

Recent developments in the TRIPOLI-4[®] Monte-Carlo code for shielding and radiation protection applications

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Abstract. TRIPOLI-4[®] is a 3D continuous-energy Monte-Carlo particle transport code developed by CEA (SERMA) and devoted to shielding, reactor physics, criticality-safety and nuclear instrumentation. In this paper, we present the recent developments in the TRIPOLI-4[®] for shielding and radiation protection applications. Some of these additional features are already available in the TRIPOLI-4[®] version 10 released in December 2015. Other features are in development.

1 Introduction

TRIPOLI-4[®] is a three-dimensional and continuous-energy Monte-Carlo particle transport code developed by the “Service d’Etudes des Réacteurs et de Mathématiques Appliquées” (SERMA), at the CEA Paris-Saclay center. It is devoted to shielding, reactor physics, criticality safety and nuclear instrumentation [1].

TRIPOLI-4[®] has been developed starting from the mid of 1990s in C++. A new version of the code is typically released every two years. The TRIPOLI-4[®] version 10 has been released in December 2015 with in particular a Monte-Carlo depletion feature.

In this paper, we present the recent developments in the TRIPOLI-4[®] for shielding and radiation protection applications. Some of these additional features are already available in the TRIPOLI-4[®] version 10 released in December 2015. Other features are in development.

2 TRIPOLI-4[®] key features [1]

2.1 Tracked particles

TRIPOLI-4[®] is currently able to simulate four kinds of particles (with coupling):

- 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.

2.2 Nuclear Data

TRIPOLI-4[®] uses continuous energy cross sections processed with NJOY from any ENDF-6 format

evaluation including JEFF-3, ENDF/B-VII, FENDL-2, JENDL-4. TRIPOLI-4[®] uses also probability tables from CALENDF in the unresolved resonance range.

2.3 Geometry

TRIPOLI-4[®] has its own geometry module allowing both surface-based and combinatorial representations. TRIPOLI-4[®] is also directly compatible with a geometry developed in the format of the ROOT software [2]. Thanks to its modularity, the code may be linked with any third party geometry with limited development effort.

2.4 Simulation modes

Three simulation modes are available in the TRIPOLI-4[®] code:

- “**Shielding**” mode, fixed-source simulation typically used for radiation protection and shielding analysis.
- “**Fixed_Sources_Criticality**” mode, fixed source simulation with treatment of fission events, typically used for subcritical fissile instrumentation problems.
- “**Criticality**” mode, used to find the fundamental mode and the associated fundamental eigenvalue of the critical Boltzmann equation.

2.5 Tallies

A non-exhaustive list of the tallies available in the TRIPOLI-4[®] code includes: volume, surface and point fluxes, surface currents, mesh tallies, reaction rates, deposited energy, built-in KERMA response functions, dose equivalent rate, dpa, gamma spectroscopy and effective multiplication factor k_{eff} .

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2.6 Variance reduction techniques

Standard variance reduction techniques are available in TRIPOLI-4[®], such as implicit capture, particle splitting and Russian roulette. Moreover, TRIPOLI-4[®] has a special built-in variance reduction module, called INIPOND, based on the Exponential Transform Method, with an automatic pre-calculation of the importance map.

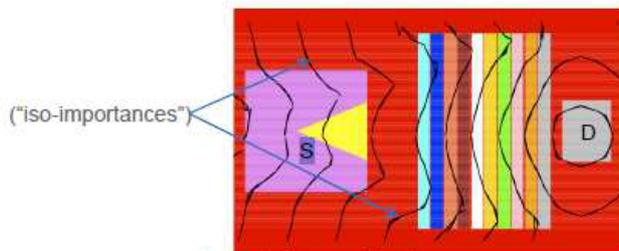


Fig. 1 Two-dimensional view with iso-importance lines of the photon importance map produced by TRIPOLI-4[®]. The source is on the left side and the detector on the right side [2].

2.7 Doppler broadening of the elastic scattering kernel

For the Doppler broadening of the elastic scattering kernel, the algorithm “Sampling of the Velocity of the Target nucleus” (SVT) is by default used in the TRIPOLI-4[®] code. The “Doppler Broadening Rejection Correction” (DBRC) and the “Weight Correction Method” (WCM) have been implemented in TRIPOLI-4[®] (version 9) to overcome the SVT limitations that affect resonant nuclei (such as ²³⁸U) typically in the epithermal region.

