TRIPOLI-4® calculations of neutron multiplicity counting rates of ^{3}He array detectors and verification tests of an automatic MCNP-to-TRIPOLI conversion tool for recent ICSBEP subcritical experiments

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Abstract. TRIPOLI-4® is a general-purpose Monte Carlo radiation transport code developed at CEA Paris-Saclay center. It uses continuous-energy nuclear data to simulate neutron transport for diverse nuclear engineering fields. Neutron multiplication calculations of subcritical systems are important for application areas including criticality safety, reactor ex-core monitoring, and non-proliferation of nuclear materials. Subcritical experiments were performed by the LANL teams to improve subcritical simulation capabilities of MCNP code and to validate ^{3}He based array detectors. Three of these experimental series based on Ni, W, and Cu reflected Pu spheres and related MCNP calculations were published on 2020 ICSBEP handbook. New automation conversion tool of MCNP geometries to TRIPOLI-4® ones has been available. In this study, the traditional manual modelling of above Pu-W and Pu-Cu cases (17 configurations including Cu and polyethylene reflectors) was first prepared. The MCNP/TRIPOLI-4® converted ones were secondly set for Pu-Cu cases. Finally the singles counting rate R1 (cts/s) in a single NPOD detector for Pu-W cases and in two NoMAD detectors for Pu-Cu cases were calculated. Generally, a good agreement of R1 was obtained between the TRIPOLI-4® calculations and the ICSBEP reported results. When using the polyethylene reflector layers in some Pu-Cu experiments, a difference of 5 to 16 % for R1 was observed between TRIPOLI-4 (Converted) results and the ICSBEP measured ones.

1 Introduction

TRIPOLI-4® is the French reference Monte Carlo radiation transport code developed by the Service d'Études des Réacteurs et de Mathématiques Appliquées at CEA Paris-Saclay center [1]. Its development is also supported by EDF (Électricité de France). TRIPOLI-4® code uses continuous-energy nuclear data to simulate neutron, photon, electron and positron transport in fields like radiation protection and shielding, fission reactor physics, nuclear criticality

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safety, and nuclear instrumentation. Three calculation modes are available to run the code: fixed-source shielding mode, criticality mode, and fixed-sources criticality mode.
Neutron multiplication calculations of subcritical systems are important for several application areas including criticality safety, reactor ex-core monitoring, and non-proliferation of nuclear materials. Several subcritical experiments were performed by the LANL teams to improve subcritical simulation capabilities of MCNP code and to verify and validate ^{3}He based array detector systems. Three of these experiments based on Ni, W, and Cu reflected plutonium spheres and related MCNP calculations were recently published on ICSBEP handbook [2-4].

The neutron collar detector and the slab monitor are widely used in the safeguards to verify the nuclear fuel assemblies and to monitor the movements of Pu, PuO_2 powder and MOX fuel. Their detection efficiency depends not only on the volume, the ^{3}He fill pressure and the number of detector tubes but also on the thickness and density of the polyethylene moderator. The use of fixed-source shielding mode of TRIPOLI-4® code for neutron counting rates calculations of ^{3}He array detector were already validated against experiments using ^{252}Cf neutron source. [5]

New automation conversion tool, t4-geom_convert, of MCNP geometries to TRIPOLI-4® ones has been available [6]. In this study, the traditional manual modelling of above Pu-W (8 configurations) [4] and Pu-Cu (17 configurations) [3] cases was first prepared. The MCNP/TRIPOLI-4® converted ones were secondly set using the conversion tool for Pu-Cu cases. The T4G display tool of TRIPOLI-4® code was used to verify both models. Finally both the singles counting rate R1 (cts/s) in a single NPOD detector for Pu-W cases and in two NoMAD detectors for Pu-Cu cases were calculated with the fixed-sources criticality mode of TRIPOLI-4® code.

2 Neutron multiplication measurement of subcritical experiments

The three recent published subcritical experiments are available from the ICSBEP handbook. Two of them were used in this study. They are the experiments based on W and Cu reflected plutonium spheres (See Figs 1-4). For the Pu-W (also called BeRP/W [4]) experiments, 8 different thicknesses of tungsten reflectors were taken into account to study the various degree of subcritical configurations. For the Pu-Cu (also called SCRαP [3] - Subcritical Copper-Reflected α-phase Plutonium) experiments, 17 configurations of copper or/and polyethylene reflected plutonium ball configurations were arranged (See Fig. 2-5).

