Fluence Rate Benchmarking of the Stochastic Neutronic Code ANET

Thalia Xenofontos\textsuperscript{a,b,c}
\textsuperscript{a}Institute of Nuclear and Radiological Sciences & Technology, Energy & Safety, National Centre for Scientific Research Demokritos
15310, Aghia Paraskevi, Greece
\textsuperscript{b}Department of Electrical & Computer Engineering, Aristotle University of Thessaloniki
Egnatia Str., University Campus
54124, Thessaloniki, Greece
\textsuperscript{c}Physics Department, Ecole Polytechnique Saclay Str.
91128, Palaiseau Cedex, France
thalia.xenofontos@ipta.demokritos.gr

G.-K. Delipei\textsuperscript{d}, P. Savva\textsuperscript{a}, M. Varvayanni\textsuperscript{a}, N. Catsaros\textsuperscript{a}, J. Maillard\textsuperscript{d}, J. Silva\textsuperscript{e}
\textsuperscript{d}Institut du Développement et des Ressources en Informatique Scientifique, CNRS
John Von Neumann Str., Campus Universitaire d'Orsay
91403 Orsay Cedex, France
\textsuperscript{e}Université Pierre et Marie Curie
Campus Jussieu
75252 Paris Cedex 05, France
Delipei_Gregory@hotmail.com, savvapan@ipta.demokritos.gr,
melina@ipta.demokritos.gr, nicos@ipta.demokritos.gr,
jacquesmaillard@wanadoo.fr, jorge.silva@upmc.fr

ABSTRACT

ANET is a new stochastic neutronics code which is being developed based on the high energy physics code GEANT of CERN, for simulating both GEN II/III reactors as well as innovative nuclear reactor designs. ANET has already been successfully tested with respect to criticality computations, while in this work its reliability in computing neutron fluence rates is examined in the framework of the code benchmarking and validation. The Portuguese Research Reactor (RPI) after its conversion to low enrichment in U-235 was considered appropriate for the present study, since its core is supplied with purely fresh fuel while fluence rate measurements are available at various characteristic core positions. Following the measurement protocol, thermal, epithermal and fast neutron fluence rates were computed in a 15 cm segment immediately below the fuel mid-height in a critical core. In addition, fluence rate profiles were obtained in 3 cm segments along the fuel height. ANET computations were compared with measurements as well as with corresponding results obtained by two different stochastic codes, i.e. TRIPOLI and MCNP, while mention is also made concerning comparisons with earlier deterministic results (by XSDRN/CITATION). The comparisons were performed in representative core positions, i.e. standard fuel assemblies, dummy (non-fuelled) assemblies and beryllium reflector. The obtained results show that ANET is capable of satisfactorily simulating the neutron energy spectrum in the core of a Material Testing Reactor.
1 INTRODUCTION

The Monte Carlo code ANET has been derived from the open-source version of the high energy physics code GEANT3.21 [1] of CERN. Its aim is to inherently simulate GEN II/III reactors as well as Accelerator Driven Systems (ADSs) [2]. Hadronic showers, nuclear cascades in addition to creation and collision of particles are treated in ANET. Whereas FLUKA [3], which is incorporated in GEANT3.21, accounts for neutrons of energy above 20 MeV, special procedures added in ANET allow for the simulation of transport and interactions, i.e. elastic collision, capture and fission, of neutrons with energies below 20 MeV. At the current stage, the JEFF3.1.2 neutron cross section library is used while inclusion of ENDF/B-VI and ENDF/B-VII libraries is scheduled for the near future. Details about ANET structure and applications for ADSs can be found in [4], [5].

Following the standard Monte Carlo procedure for the computation of neutron fluence rates utilized in stochastic codes, e.g. MCNP [6], TRIPOLI [7] and OpenMC [8], both the collision and the track-length estimators are implemented in ANET. The formulae used for the collision and the track-length estimator are presented in Equations (1) and (2) respectively.

\[
\phi = \frac{1}{W} \sum_{i \in C} \frac{w_i}{\Sigma_t(E_i)}
\]

\[
\phi = \frac{1}{W} \sum_{i \in T} w_i \ell_i
\]

where \( W \) is the total starting weight of the particles, \( w_i \) is the pre-collision weight of the particles, \( C \) is the set of all events resulting in a collision with a nucleus, \( \Sigma_t(E_i) \) is the total macroscopic cross section of the target material at the incoming energy of the particle \( E_i \), \( T \) is the set of all the particle’s trajectories within the desired volume and \( \ell_i \) is the length of the \( i \)-th trajectory.

