COMSOL-based Nuclear Reactor Kinetics Studies at the High Flux Isotope Reactor

HFIR

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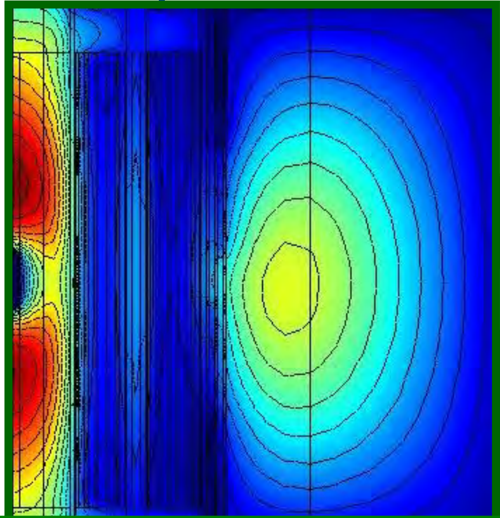

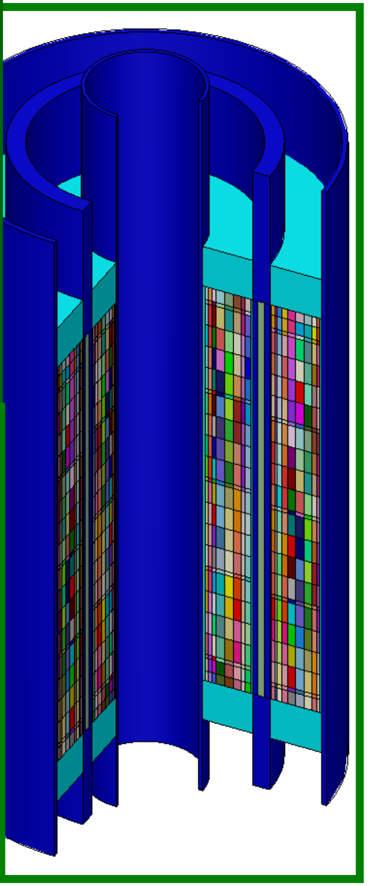

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THE UNIVERSITY of TENNESSEE UT KNOXVILLE

OAK RIDGE NATIONAL LABORATORY
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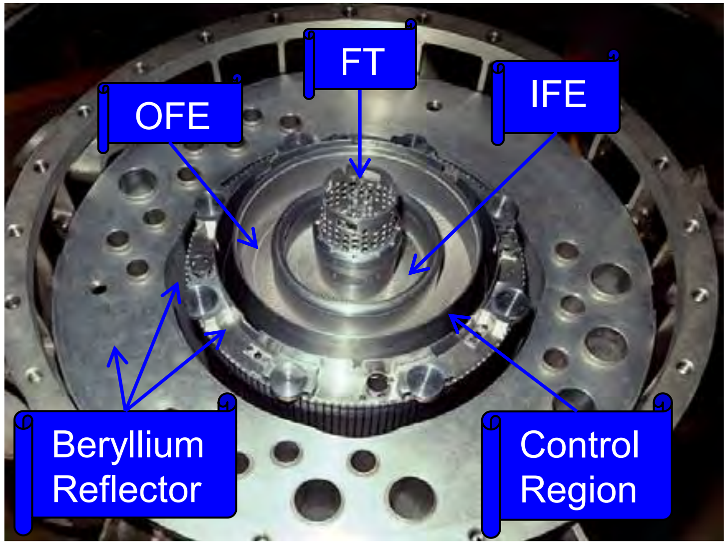
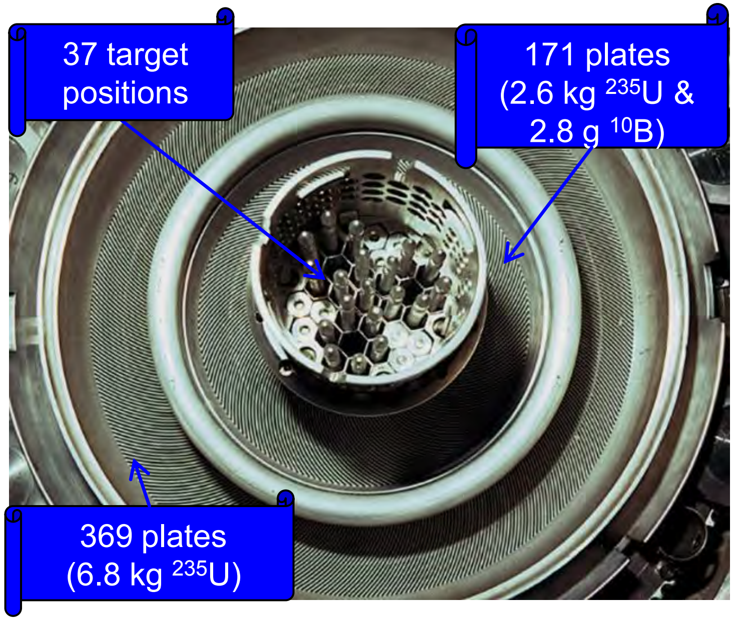
Presentation Outline

