Rigorous-two-Steps scheme of TRIPOLI-4[®] Monte Carlo code validation for shutdown dose rate calculation

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Abstract. After fission or fusion reactor shutdown the activated structure emits decay photons. For maintenance operations the radiation dose map must be established in the reactor building. Several calculation schemes have been developed to calculate the shutdown dose rate. These schemes are widely developed in fusion application and more precisely for the ITER tokamak. This paper presents the rigorous-two-steps scheme implemented at CEA. It is based on the TRIPOLI-4[®] Monte Carlo code and the inventory code MENDEL. The ITER shutdown dose rate benchmark has been carried out, results are in a good agreement with the other participant.

1 Introduction

To safely conduct maintenance operation or repair in a nuclear reactor (fission or fusion) the radiation dose map in the reactor building must be well known. These doses are due to the decay gamma emitted by the activated structures and the fuel in fission reactor. For fission reactor a strong feedback (measures) is available to address this problem. For the futures fusion devices like ITER the shutdown dose map must be calculated. Two methods have been developed to perform shutdown dose rate (SDR) mapping in the complex geometry of fusion reactors: the Rigorous Two Steps (R2S) and the Direct One Step (D1S) method. They are well described in [1]. A summary of the SDR mapping tools currently existing in Europe is given in [2]. There is one based on direct-one-step (D1S) treatment [3] and three following the rigorous-two-step (R2S) coupling methodology [4], [5] and [6].

In this context, CEA develops his own SDR scheme with its codes TRIPOLI-4[®] [7] and MENDEL [8]. This development is supported by a EUROfusion [9] task: *Monte Carlo code development*. This new tool will support the CEA activities in ITER and DEMO nuclear analysis and decommissioning preparation.

2 R2S Scheme developed with TRIPOLI-4[®] and MENDEL

Two activation schemes are commonly proposed for the shutdown dose rate calculations: D1S use only one coupled neutron-photon Monte Carlo transport calculation, prompt photons are replaced by decay photons.

R2S use two Monte Carlo transport calculation one for the neutrons to calculate the activation and one for photons emitted by activated materials. The methodology developed in TRIPOLI-4[®] follows the R2S approach. The scheme of Figure 1 details these two steps.

Figure 1. Flow chart of TRIPOLI-4[®] R2S scheme

2.1 Presentation of TRIPOLI-4[®] and MENDEL codes

2.1.1 TRIPOLI-4[®]

TRIPOLI-4[®] is a three-dimensional and continuous-energy Monte Carlo particle transport code dedicated to shielding, reactor physics with depletion, criticality safety and nuclear instrumentation. TRIPOLI-4[®] is currently able to simulate four kinds of 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. TRIPOLI-4[®] verification and validation operations are mainly based on ICSBEP [10] criticality cases

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(around 1000), SINBAD [11] shielding cases (ASPIS, NESDIP, REPLICA and FNG). More particularly, numerous benchmarks on fusion applications were recently conducted [12-16].

2.1.2 MENDEL

MENDEL is a depletion code developed at CEA dedicated to radioactivity calculations related to neutron irradiation and based on deterministic depletion solvers. MENDEL is the successor of the DARWIN/PEPIN2 code [17]. MENDEL is developed in C++ with an object-oriented architecture allowing other codes to be easily coupled. For example, the depletion solvers of MENDEL are currently used in the deterministic transport code APOLLO3[®] [18] and in the Monte Carlo transport code TRIPOLI-4[®], in order to perform depletion calculations. Recently, a new capability has been added to handle the propagation of the nuclear data uncertainties by a probabilistic approach [8] based on URANIE [19], the CEA uncertainty and sensitivity platform.

2.2 General principle of TRIPOLI-4[®] R2S scheme

The implemented R2S scheme is divided into three steps. In **step1a**, TRIPOLI-4[®] performs a neutron transport calculation in order to compute the flux and/or the energy integrated reaction rates in each region susceptible to produce decay gammas; in **step1b** MENDEL computes the decay photon sources for each region based on the neutron fluxes and/or the reaction rates calculated in step1a, as well as the specified irradiation and cooling times. Finally, in **step2** TRIPOLI-4[®] transports the decay photons and computes the dose rates in each region of interest.

