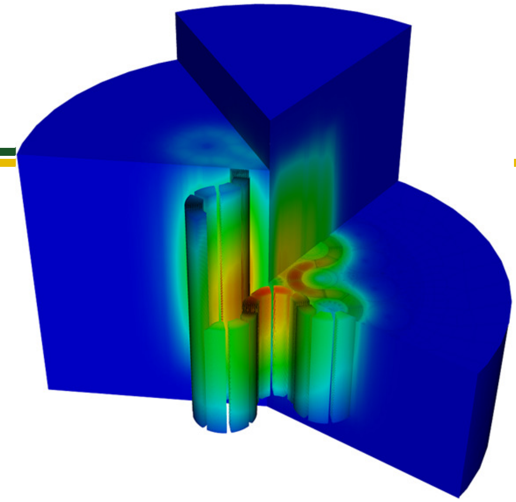
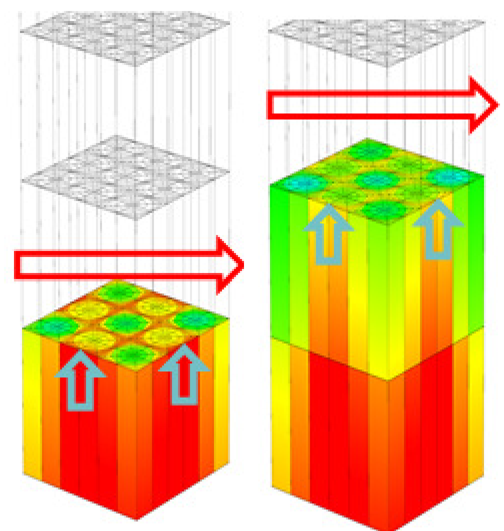
PROTEUS

- **High-fidelity neutron transport code**
  - 2^{nd} order discrete ordinate (SN)
  - 3D MOC : a rigorous formulation with 2D MOC + Galerkin finite element based method in the axial direction, based on extruded geometry
  - Can simulate geometric deformations
- **Unstructured finite element mesh with DOFs >10^{12}**
- **Parallelization in space, angle, and energy**
  - 90% strong scaling, 75% weak scaling
- **Transient capability (adiabatic)**
  - Improved Quasi-Static (IQS) option is being developed under a NEUP project
- **NODAL solver option available**





MOC

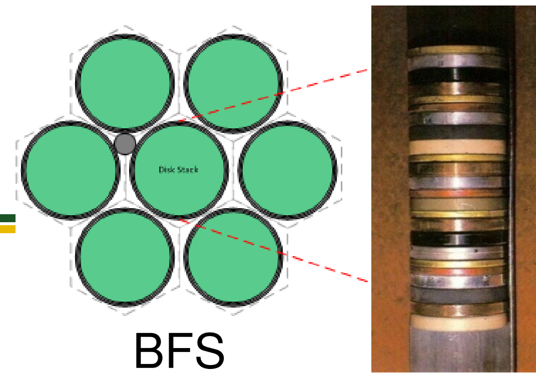
MC²-3

Neutron cross sections

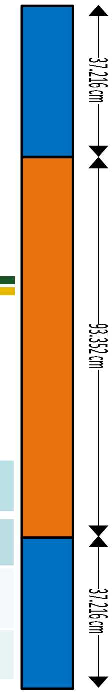
- Resonance self-shielding with analytic Doppler broadening, ultrafine-group (~2000 groups) transport calculations
- Supports both conventional and high-fidelity codes
- Recently, updated thermal cross section library and added a 3-D MOC capability (same as PROTEUS-MOC)
- Substantial V&V tests against fast reactor benchmark problems as well as experiments including LANL, ZPPR, ZPR, BFS, Monju, EBR-II

Gamma heating and cross sections

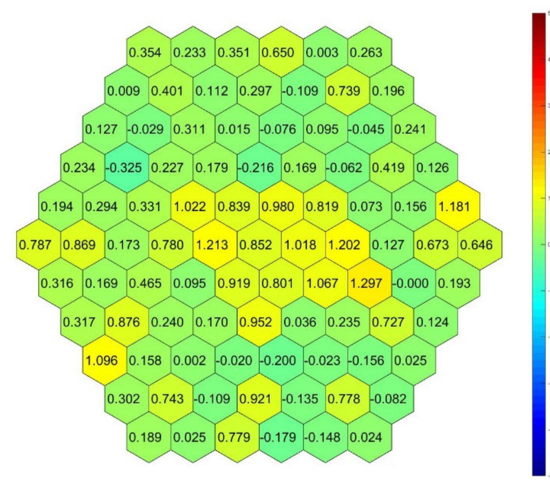
- Recently extended from 21 to 94 groups



BFS

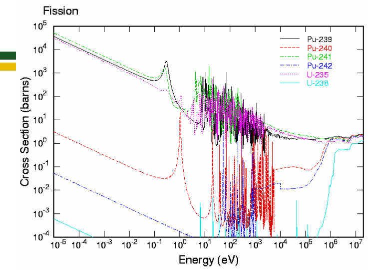


Model	MC²-3 (Δk pcm)	
	1-D	3-D
Unit Cell	-163	12
Wrapper Tube	-310	5



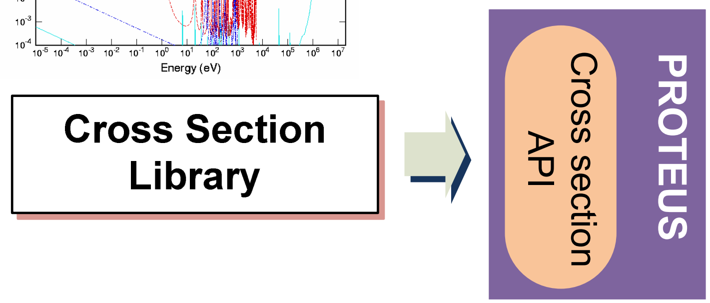
EBR-II

Other Cross Section Generation Options



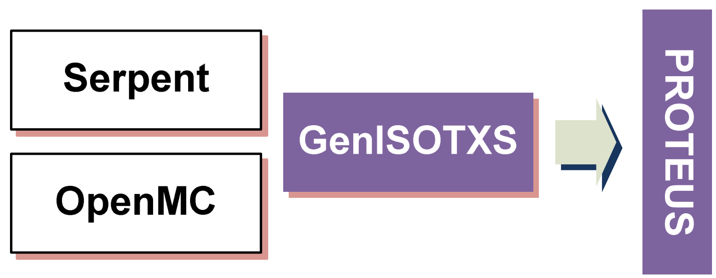
Cross section library

- Is generated using NJOY and MC²-3, based on the <u>subgroup</u> method or the <u>resonance table</u> method
- <u>The cross section API</u> generates cross sections inside PROTEUS on the fly
- Cross sections for thermal reactors
- Up to a few hundred groups



