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Adaptation of GEANT-4 to Criticality Calculations for Nuclear Reactors

ENSAR2 workshop: GEANT4 in nuclear physics 2018

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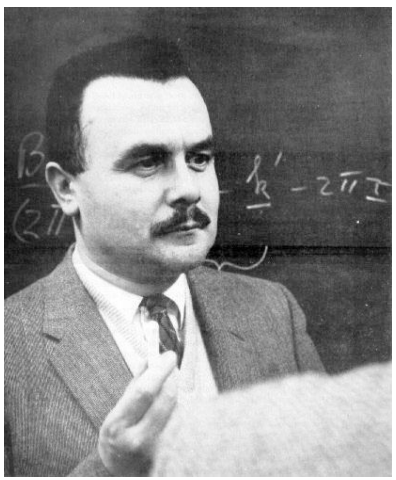
The Stage: McMaster

- **McMaster Nuclear Reactor** Critical **April 1959** (First RR at a Commonwealth University) (CERN:1952)
- **Bertram Brockhouse** shared the 1994 Nobel Prize in Physics with American Clifford Shull for developing neutron scattering techniques for studying condensed matter.



Today: McMaster Research Funding about $400M – one of Canada's most research intensive Universities

MNR:

- Intense positron beam
- Small-angle neutron scattering
- Neutron activation analysis
- Neutron radiography

MNR: Commercial production of radio-isotopes for medical purposes (I-125, Lu-177, Re-186, …)
Accelerators (F-18), Hot cells, Sources.
https://nuclear.mcmaster.ca/

Analyzing Nuclear Reactors

- Neutron transport equation describes the behaviour of neutrons in a reactor:

$$\frac{\partial}{\partial t} n(\mathbf{r}, E, \hat{\mathbf{\Omega}}, t) =$$

$$\frac{1}{v}\frac{\partial}{\partial t}\varphi(\mathbf{r}, E, \hat{\mathbf{\Omega}}, t) = -\Sigma_t(\mathbf{r}, E)\varphi(\mathbf{r}, E, \hat{\mathbf{\Omega}}, t) - \hat{\mathbf{\Omega}} \cdot \nabla\varphi(\mathbf{r}, E, \hat{\mathbf{\Omega}}, t) +$$
$$+ \int_0^\infty dE' \int_{4\pi} d^2\hat{\mathbf{\Omega}}' \; \Sigma_s(E' \to E, \mathbf{\Omega}' \to \Omega)\varphi(\mathbf{r}, E', \hat{\mathbf{\Omega}}', t) +$$
$$+ \frac{\chi(E)}{4\pi}\int_0^\infty dE' \int_{4\pi} d^2\hat{\mathbf{\Omega}}' \; \nu(E')\Sigma_f(E')\varphi(\mathbf{r}, E', \hat{\mathbf{\Omega}}', t) +$$
$$+ s(\mathbf{r}, E, \hat{\mathbf{\Omega}}, t) \qquad (1)$$

Total Absorption

Streaming

Scattering

Fission

External source

Steady State

- Traditionally, analysis done in steady state:

$$\frac{\partial}{\partial t} = 0$$

- Concept of criticality:

$$k \equiv \frac{\text{rate of neutron production in reactor}}{\text{rate of neutron loss in reactor}} \equiv \frac{P(t)}{L(t)}. \tag{1}$$

criticality is now given by:

$$k < 1 \qquad \text{subcritical} \tag{2}$$

$$k = 1 \qquad \text{critical} \tag{3}$$

$$k > 1 \qquad \text{supercritical} \tag{4}$$

- Transport equation may be solved numerically.

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Kinetics

- Dynamic changes in the reactor core are usually dealt with by Point Kinetics:
  - Flux shape remains the same.
  - Overall flux (neutron density) changes with time

$$\frac{\partial n(t)}{\partial t} = \frac{(\rho - \beta)}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i \mathbb{C}_i(t)$$

$$\frac{\partial}{\partial t}\mathbb{C}_i(t) = -\lambda_i \mathbb{C}_i(t) + \frac{\beta_i}{\Lambda} n(t), \;\; i = 1 \ldots 6$$

β: delayed fraction
ρ: reactivity (1-1/k)
λ :decay constant
Λ: neutron generation time

  - Reactors only work because of delayed neutrons!

Numerical Methods

- Direct solution of the transport equation;
  - Through a variety of techniques.
  - (WIMS, NEWT, DRAGON)
  - Very time consuming, small geometries only (lattice cell)
  - Accurate
- Diffusion calculation;
  - (NESTLE, PARCS, DONJON)
  - Quick, but not always accurate
- Monte Carlo techniques;
  - (MCNP, KENO, SERPENT, OPENMC, SUPERMC)
  - Very accurate, but slow

- Common to all methods: need for **nuclear data libraries**

Monte Carlo

- Follow neutrons (protons, electrons, gammas) through the geometry (core)
- Submit them to physics:
  - Scattering (elastic, inelastic)
  - Absorption (n,gamma) → energy deposition
  - Fission: creation of new neutrons
- Account for material properties:
  - Density
  - Temperature (Doppler broadening of resonances)
  - Population control (combing)
- Accuracy determined by statistics

