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# TRIPOLI-4®, CEA, EDF and AREVA reference Monte Carlo code

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ABSTRACT

This paper presents an overview of TRIPOLI-4®, the fourth generation of the 3D continuous-energy Monte Carlo code developed by the Service d'Etudes des Réacteurs et de Mathématiques Appliquées (SERMA) at CEA Saclay. The paper surveys the generic features: programming language, parallel operation, tracked particles, nuclear data, geometry, simulation modes, standard variance reduction techniques, sources, tracking and collision algorithms, tallies, sensitivity studies. Moreover, specific and recent features are also detailed: Doppler broadening of the elastic scattering kernel, neutron and photon material irradiation, advanced variance reduction techniques, Green's functions, cycle correlation correction, nuclear data management and depletion capabilities. The production tools (T4G, SALOME TRIPOLI, T4RootTools), the verification and validation process and the distribution and licensing policy are finally presented.



## 1. Introduction

### 1.1. The TRIPOLI family

TRIPOLI® is the generic name of a Monte Carlo radiation transport codes family dedicated to shielding, reactor physics with depletion, criticality safety and nuclear instrumentation. Monte Carlo codes have been continuously developed at CEA since the mid-60s, at Fontenay-aux-Roses first, then at Saclay. The code TRIPOLI-4® (TRIPOLI-4 Project Team, 2012; Both et al., 1994; Diop et al., 2007), the fourth generation of the family, is the cornerstone of the CEA Radiation Transport Software Suite, which also includes APOLLO2 and APOLLO3® (Sanchez et al., 2010), a lattice and core family of deterministic codes dedicated to reactor physics analyses, MENDEL, a depletion code, NARMER, a photon point-kernel code with buildup factors, CONRAD (de Saint Jean et al., 2008; Archier et al., 2013) and GALILEE (Coste-Delclaux, 2008) for nuclear evaluation and data processing. TRIPOLI-4® is the reference industrial code for CEA (laboratories and reactors), EDF (operating 58 PWRs), and branches of AREVA. It is also the reference code of the CRISTAL (Gomit et al., 2011) Criticality Safety package developed with IRSN and AREVA.

### 1.2. The developers team at CEA

TRIPOLI-4®, APOLLO3®, MENDEL, NARMER and GALILEE are developed by SERMA (Service d'Etudes des Réacteurs et de Mathématiques Appliquées), a 75 permanent staff R&D Unit of the Nuclear Energy Division (DEN) of CEA, whose focus is nuclear energy from fission. More than 10 people contribute to TRIPOLI-4®, their activities covering development, V&V, documentation, user support, distribution and licensing. For historical reasons, the main focus of TRIPOLI-4® and CEA DEN is on fission energy. Fusion has also been covered, mainly in the context of radiation shielding, with application to TORE SUPRA and INTOR in the Eighties and now to ITER magnetic fusion program at the Fundamental Physics Division (DSM) of CEA, and to LMJ inertial fusion program at the Defense Division (DAM) of CEA.

## 2. Generic features

### 2.1. Programming language, computer platforms

TRIPOLI-4® has been developed starting from the mid 90s in C++, with a few parts in C and Fortran. It is available on 32 and 64 bits Linux, as well as on some proprietary UNIX (IBM, HP), and on massively parallel machines (CEA Center for Research and Computing Technology).

### 2.2. Parallel operation

The standard mode of TRIPOLI-4® is scalar (or mono-processor). Moreover, TRIPOLI-4® has its own implementation of parallel operations (Both et al., 1990). This mode does not rely on a dedicated third-party library. It is based on a proprietary, built-in, communication library. It uses BSD sockets under the GNU C library Lesser

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General Public License, and can access any CPU on the network without the need of MPI or Open MP. It may run on single multi-core machines as well as on heterogeneous networks of stations or massively parallel machines Both and Pénéliau (1999).

### 2.3. Tracked particles

TRIPOLI-4® can simulate neutral particles: neutrons in the energy range from 20 MeV to $10^{-5}$ eV, and photons in the energy range from 20 MeV to 1 keV. Moreover, electrons and positrons can also be simulated down to 1 keV (Pénéliau, 2000), mainly in the context of radiation detection problems and nuclear instrumentation. Neutron-photon coupling is handled by default. Photo-nuclear reactions may be simulated as well, if requested. The coupling between photons, electrons and positrons is taken into account by tracking the entire electro-magnetic shower.

### 2.4. Nuclear data

The particle transport in TRIPOLI-4® is performed in continuous-energy, and the necessary nuclear data (i.e., point-wise cross-sections, scattering kernels, secondary energy-angle distributions, secondary particle yields, fission spectra, and so on) are readby TRIPOLI-4® from any evaluation written in ENDF-6 (McLane, 2004) format, including (but not limited to) JEFF-3.1.1, ENDF/B-VII.1, JENDL-4.0 and FENDL-2.1 libraries. TRIPOLI-4® can directly access files in ENDF and PENDF format. For additional information, see Subsection 3.6.