The geometrical regions where decay gamma can be produced, corresponding to spatial regions where the neutron flux and/or the reaction rates are calculated during the first step can be defined cell by cell or by a mesh superposed to the geometry. In the current version of the code, an important hypothesis is done: each mesh cell should contains only one homogeneous material.

3 ITER Shutdown Dose Rate Benchmark

The ITER Shutdown Dose Rate (SDR) Benchmark was defined to compare the different SDR calculation schemes developed at UNED, CCFE, KIT and ENEA. The case studied is relatively simple but relevant for fusion applications. It aims to represent the typical configuration of a port plug in ITER. Focusing on a streaming path that contribute to activate a steel chamber.

The geometry considered is cylindrical (Figure 2). The radius of the outermost cylinder is 100cm. All radiation is lost beyond this cylinder. The source cell is 10cm thick. Neutron source is isotropic and emitted at 14 MeV, the source intensity is given in Table 2. There is then a gap of 100cm. The material (Table 1) section consists of an outer steel (density is equal to 7.93 g/cm³) cylinder that is 550cm long with a 50cm radius hole

through it. The first 210cm of this hole is nearly filled with a mixed steel-water (density is equal to 6.536 g/cm³) cylinder, which itself has a 7.5cm radius hole through its centre. There is a 2cm gap between the steel-water cylinder and the outer steel cylinder. There is a 15cm thick steel plate at the end of outer steel cylinder. There is a 2cm gap between this plate and the outer cylinder. The tally cells are four concentric circular cells in a void at the rear of the material. These cells begin 30cm from the back of the steel and are 10cm thick (i.e. the centre of the tally cells is 35cm from the plate's rear face). The outer radii of these tally cells are 15, 30, 45, and 60cm respectively.

The steel and water region represent an experimental device of ITER typically steel cooled by water. The rear plate model the closure plate between the port plug and the inter-port region. In ITER SDR are calculated in the inter-port and the closure plate activation play a major role in the dose rate. The irradiation scenario (table 2) is typical to ITER experiment: low power at the beginning and high power cycles at the end of reactor life.

Figure 2. ITER SDR Benchmark.

Table 1. Materials definition in atom fraction.

	Steel and Water	Steel		Steel and Water	Steel
H	1,46E-1	-	Mn	1,42E-2	1,82E-2
B	4,02E-5	5,14E-5	Fe	5,03E-1	6,44E-1
C	8,14E-4	1,04E-3	Co	3,68E-4	4,71E-4
N	2,17E-3	2,78E-3	Ni	9,06E-2	1,16E-1
O	7,29E-2	6,95E-5	Cu	2,05E-3	2,62E-3
Al	8,04E-4	1,03E-3	Zr	9,52E-6	1,22E-5
Si	7,73E-3	9,89E-3	Nb	4,67E-5	5,98E-5
P	3,50E-4	4,48E-4	Mo	1,13E-2	1,45E-2
S	1,02E-4	1,30E-4	Sn	7,31E-6	9,36E-6
K	5,55E-6	7,10E-6	Ta	2,40E-5	3,07E-5
Ti	1,36E-3	1,74E-3	W	2,36E-6	3,02E-6
V	3,41E-5	4,36E-5	Pb	1,68E-6	2,14E-6
Cr	1,46E-1	1,87E-1	Bi	1,66E-6	2,13E-6

Table 2. Irradiation scenario.

Source Intensity in n/s	Duration	Number of cycles
1.0714×10^{17}	2 years	1
8.25×10^{17}	10 years	1
0	0.667 years	1
1.6607×10^{18}	1.33 years	1
0	3920 sec	17
2.0×10^{19}	400 sec	
0	3920 sec	4
2.8×10^{19}	400 sec	

4 Results

The ITER SDR benchmark was modelled with the TRIPOLI-4[®] R2S scheme. The FENDL-2.1 [Erreur ! Source du renvoi introuvable.] nuclear data library was used for the transport (neutron and photon) and the EAF2003 [21] library for the depletion calculation. The figure 3 shows the total neutron flux distribution over the ITER SDR benchmark geometry. Variance reduction techniques have been used (the neutron flux is attenuated by five decades between the front face and the rear face). The INIPOND module of TRIPOLI-4[®] automatically produces an importance map (figure 4). Classical techniques are used with this map: Russian roulette and splitting plus the exponential transform method.