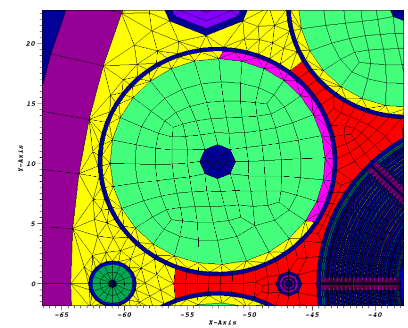
Monte Carlo codes

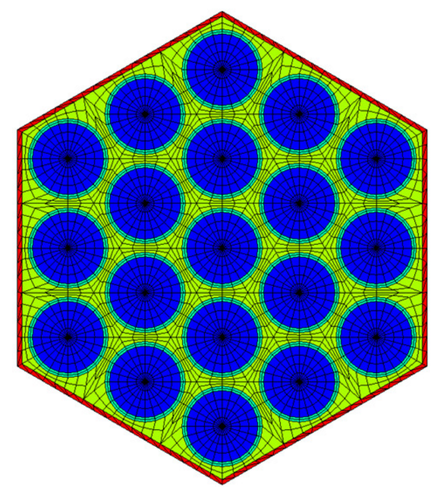
- Cross sections for thermal or fast reactors are generated using Serpent or OpenMC Monte Carlo codes and converted to the format that PROTEUS or conventional codes can read

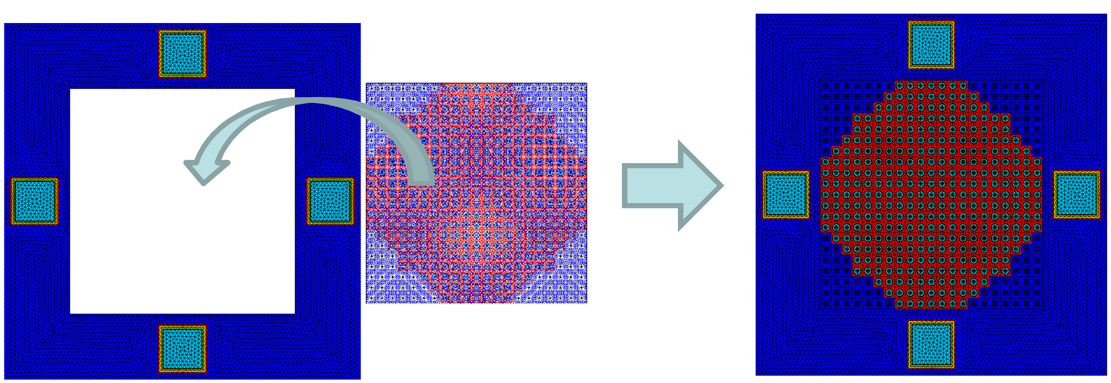


Mesh Generation

- Can use any meshing tools that generate Exodus-II format
- CUBIT (developed by SNL)
  - An option for very complex geometries such as ATR
  - User must create geometry model as well as the mesh
- In-house meshing tools (User Friendly mesh)
  - Automates meshing of standard reactor configurations
    - Assembly ducts, pin cells, boundary layers
  - No CUBIT or other external software is required
  - Extrusion is the only option for 3D



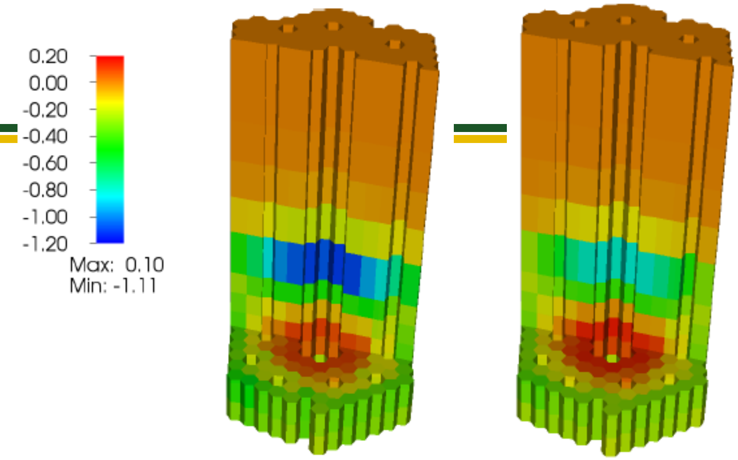




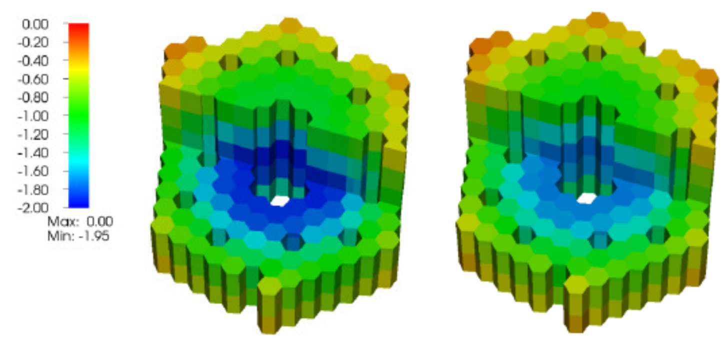
CUBIT UFmesh

PERSENT

- **Reactivity Perturbation & Sensitivity Analysis**
- **Spatial distribution of perturbations for a given reactor system**
  - Very useful in understanding how different parts of a reactor (core, blanket, reflector) contribute to the total reactivity worth
- **High leakage or strong heterogeneity**
  - Diffusion theory shows considerable errors compared with transport results
  - PERSENT provides both 3D diffusion and <u>**transport**</u> perturbation options