2.8 Reactor period calculation

The asymptotic time behavior of neutron transport can be used in reactor start-up analysis or kinetics studies of nuclear systems. In TRIPOLI-4[®] version 10, the asymptotic reactor period is calculated as the inverse of the dominant eigenvalue. The algorithm is based on a modified alpha-k power iteration scheme [3].

2.9 Kinetics parameters computing

Kinetics parameters are key to the study of nuclear reactor dynamics and to safety issues in the context of transient or accidental reactor behavior. The Iterated Fission Probability (IFP) method implemented in TRIPOLI-4[®] version 10 allows computing the adjoint-weighted kinetics parameters: the delayed neutron fraction, the mean generation time and the Rossi Alpha [4].

2.10 Deposited charge

It is possible to calculate the spectrum of the charge deposited in a given volume by charged particles (electrons and positrons) using the DEPOSITED_CHARGE response recently implemented in TRIPOLI-4[®] version 10. The charge deposition can be used for nuclear instrumentation in the interpretation of signal of sensors irradiated in nuclear reactors, such as Self-Powered Neutron Detectors (SPNDs).

2.11 3D core fuel-depletion calculation

TRIPOLI-4[®] has been recently extended so as to cover depletion calculations by coupling the code to the MENDEL depletion solver developed by SERMA [5]. This coupling allows solving the Boltzmann-Bateman system of equations governing the evolution of materials under neutron irradiation. At a given time step, TRIPOLI-4[®] computes first the reaction rates in each depleted medium. Then, the MENDEL depletion solver calculates the end-of-step nuclide concentration for each region. TRIPOLI-4[®] version 10 depletion capability is based on C++ interfaces (accessible via C++ interpreter of ROOT [4]) that wrap the methods of both TRIPOLI-4[®] and MENDEL.

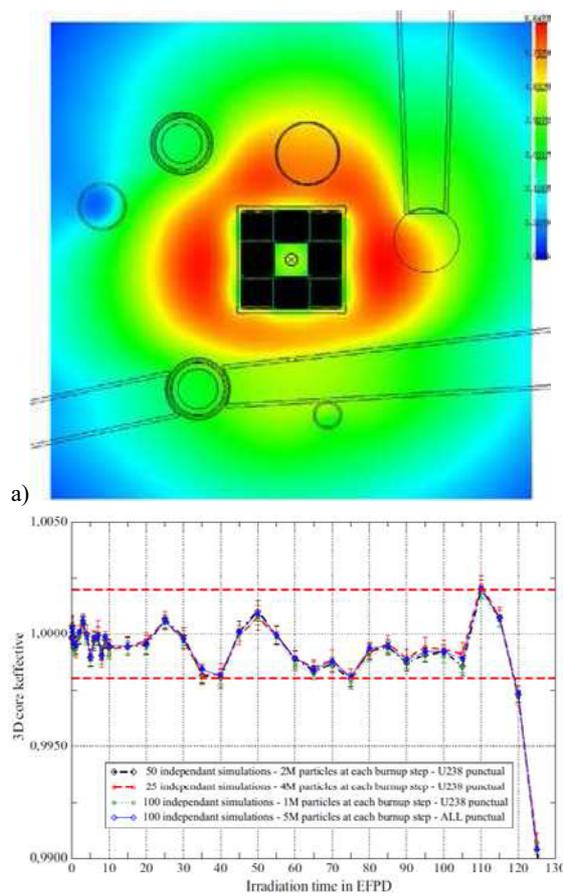


Fig. 2 a) Radial thermal flux distribution of the ORPHEE reactor (CEA, Saclay) calculated by TRIPOLI-4[®] for 3D core-depletion analysis. b) Evolution of the k_{eff} during irradiation. Time is expressed in effective full-power days (EFPD). Controls rods insertion is adjusted during irradiation.

2.12 Verification and Validation

The V&V test base is composed of several parts: elementary verification tests, criticality-safety benchmarks, shielding benchmarks, tests concerning parallel operations, tests covering the new features of the code. It includes several ICSBEP and SINBAD benchmarks, as well as proprietary benchmarks concerning CEA experimental facilities from CEA research centers [1].