The Portuguese Research Reactor (RPI) [9] is a 1 MW pool-type reactor built by American Machinery and Foundry (AMF) Atomics, USA, and commissioned in 1961. Its core conversion to low enrichment U-235 (19.75% nominal U-235) was realized in 2007. Neutron fluence rate measurements were performed shortly after its commissioning, hence fresh fuel conditions can be assumed for subsequent studies while the results are suitable for codes’ benchmarking. In the present work, the RPI reactor is simulated by three stochastic codes, i.e. ANET, TRIPOLI-4.8 and MCNP so as to validate and verify ANET’s capability to satisfactorily determine neutron fluence rates throughout the neutron energy spectrum in high density, compact size pool type LEU cores, using MTR fuel elements of slab geometry. The obtained results are compared with measurements [10].

2 CORE CONFIGURATION

A 9x6 orthogonal lattice of seven standard and five control LEU fuel assemblies of the Materials Test Reactor (MTR) type, composes the core configuration which is studied in the present work (Figure 1). Standard and control fuel assemblies contain 18 and 10 fuel plates of 62.5 cm length respectively while the meat is U\(_3\)Si\(_2\) powder dispersed in pure Al, cladded in AG3NE Al alloy.

The control of the reactor is achieved using 4 shim-safety rods and one regulating rod, located in the central channels of the control assemblies. The absorbing material is 1 mm-thick Cd layer covered and supported by 1.5 mm-thick stainless steel. 2.2 mm-thick stainless
steel constitutes the regulating rod. Both shim-safety and regulating rods have oval cross-sectional shapes and 61 cm length.

![Diagram of RPI core](image)

**Figure 1:** Horizontal cross section of the simulated RPI core. The notation used is as follows.
- **W:** Light Water; **FA:** Fuel Assembly; **DA:** Dummy Assembly; **RR:** Regulating Rod; **CR:** Control Rod; **Be:** Beryllium; **TC:** Thermal Column.

The requirement of the thermal hydraulic safety margin improvement is fulfilled by the introduction of four dummy (non-fuelled) assemblies in the periphery of the core. All the assemblies have the same external structure nevertheless dummy assemblies contain only a 10.3 mm-thick aluminium tube located at the central region of the assembly. Finally, three types of neutron reflector are utilized inside the reactor core, i.e. graphite (in the thermal column), beryllium and light water. It should be noted that in all simulations, the gap between the graphite and the core has been assigned an average value of 7.5 mm. Further details concerning the assemblies design and the core configuration are presented in [10].

### 3 FLUENCE RATE ASSESSMENT

#### 3.1 Measurements

Neutron fluence rate measurements for three energy groups, i.e. thermal (neutron energy $E < 0.5$ eV), lower epithermal ($0.5$ eV < $E < 10$ keV) and fast ($1$ MeV < $E < 20$ MeV), were performed within a large part of the RPI core. The method of foil activation was utilized for the characterization of the energy groups. More particularly, gold foils were used for the thermal and epithermal region of the neutron spectrum, while the distinction between these energy regions was based on the cadmium-ratio method. Fluence rates of fast neutrons were determined by the use of indium, nickel and aluminum foils, wrapped in cadmium so as to decrease target irradiation by thermal neutrons.

Criticality throughout all the measurements was achieved by the withdrawal of the safety and regulation rods, by 56% and 40% respectively. In the present work, two sets of neutron fluence rates measurements are exploited. The determination of relative fluence rate profiles along the fuel height was realized in positions E3 (standard fuel assembly), E4 (dummy assembly) and in the beryllium reflector Be-N identified in Figure 1. In addition, fluence rate measurements were performed immediately below the fuel mid-height in nine core positions, i.e. in positions E2, B3, D3 and E3 (standard fuel assemblies), F2, F3, E4 and A3 (dummy assemblies) and finally in beryllium reflector Be-N, also shown in Figure 1. Detailed information about the conduction of the measurements can be found in [10].
As stated in [10], propagation of uncertainties in the measured responses and data constants, results into uncertainties for fluence rates measurements at full length of the neutron spectrum. In particular, for thermal and epithermal fluence rates uncertainties of 12% and 10% are respectively observed at the fuel assemblies, whereas for fast neutrons uncertainties of 5% are mentioned in all irradiation positions.

### 3.2 Simulations

ANET’s capability of simulating successfully neutron fluence rates throughout the neutron energy spectrum is tested here using the JEFF3.1.2 neutron cross section library. The stochastic codes TRIPOLI-4.8 and MCNP are employed for cross-verification and validation of ANET’s results for the present application. The JEFF3.1.2 library is applied in MCNP while in TRIPOLI the CEAV5.1.1 library, which is mainly based on JEFF3.1.1, is incorporated.