Diffusion Transport
30% error in Sodium Density



Diffusion Transport
15% error in Fuel Density

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Applications

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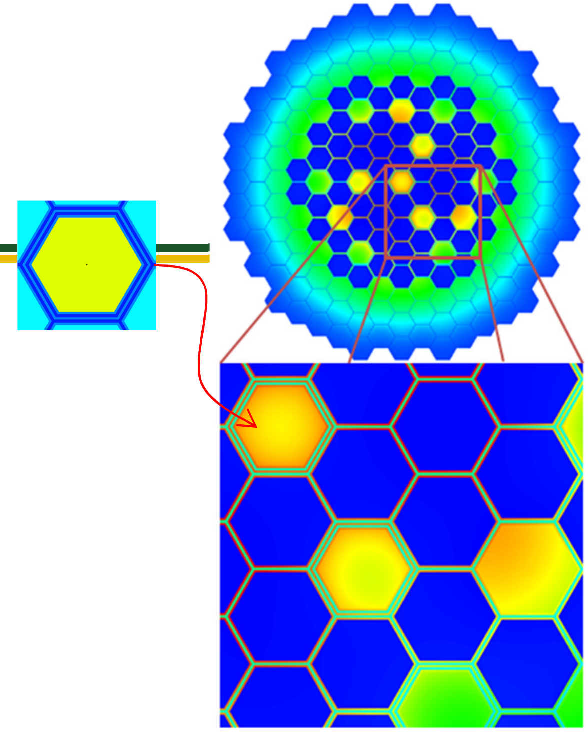
Fast Reactors

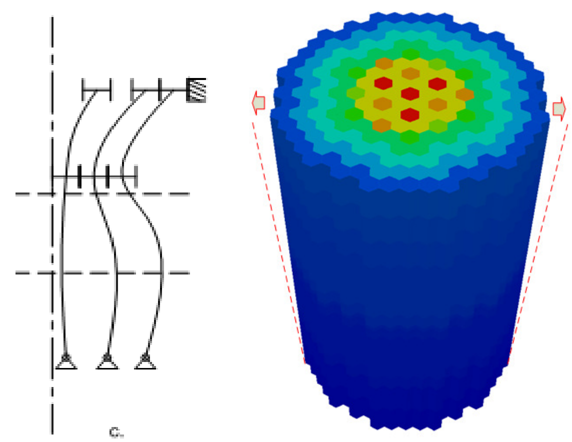


■ ABTR Simulation with PROTEUS

- Multi-group cross section generation using MC^2-3
- Two models in terms of heterogeneity
  - Partially homogeneous assemblies (heterogeneous duct + homogeneous fuel)
  - ~1% error on control rod worth relative to MCNP
  - Less than 200 pcm error in k-effective
  - Full spatial resolution

■ Non-uniform structural deformation

- Is capable of detailed neutronics modeling any type of deformed geometry given from structure codes like Diablo or NUBOW
- Can be performed fully in-memory



Fast Reactors (Cont'd)

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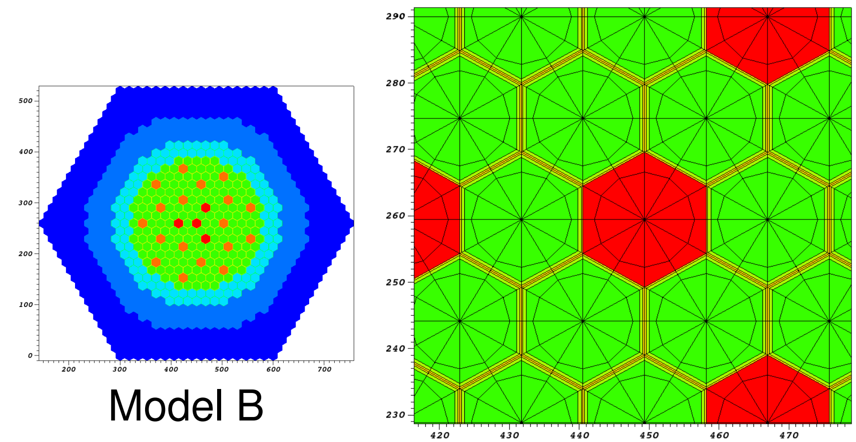
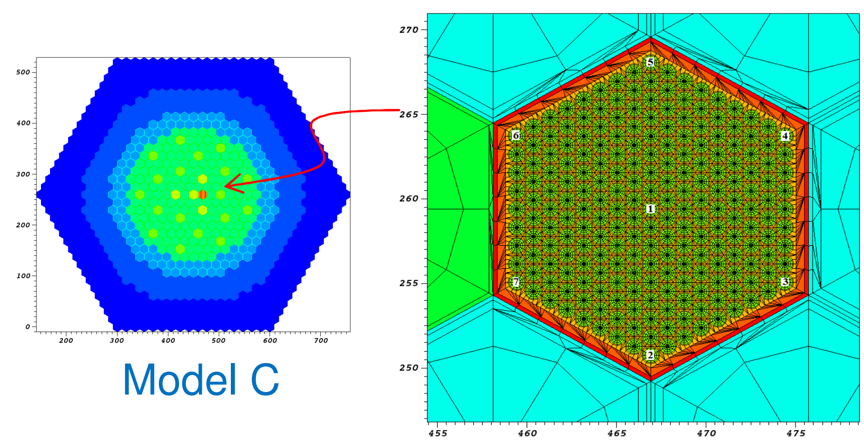
- **Multi-resolution calculation with mixed local resolutions**
  - Model A - Homogenized assembly model (as generally considered in applications of current deterministic codes, notably DIF3D-VARIANT)
  - Model B - Explicit representation of wrapper tube and inter-assembly sodium gap for all fuel regions
  - Model C - Explicit pin by pin representation of a single assembly in the inner core, leaving a full material homogenization in all other assemblies



Model B



Model C

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Fast Reactor (Cont'd) Shielding