### 2.5. Geometry package

TRIPOLI-4® has its own native geometry package, allowing for both a pure surface-based representation, and a combinatorial representation with predefined shapes and Boolean operators (any combination of these two kinds of representations can be adopted). TRIPOLI-4® hasbeen also made compatible with any geometry developed in the format of the ROOT software (Brun and Rademakers, 1997): this allows the user to directly use (without recompiling) an already built ROOT geometry (see Fig. 1).

More generally, TRIPOLI-4® may be linked to any third-party geometry module providing an Application Programming Interface for the current particle position and the next intersection in the direction of flight. Successful tests have been for instance performed by coupling TRIPOLI-4® with the geometry of GEANT4 (Allison et al., 2006).

Details concerning visualization tools for building and checking the geometry will be provided in Section 5.

### 2.6. Simulation modes

For convenience, particles are organized in batches, which are consecutively simulated according to the simulation mode. The code offers both fixed-source and criticality simulation modes.

In the former, the Monte Carlo code is used to solve the stationary Boltzmann equation with a given source. The necessary source is imposed by the user (manually, or by importing the initial particle distribution generated by an external code), and particles are then tracked from the source until disappearance (see Subsection 2.9). Each batch begins with the same imposed source, hence the name of the simulation mode. Fixed-source mode is typically used for radiation protection and shielding analysis. Fission events can be either treated as sterile captures (in which case fission neutrons are discarded), or explicitly simulated (in which case the secondary fission neutrons are also tracked within the same batch together with the parent particle, and the neutron multiplication factor may be calculated).

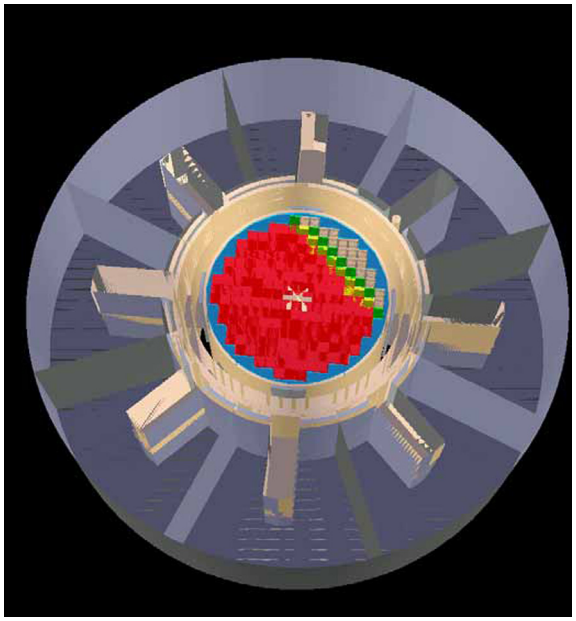

**Fig. 1.** 3D PWR model in ROOT geometry for direct use in TRIPOLI-4®.

In the criticality mode, the Monte Carlo code is used to solve the $k_{\text{eff}}$ eigenvalue equation, i.e., to find the fundamental mode and the associated fundamental $k_{\text{eff}}$ eigenvalue. An initial (guess) neutron source is initially set for the first batch, and the equilibrium neutron distribution corresponding to the $k_{\text{eff}}$ eigenvalue equation is then sought. To this aim, the power iteration scheme is adopted, which means that at the end of each batch the secondary neutrons generated from fissions are used as a source for the next batch (in between batches, a normalization procedure is applied, as customary). After several such steps, when the distribution of fissions has attained convergence, the neutron distribution obeys the fundamental mode of the $k_{\text{eff}}$ eigenvalue equation. Then, the physical quantities of interest can be scored. The convergence criterion can be either established by the user, or automatically set by the code by resorting to statistical tests so as to assess whether equilibrium has been attained.

### 2.7. Variance reduction techniques

By default, TRIPOLI-4® uses common variance reduction techniques such as implicit capture, particle splitting and Russian roulette, so that particle transport is non-analog. Moreover, TRIPOLI-4® has a special built-in variance reduction module called INIPOND. The key algorithm of INIPOND is based on the Exponential Transform method (Clark, 1966), with an automatic pre-calculation of the importance map. The INIPOND module is detailed in Subsection 3.3.

### 2.8. Sources description

The particle sources are defined by a set of spatial, angular, energy and time distributions. By combining these distributions, the user can model virtually any kind of source according to the problem at hand. Additionally, it is also possible to call from TRIPOLI-4® an external FORTRAN module previously defined for use with the MCNP (Brown et al., 2011) code. This may be done without recompiling TRIPOLI-4® by means of a dynamic library. In the case of a biased simulation using an importance map pre-calculated by TRIPOLI-4® (see Subsection 3.3), source particles are sampled according to a biased distribution obtained by

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