- Brief HFIR background
- Brief review of reactor physics concepts
- Reactor Kinetics Studies
  - Nuclear data generation via NEWT
  - Control cylinder ejection transient
  - Space-time kinetics equation-based modeling methodology
- Results
- Conclusions

Beryllium reflected, light-water cooled, pressurized, flux-trap type reactor.

- Currently operates at 85 MW_{th}
- Cycle length 21 – 26 calendar days
- Two Fuel Elements [Inner Fuel Element (IFE) and Outer Fuel Element (OFE)]
- Highly Enriched Uranium fuel (~93 wt.% ^{235}U) in the form of U_3O_8-Al with Al-6061 clad
- Two Control Elements (CEs) for regulation and safety purposes
- Cold and thermal neutron scattering, isotope production, materials irradiation, Neutron Activation Analysis



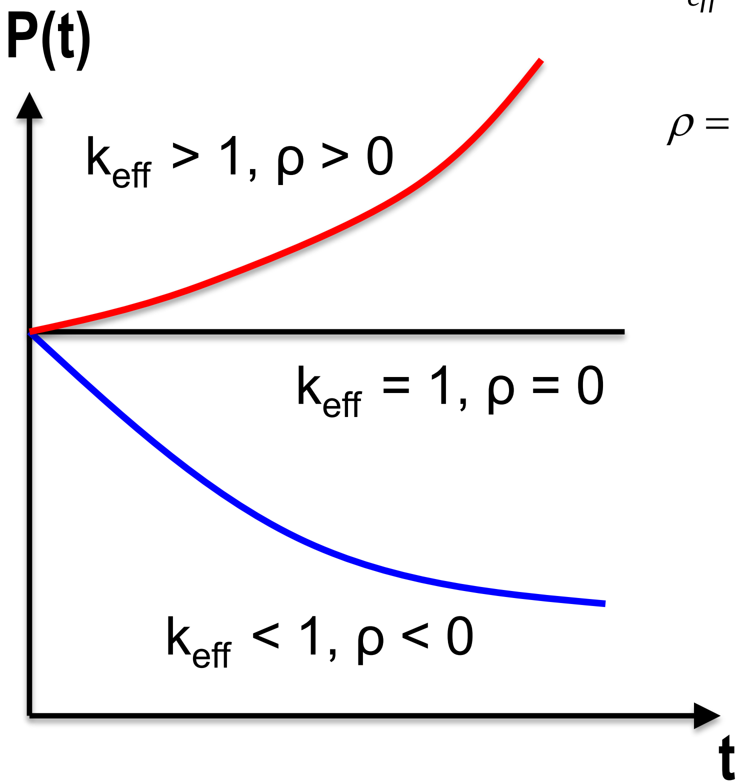


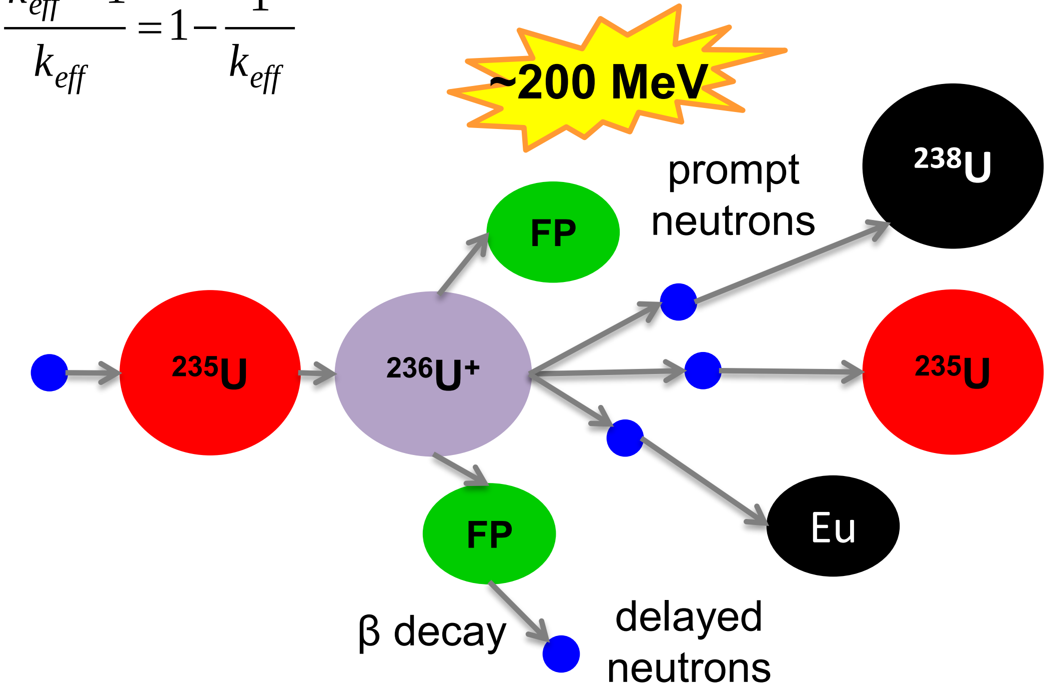
If positive reactivity is inserted, the power will increase. If negative reactivity is inserted, the power will decrease.