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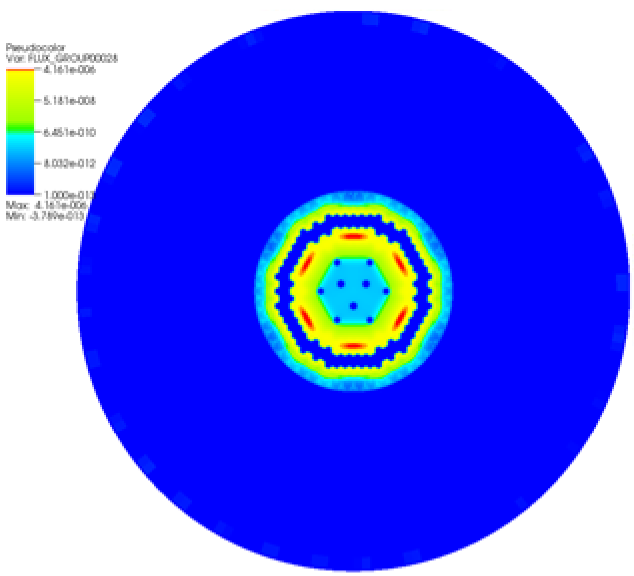
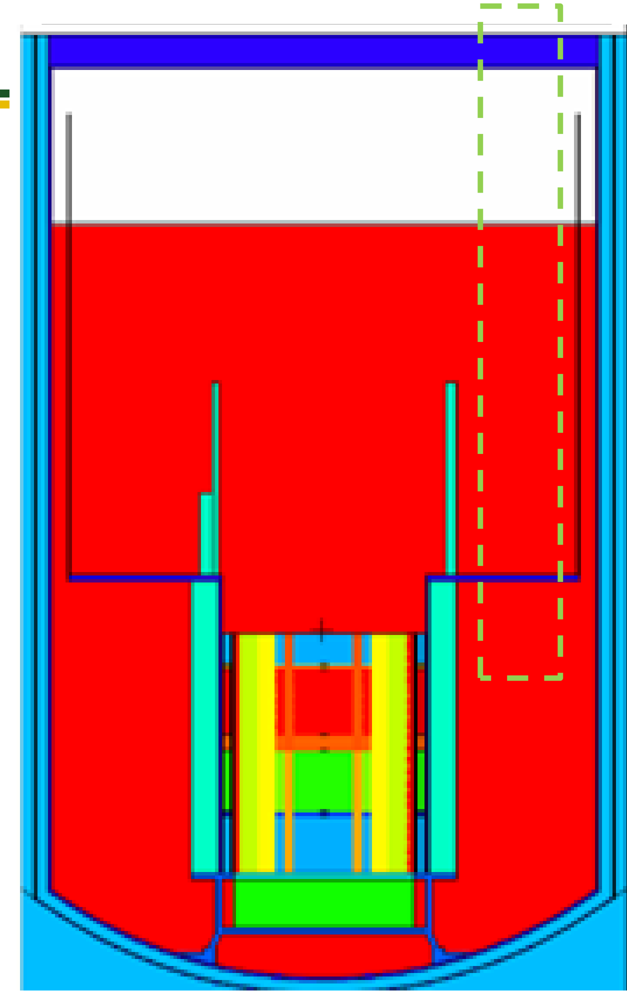
- **PGSFR simulation using PROTEUS-SN for shielding calculation**
  - Challenging with conventional codes to accurately estimate neutron fluxes at outside core regions
  - PROTEUS eigenvalue agrees well with MCNP within ~100 pcm for 2D problems and detailed shielding calculation is ongoing





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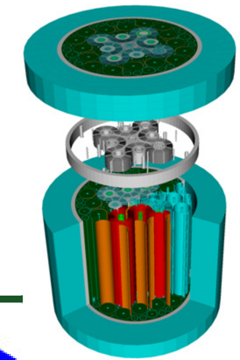
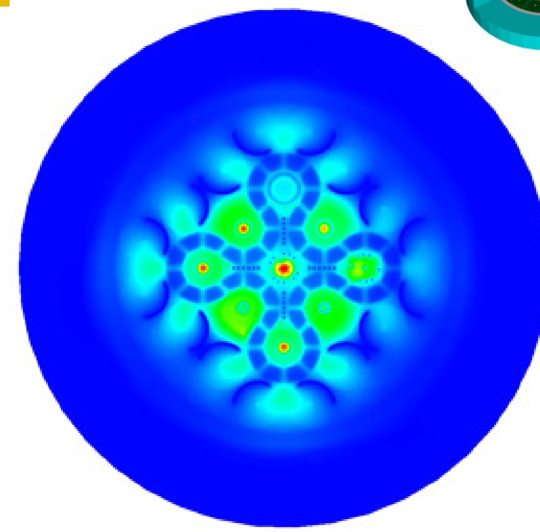
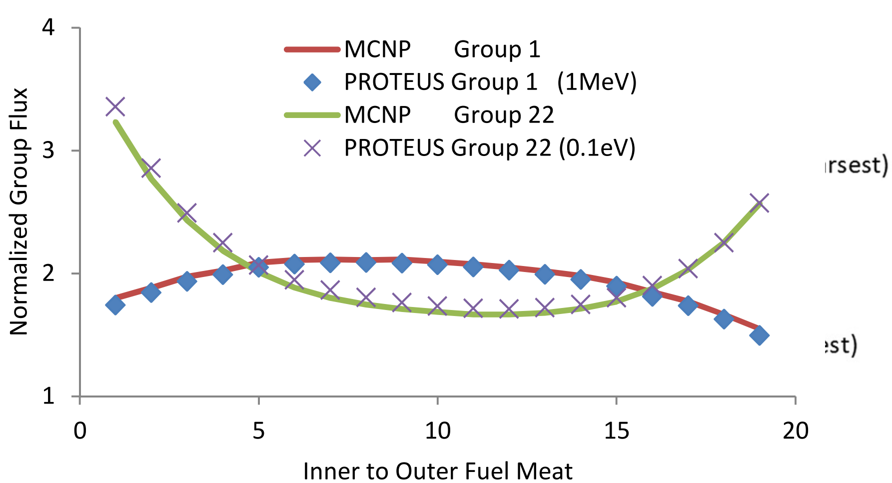
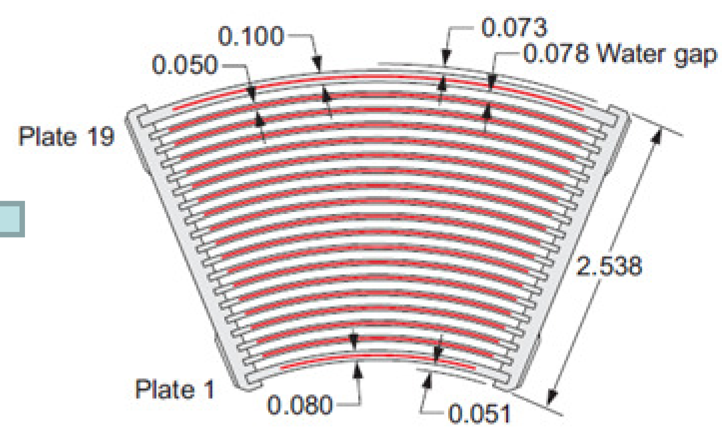
Advanced Test Reactor (ATR)



- **Complex geometry and composition assignment**
  - Complex serpentine core design
  - Very narrow fuel regions
  - 93% enriched uranium in aluminum matrix
- **Good agreement in eigenvalue (< 300 pcm) and flux distributions (< 4.5%) at the fuel region between PROTEUS and MCNP**