We mention here an example recent shielding-V&V work that has been carried out on NAIADA 1 Water shielding benchmark [7]. For the nuclear decommissioning application, TRIPOLI-4® code capabilities on fission neutron deep penetration calculations were demonstrated. Both the shielding mode and the fixed-source sub-criticality mode of the code were validated against the NAIADA 1 water shielding benchmark. The variance reduction options of TRIPOLI-4® code are helpful to perform these calculations.

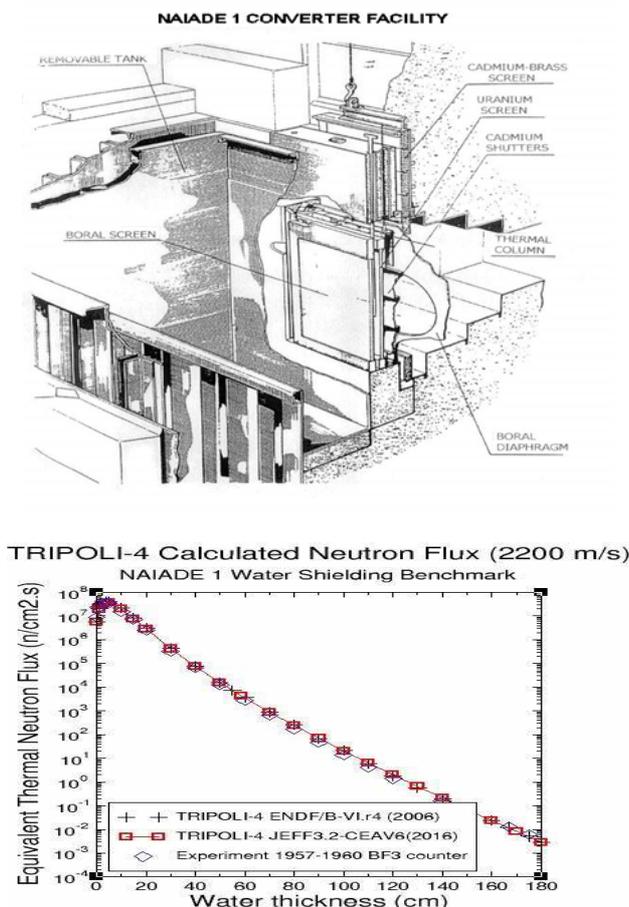


Fig. 3 Recent example of shielding-V&V work: NAIADA 1 Water shielding benchmark [7]

3 New features of TRIPOLI-4® version 10 for shielding and radiation protection applications

3.1 Thick-Target Bremsstrahlung for electromagnetic shower simulation

A simplified simulation mode for the electromagnetic shower, called Thick-Target Bremsstrahlung (TTB), has been implemented in TRIPOLI-4® version 10 to speed up coupled photon-electron-positron calculations. When this option is activated, secondary electrons and positrons produced by photon collisions are not transported, but part of their energy is converted into new bremsstrahlung photons. Fig. 4 shows a recent example of the use this feature for a benchmark of a sphere with a 20-MeV photon source in the center [8]. The simulation of the

electromagnetic shower with TTB implicates a maximum difference of 30% in the deposited energy against a full coupled photon-electron-positron simulation, but the use of TTB speeds up calculations up 10 times.

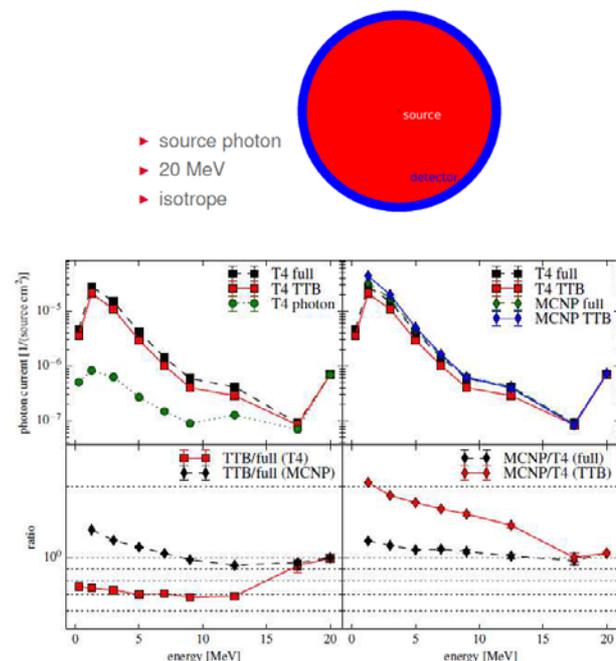


Fig. 4 Recent example of the use of the TTB feature. Here TTB vs full electromagnetic shower simulation: a maximum difference in deposited energy of 30% but acceleration up 10 times.