- **The effective neutron multiplication factor (k_{eff}) is the ratio of the number of neutrons produced in generation "i+1" to the number produced in generation "i"**
- **Reactivity (ρ cents,** dollars, $\Delta k/k$, etc.**) is a measure of the deviation from critical**

$$k_{eff} = \frac{\#\text{ of neutrons in generation "i+1"}}{\#\text{ of neutrons in generation "i"}} = \frac{\text{production}}{\text{absorption} + \text{leakage}}$$

$$\rho = \frac{k_{eff} - 1}{k_{eff}} = 1 - \frac{1}{k_{eff}}$$





PDE coefficient form application mode.

Multi-Energy-Group Neutron Diffusion

$$\frac{1}{v^g}\frac{\partial \phi^g}{\partial t} - \nabla\cdot(D^g\nabla\phi^g) + \left(\Sigma_a^g + \sum_{g'=1,\neq g}^{G}\Sigma_s^{g\to g'}\right)\phi^g = (1-\beta_{eff})\chi_p^g\sum_{g'=1}^{G}\upsilon\Sigma_f^{g'}\phi^{g'} + \sum_{g'=1,\neq g}^{G}\Sigma_s^{g'\to g}\phi^{g'} + \sum_{i=1}^{I}\lambda_i\chi_i^g C_i$$

$$\boxed{g = 1:3}$$

$$\boxed{i = 1:6}$$

ϕ^g	neutron flux (neutrons/m^2-s)
v^g	average neutron velocity (m/s)
D^g	diffusion coefficient (m)
Σ_a^g	absorption cross section (1/m)
$\Sigma_s^{g\to g'}$	scattering cross section g→g' (1/m)
χ_p^g	probability of prompt neutron born in g
υ	average # of neutrons emitted per fission
$\Sigma_f^{g'}$	fission cross section (1/m)

Delayed Neutron Precursor Concentration

$$\frac{\partial C_i}{\partial t} + \lambda_i C_i = \beta_i\sum_{g=1}^{G}\upsilon\Sigma_f^g\phi^g$$