Monte Carlo Codes

- Examples:
  - Standard code is MCNP (developed originally for highly super-critical devices.)
  - KENO (part of the SCALE package)
  - SERPENT (European code)
- Features:
  - Need licence (half of your students can't use half of these codes)
  - Provided as executables only.
    Models are entered by input cards;

MCNP

- KCODE calculation:
  1. Start with neutron source distribution (*r*,*v*)
  2. If absorbed by fissile material, create ν new source neutrons as result of fission.
  3. Follow neutrons until all have absorbed
  4. Obtain k_{eff} by new/old number of neutrons.
  5. Renormalize source (combing)
  6. Goto 1.
- Variance reduction techniques (weighting)
- Generation-based calculation:
  no concept of time! (shakes)

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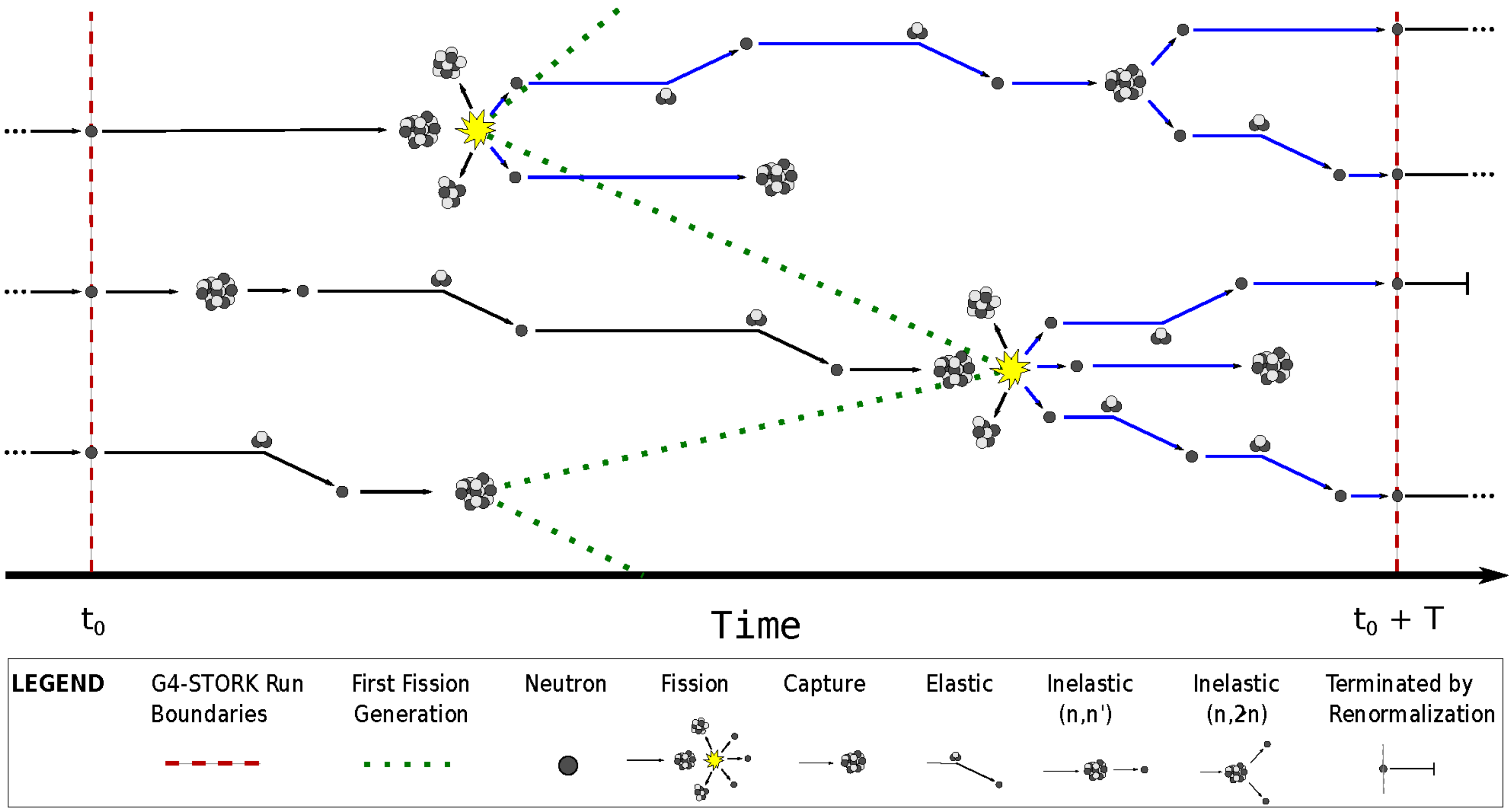
Geant4 (G4-STORK)