The core configuration and geometrical assumptions applied in all simulations were identical. Both local fluence rates and vertical fluence rate profiles are computed in all the positions mentioned in section 3.1. Fluence rates are calculated in segments of 15 cm length located immediately below fuel mid-height. The detection volumes are water cylinders of 10 mm diameter in all positions, apart from the case of the standard assembly where the diameter is 3 mm. The average fluence rates in a 15 cm segment below fuel mid-height for thermal, epithermal and fast neutrons assessed by ANET, TRIPOLI-4.8 and MCNP, along with the corresponding measurements are shown in Tables 1, 2 and 3 respectively. The discrepancies from measurements given from \((\Phi_c - \Phi_m)/\Phi_m\), where \(\Phi_c\) and \(\Phi_m\) stand for computed and measured fluence rates, are also shown in Tables 1-3.

**Table 1:** ANET computations of thermal neutrons average fluence rates \((\Phi_t)\) in comparison with other stochastic results and corresponding measurements. \(\text{DiM} = \text{Discrepancy from Measurements}\)

<table>
<thead>
<tr>
<th>Position</th>
<th>Standard Assemblies</th>
<th>Dummy Assemblies</th>
<th>Be</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\Phi (\times 10^{-12}))</td>
<td>(\Phi (\times 10^{-13}))</td>
<td>(\Phi (\times 10^{-13}))</td>
</tr>
<tr>
<td></td>
<td>(\text{DiM} (%))</td>
<td>(\text{DiM} (%))</td>
<td>(\text{DiM} (%))</td>
</tr>
<tr>
<td>Measurements</td>
<td>E2</td>
<td>E3</td>
<td>D3</td>
</tr>
<tr>
<td>Measurements</td>
<td>8.71</td>
<td>8.94</td>
<td>9.81</td>
</tr>
<tr>
<td>ANET</td>
<td>8.46</td>
<td>7.48</td>
<td>10.71</td>
</tr>
<tr>
<td>TRIPOLI</td>
<td>7.41</td>
<td>6.77</td>
<td>9.55</td>
</tr>
<tr>
<td>MCNP</td>
<td>8.35</td>
<td>7.45</td>
<td>10.82</td>
</tr>
</tbody>
</table>
| Detailed vertical fluence rate profiles are obtained using adjacent volumes of 3 cm length, along the fuel height. Diameter restrictions are as stated above. ANET results are compared with MCNP and TRIPOLI computations in Figures 2, 3 and 4 for positions E3, E4 and Be-N respectively.
Table 2: ANET computations of epithermal neutrons average fluence rates ($\Phi_e$) in comparison with other stochastic results and corresponding measurements. DfM = Discrepancy from Measurements

<table>
<thead>
<tr>
<th>Position</th>
<th>E2</th>
<th>E3</th>
<th>D3</th>
<th>B3</th>
<th>F2</th>
<th>F3</th>
<th>E4</th>
<th>A3</th>
<th>Be-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurements</td>
<td>1.14</td>
<td>1.04</td>
<td>1.59</td>
<td>1.39</td>
<td>4.80</td>
<td>3.97</td>
<td>5.35</td>
<td>5.96</td>
<td>8.44</td>
</tr>
<tr>
<td>ANET</td>
<td>1.42</td>
<td>1.10</td>
<td>1.66</td>
<td>1.39</td>
<td>4.94</td>
<td>4.19</td>
<td>4.85</td>
<td>5.68</td>
<td>6.49</td>
</tr>
<tr>
<td>TRIPOLI</td>
<td>1.26</td>
<td>1.01</td>
<td>1.53</td>
<td>1.30</td>
<td>4.52</td>
<td>3.89</td>
<td>4.68</td>
<td>5.47</td>
<td>6.69</td>
</tr>
<tr>
<td>MCNP</td>
<td>1.41</td>
<td>1.11</td>
<td>1.73</td>
<td>1.48</td>
<td>4.89</td>
<td>4.17</td>
<td>5.08</td>
<td>6.14</td>
<td>7.48</td>
</tr>
</tbody>
</table>

Table 3: ANET computations of fast neutrons average fluence rates ($\Phi_f$) in comparison with other stochastic results and corresponding measurements. DfM = Discrepancy from Measurements