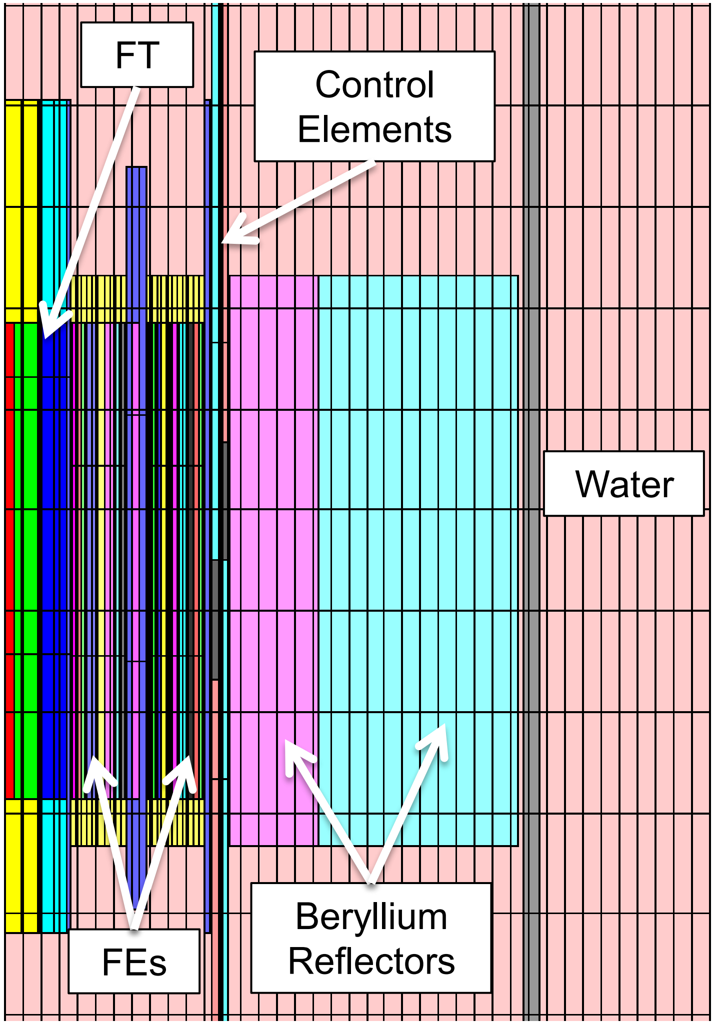
C_i	DNP concentration (neutrons/m^3)
λ_i	Decay constant (1/s)
χ_i^g	probability of delayed neutron born in g
β_i	fraction of neutrons born delayed

$$\beta_{eff} = \sum_{i=1}^{6}\beta_i$$

The TRITON/NEWT sequence in SCALE is used to calculate nuclear data.

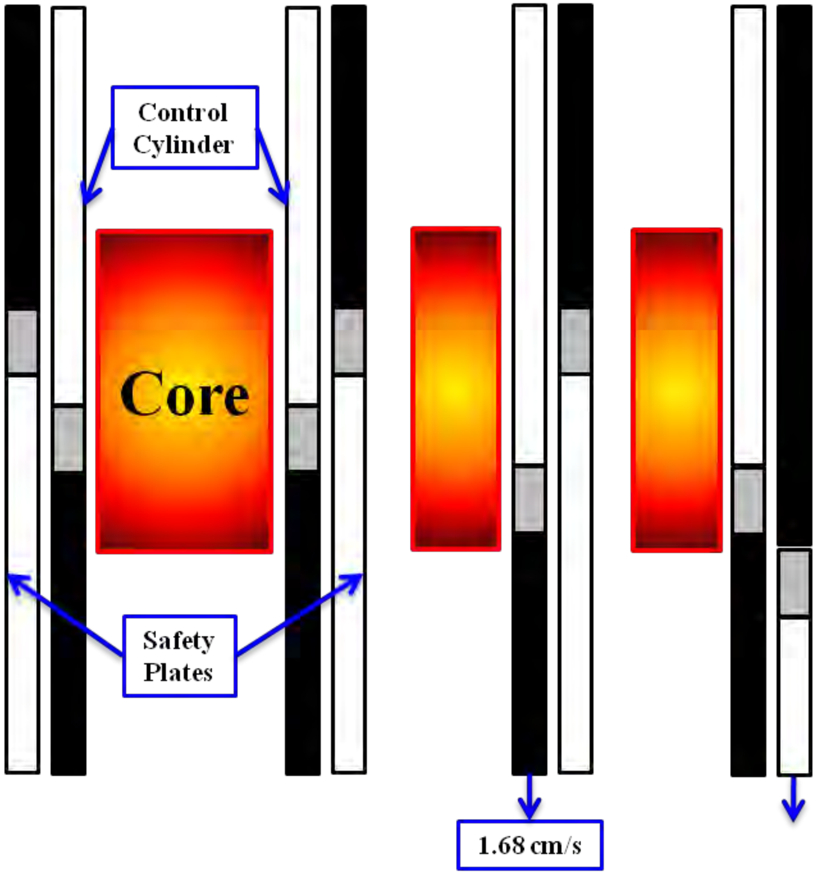
- 2-D neutron discrete-ordinates code
- Provides a solution for multigroup transport calculations
- Calculates the spatial flux distribution and prepares collapsed cross sections

3-group #	238-group #	Lower Energy
1	44	100 keV
2	199	0.625 eV
3	238	10 µeV



NEWT input modified from the model documented in:
Dr. G. Ilas, et. al., New Cross Section Processing Methodology for HFIR Core Analysis, PHYSOR-2008, Interlaken, Switzerland, Sep. 2008.

If the control cylinder is ejected, positive reactivity would be inserted; thus, giving rise to a power transient.



