G4-STORK: Stochastic Calculations of Reactor Kinetics
Geant4 neutron mini workshop

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- 1982-1986: Grad student PEP9/SLAC
- 1986-1994: Fellow/staff OPAL/CERN
- 2002-2008: Reactor Physics Atomic Energy of Canada Limited
- 2009- Now: Professor Engineering Physics McMaster University

At McMaster:
- Liam Russell: Original code developer (now with AMEC NSS)
- Salma Mahzooni: ZED-2 Subcritical experiment
- Andrew Tan: SLOWPOKE rod-extraction transient
- Wesley Ford: Super-Critical Water Reactor design

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Outline

- Background, why apply GEANT4 to nuclear reactors?
- Method, implemented in G4-STORK
  - Combing;
  - Criticality calculation;
  - Time evolution.
- Some examples, results
- Issues, future work
  - Nuclear data libraries;
  - (On the fly) Doppler broadening;
  - Delayed neutrons;
  - Feedback to geometry;
  - Adjoint flux.
Background

Nuclear reactors:

- Nuclear reactors are all about neutrons. And photons. And electrons. Not neutrinoes.
- In Canada, we have CANDU reactors.
- About as big as, say the OPAL experiment.
- Has many detectors, too: $> 100$.

Simulation of nuclear reactors:

- Traditionally, neutrons have been treated as a gas:
  - Neutrons move freely;
  - Don’t interact;
- Balance between absorption of neutrons and creation of new neutrons in fission reactions: critical reactor

\[ k_{\text{eff}} = 1 \quad \text{or} \quad \rho = 1 - \frac{1}{k_{\text{eff}}} = 0. \quad (1) \]

- Use diffusion equations to calculate neutron populations;
CANDU 6 Reactor Assembly

1 CALANDRIA
2 CALANDRIA END SHIELD
3 SHUT-OFF AND CONTROL RODS
4 POISON INJECTION
5 FUEL CHANNEL ASSEMBLIES
6 FEEDER PIPES
7 VAULT
CANDU 6 Fuel Channel

1. channel closure
2. closure seal insert
3. feeder coupling
4. liner tube
5. end fitting body
6. outboard bearings
7. annulus spacer
8. fuel bundle
9. pressure tube
10. calandria tube
11. calandria tubesheet
12. inboard bearings
13. shield plug
14. endshield shielding balls
15. endshield lattice tube
16. fuelling tubesheet
17. channel annulus bellows
18. positioning assembly
Obviously, Monte Carlo is the most precise method to simulate a reactor.

Obviously, computing power is limiting the usefulness of Monte Carlo.

Has been used for small assemblies, of the exploding kind.

For example, MCNP. Also used for dose calculations in LHC.

Recently, also used for static full-core calculations.
Monte Carlo Procedure for Static Calculations

- Define geometry
- Generate, say, 1,000,000 neutrons;
- Follow them until they die.
- Say 41% of them cause a fission reaction in, say, U-235.
- Then the $k_{\text{eff}} = 0.996$ for this cycle; it is subcritical.\(^1\)
- The distribution of fission sites is now the source of neutrons for the next cycle.
- In the next cycle, 40% cause a fission reaction, $k_{\text{eff}} = 0.972$, and so on.
- You need many cycles, to achieve convergence on:
  - Source distribution: where is the power in the reactor produced?
  - $k_{\text{eff}}$: is the reactor critical?

\(^1\)each fission produces 2.43 new neutrons...
Combing

If multiplication constant not unity ($k_{\text{eff}} \neq 1$), then

- If $k_{\text{eff}} > 1$: exponential growth from cycle to cycle; run out of computer memory soon;
- If $k_{\text{eff}} < 1$: exponential decline from cycle to cycle; run out of statistics;

Remedy by combing:

- If $k_{\text{eff}} > 1$: randomly remove fission sites;
- If $k_{\text{eff}} < 1$: randomly add fission sites;

In both cases, preserve the fission source distribution.

Can be tricky, needs to be done efficiently.