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Transient Reactor Test Facility (TREAT)

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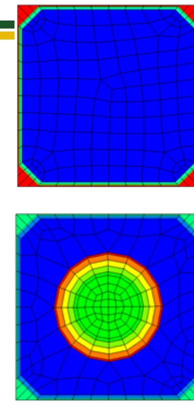
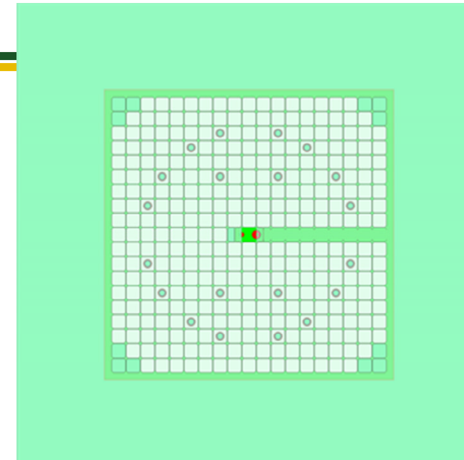
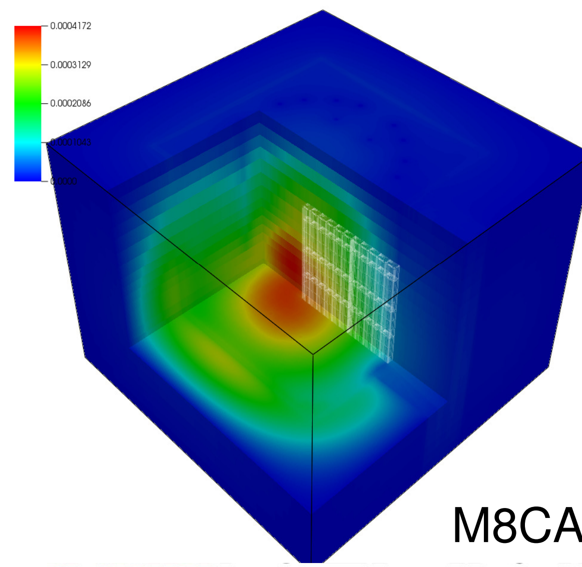
- **Experiment performed in early TREAT operation**
  - Minimum Critical Core (MinCC)
  - Complex-geometry components
- **Latest, best-documented historic TREAT experiments**
  - M8 power calibration experiment (M8CAL)
- **IRPhEP benchmark problems**





M8CAL



M8CAL

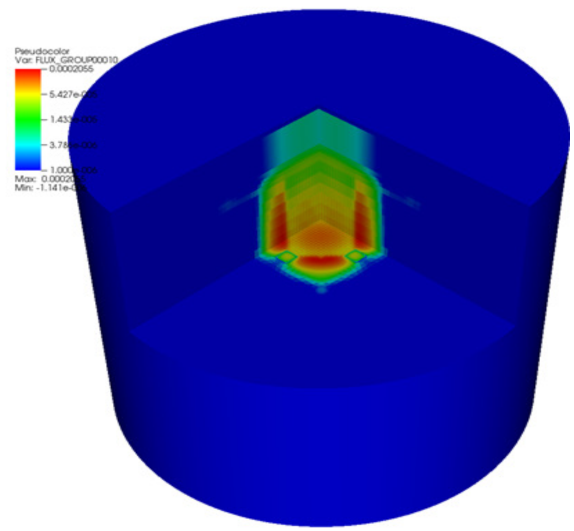
Core	Case	MCNP or Serpent	PROTEUS (Δk, pcm)
MinCC	2D partial core	1.29939 (±15)	-167
	3D core	1.00490 (±19)	115
M8CAL	3D partial core	1.37609 (±16)	147
	3D core *	1.00497 (±18)	148

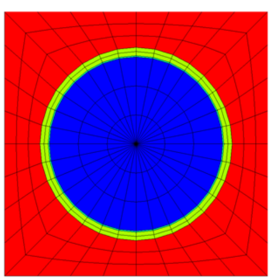
* simplified model

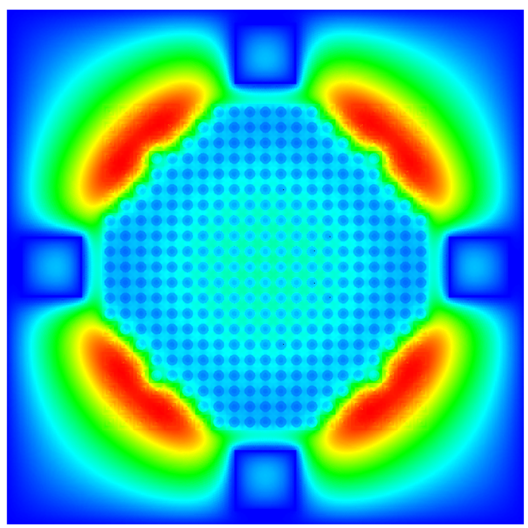
RPI Research Reactor

- **The only university research reactor in the US to use fuel rods similar to operating commercial LWRs**
  - Generated meshes using CUBIT + UFmesh
  - Excellent agreement in eigenvalue between PROTEUS-MOC and Serpent

Core	Case	MCNP or Serpent	PROTEUS (Δk, pcm)
RCF	2D partial core	1.26661 (±9)	-4
	3D core	0.99337 (±10)	24