- Transient initiated by a control cylinder ejection
  - v_{cc} = -1.68 cm/s (-0.662 in/s)
- Initial reactor power = 1 kW
  - Zero power condition (lowest critical power and worst case scenario)
- Power scram set point = 5.001 MW
- Safety plate response time = 10 ms

$$\frac{d^2\Delta z_{sp}(t)}{dt^2} = -[4g - 19.7g\Delta z_{oce}]\frac{m}{s^2},\ for\ a \geq g$$

$$otherwise,\quad \frac{d^2\Delta z_{sp}(t)}{dt^2} = -g\left(\frac{m}{s^2}\right)$$

Three study steps are solved in sequential order.

1. Eigenvalue study

- Good spatially-dependent solution, but normalized to maximum value
- Solution used as the initial values (starting guesses) for study step 2

2. Stationary study

- Set up constraint (ODE) to normalize fluxes and determine k_{eff}

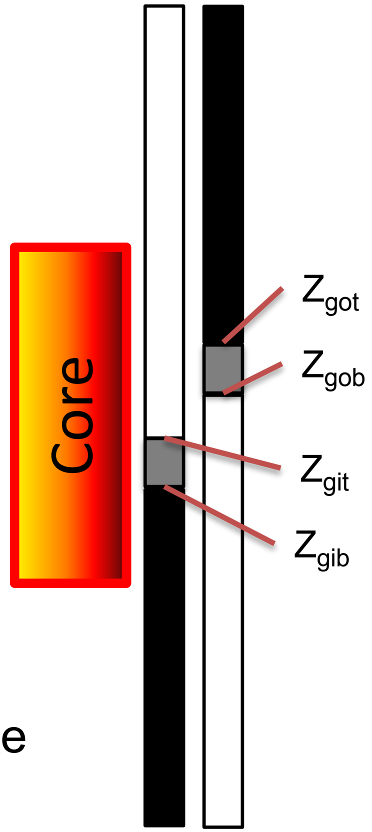
$$k_{eff} : \left(\iiint_V \sum_{g=1}^{3} \kappa \Sigma_f^g \phi^g \, dV \right) - P_o = 0 \qquad (\kappa \approx 3.1\text{x}10^{-11} \text{ J/fission})$$

- Solution used as initial values for study step 3

3. Time-dependent study

- Define moving interfaces, i.e. $Z_{gib}(t)$=-2.54[cm]-1.68[cm/s]*t[s]
- Assign axially-dependent properties (cross sections) to simulate control element movement, i.e. if(z<Z_{gib},Σ_{bi},if(z<Z_{git},Σ_{gi},Σ_{wi}))
- Smoothing functions applied to transitions from high absorption to low absorption, i.e. flc2hs(z–z_2,scale)
- Track power as a function of time