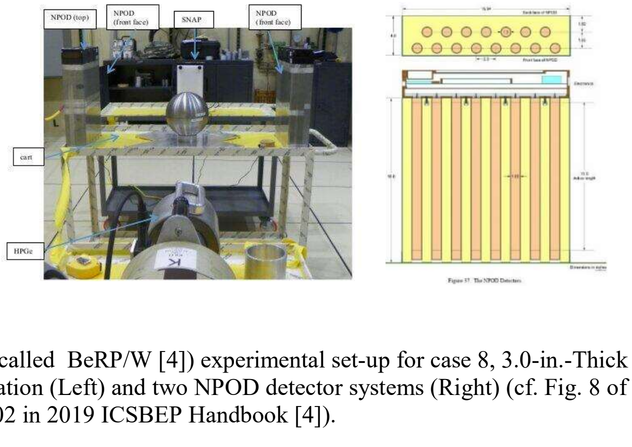


Fig. 1. Pu-W (also called BeRP/W [4]) experimental set-up for case 8, 3.0-in.-Thick Tungsten Reflector Configuration (Left) and two NPOD detector systems (Right) (cf. Fig. 8 of FUND-NCERC-PU-HE3-MULT-002 in 2019 ICSBEP Handbook [4]).

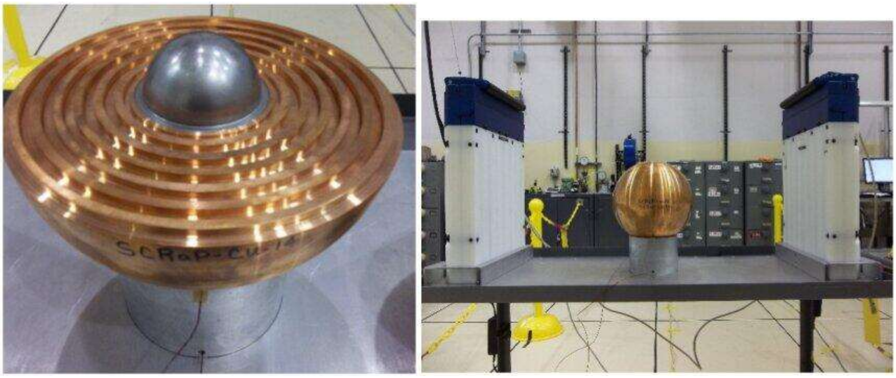


Fig. 2. Pu-Cu (also called SCRαP - Subcritical Copper-Reflected α-phase Plutonium) experimental set-up. Case 10, Pu ball and 7 copper reflector layers configuration (Left) and two ^{3}He array detectors (Right) (cf. Fig. 11 of FUND-NCERC-PU-HE3-MULT-003 in 2019 ICSBEP Handbook [3]).

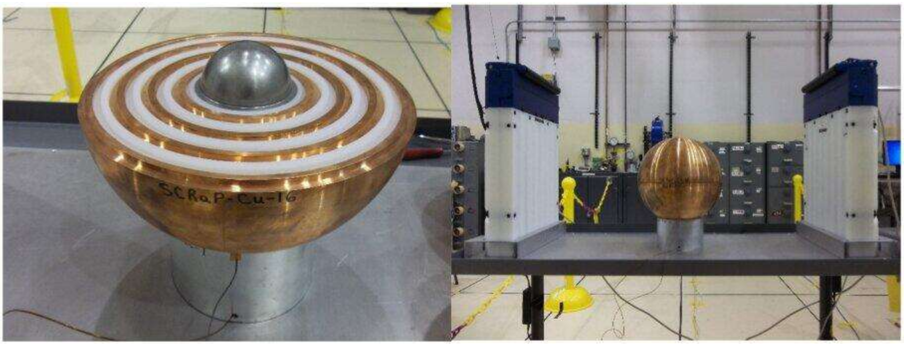


Fig. 3. Pu-Cu (also called SCRαP - Subcritical Copper-Reflected α-phase Plutonium) experimental set-up. Case 7, Pu ball and 8 reflector layers: polyethylene layer followed by alternating layers of copper and polyethylene configuration (Left) and two ^{3}He array detectors (Right) (cf. Fig. 8 of FUND-NCERC-PU-HE3-MULT-003 in 2019 ICSBEP Handbook [3]).