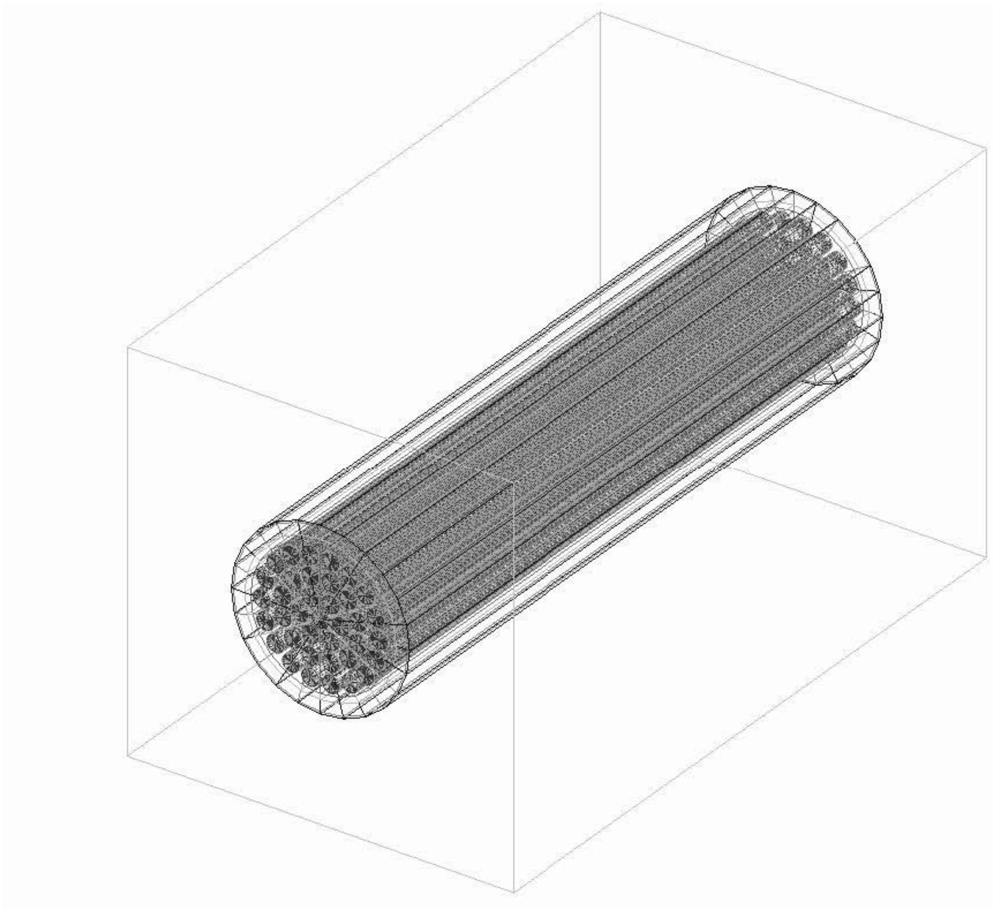
- No licence required
- Hard-code the model
  - Very detailed geometry
  - Allows to change the geometry “on the fly”
  - Allows for temperature change (feedback)
  - On-the-fly Doppler broadening
  - Many physics models
- Simulation accounts for time!
- Population control still needed
- Need to think about k_{eff}.

Show and Tell



Benchmarking with Transport Code

- Test of flux distribution
- Use CANDU reactor fuel bundle.
- Fresh fuel (only U in the libraries)