3.2 Analog neutron or photon transport with analog fission sampling

It is already possible with TRIPOLI-4® to perform a fully analog simulation (concerning both collisions and transport between collisions) for neutron and photon transport. TRIPOLI-4® version 10 enables analog fission simulation by sampling a full fission neutron multiplicity distribution using a coupling between TRIPOLI-4® and an external fission model providing fission sampling data (standard nuclear data libraries provide averaged neutron multiplicities only). It allows addressing time-dependent nuclear instrumentation applications needing detailed correlations between fission chains [9].

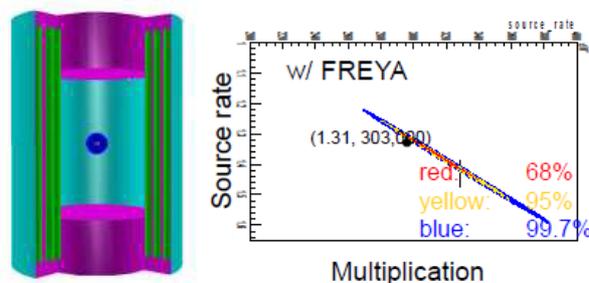
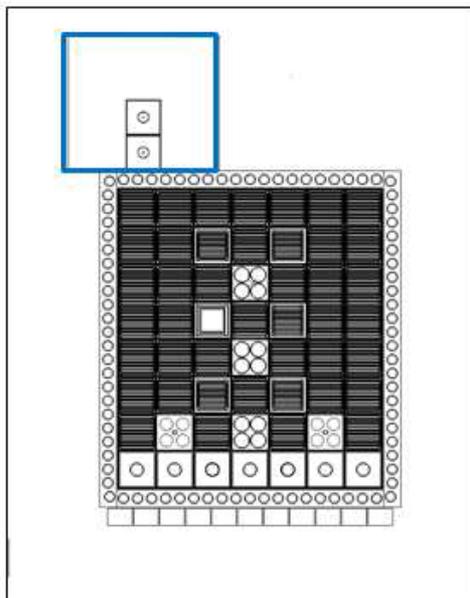


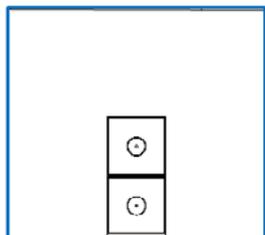
Fig. 5 Example of application: NMC (Neutron Multiplicity Counting) properly simulated by reconstructing the mass and multiplication of two objects by analyzing the measured signal from 3He tubes in a well counter [9].

3.3 “Replicate” option upgrading

With TRIPOLI-4[®], we can perform a two-step calculation using first a global geometry to store the properties (energy, position, direction, weight) of particles crossing a given surface. Then, we use stored particles as surface sources for simulation on a local geometry. The REPLICATE option activates the particle splitting at the second-step simulation. This technique of variance reduction allows for an improved exploration of the whole phase space, especially when only a limited number of particles has been stored.



a) 1st step (global geometry)



b) 2nd step (local geometry)

Fig. 6 Example of a two-step calculation in the case of the OSIRIS MTR reactor (CEA, Saclay). The blue rectangle (horizontal cross-section 30 cm x 30 cm) shows the boundary used for the storing of the particle characteristics. Inside the rectangle, we have two water boxes (horizontal cross-section 8 cm x 8 cm) with SPNDs monitors irradiated in the centers (about 3 mm of diameter) [8].

4 Features for shielding and radiation protection applications in development

4.1 Analog simulation with analog fission sampling

TRIPOLI-4[®] Monte Carlo transport code and FIFRELIN fission model (developed by CEA, Cadarache center, SPRC) have been coupled by means of external files so

that neutron transport can then take into account fission distributions (multiplicities and spectra) that are not averaged, as is the case when using evaluated nuclear data libraries. Spectral effects on responses in shielding configurations with fission sampling are then expected [9].