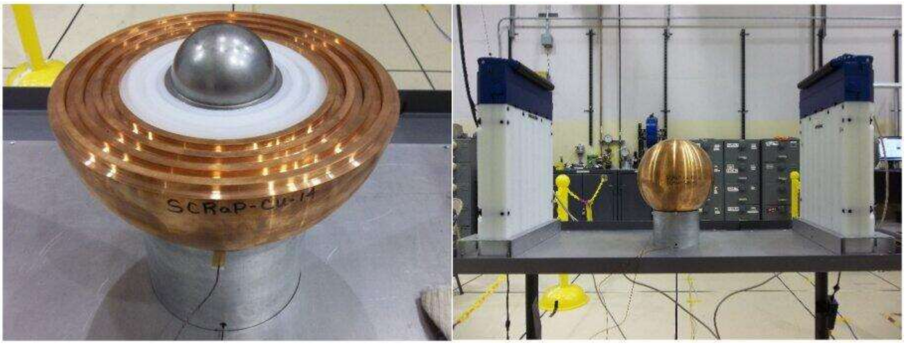
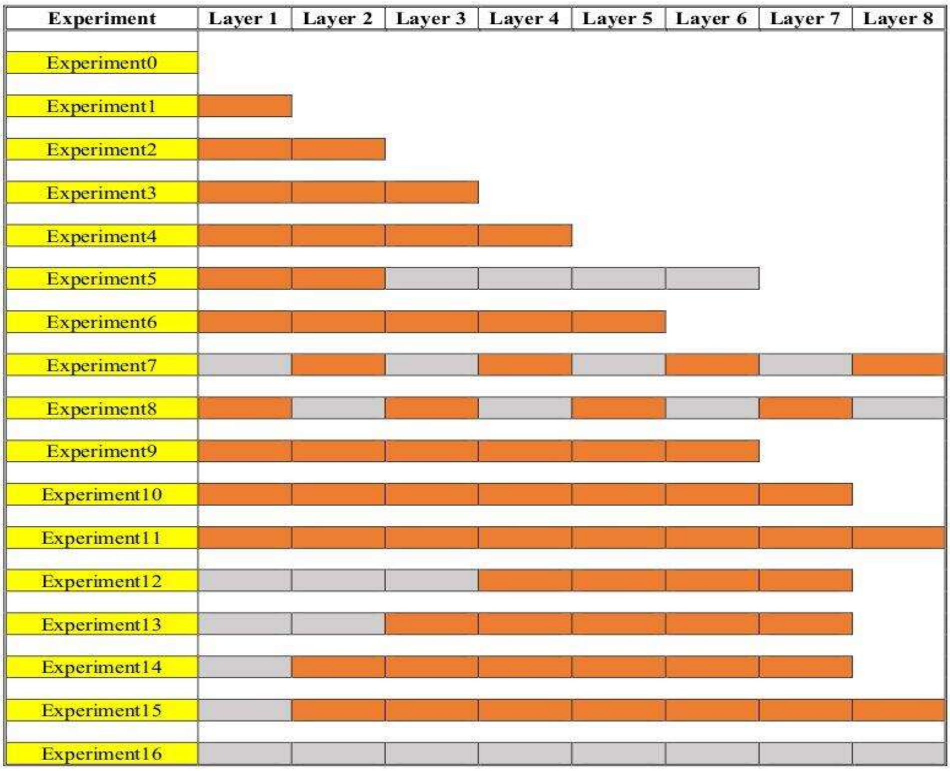


Fig. 4. Pu-Cu (also called SCRαP - Subcritical Copper-Reflected α-phase Plutonium) experimental set-up. Case 12, Pu ball and 7 reflector layers: 3 polyethylene layers followed by 4 layers of copper (Left) and two ^{3}He array detectors (Right) (cf. Fig. 13 of FUND-NCERC-PU-HE3-MULT-003 in 2019 ICSBEP Handbook [3]).



Experiment	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
Experiment0								
Experiment1	🟧							
Experiment2	🟧	🟧						
Experiment3	🟧	🟧	🟧					
Experiment4	🟧	🟧	🟧	🟧				
Experiment5	🟧	🟧	▨	▨	▨	▨		
Experiment6	🟧	🟧	🟧	🟧	🟧			
Experiment7	▨	🟧	▨	🟧	▨	🟧	▨	🟧
Experiment8	🟧	▨	🟧	▨	🟧	▨	🟧	▨
Experiment9	🟧	🟧	🟧	🟧	🟧	🟧		
Experiment10	🟧	🟧	🟧	🟧	🟧	🟧	🟧	
Experiment11	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Experiment12	▨	▨	▨	🟧	🟧	🟧	🟧	
Experiment13	▨	▨	🟧	🟧	🟧	🟧	🟧	
Experiment14	▨	🟧	🟧	🟧	🟧	🟧	🟧	
Experiment15	▨	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Experiment16	▨	▨	▨	▨	▨	▨	▨	▨

Fig. 5. Pu-Cu (also called SCRαP - Subcritical Copper-Reflected α-phase Plutonium) benchmark experiments. Seventeen subcritical configurations consisting of either a bare plutonium sphere or the sphere reflected by various thicknesses of copper and polyethylene were measured. Eight reflector layers are of 0.465, 0.955, 1.445, 1.935, 2.425, 2.915, 3.405, and 3.895 in of thickness. The orange layer corresponds the copper reflector and the grey layer the polyethylene one. (See Table. 1 of FUND-NCERC-PU-HE3-MULT-003 in 2019 ICSBEP Handbook [3]).