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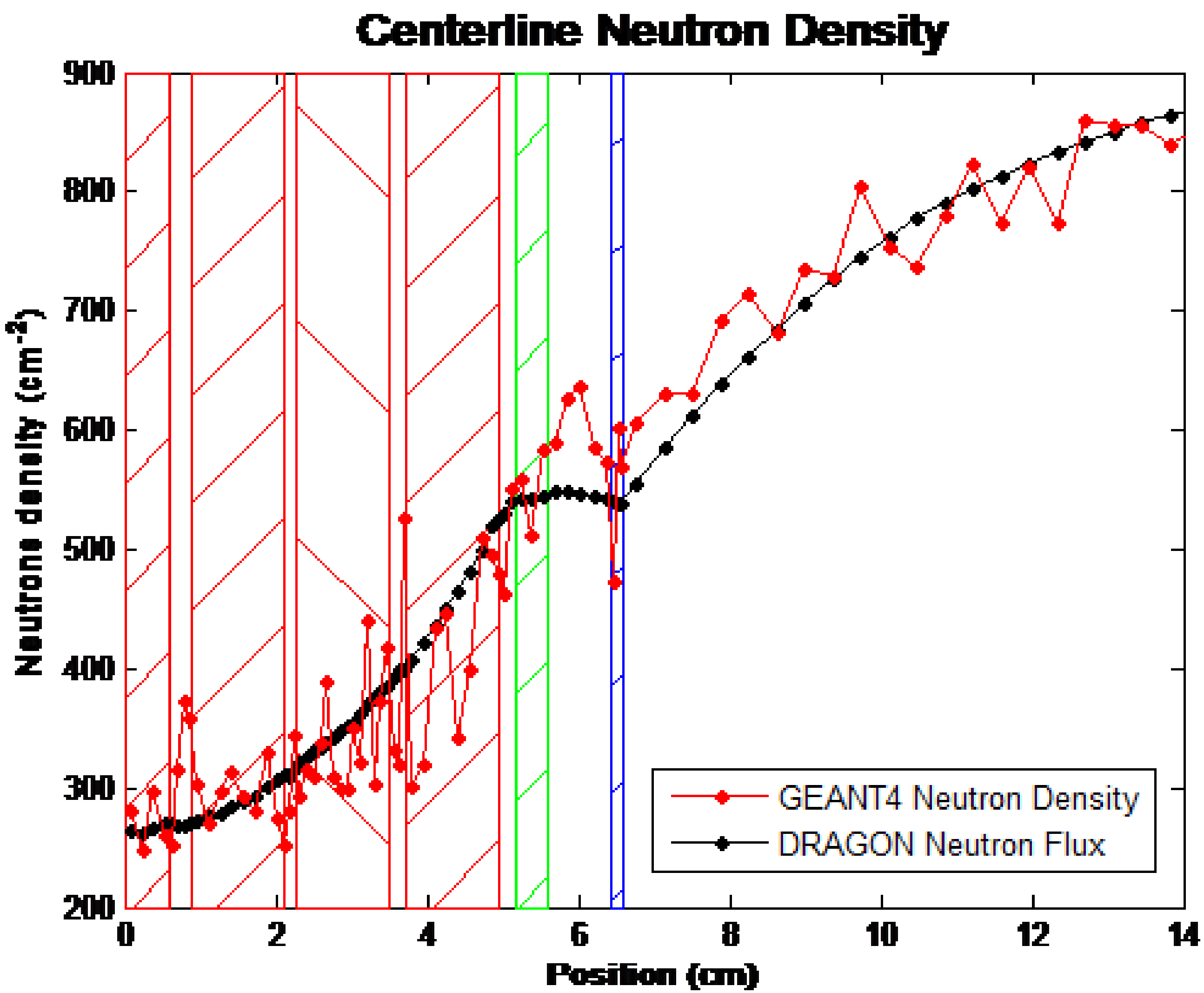
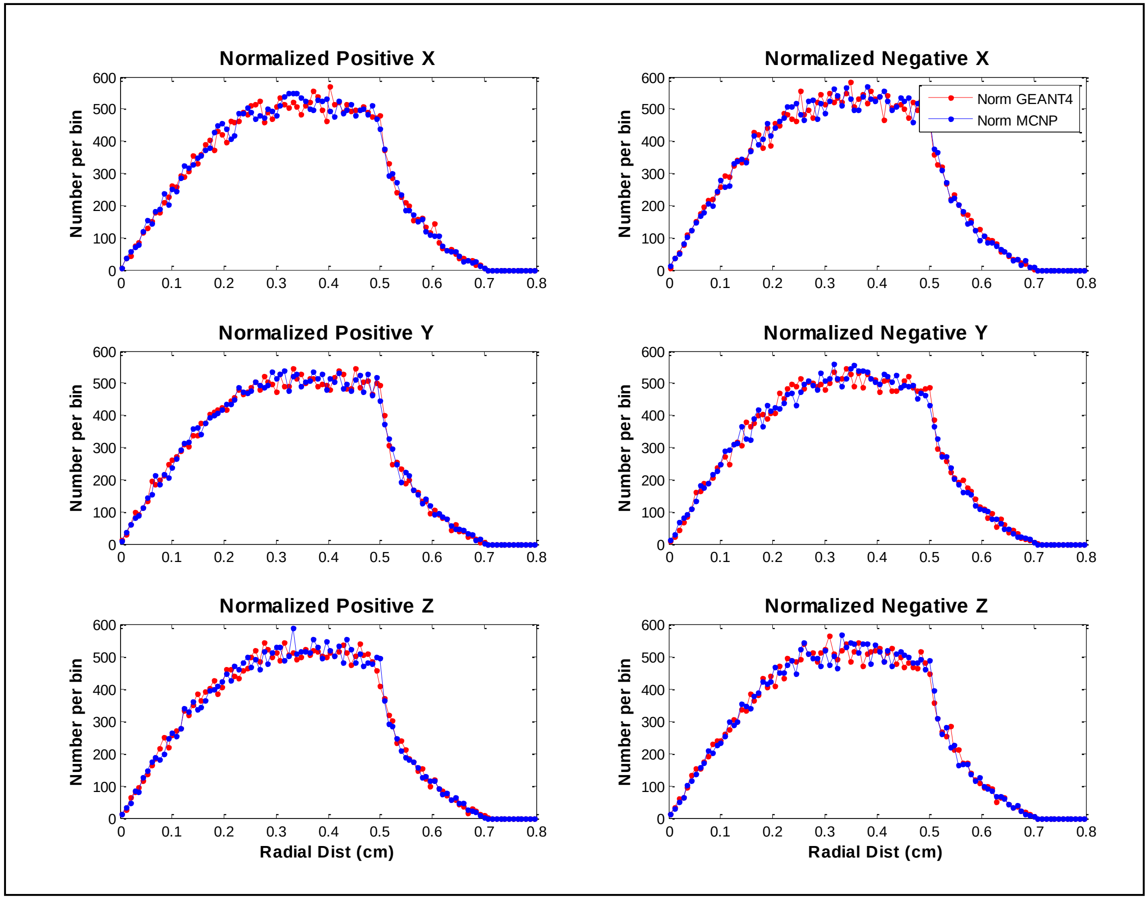
Compare to DRAGON