Figure 3. Total neutron flux distribution over the geometry **Figure 4.** Importance map calculated by the INIPOND module (back curves are the iso-importance profile)

The neutron flux at the front face (facing the source) and at the rear face (near the tally region) were compared between the TRIPOLI-4[®] code and the MCNP5 code. The figure 5 shows a very good agreement around 0.4% for the front face and [-2%;+10%] for the rear face. These discrepancies are included in the statistical error.

Dose rate were calculated with the R2S scheme of TRIPOLI-4[®] and compared with R2SUNED [22] ones.

Results are gathered in table 3, there is a good agreement discrepancies ranges between -2% up to + 3%. The statistical uncertainty could explain these discrepancies. The gamma dose rate is well converged in both calculation but neutron flux statistical error are around [2%; 5%] in both case. A better estimation in statistical error propagation would be necessary to conclude (§5). Another fact could explain the discrepancies: the activation library EAF2003 for TRIPOLI-4[®], EAF2007 for R2SUNED. EAF2010 processing for its use in MENDEL is underway to estimate the effect of the activation library.

The dose rate contributors were investigated. The rear plate activation contributes to 99.7% except for the outermost tally (93.7%) placed in front of a streaming gap. In terms of isotopes ⁵⁸Co, ⁵⁴Mn, ⁶⁰Co contribute to 96% of the dose rate, respectively 58%, 28%, 10%.

Table 3. Shutdown dose rates.

Inner Radius [cm]	Outer Radius [cm]	R2SUNED dose rate [mSv/h]	R2S TRIPLI-4 [®] dose rate [mSv/h]
0	15	$16.9 \pm 0.7\%$	$17.4 \pm 0.7\%$
15	30	$13.7 \pm 0.4\%$	$13.8 \pm 0.4\%$
30	45	$9.3 \pm 0.4\%$	$9.1 \pm 0.4\%$
45	60	$5.8 \pm 0.4\%$	$5.8 \pm 0.4\%$

Figure 5. Neutron flux spectrum calculated with TRIPOLI-4[®] and MCNP5 at the front face and the rear face of the geometry

5 Futures developments

One important issue of the classical R2S approach is the materials handling inside a mesh. Currently, in each mesh only one material can be treated if not some bias may occur [22]. The mesh tallies of TRIPOLI-4[®] will be improved to calculate the flux and other quantities in each material of in a mesh-cell, this development will enable the materials handling inside mesh.

To estimate the doses uncertainties due to statistics (statistical error of the decay gamma simulation plus propagation of the statistical error on neutron flux) independent simulations will be used (making N complete R2S calculations with a different seed initialisation, Figure 6).

Figure 6. Statistical uncertainties propagation scheme (independent replicas)

Finally the MENDEL calls will be parallelized to accelerate the depletion calculation.

6 Conclusions

A shutdown dose rate calculation scheme was implemented in the TRIPOLI-4[®] code. It is based on the rigorous-two-step methodology (first step: neutron transport + depletion calculation, second step: decay gamma transport). The MENDEL inventory code was used for depletion calculation. This paper presents a numerical benchmark (ITER SDR benchmark) to validate the TRIPOLI-4[®] R2S. Results are in good agreement with the other participant (UNED). Improvement of the R2S scheme are planned: to accelerate the calculation (MENDEL parallelization), to propagate the statistical error of the first step and to handle different materials in a mesh-cell. Extended validation exercises will be carried out with the Frascati Neutron source Generator SDR experiment [11] and the JET SDR measurement [23]. TRIPOLI-4[®] R2S should be used in near-term for ITER neutronic analysis at CEA [24]. The R2S feature should be available in the next version of TRIPOLI-4[®] (v11, 2018). Beyond fusion applications, this new feature will be by very helpful for fission applications like reactor decommissioning analysis, dosimetry and activation calculation.

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