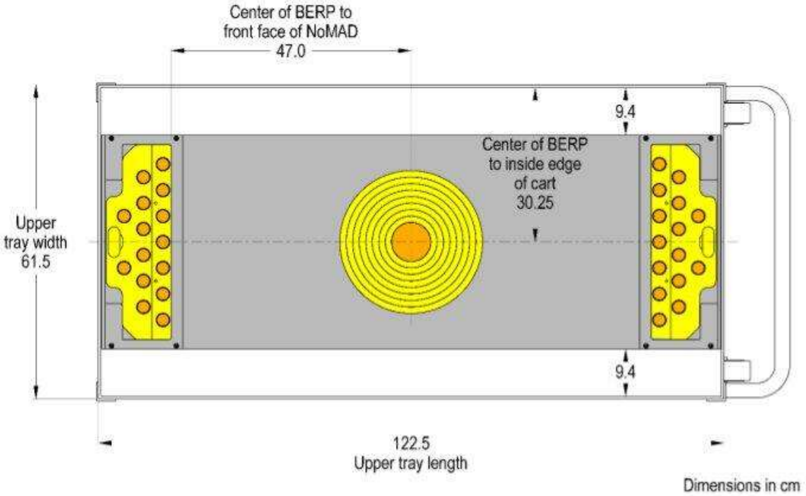


Fig. 6. Overview of full setup for Pu-Cu (also called SCRαP - Subcritical Copper-Reflected α-phase Plutonium) experiment. Horizontal slice. (cf. Fig. 18 of reference [3]).

Different detector systems were used in these experiments to measure the leakage neutron and photon particles from the plutonium core. NPOD and NoMAD neutron detectors were respectively used for Pu-W and Pu-Cu experiments [3, 4]. NPOD contains 15 tubes of ^{3}He arranged in two arrays (See Fig. 1, Left side). NoMAD also contains 15 tubes of ^{3}He encased in polyethylene and arranged in three arrays to measure neutrons (See Fig. 6 and 9).

These ^{3}He tubes serve as the capture-based detection system for neutron multiplicity measurements. The polyethylene moderates incoming neutrons, increasing their interaction probability within individual ^{3}He tubes. When neutrons interact with the ^{3}He tubes, they undergo a (n,p) process, resulting in the emission of protons. The detection system records and measures them as a current, and convert them to neutron counts. NPOD and NoMAD also play an essential role in tracking neutron lifespans [7] and, using the event-by-event FREYA fission model in TRIPOLI-4® code [8], this part will be treated in the next study.

3 TRIPOLI-4® modeling and calculations

The manual modelling of above Pu-W configurations for TRIPOLI-4® calculations was already presented in Ref. [4]. Similar method was applied on the Pu-Cu cases. Figure 7 shows the bare Pu ball and the NPOD detectors modeling case using the T4G display tool [4].

Using the automatic conversion of MCNP geometries to TRIPOLI-4® ones [6], the MCNP files from the ICSBEP handbook [3] were converted into TRIPOLI-4® format [1]. Figures 8 and 9 show the detailed models of converted one displayed with T4G tool of TRIPOLI-4® code. Due to the present conversion tool (t4_geom_convert, version v1.0.0) only treating geometrical data and material compositions, it is necessary to add manually neutron source data, reaction rates tallies, and simulation options for the TRIPOLI-4® input file.

To verify the validity of the MCNP/TRIPOLI-4® converted files, traditional manual made TRIPOLI-4® input files were also prepared according to the ICSBEP benchmark document [3]. Figures 10 and 11 show the simplified models of Pu-Cu cases (experiments 7 and 12, cf Figures 3-5) based on the manual made TRIPOLI-4® input files.

The neutron driving source originates from two different processes: spontaneous fissions and (α,n) reactions occurring inside the plutonium ball. The spontaneous fission source strength has been computed and they are also available from the Table 142 of reference [3]. The spontaneous fission source is dominated by the contribution of ^{240}Pu and the (α,n) neutron source rate contributes only 1.49 % of the total neutron source rate.