Simple Comparison to MCNP

- Mono-chromatic beam on a U-235 slab.
- Beam E = 0.0253 eV



k_{eff}

True multiplication constant

$$k_{\text{dyn}} = \frac{R_{\text{prod}}}{R_{\text{lost}}} = \frac{\Delta N_{\text{prod}}/\Delta T}{\Delta N_{\text{lost}}/\Delta T} = \frac{\bar{N}_{\text{prod}}}{\bar{N}_{\text{lost}}}$$

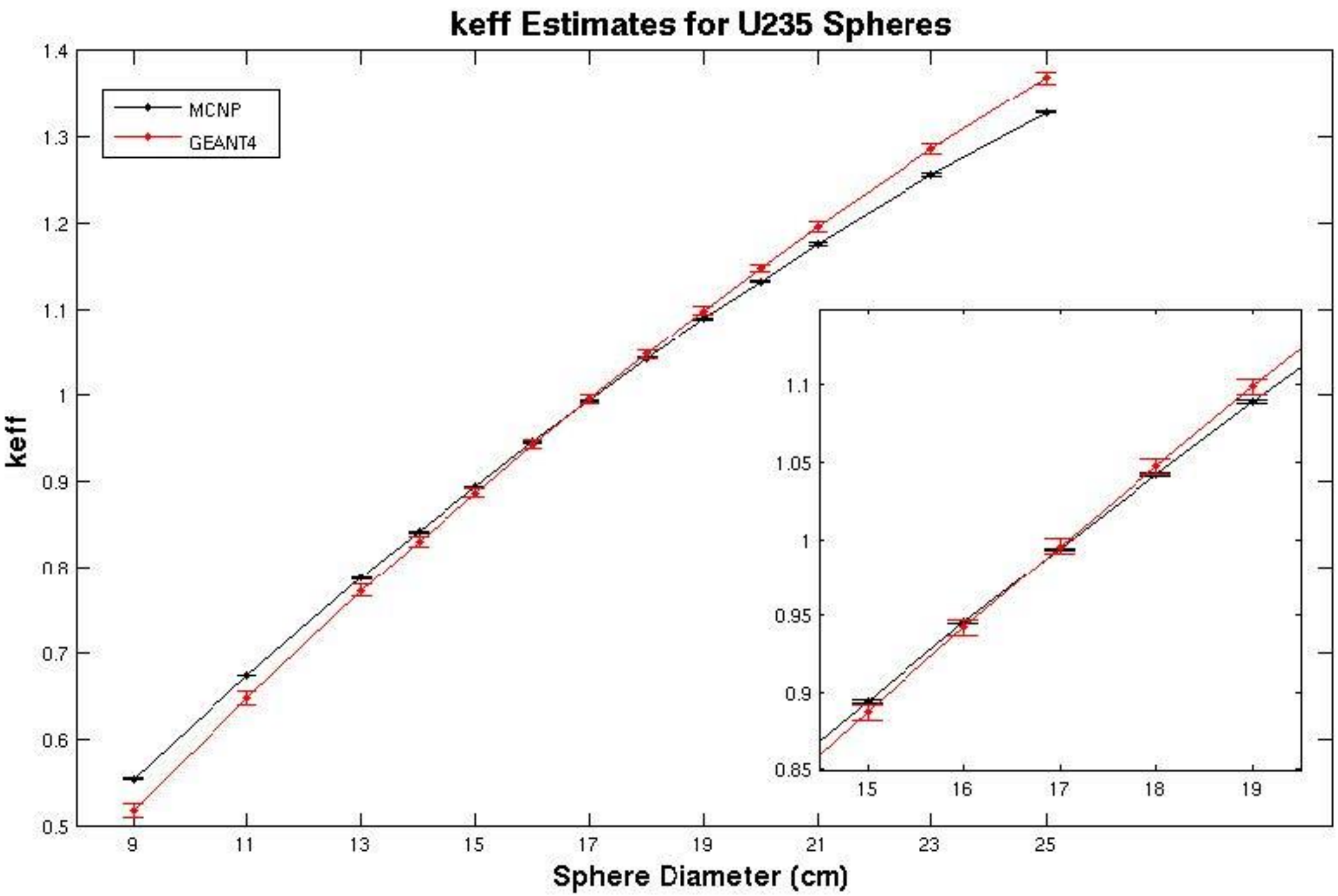
Whereas the generational k is given by

$$k_{\text{gen}} = \frac{N(\text{generation } i+1)}{N(\text{generation } i)}$$

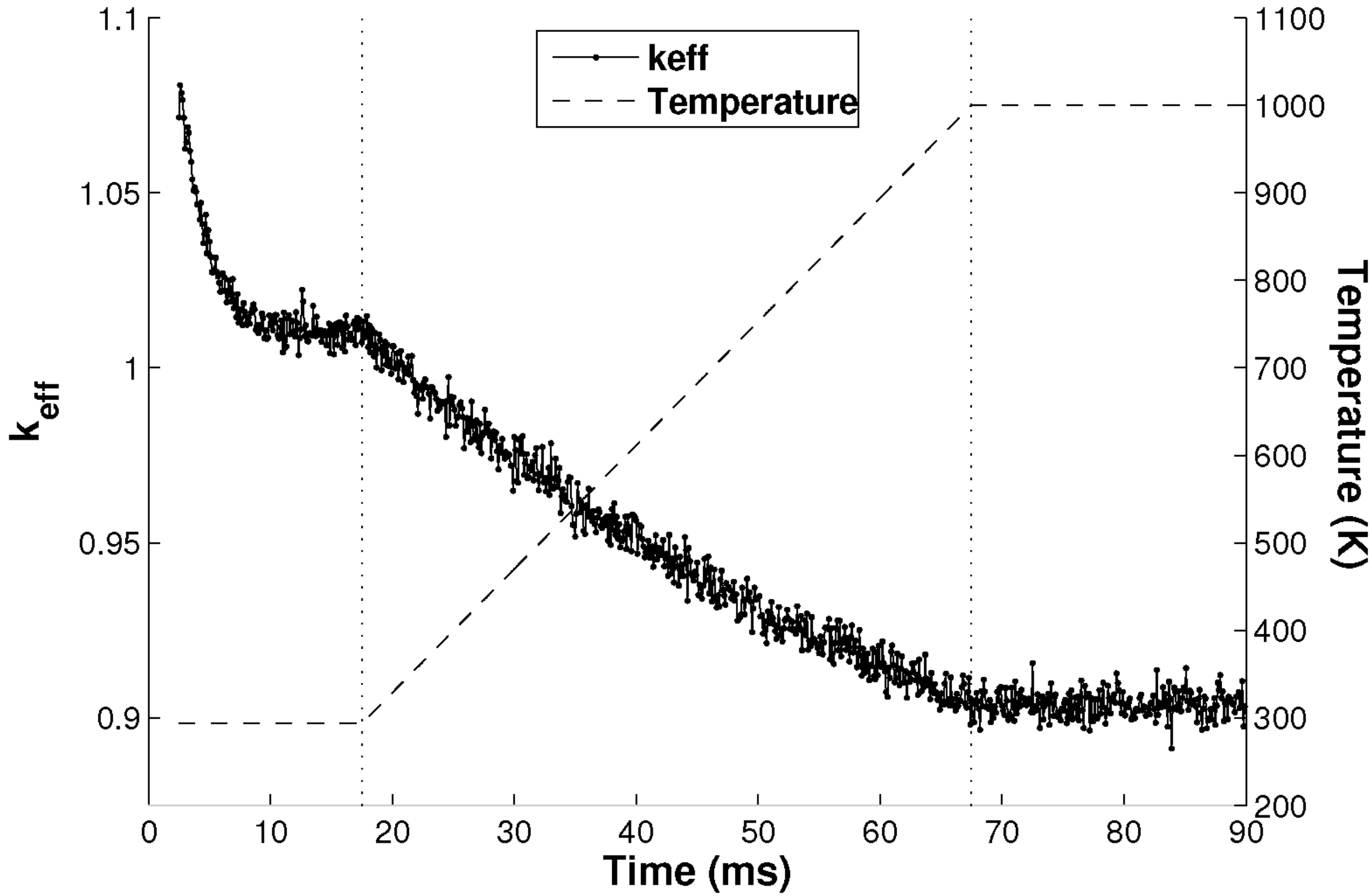
They are identical for $k = 1$.

k_{eff}

- Converged source (Shannon Entropy)



Time Evolution



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Validation with Reactor

- SLOWPOKE

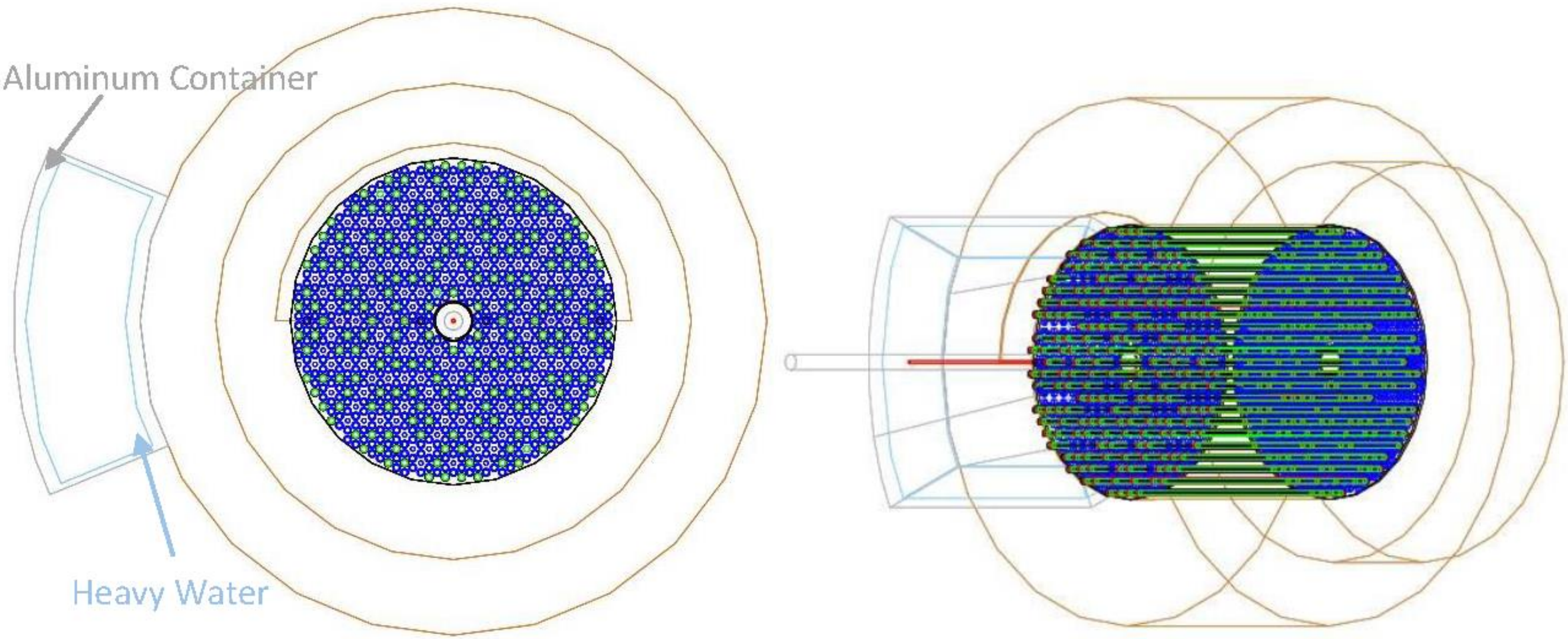
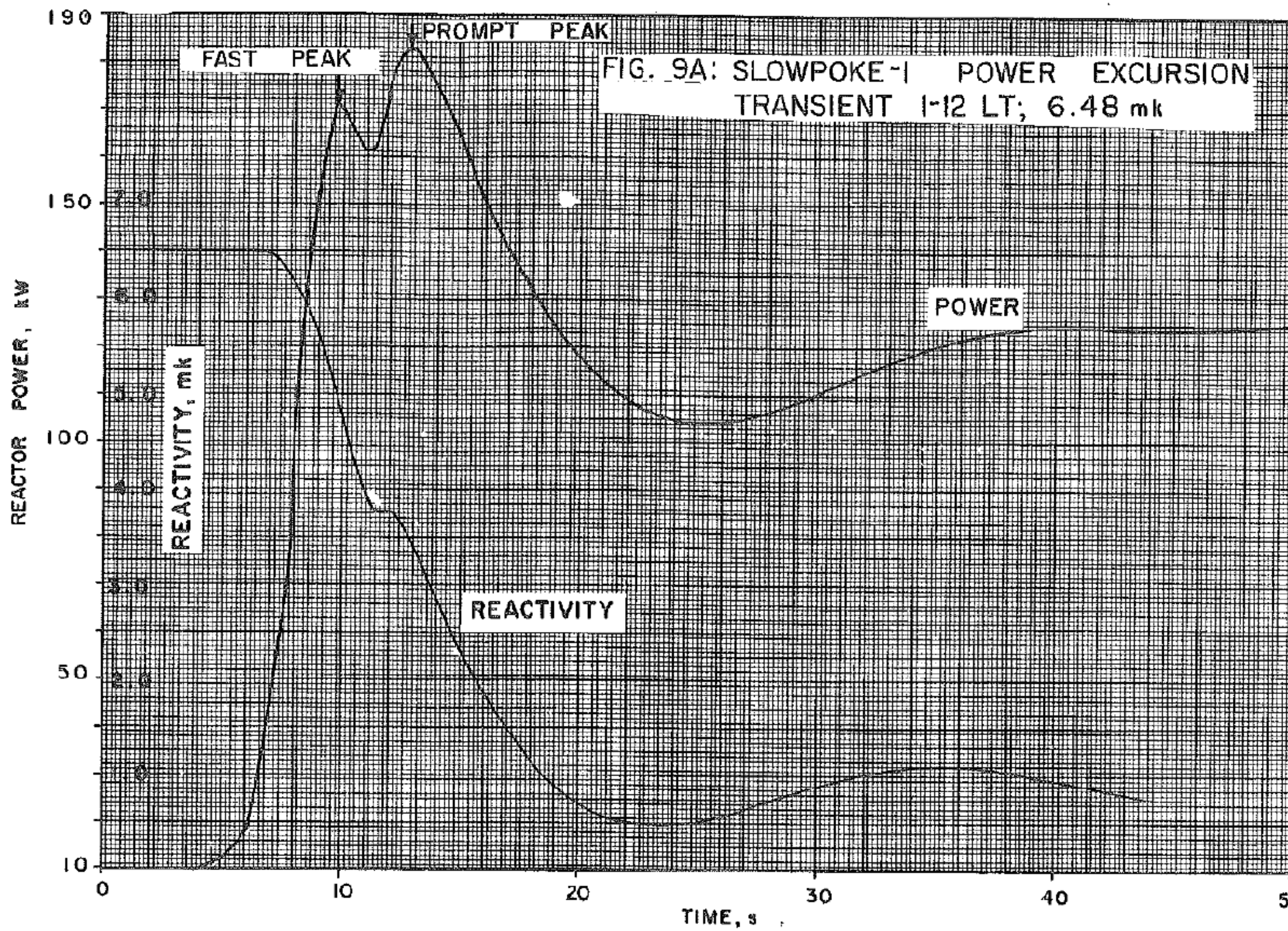


Figure 10 Reactor with added D_2O thermal column (On the left is a top view and on the right is a 45 degree view)

Transient


FAST PEAK
PROMPT PEAK
FIG. 9A: SLOWPOKE-I POWER EXCURSION
TRANSIENT I-12 LT; 6.48 mk
POWER
REACTIVITY
REACTOR POWER, kW
REACTIVITY, mk
TIME, s
190
150
100
50
10
0
10
20
30
40
50

Delayed Neutrons

- From delayed precursors (fission products)
- Do not identify precursors, rather combine them in groups
- Establish equilibrium concentration
- Determine decay time.
- Need to do population control as well

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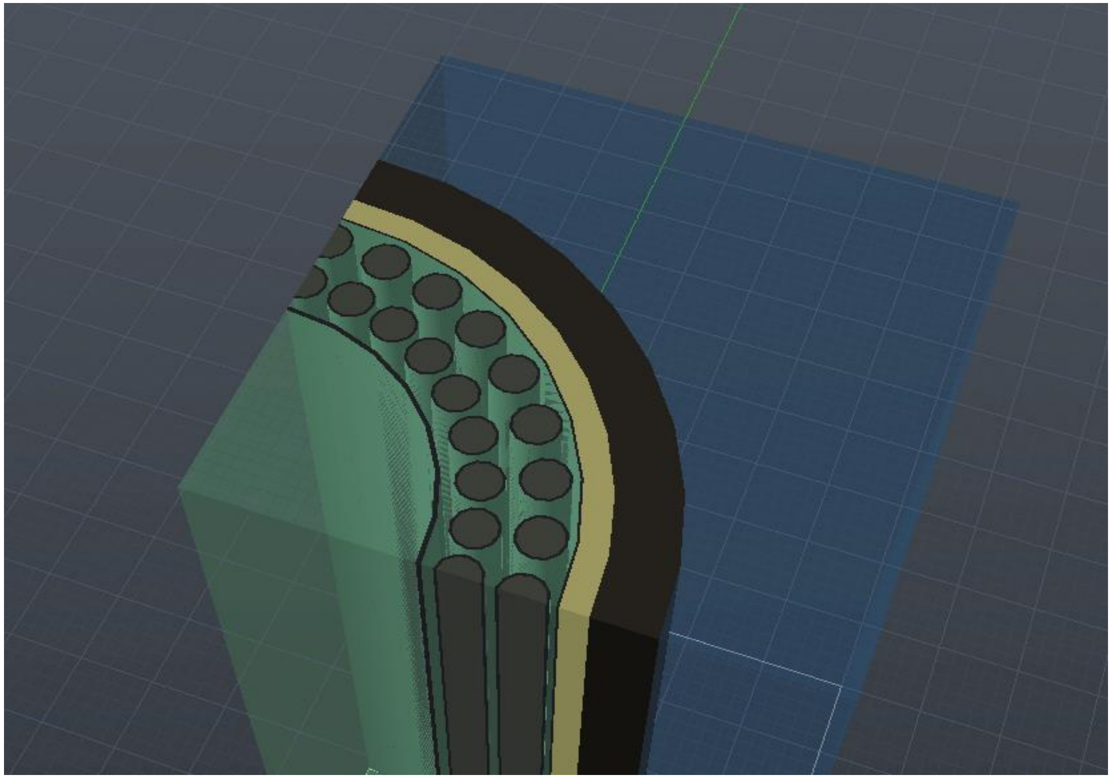
Detailed Benchmark with MCNP

- Case: Super-critical water reactor
- Crucial parameter: coolant void reactivity



G4-STORK-MCNP for SCWR

MCNP6.1 Settings:

- Same as G4-STORK
- Using thermal scattering
- Using implicit absorption
- Using unresolved resonance regime model

K_{inf} Cases	Fully Cooled	Void Inner Coolant	Void Outer Coolant	Void all Coolant	CVR (mk)
G4STORK	1.253 ± 0.003	1.206 ± 0.001	1.258 ±0.003	1.215 ± 0.002	-25.0±1.1
MCNP6.1	1.286 ± 0.0001	1.249 ± 0.0003	1.298 ± 0.0003	1.266 ± 0.0002	-12.09±0.07

Apples-to-Apples

K_{inf} Cases	Fully Cooled	Void inner Coolant	Void Outer Coolant	Void all Coolant	CVR (mk)
G4-STORK	1.2978±0.0007	1.2499±0.0007	1.3057±0.0008	1.2639±0.0006	-20.7±0.61
MCNP 6.1	1.2979±0.0002	1.2562±0.0003	1.3085±0.0002	1.2708±0.0002	-16.4±0.17

- The generational criticality method has been implemented in G4-STORK;
- in MCNP
  - the thermal scattering data,
  - unresolved resonance, and
  - implicit capture models

  were turned off.

Summary

- GEANT4 can be used to simulate "neutron-multiplying systems"
- Well-suited for transient calculations
- Very much limited by speed.
- Requests:
  - General speed-up of the code, but especially
  - Improve on-the-fly Doppler algorithm
  - Provide the tool to create G4NDL