$$P(W) = \iiint_V \sum_{g=1}^{3} \left(k^g \Sigma_f^g \phi^g \right) dV$$

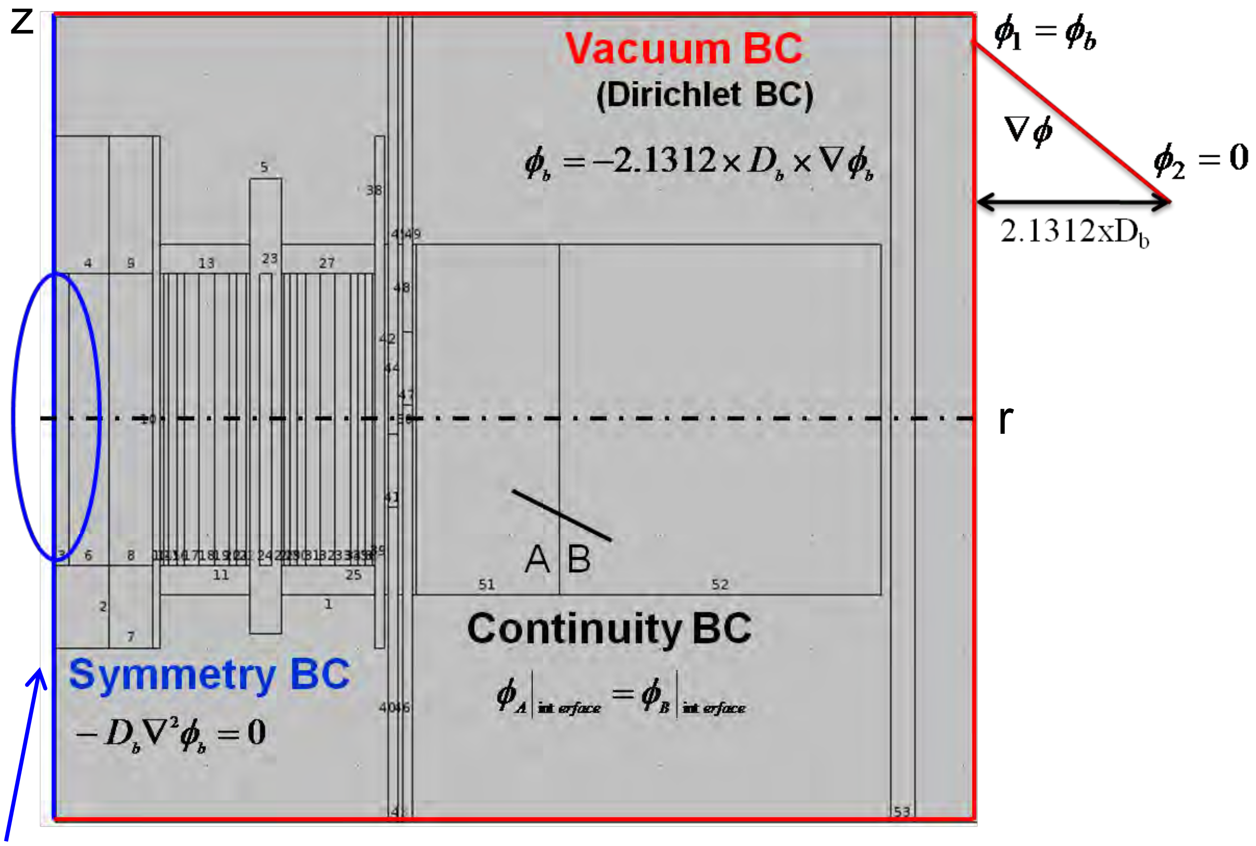


2-D axisymmetric geometry and vacuum boundary conditions are utilized.

$$\left.\begin{aligned}\mathbf{n}\cdot(c\nabla u+\alpha u-\gamma)+qu=g-h^{T}\mu\\ hu=r\end{aligned}\right\}$$

on boundary (dΩ)

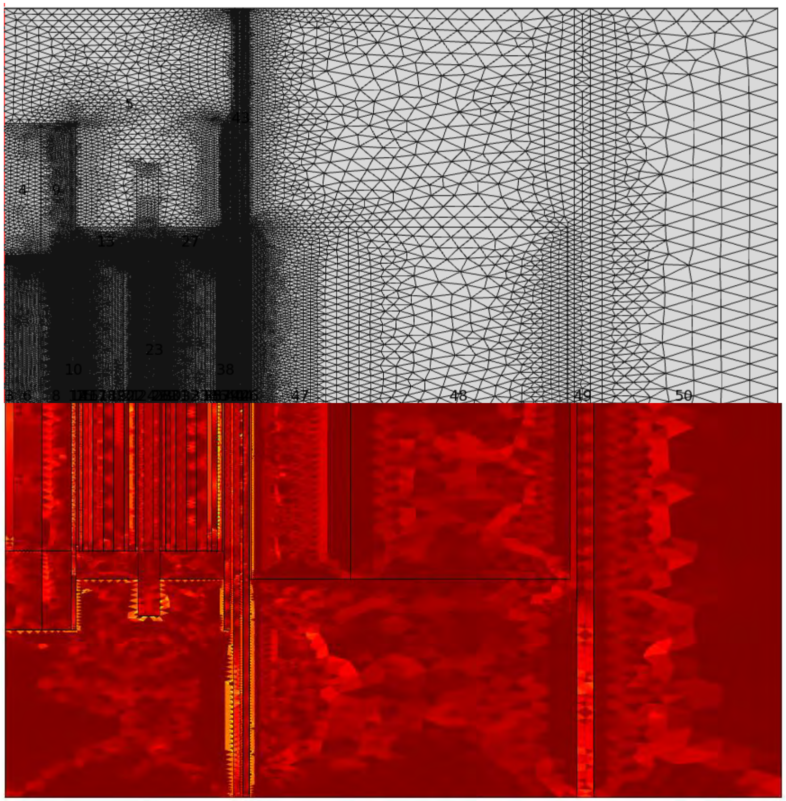
- Symmetry BC defined at the axial centerline
- Vacuum BCs defined at the 3 outer pool boundaries
- Continuity BCs defined for all interior boundary interfaces



