Recent Developments in the TRIPOLI-4® Monte-Carlo Code for Shielding and Radiation Protection Applications

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I - General presentation of TRIPOLI-4®

II - New features of TRIPOLI-4® version 10

III – Main ongoing developments in TRIPOLI-4® for shielding and radiation protection applications

TRIPOLI-4® is a registered trademark of CEA, we gratefully acknowledge EDF long time support of TRIPOLI-4®
I - GENERAL PRESENTATION OF THE TRIPOLI-4® CODE
TRIPOLI-4 is a general purpose radiation transport code. It uses the continuous-energy Monte Carlo method to simulate neutron, photon, electron and positron transport in 3D geometry.

TRIPOLI-4 application fields include radiation shielding, criticality safety, fission reactor physics, fusion reactor design, and nuclear instrumentation.

Basic features of TRIPOLI-4 and main ongoing developments for radiation shielding and radiation protection applications will be presented in this talk.
TRIPOLI-4 MONTE CARLO CODE & NUCLEAR ENGINEERING CALCULATIONS

- GALILEE
  JEFF, ENDF/B, ENDL

- APOLLO
  DETERMINISTIC
  CELL / CORE CODES

- MENDEL
  BATEMAN
  EQUATIONS SOLVER

- NARMER
  POINT KERNEL CODE
Based on previous versions TRIPOLI-2 (1980) & TRIPOLI-3 (1990)
- Developed from the mid of 1990s
- ~500 000 code lines of C++
- Geometry, Data Library, Perturbation, Parallel mode, T4G, Burnup,
- Variance Reduction – INIPOND, AUTO, DATA, AMS …

Tracked particles
- Neutrons from 20 MeV down to 10^{-5} eV
- Photons from 50 MeV down to 1 keV
- Electrons and positrons from 100 MeV down to 1 keV

Three simulation modes
- “Criticality” mode: Kinf, Keff, power map, rod worth …
- “Shielding” mode: fixed-source simulation
- “Fixed-sources sub-criticality” mode: factor M

Tallies
- volume, surface, point fluxes, mesh tallies, current
- reaction rates, dose equivalent rate, KERMA, deposited energy
- dpa & gas production, gamma spectrometry
Geometry module – (NAIADE light water shielding experiment)

Surface-based geometry

Combinatorial geometry

2.5 m x 3 m x 3 m
Standard techniques: implicit capture, particle splitting and Russian roulette

INIPOND module (Exponential Transform Method):
- with an automatic pre-calculation of the importance map
- with possible adjustment of the input parameters of INIPOND in order to adjust the global strength of the biasing)

**Iso-importance curves** of the importance map produced by TRIPOLI-4
The fission source is on the left side and the detector on the right side
Standard techniques: implicit capture, particle splitting and Russian roulette

INIPOND module (Exponential Transform Method):
- with an automatic pre-calculation of the importance map
- with possible adjustment of the input parameters of INIPOND in order to adjust the global strength of the biasing)

Neutron collisions sites produced by TRIPOLI-4
Analog run on the left side  INIPOND run on the right side

More than 1,000 benchmark cases from OECD/NEA are available in the TRIPOLI-4 validation database.
- SINBAD database for fission & fusion shielding
- ICSBEP handbook for criticality safety & shielding
- IRPhE database for reactor physics applications.

TRIPOLI-4 – V&V other benchmarks

C/T, C/E, C/C, Vn/Vn+1 => PENEOLOPE, MCNP ..
Component & Integral results
Code (options) => Neutron, Photon & Electron
Data lib. (element, interaction)
Modeling
User
II – NEW FEATURES OF TRIPOLI-4®
VERSION 10
Evolution of the keff during irradiation.
Time is expressed in effective full-power days (EFPD). Controls rods insertion is adjusted during irradiation.