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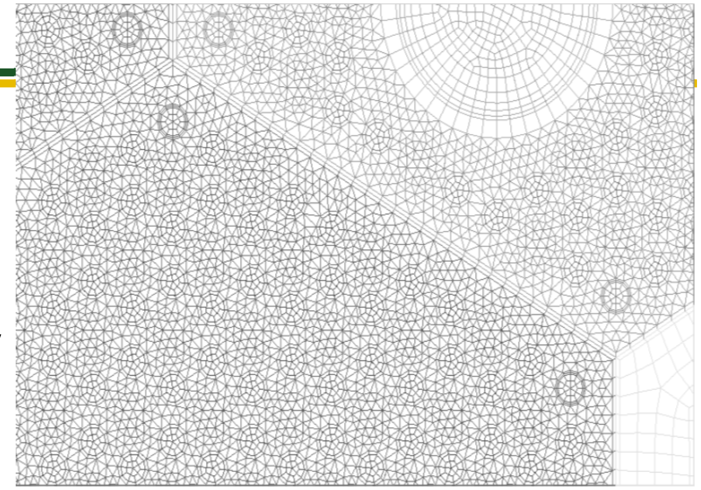
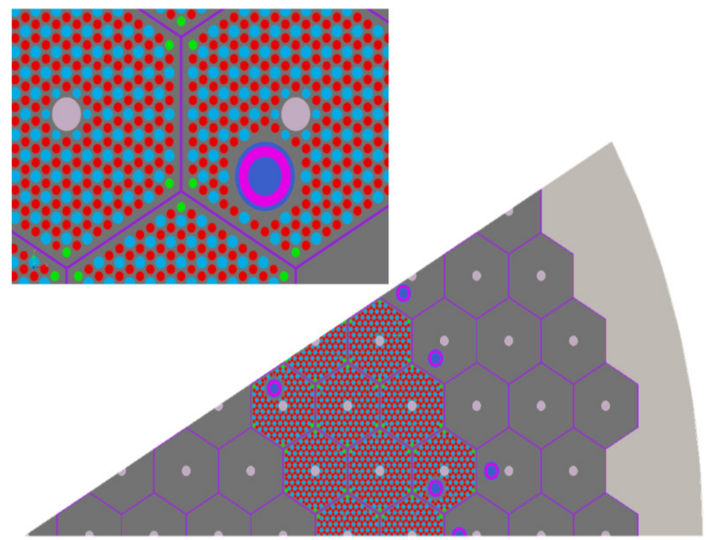
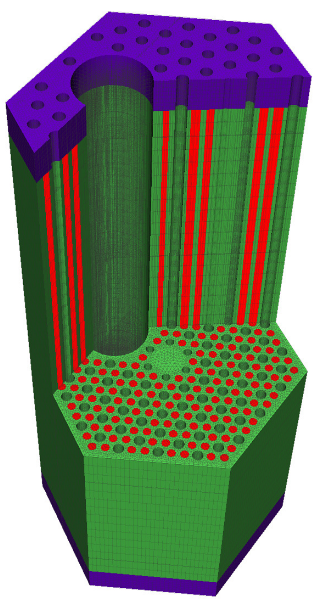
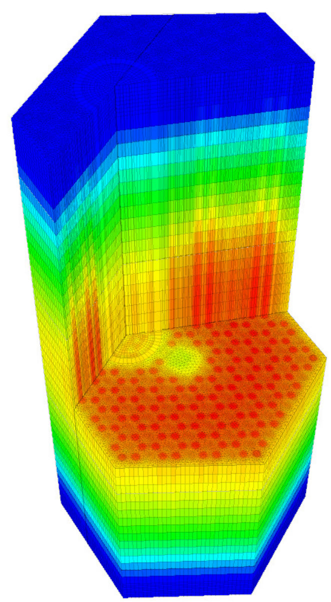
Very High Temperature Reactor (VHTR)



- PROTEUS-MOC is able to provide accurate solutions for neutron streaming through large CR holes
- Preliminary calculations on 3D fuel assembly problems indicated good agreement (< 90 pcm) with Monte Carlo solutions without introducing any methodology patches







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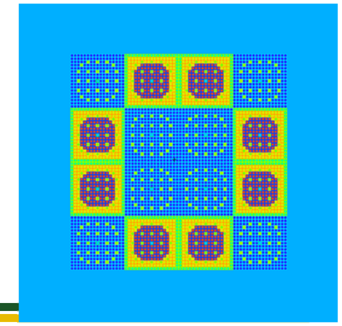
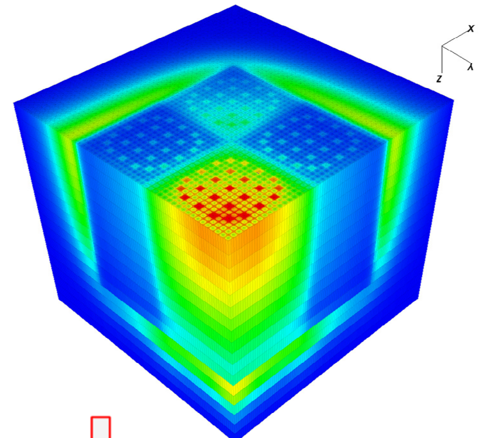
Light Water Reactor

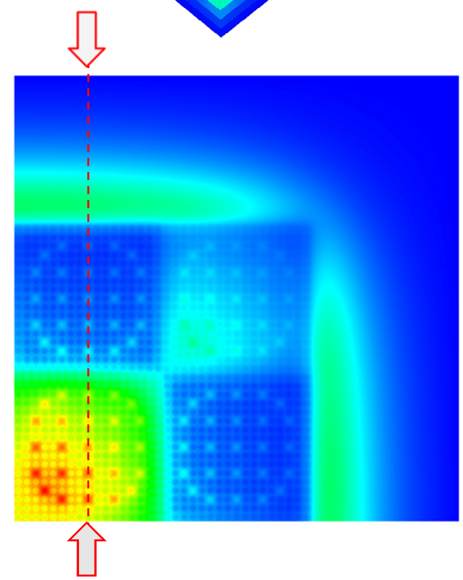


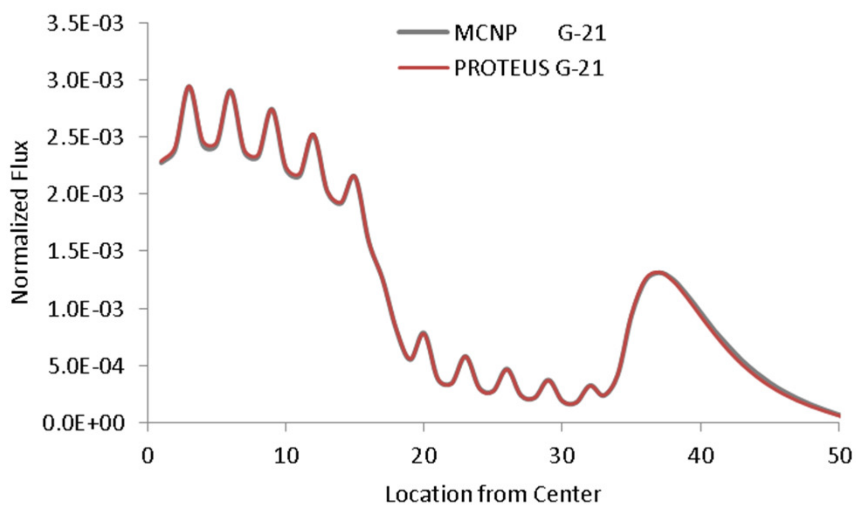
C5G7 PWR Benchmark



Case	MCNP	PROTEUS	Δk, pcm
Unrodded	1.14308 (3)	1.14310	2
Rodded A	1.12821 (3)	1.12817	-4
Rodded B	1.07777 (3)	1.07750	-27