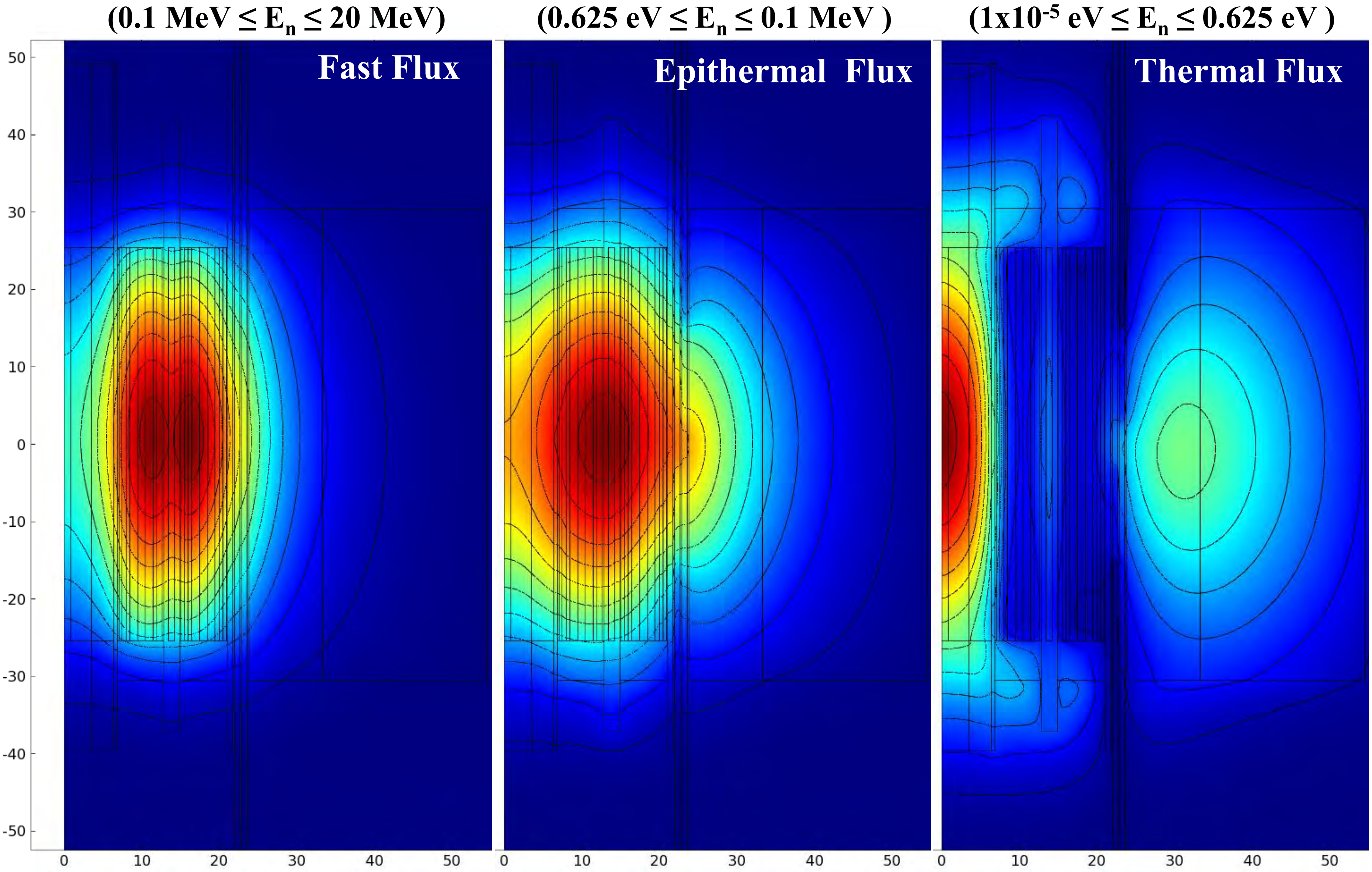
core axial centerline.

COMSOL's built-in mesh generator used to discretize the geometry and Direct solvers are utilized.