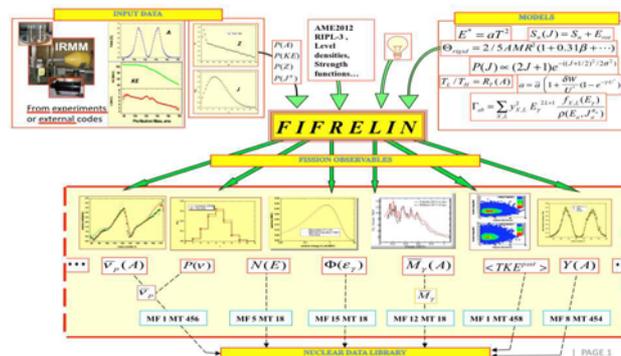


Fig. 7 FIFRELIN code (CEA, Cadarache) simulates the prompt part of the deexcitation process of binary fission.

4.2 TRIPOLI-4[®]/Geant4 coupling

The capability to simulate the transport of charged and/or high-energy hadrons (especially protons) is useful for, shielding, radiation protection and nuclear instrumentation applications. In the context of Monte-Carlo particle transport codes, solving these problems often requires the use of advanced variance-reduction techniques. TRIPOLI-4[®] is a reference Monte-Carlo particle transport code for the simulation of low-energy (< 20 MeV) neutrons and photons and offers a wide range of sophisticated variance-reduction schemes; however, it cannot be applied to the problems mentioned above because it lacks the capability to transport charged, high-energy hadrons. This limitation can be circumvented by coupling TRIPOLI-4[®] with the Geant4 particle transport toolkit (CERN) [10].

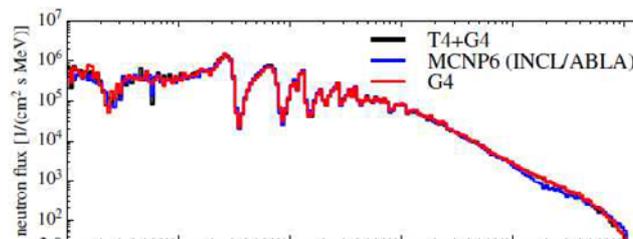
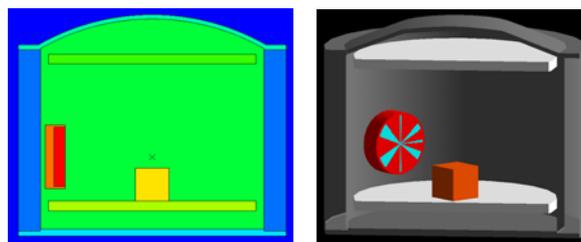


Fig. 8 Example of calculation of the APOLLON high intensity laser facility (CEA, Saclay) using TRIPOLI-4[®]/Geant4 coupling: proton-electron source; neutron-photon outgoing fluxes [13].

4.3 Rigorous two-step scheme for shutdown dose rate calculation

An activation scheme has been developed in TRIPOLI-4[®] for the shutdown dose rate calculations based on the Rigorous two-step approach (R2S). Two Monte Carlo transport calculations are used, the first for the neutrons to calculate the activation and second for photons emitted by activated materials. The production of the decay photons is performed by MENDEL inventory code (CEA) [14].

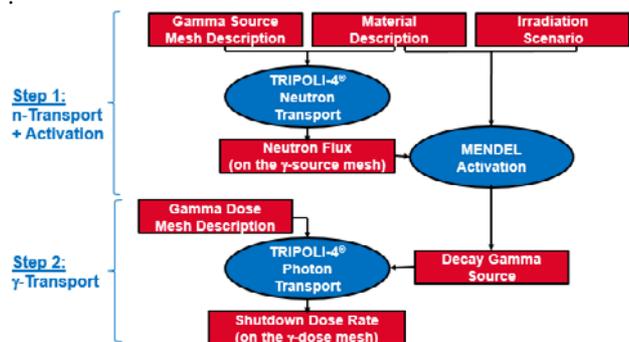


Fig. 9 the Rigorous two-step scheme for shutdown dose rate calculation using TRIPOLI-4[®] and MENDEL codes.

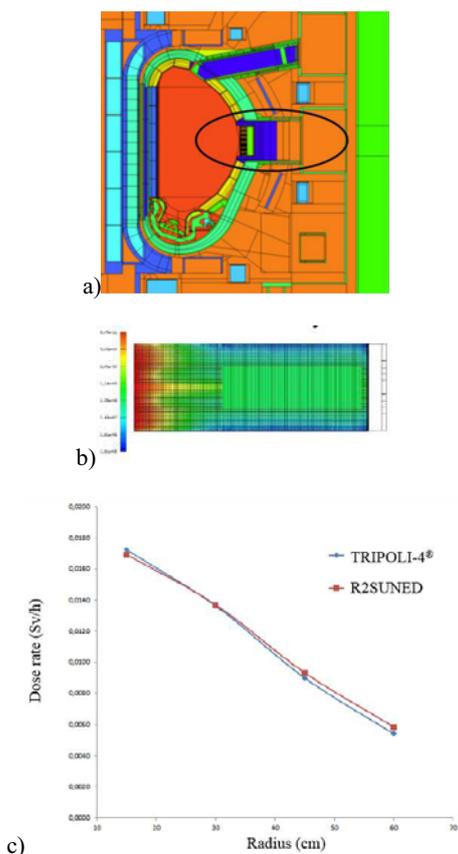


Fig. 10 Example of shutdown dose rate calculation using R2S TRIPOLI-4[®] in the case of a typical configuration of a port plug in ITER fusion facility [15]. a) ITER Equatorial Port Plug, b) Distribution of the total neutron flux calculated by TRIPOLI-4[®], c) Shutdown dose rate at the rear face.

4.4 Variance Reduction using the method of Adaptive Multilevel Splitting (AMS)

A new technique of variance reduction based on the method of Adaptive Multilevel Splitting (AMS) has been developed in the TRIPOLI-4 code [14]. The AMS algorithm is an iterative method to help simulate rare events. Each iteration includes the definition of a single splitting level alongside with the corresponding splitting process:

- Classify simulated particle tracks and define a splitting level;
- Remove the particles that have not reach the threshold;
- Re-sample removed particles by splitting remaining ones.

These preliminary results show that the use of the Adaptive Multilevel Splitting algorithm in TRIPOLI-4[®] reduces significantly the variance. Furthermore, its connection to the TRIPOLI-4[®] importance map calculation module makes it quite simple to use [16].

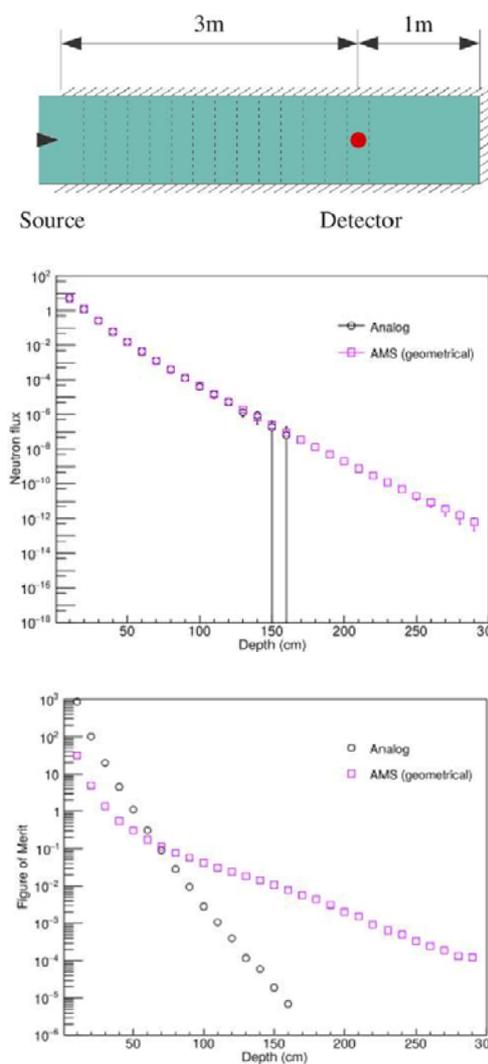


Fig. 11 Example of the use of the AMS method in TRIPOLI-4[®] in the case of a Deep penetration problem in water [16].

Acknowledgments

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