- Pin power error in the unrodded case: max 0.9%, RMS 0.2%





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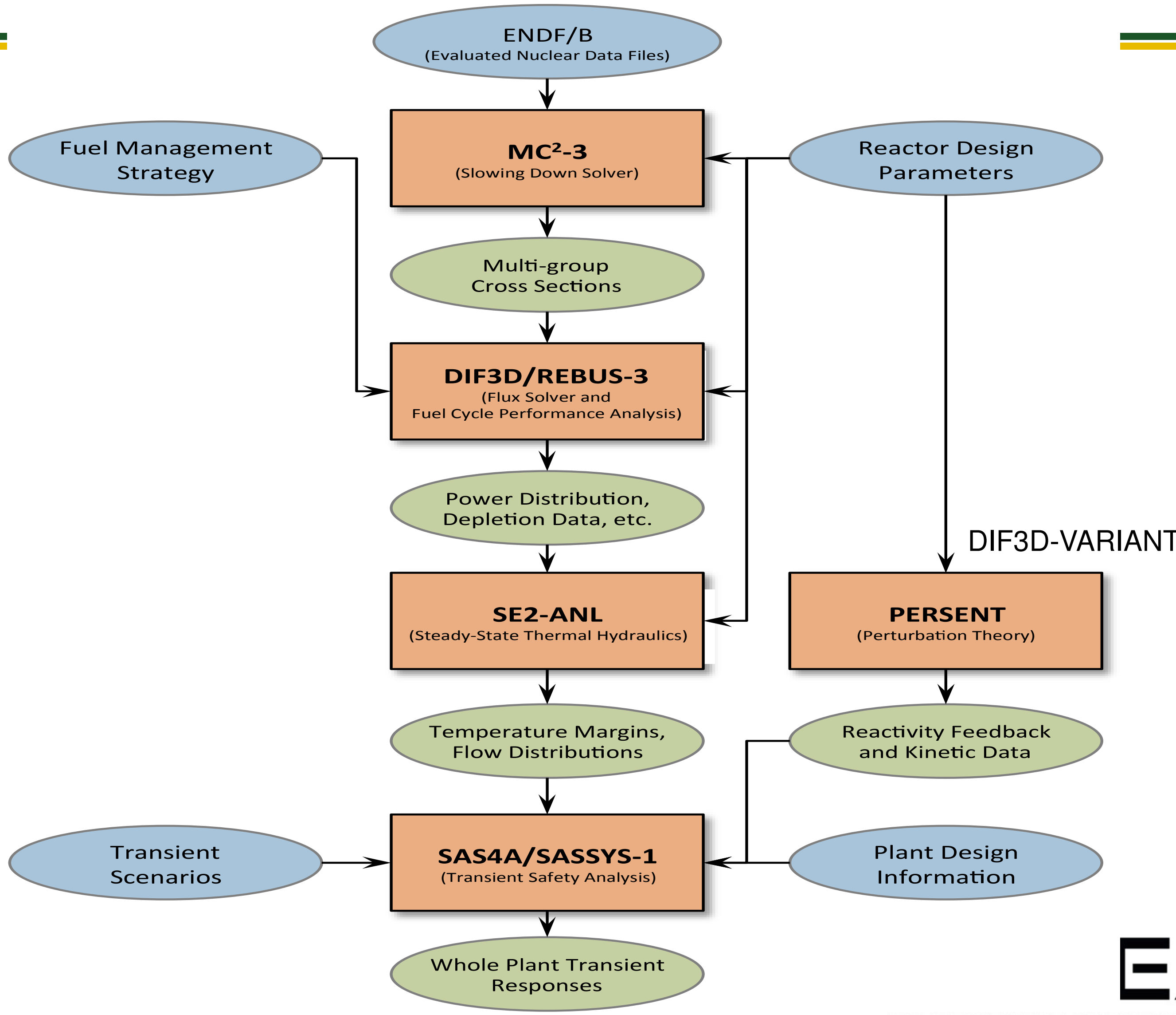
Argonne Fast Reactor Codes



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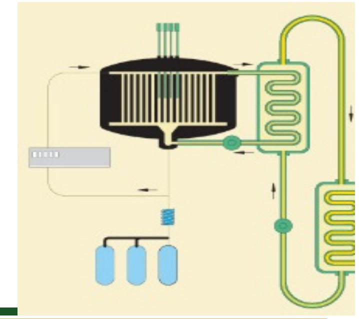
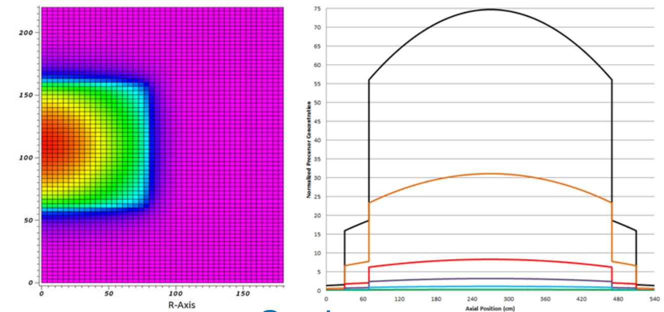
Molten Salt Reactor (MSR)



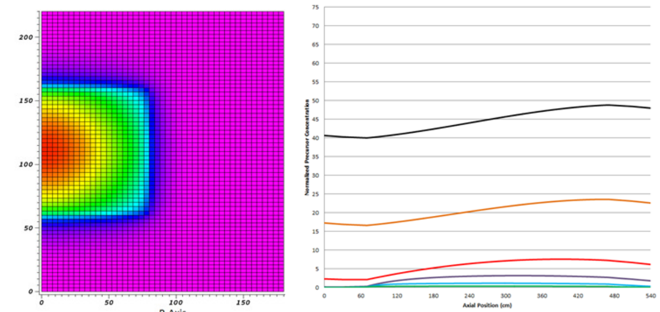
- **Stability questions**
  - Impact of coolant density change during core transit
  - Most designs consider activated fuel leaving the core
  - Loss of flow leads to positive feedback in the core
  - Impact of multiple flow paths (blanket/core) on control system

- **Updated a version of DIF3D to explore the stability problems associated with moving fuel**
  - Allows multiple coolant flow channels through reactor
  - Tracks precursor distribution in-core and ex-core
  - Different channel time delays for reprocessing bleed

- **Analysis showed that fuel cycle behavior is not impacted by flowing fuel behavior**
  - k_{eff} can drop by 200 pcm depending upon flow
  - Significant radiation source in out-flow reflector/shielding and ex-core piping



Stationary



Flowing

Flow Path

Delay neutrons do not impact the flux shape significantly

Precursor Distribution

Each family shows drop in total source.