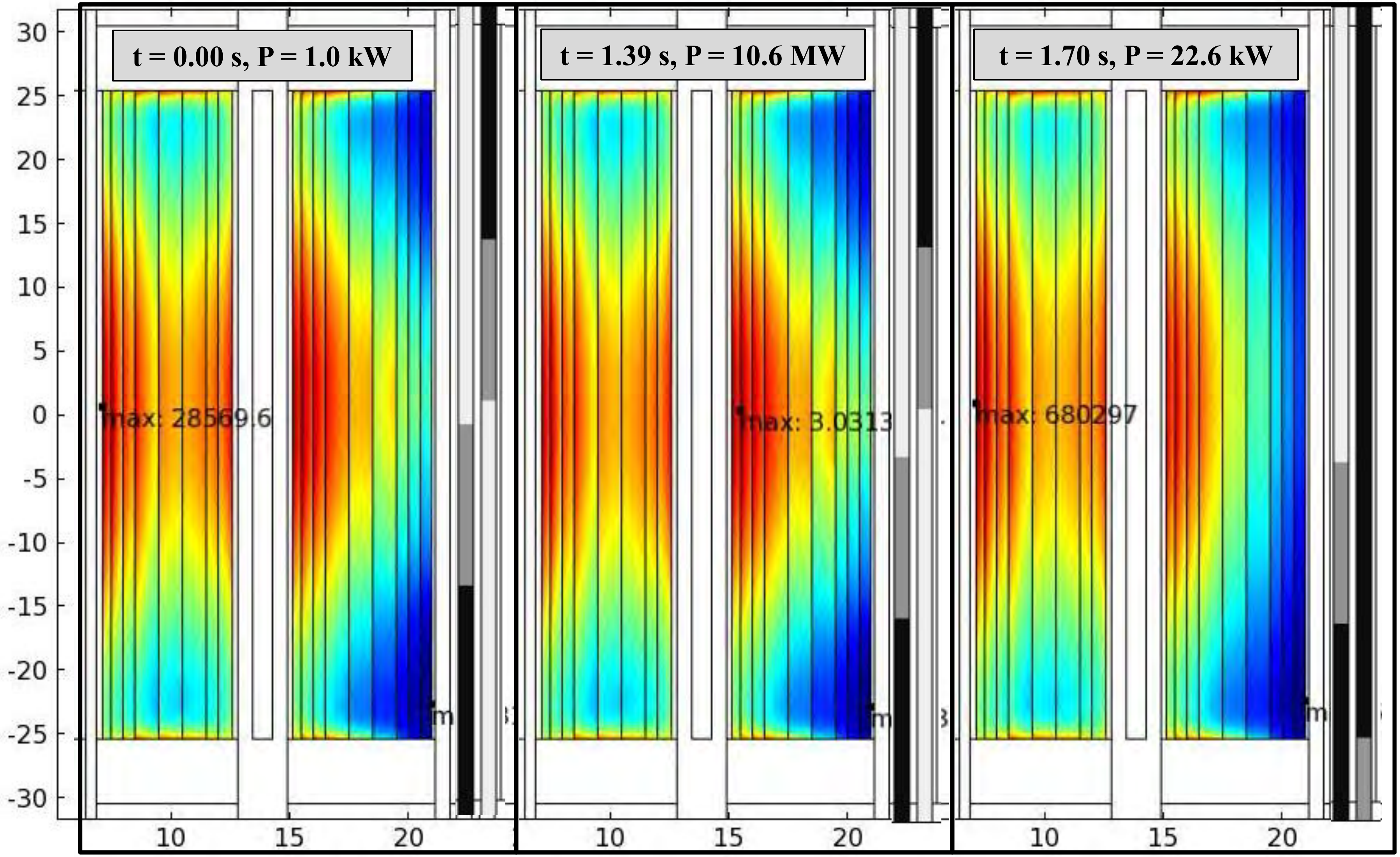
- Mapped mesh in moving domains
- Boundary layers in narrow domains located near steep flux gradients
- Free triangular mesh elsewhere
  - "Extremely fine" in core region (+refinements)
  - "Extra fine" in pool water outside of Be reflector
- Each model set up with ~100-150k elements
  - ~1-2 million DOF → 24 hr solution time
  - 3 compute nodes, dual quad core processors, 64 GB RAM
- PARDISO for stationary and eigenvalue
  - Efficient, but does not run in distributed parallel mode
- MUMPS for transient calculations
  - Less efficient, but runs in distributed parallel mode



Beginning-of-cycle neutron fluxes.



Power shifts to the OFE during control cylinder ejection and then back to IFE during safety plate insertion.



Summary and Conclusions

- **COMSOL-based neutron diffusion models of HFIR were created via equation-based modeling**
  - 3 neutron energy groups and 6 delayed neutron precursor groups
  - 2-D axisymmetric geometry
  - Nuclear data derived from TRITON/NEWT sequence in SCALE
- **New space-time (PDE and ODE modes) and point kinetics (ODE mode) methodologies were developed in COMSOL**
  - Point kinetics are much more computationally efficient and were shown to produce accurate results for small perturbations
- **Additional results and methods documented in full length paper**
- **COMSOL is also being used at the HFIR for thermal hydraulic and structural analyses**