Sidenote: when parallellizing, neutrons are independent, but each cycle constitutes a barrier.
Fule Bundle Model in Geant-4
Results for CANDU Fuel Bundle

Centerline Neutron Density

Neutrons density (cm⁻²)

Position (cm)

GEANT4 Neutron Density
DRAGON Neutron Flux
Why GEANT-4?

Why GEANT-4? Because:

- It’s there.
- Traditional MC’s work with cycles and generations. The concept of time is lost because some neutrons live longer than others;
- Geant-4 tracks particles in ”real” time.
Time Evolution of Neutron Population

![Diagram of neutron population evolution over time.](image)

### Table 2: Summary of Criticality Results

<table>
<thead>
<tr>
<th>Material</th>
<th>keff_1000us</th>
<th>keff_5us</th>
</tr>
</thead>
<tbody>
<tr>
<td>U235 (0.077%)</td>
<td>0.9</td>
<td>276.01</td>
</tr>
<tr>
<td>O (89.270%)</td>
<td>1.1</td>
<td>200.92</td>
</tr>
<tr>
<td>Ba (8.760%)</td>
<td>1.0</td>
<td>200.92</td>
</tr>
</tbody>
</table>

**Error T−G4**

<table>
<thead>
<tr>
<th>Interval (us)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.012</td>
</tr>
<tr>
<td>25</td>
<td>0.005</td>
</tr>
<tr>
<td>50</td>
<td>0.002</td>
</tr>
<tr>
<td>125</td>
<td>0.001</td>
</tr>
<tr>
<td>250</td>
<td>0.000</td>
</tr>
<tr>
<td>1000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**End users of G4-STORK can create any simulation geometry that can be defined in Geant4.**
Neutrons are now followed in "runs" rather than "cycles";
One run is typically a few ms.
For parallelisation, fixed point in time is now the barrier.
Since neutrons are now followed in time, the geometrical properties may be changed in time as well: feedback between number of fissions (power), causing fuel to heat up, causing absorption to increase, causing the number of fissions to decrease, etc. (self-terminating power excursion).
Essential ingredient: On the fly Doppler broadening.
Figure 5.22: Transient for a 87.5 cm UHW sphere where the temperature rises from 293.6 to 1000 K (delayed neutrons not simulated).
Application: SLOWPOKE Rod Extraction

The resulting volume looks as follows:

Figure 10 Reactor with added D$_2$O thermal column (On the left is a top view and on the right is a 45 degree view)
Design Philosophy

- Inherently safe
  - Maximum excess reactivity less than prompt critical
  - Core lattice undermoderated
  - Negative temperature and void coefficients
  - Self-limiting power excursion
- No electromechanical safety devices
Purpose of the Application

- Validation of fuel temperature coefficient (Doppler broadening); important for reactor licencing.
- Crucial ingredient: delayed neutrons. Fission products emit additional neutrons after a certain time. These neutrons affect the reactivity of the core as a function of time.
- Delayed neutrons must be combed, too.
Sub/super-Critical Systems

- MCNP inherently unsuited for calculation of deep sub-critical and super-critical systems.
- Comparison of MCNP and G4-STORK for U-235 sphere of different sizes:
Other Applications: ZED-2 Subcritical Experiment

ZED-2 (Zero Energy Deuterium) Reactor in Chalk River, Canada:
ZED-2 Subcritical Experiment

Moderator drain experiment. Measurement of sub criticality.

Reactivity Measurements

K-effective vs. Moderator Height (cm)

- Voided Outer Ring
- Flooded Outer Ring
Summary and Conclusions

- We have produced a user code for GEANT4 (G4-STORK), which:
  - Follows neutron population in fissioning materials;
  - Maintains population size through a combing algorithm;
  - Includes delayed neutrons;
  - Calculates converged fission source distribution and $k_{\text{eff}}$;
  - Allows for feedback between neutronics and material properties;

- Issues and challenges:
  - Nuclear data format. Reverse engineered the format to be able to generate files from MCNP data;
  - On-the-fly Doppler broadening. Essential part of the code, but rather slow up to now.
  - Proper treatment of delayed neutrons;
  - Increase time span of the calculation;
  - Adjoint flux calculation.