Reduces β_{eff}
Reduces k_{eff}

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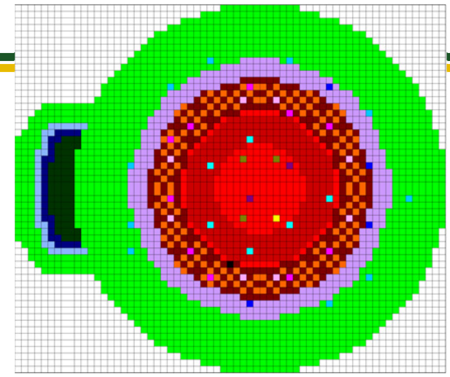
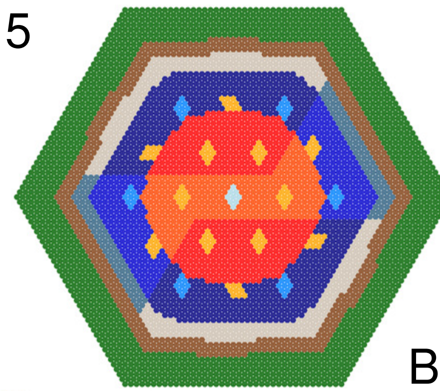
Validation Database



ZPPR-15

ZPPR-15 experiments

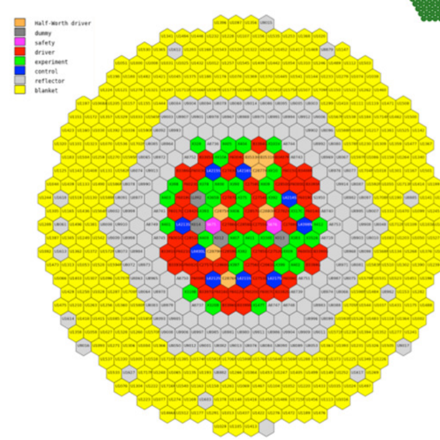
- Doppler measurement
- Axial expansion measurements
- Foil measurement
- Neutron spectrum measurements
- Gamma dose measurements
- B-10 reaction rate measurements
- Control rod and sodium void worth measurements



BFS

BFS experiments (I-NERI with KAERI)

- Control rod worth, sodium void worth, aluminum rod worth, axial and radial expansion measurements



EBR-II

EBR-II experiments

- Core follow for 10 years (1984 – 1994)
- Depletion data

Summary

- **NEAMS neutronics tools**
  - Neutronics transport code: PROTEUS (SN, MOC, NODAL)
  - Cross section generation tools: MC^2-3, Cross section API, Monte Carlo
  - mesh generation tool: UFmesh
  - Perturbation and sensitivity analysis tool: PERSENT
  - Software development QA : BuildBot
- **V&V tests**
  - Fast reactors (ZPPR, ABTR) and various thermal reactors (ATR, TREAT, PWR (C5), RPI research reactor, VHTR, etc.)
- **Improved ANL code suite**
  - MC^2-3, DIF3D/REBUS, PERSENT
  - Substantial V&V practices against ZPPR-15, EBR-II, etc.
  - Being used by ART, TerraPower, KAERI for actual fast reactor design

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Software Status

- **Software QA**
  - All codes are under the SVN version control, tracking source code changes and impacts on verification test suite
  - Nightly regression tests using BuildBot (http://buildbot.net/) to ensure continued accuracy and performance
- **Software availability / deployment / licensing**
  - All physics codes are export controlled (licensing required; free for government use)
  - ANL TDC personnel supports for code licensing
    - Elizabeth K. Jordan (ekjordan@anl.gov) at the TDC division or nera-software@anl.gov
- **Required computational resources**
  - PROTEUS requires parallel machines with 500 – a few tens K processors
  - All other codes can run in a serial mode on a regular Linux machine
- **Training upon request**
  - Methodology / user manuals and training material are available
  - April 2015, July 2016 at ANL, Feb. 2017 at U. of Florida
- **Contact: nera-software@anl.gov**

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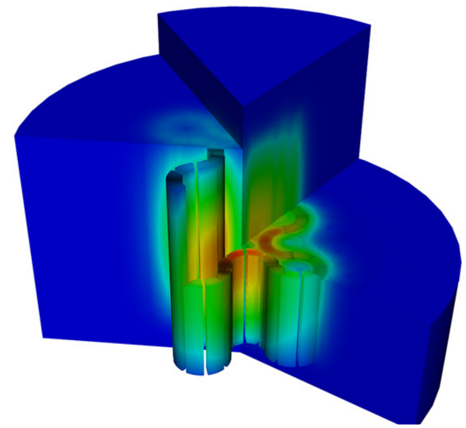
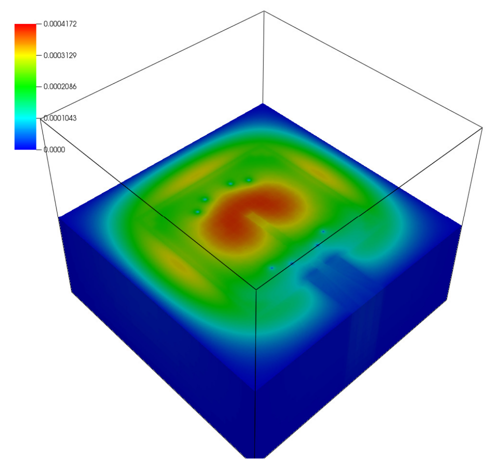
Questions ?

- **PROTEUS Users**
  ART, CESAR, ORNL, INL, RPI, Purdue, Florida, Penn State, UM, KSU, NCSU, UMass-Lowell, Rnet-tech

- **MC²-3 Users**
  ART, TerraPower, ORNL, INL, BNL, Berkley, MIT, Purdue, Georgia Tech, Tennessee, NCSU, Florida, (Korea) KAERI, UNIST, SNU

- **PERSENT Users**
  ART, KAERI





NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM