DE LA RECHERCHE À L'INDUSTRIE

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

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and the TRIPOLI-4® Team,
presented by Jean-Christophe Trama

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www.cea.fr

OUTLINE

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

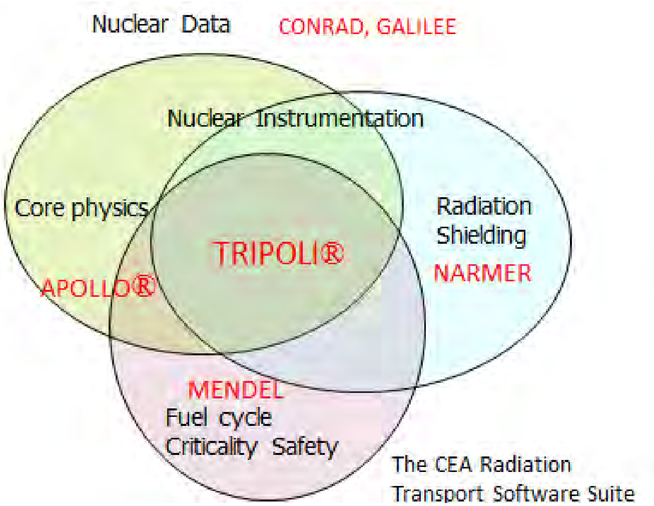
TRIPOLI-4® is a registered trademark of CEA, we gratefully acknowledge EDF long time support of TRIPOLI-4®

I - GENERAL PRESENTATION OF THE TRIPOLI-4® CODE

TRIPOLI-4® GENERIC FEATURES

- TRIPOLI-4® is a three-dimensional and continuous-energy Monte-Carlo particle transport code, developed by CEA

- TRIPOLI-4® is the corner stone of the CEA Radiation Transport Software Suite, which also includes:
  - APOLLO®: Deterministic codes dedicated to reactor physics analyses (lattice- and core-level)
  - MENDEL: Depletion code (nuclide inventory code)
  - NARMER: Photon point-kernel code
  - CONRAD and GALILEE: Nuclear data evaluation and processing



TRIPOLI-4® GENERIC FEATURES

- **Production Monte Carlo code**
  - Developed from the mid of 1990s
  - ~500 000 code lines of C++
  - TRIPOLI-4® version 10 : Monte-Carlo Depletion functionality

- **Application domains**
  - Shielding and radiation protection
  - Criticality-safety
  - Reactor physics analysis
  - Nuclear instrumentation

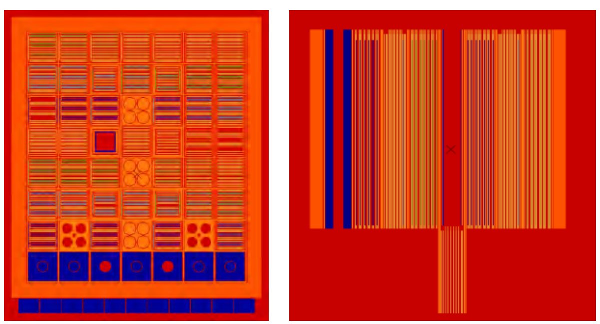
- **Tracked particles**
  - Neutrons from 20 MeV down to 10^{-5} eV
  - Photons from 50 MeV down to 1 keV
  - Electrons and positrons from 100 MeV down to 1 keV

- **Three simulation modes**
  - "Criticality" mode: critical Boltzmann equation
  - "Shielding" mode: fixed-source simulation
  - "Fixed-sources sub-criticality" mode: fixed source simulation with treatment of fission events

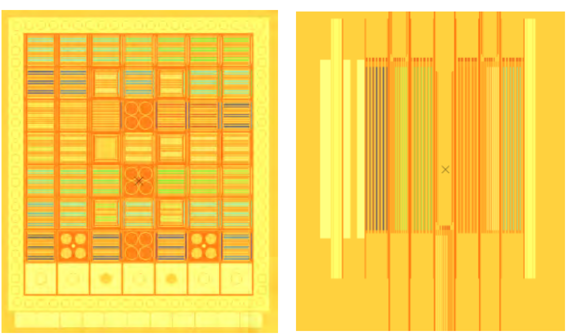
TRIPOLI-4® GENERIC FEATURES

- **Tallies**
  - volume, surface, point fluxes, reaction rates, mesh tallies, gamma spectroscopy, dose equivalent rate, built-in KERMA response functions, deposited energy, dpa, k_{eff} …

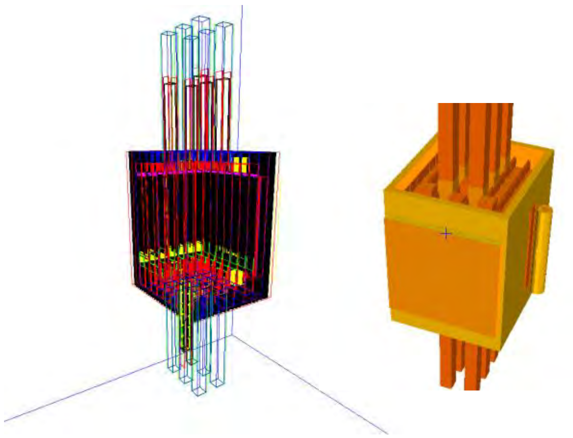
- **Geometry module**
  - Both surface based and combinatorial representations
  - Also directly compatible with the ROOT geometry
  - Possible linking with any third party geometry



Surface-based geometry



Combinatorial geometry

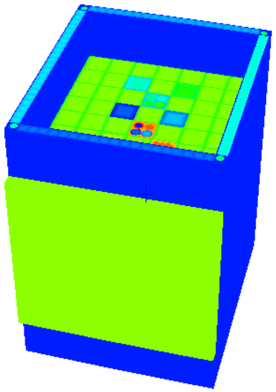


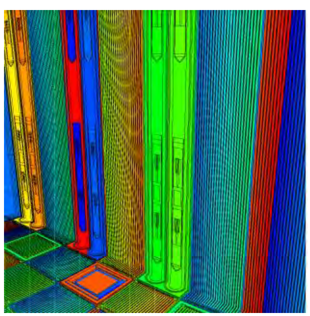
ROOT geometry

Example of different types of TRIPOLI-4® geometries for the OSIRIS reactor

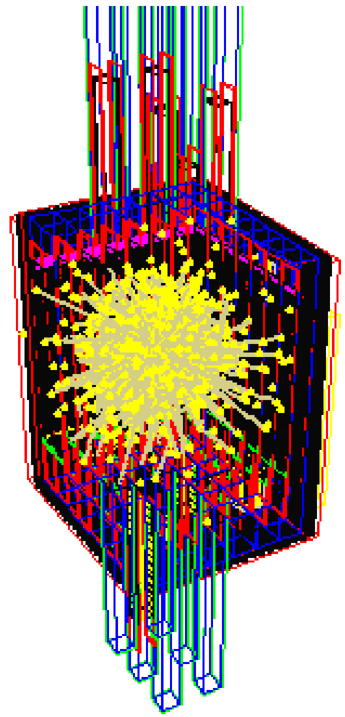
TRIPOLI-4® : PRE/PRO-PROCESSING TOOLS

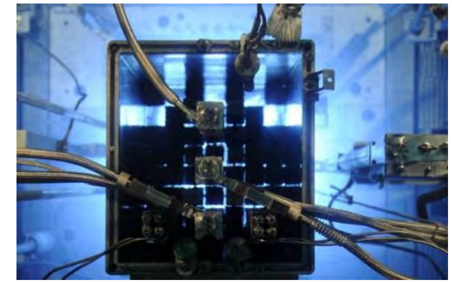
OSIRIS reactor nuclear heating calculation using neutron-photon coupled simulations with TRIPOLI-4®

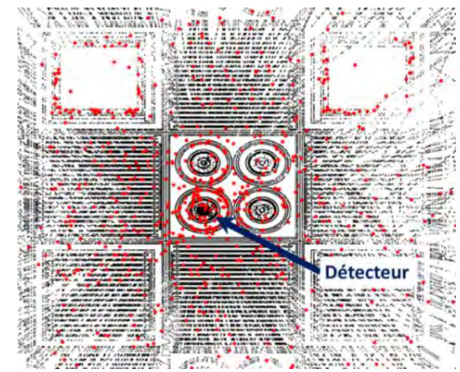




TRIPOLI-4® geometric model of the CALMOS calorimeter in the OSIRIS core







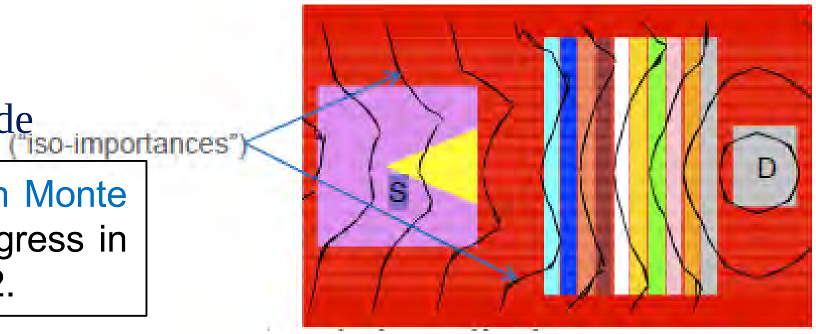
Trajectories of photons from their birth to their interaction in the central water box in the OSIRIS core (representation based on TRIPOLI-4® simulations)

A. Péron, F. Malouch, and C. M. Diop, "Improvement of Nuclear Heating Evaluation inside the Core of the OSIRIS Material Testing Reactor". 15th International Symposium on Reactor Dosimetry (ISRD15), Aix en Provence, May 2014.

TRIPOLI-4® VARIANCE REDUCTION AND V&V

- Standard techniques: implicit capture, particle splitting and Russian roulette
- Special built-in variance reduction module INIPOND (based on the Exponential Transform Method):
  - with an automatic pre-calculation of the importance map
  - with possible adjustment of the importance map (input parameters of INIPOND can be applied in order to adjust the global strength of the biasing)

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



O. Petit, Y.K. Lee, C. Diop, "Variance reduction adjustment in Monte Carlo TRIPOLI-4® neutron gamma coupled calculations", Progress in Nuclear Science and Technology Volume 4 (2014) pp. 408-412.

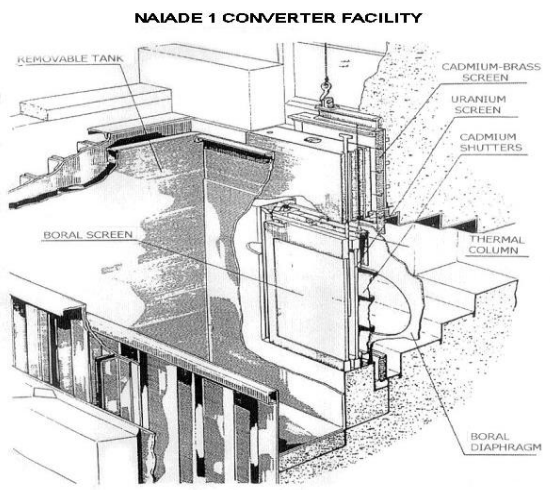
Verification and Validation

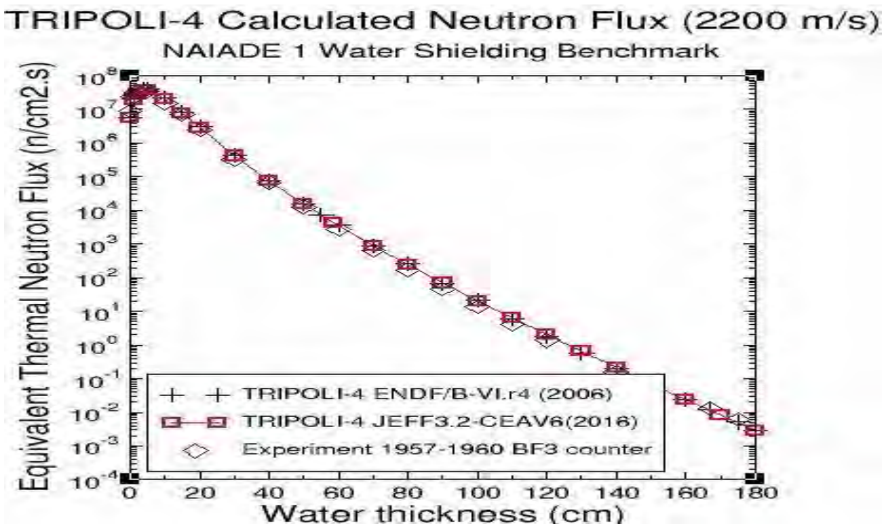
- The V&V Test Base comprises several ICSBEP and SINBAD benchmarks
- as well as proprietary benchmarks on CEA experimental facilities

TRIPOLI-4® Project Team, ''TRIPOLI-4®, CEA, EDF and AREVA reference Monte Carlo code'', Annals of Nuclear Energy, Volume 82, August 2015, Pages 151–160

Recent example: NAIADE 1 Water shielding benchmark

- Both the shielding mode and the fixed-source sub-criticality mode of the code were validated against the NAIADE 1 water shielding benchmark. All the variance reduction options of TRIPOLI-4® code have been used to perform these calculations.

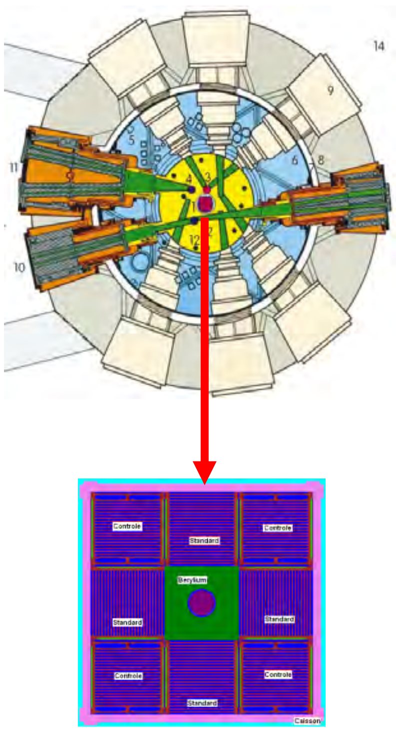


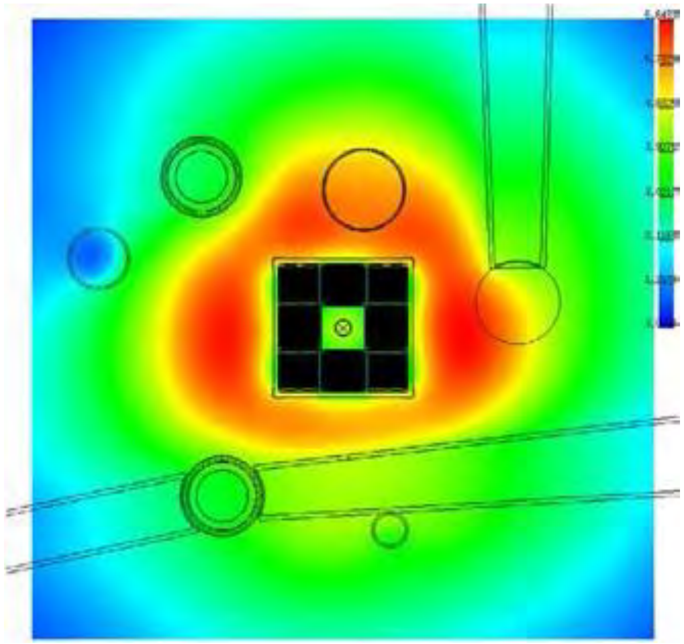


Y.K. Lee, "Neutron Deep Penetration Calculations in Light Water with Monte Carlo TRIPOLI-4® Variance Reduction Techniques", ICRS-13 & RPSD2016, Paris, France, October 3-6, 2016

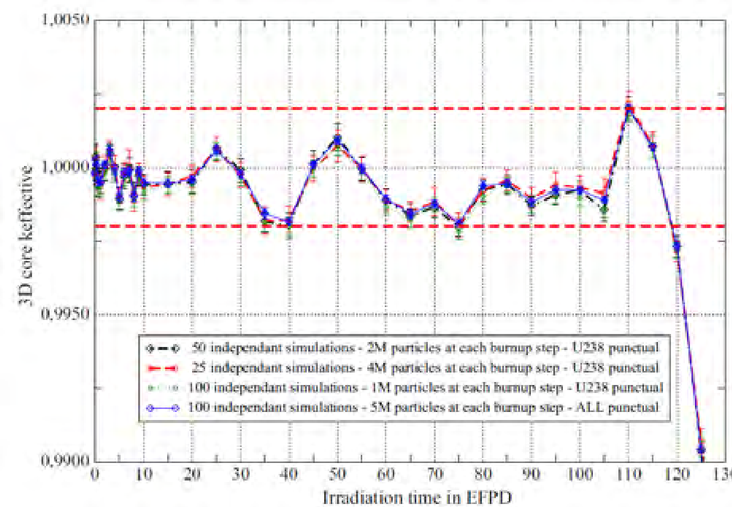
II – NEW FEATURES OF TRIPOLI-4® VERSION 10

ORPHEE reactor 3D core-depletion analysis performed with TRIPOLI-4® v10





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



Evolution of the keff during irradiation. Time is expressed in effective full-power days (EFPD). Controls rods insertion is adjusted during irradiation

F. Damian and E. Brun, "ORPHEE research reactor: 3D core depletion calculation using Monte-Carlo code TRIPOLI-4®". Annals of Nuclear Energy 82 (2015) 203–216.

TRIPOLI-4® V10 NEW FEATURES

- **Asymptotic Reactor period calculation**
  - Inverse of the dominant eigenvalue (i.e. the fundamental α eigenvalue of the Boltzmann operator)
  - Algorithm based on a modified α-k power iteration scheme

A. Zoia, E. Brun, F. Damian, F. Malvagi, "Monte Carlo methods for period calculations", Annals of Nuclear Energy, Volume 75, 2015, Pages 627–634

- **Kinetics parameters computing**
  - Iterated Fission Probability method (IFP)
  - Adjoint-weighted kinetics parameters: β_{eff}, Λ_{eff}, α_{Rossi}

G. Truchet, P. Leconte, A. Santamarina, E. Brun, F. Damian, A. Zoia, "Computing adjoint-weighted kinetics parameters in TRIPOLI-4® by the Iterated Fission Probability method", Annals of Nuclear Energy, Volume 85, 2015, Pages 17–26

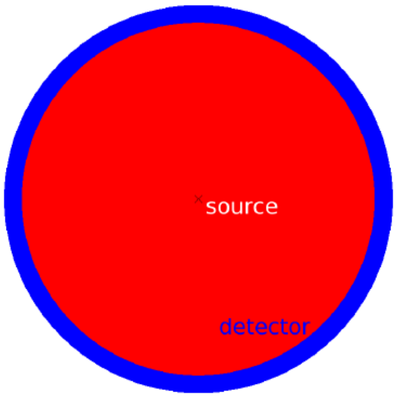
- **Deposited charge**
  - Calculation of the spectrum of the charge deposited in a given volume by charged particles (electrons and positrons)
  - useful for nuclear instrumentation in the interpretation of signal of sensors irradiated in nuclear reactors

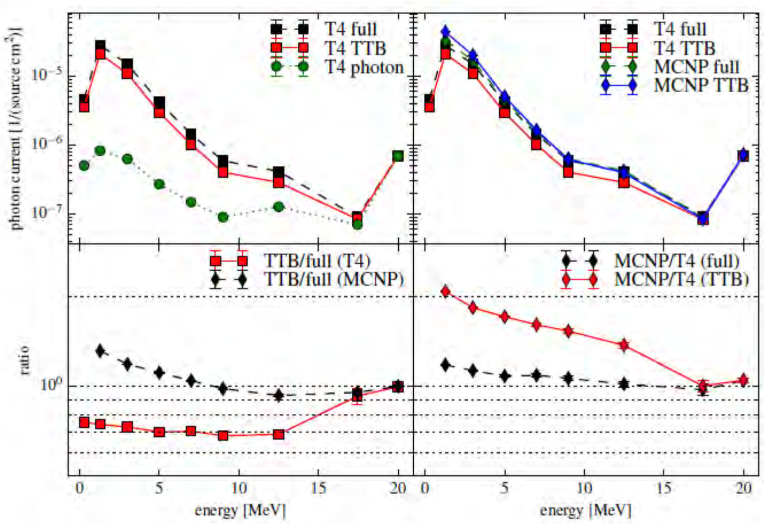
TRIPOLI-4® V10 NEW FEATURES FOR SHIELDING AND RADIATION PROTECTION APPLICATIONS

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

- source photon
- 20 MeV
- isotrope





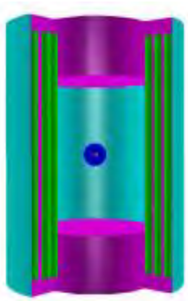
Riz et al.
PHYSOR-2000 proceedings

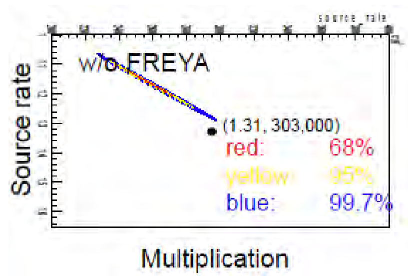
Courtesy of D. Mancusi
CEA, Saclay, SERMA

TRIPOLI-4® V10 NEW FEATURES FOR SHIELDING AND RADIATION PROTECTION APPLICATIONS

Analog simulation with analog fission sampling

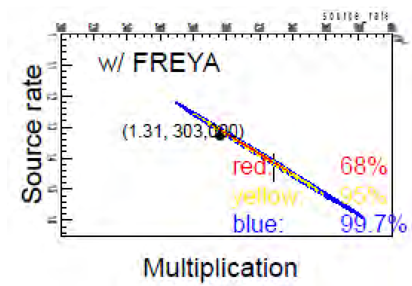
- Fully analog simulation for neutron and photon transport:
  - concerning both collisions and transport between collisions
- Analog fission simulation by sampling a full fission neutron multiplicity distribution
- Coupling between TRIPOLI-4® and an external fission model providing fission sampling data:
  - 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.





← TRIPOLI-4®

TRIPOLI-4® + FREYA →



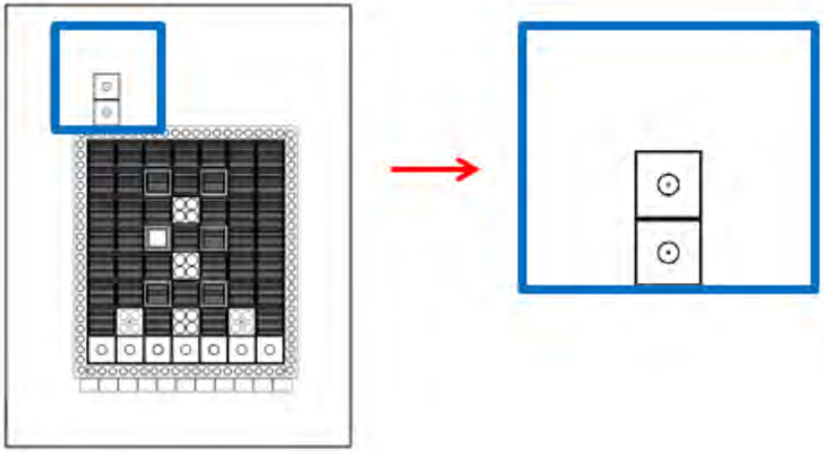
J. M. Verbeke, O. Petit, "Stochastic Analog Neutron Transport with TRIPOLI-4 and FREYA: Bayesian Uncertainty Quantification for Neutron Multiplicity Counting", Nuclear Science and Engineering, Vol. 183, Nb 2, June 2016, p. 214-228

TRIPOLI-4® V10 NEW FEATURES FOR SHIELDING AND RADIATION PROTECTION APPLICATIONS

“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

1st step
(Global geometry)



2nd step
(Local geometry)

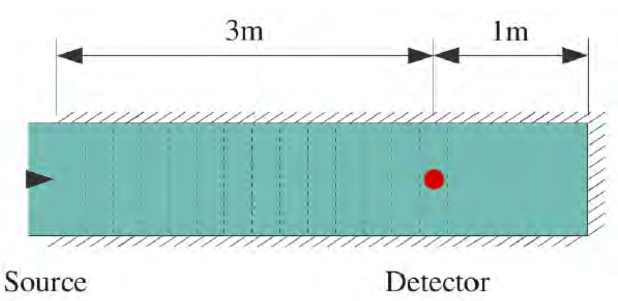
Example of a two-step calculation: Global geometry + Local geometry

F. Malouch, F. Lopez, L. Barbot, D. Fourmentel, “Calculation of neutron and gamma fluxes in support to the interpretation of measuring devices irradiated in the core periphery of the OSIRIS Material Testing Reactor”, ANIMMA2015, Lisbon Portugal, April, 20-24, 2015.

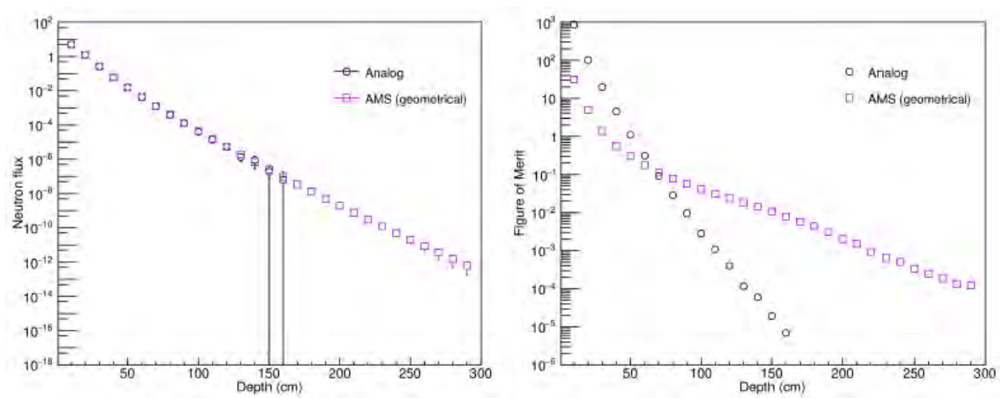
III - MAIN ONGOING DEVELOPMENTS IN TRIPOLI-4® FOR SHIELDING AND RADIATION PROTECTION APPLICATIONS

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 reach the threshold
  - Re-sample removed particles by splitting remaining ones



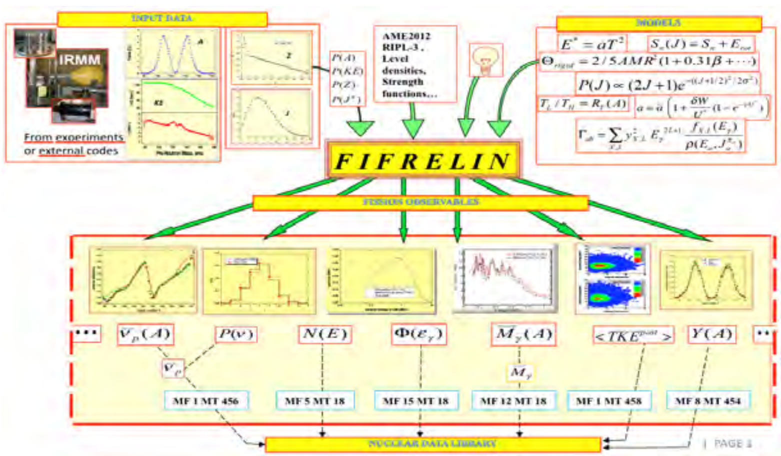
Deep penetration problem (in water)

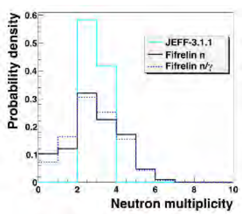


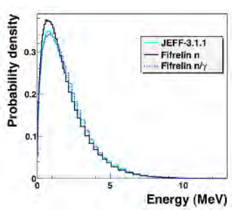
H. Louvin, C. Diop, E. Dumonteil, T. Lelièvre, M. Rousset, ”Adaptive Multilevel Splitting for Monte Carlo particle transport”, ICRS-13 & RPSD2016, Paris, France, October 3-6, 2016

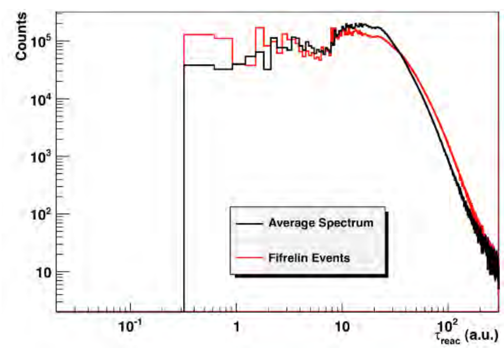
Analog simulation with analog fission sampling

- FIFRELIN-TRIPOLI-4® coupling for Monte-Carlo simulations with a fission model
- FIFRELIN (CEA, Cadarache): Simulates the prompt part of the deexcitation process of binary fission:
  - n-γ uncoupled mode: Weisskopf statistical theory
  - n-γ coupled mode: Hauser-Feshbach formalism
- Recent shieling application: variations on ASPIS benchmark







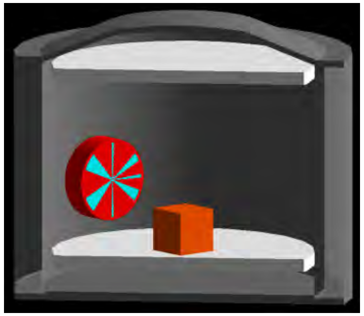


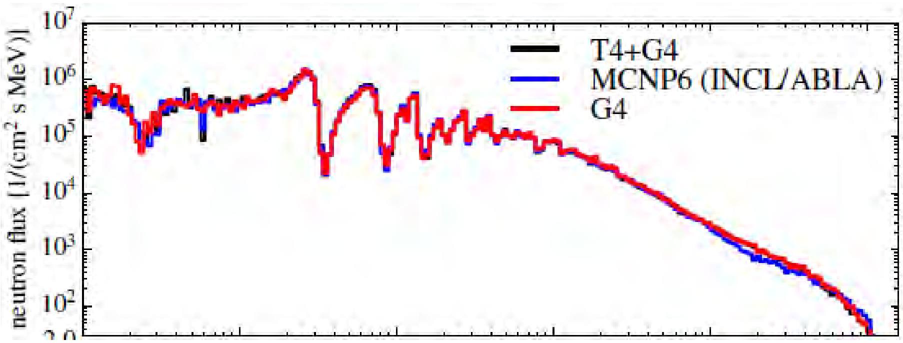
ASPIS benchmark:
Distribution of ^{103}Rh reaction rate
(with FIFRELIN n-γ uncoupled mode)

O. Petit et al., "FIFRELIN-TRIPOLI-4® coupling for Monte-Carlo simulations with a fission model. Application to shielding calculations", ICRS-13 & RPSD2016, Paris, France, October 3-6, 2016

TRIPOLI-4® - Geant4 Coupling

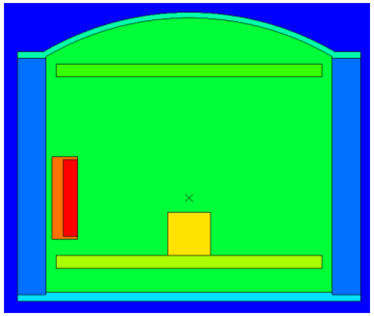
- To extend TRIPOLI-4®'s application scope via a coupling with Geant4
  - Radiation protection, decommissioning, instrumentation
- Using a Geant4 geometry and source in a TRIPOLI-4® calculation
- Delegating to Geant4
  - High-energy particles,
  - Other charged particles (protons, alpha, etc.)
- Collect all relevant scores on the TRIPOLI-4® side





APOLLON

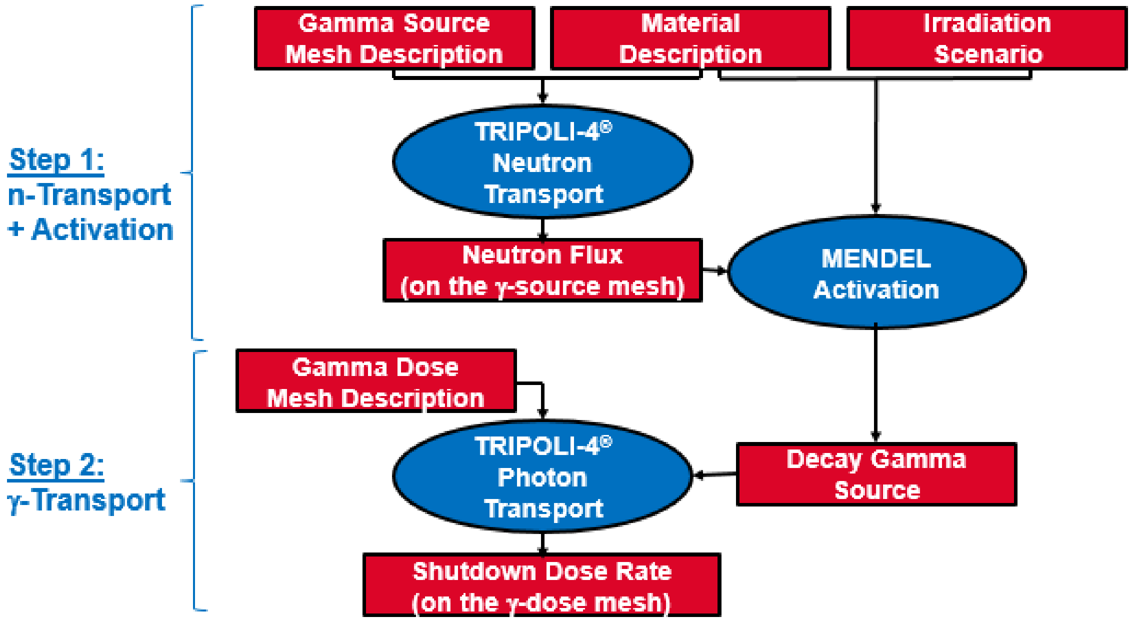
- high-intensity laser (10^{16} W!)
- proton + electron source
- neutron + photon outgoing fluxes



D. Mancusi, O. Bringer, P. Monot, "Progress on the TRIPOLI-4®-Geant4 coupling", ICRS-13 & RPSD2016, Paris, France, October 3-6, 2016

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

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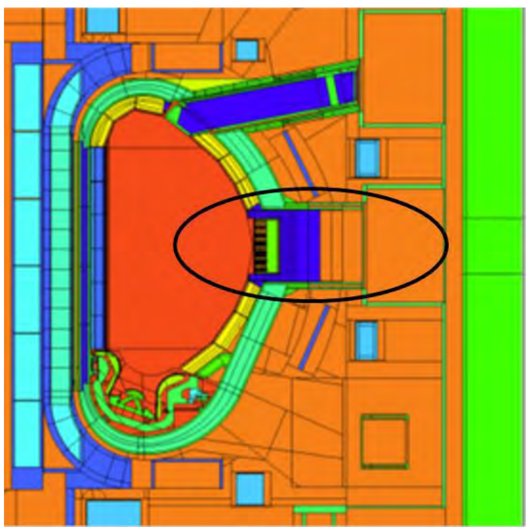
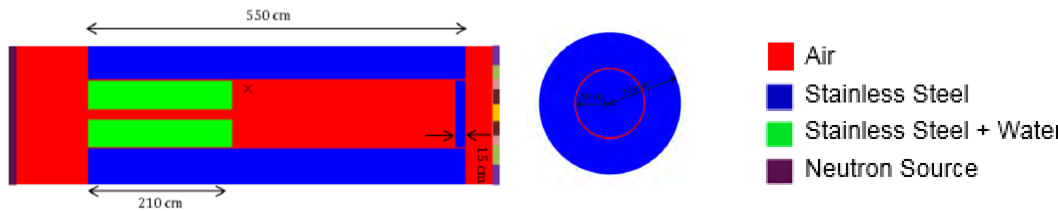
TRIPOLI-4® FEATURES FOR SHIELDING APPLICATIONS

Rigorous two-step scheme for shutdown dose rate calculation

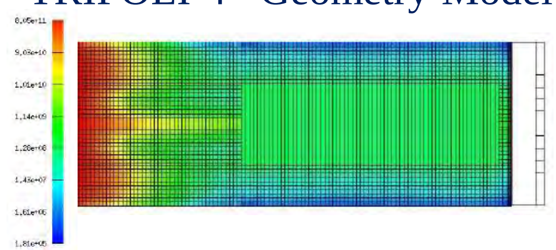
- Comparison with the different SDR calculation schemes (based on MCNP)
- Typical configuration of a port plug in ITER
- Focusing on a streaming path that contributes to activate a steel chamber



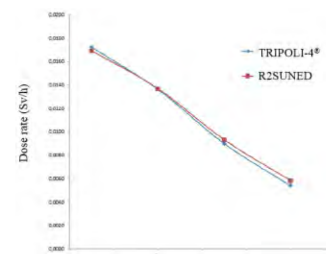
ITER Equatorial Port Plug



TRIPOLI-4® Geometry Model for ITER SDR Benchmark



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



Shutdown dose rate at the rear face

J.C. Jaboulay, "Rigorous-two-Step scheme of TRIPOLI-4® Monte Carlo code validation for shutdown dose rate calculation", ICRS-13 & RPSD2016, Paris, France, October 3-6, 2016

SUMMARY AND PERSPECTIVES

- 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 calculation

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

TRIPOLI-4® DISTRIBUTION AND LICENSING

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.

Contact at CEA, Saclay, SERMA

- Fadhel MALOUCH: fadhel.malouch@cea.fr (TRIPOLI-4® Project Leader)

Thank you for attention