Radial thermal flux distribution of the ORPHEE reactor calculated by TRIPOLI-4® (3D core-depletion analysis)

Asymptotic Reactor period calculation

- Inverse of the dominant eigenvalue (i.e. the fundamental $\alpha$ eigenvalue of the Boltzmann operator)
- Algorithm based on a modified $\alpha$-k power iteration scheme


Kinetics parameters computing

- Iterated Fission Probability method (IFP)
- Adjoint-weighted kinetics parameters: $\beta_{\text{eff}}$, $\Lambda_{\text{eff}}$, $\alpha_{\text{Rossi}}$


Deposited charge

- Calculation of the spectrum of the charge deposited in a given volume by charged particles (electrons and positrons)
- useful for nuclear instrumentation in the interpretation of signal of sensors irradiated in nuclear reactors
Thick-Target Bremsstrahlung for electromagnetic shower simulation

- Secondary $e^-$ and $e^+$ produced by photon collisions are not transported, but a part of their energy is converted into new bremsstrahlung photons.
- Simplified simulation mode for the electromagnetic shower:
  - TTB vs full calculation: a maximum difference of 30%
- Speed up coupled photon-electron-positron calculations:
  - TTB vs full: acceleration up 10 times

Riz et al. PHYSOR-2000 proceedings

Courtesy of D. Mancusi
CEA, Saclay, SERMA
Analog simulation with analog fission sampling

- Fully analog simulation for neutron and photon transport:
  - concerning both collisions and transport between collisions
- Analog fission simulation by sampling a full fission neutron multiplicity distribution
- Coupling between TRIPOLI-4® and an external fission model providing fission sampling data:
  - FREYA (Fission Reaction Event Yield Algorithm, LLNL):
  - Example of application: NMC (Neutron Multiplicity Counting) properly simulated by reconstructing the mass and multiplication of two objects by analyzing the measured signal from $^3$He tubes in a well counter.

“Replicate” option upgrading for two-step calculation

- Technique of variance reduction for two-step calculation
- Global geometry used first to store the properties of particles crossing a given surface
  - Energy, position, direction, weight
- Stored particles used as surface sources for new simulation on a local geometry
- REPLICATE option activates the particle splitting at the second-step simulation

Example of a two-step calculation: Global geometry + Local geometry

III - MAIN ONGOING DEVELOPMENTS IN TRIPOLI-4® FOR SHIELDING AND RADIATION PROTECTION APPLICATIONS
User friendly variance reduction using the method of Adaptive Multilevel Splitting (AMS)

- **Iterative** algorithm to help simulate rare events
  - **Classify** simulated particle tracks and define a splitting level
  - **Remove** the particles that have not reached the threshold
  - **Re-sample** removed particles by splitting remaining ones

Deep penetration problem (in water)

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Rigorous two-step scheme for shutdown dose rate calculation

- Development of an activation calculation scheme based on the two codes developed by CEA (Saclay, SERMA):
  - the transport code TRIPOLI-4®
  - and the depletion code MENDEL

F. Malouch et al., "Recent development in the TRIPOLI-4® Monte-Carlo code for fusion applications", 29th SOFT, Prague, Czech, September 5-9, 2016
Rigorous two-step scheme for shutdown dose rate calculation

- Comparison with the different SDR calculation schemes (based on MCNP)
- Typical configuration of a port plug in ITER
- Focusing on a streaming path that contributes to activate a steel chamber

**TRIPOLI-4® Geometry Model for ITER SDR Benchmark**

ITER Equatorial Port Plug

Distribution of the total neutron flux calculated by TRIPOLI-4®

Shutdown dose rate at the rear face

Several recent Developments in the TRIPOLI-4® Monte-Carlo code for Shielding and Radiation Protection applications

TRIPOLI-4 v10:
- Thick-Target Bremsstrahlung for electromagnetic shower simulation
- Analog simulation with analog fission sampling (FREYA coupling)
- “Replicate” option upgrading for two-step transport calculations

Main ongoing developments
- Variance Reduction using the Adaptive Multilevel Splitting (AMS) method
- Analog simulation with analog fission sampling (FIFRELIN coupling)
- TRIPOLI-4® - Geant4 Coupling
- Rigorous two-step scheme for shutdown dose rate calculation
From the OECD/NEA Data Bank and RSICC

- License covering code evaluation, teaching and R&D (fusion activities included).
- TRIPOLI-4® versions 8 and 9 are currently available
- TRIPOLI-4® version 10 soon available

From CEA

- For countries outside the OECD/NEA Data Bank and RSICC
- For companies requesting a business license
- In both cases following an specific Licence agreement with CEA.

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Thank you for attention