<table>
<thead>
<tr>
<th>Position</th>
<th>E2</th>
<th>E3</th>
<th>D3</th>
<th>B3</th>
<th>F2</th>
<th>F3</th>
<th>E4</th>
<th>A3</th>
<th>Be-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurements</td>
<td>1.39</td>
<td>1.23</td>
<td>1.66</td>
<td>1.36</td>
<td>2.68</td>
<td>2.65</td>
<td>2.78</td>
<td>2.56</td>
<td>1.94</td>
</tr>
<tr>
<td>ANET</td>
<td>1.38</td>
<td>1.10</td>
<td>1.55</td>
<td>1.31</td>
<td>2.52</td>
<td>2.14</td>
<td>2.35</td>
<td>2.56</td>
<td>2.43</td>
</tr>
<tr>
<td>TRIPOLI</td>
<td>1.26</td>
<td>1.04</td>
<td>1.44</td>
<td>1.22</td>
<td>2.44</td>
<td>2.10</td>
<td>2.25</td>
<td>2.44</td>
<td>2.09</td>
</tr>
<tr>
<td>MCNP</td>
<td>1.41</td>
<td>1.13</td>
<td>1.63</td>
<td>1.40</td>
<td>2.63</td>
<td>2.26</td>
<td>2.44</td>
<td>2.74</td>
<td>2.34</td>
</tr>
</tbody>
</table>

The fluence rate values in various core positions and the vertical fluence rate profiles computed by ANET are in satisfactory agreement with the well-established stochastic codes MCNP and TRIPOLI as well as with measurements. More specifically, the discrepancies of ANET from measurements concerning the thermal range remain below 12% in the majority of the core positions. ANET discrepancies in channels E3 and Be-N are slightly increased, reaching 16% and 15% respectively, nevertheless this applies to all codes and ANET performs slightly better than MCNP in both positions. ANET epithermal fluence rate simulations exhibit even lower discrepancies, ranging up to 9%, apart from positions E2 (25%) and Be-N (23%) where again all codes’ results are less favourable.
Figure 2a: Thermal neutron fluence rate calculated by the three codes in fuel assembly F-S7.

Figure 3a: Thermal neutron fluence rate calculated by the three codes in dummy assembly D-E4.

Figure 2b: Epithermal neutron fluence rate calculated by the three codes in fuel assembly F-S7.

Figure 3b: Epithermal neutron fluence rate calculated by the three codes in dummy assembly D-E4.

Figure 2c: Fast neutron fluence rate calculated by the three codes in fuel assembly F-S7.

Figure 3c: Fast neutron fluence rate calculated by the three codes in dummy assembly D-E4.

Figure 4a: Thermal neutron fluence rate calculated by the three codes in reflector Be-N.

Figure 4b: Epithermal neutron fluence rate calculated by the three codes in reflector Be-N.
Similarly, ANET’s fast neutron fluence rate results show less than 11% deviation from measurements for the bulk of the positions. Nonetheless, in positions F3, E4 and Be-N, the three codes’ computations display higher deviation from measurements, ranging up to 25% for ANET. It is noteworthy however, that uncertainties of 12% and 10% for thermal and epithermal fluence rates in fuel assemblies and 5% for fast fluence rates are mentioned in the measured responses in Section 3.1. In almost all cases, ANET seems to be in better accordance with MCNP results which can be attributed to the common use of the JEFF3.1.2 library. The vertical fluence rate profiles depicted in Figures 2, 3 and 4, obtained by ANET, TRIPOLI and MCNP results, show that ANET can perform quite satisfactorily these simulations. It should be noted that ANET computations are in compliance with independent corresponding simulations [11] performed by the deterministic code system XSDRN/CITATION [12]. Subsequent studies will include the incorporation of ENDF-VI and ENDF-VII libraries in ANET for further verification and validation of ANET’s fluence rate simulation capability.

4 CONCLUSIONS

The ANET Monte Carlo code aims to be capable of computing neutron fluence rates throughout the neutron energy spectrum in GEN II/III reactors and ADSs. In this work, ANET was tested with respect to its ability of computing thermal, lower epithermal and fast neutron fluence rates in various positions along with vertical profiles of thermal, epithermal and fast neutron fluence rates in four representative channels of the RPI core. The obtained calculations are compared to corresponding ones provided by other simulations as well as measurements. ANET’s results adequately demonstrate that neutron fluence rate simulation in compact size pool type LEU cores using MTR fuel elements of slab geometry can be performed successfully. The slightly different results obtained by the TRIPOLI code compared to those obtained by ANET and MCNP are mostly attributed to the different neutron cross section libraries used. Incorporation of nuclear data libraries such as ENDF will be realized in the near future in order to continue the verification and validation effort for ANET.

ACKNOWLEDGMENTS

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: Thales. Investing in knowledge society through the European Social Fund.
Authors would like to thank Dr J. Marques from Instituto Superior Técnico, ULISBOA, for his collaboration in the acquisition and exploitation of data from the RPI as well as Dr M.-T. Jaeckel from Lab. de Physique Théorique, Ecole Normale Supérieure and Professors B. Gaveau and G. Maurel from UPMC, France, for their contribution in the ANET code development and finally Prof. A. Clouvas from Dept of Electrical & Computer Engineering, Aristotle University of Thessaloniki, for his contribution to the realization of this research.

REFERENCES