In this study the energy distribution of the initial neutron source was a Watt fission spectrum of ^{240}Pu spontaneous fission. The two parameters, a and b, of Watt spectrum used in this work were taken from the Table 5 of J. Verbeke's report UCRL-AR-228518. The driving neutron source intensity for the simplified model of Pu-W and Pu-Cu cases was 1.28E5 fission/s. The TRIPOLI-4® source normalization factor for leaking neutron counting rate calculations was 2.763E5 n/s and the source volume size 228.724 cm^3.

For the reaction rate tallies, the counting rates of ^{3}He(n,p) reactions in each tube counter are different. To identify the ^{3}He counter cells in each NoMAD detector from the MCNP/TRIPOLI-4® converted files, T4G display tool was helpful [9]. The sum of the counting rates from 30 tubes of ^{3}He counter in two NoMAD detectors was recorded as R1 (cts/sec). For the Pu-W experiments, the ICSBEP reported R1 of NPOD detector values are only for 15 tubes of ^{3}He counter in one NPOD detector.

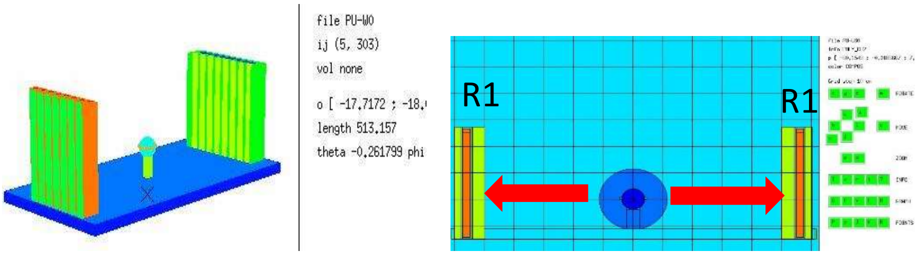


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Fig. 7. TRIPOLI-4® calculation model for the Pu-W configuration. Two NPOD neutron multiplicity ^{3}He array detector in polyethylene moderators for leakage neutron measurement of subcritical experiments [4]. Vertical view (Left) and leaking neutron counting rate R1 measurement (Right).

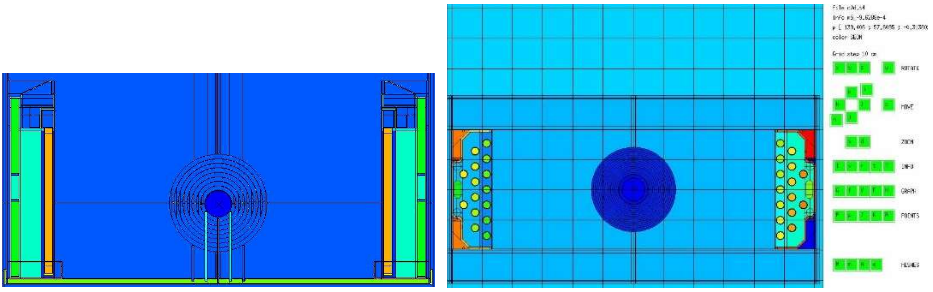

Fig. 8. TRIPOLI-4® calculation model for the Pu-Cu configuration. Two NoMAD detectors in polyethylene moderators for leakage neutron measurement of subcritical experiments. Vertical view (Left) and horizontal view (Right).

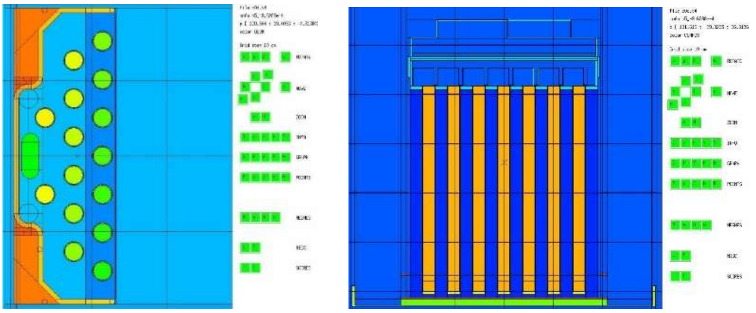

Fig. 9. TRIPOLI-4® calculation model for the modern Neutron Multiplicity ^{3}He Array Detector (NoMAD) in polyethylene moderators for leakage neutron measurement of subcritical experiments. Horizontal view of NoMAD detector including 15 ^{3}He tubes in polyethylene moderator (Left) and vertical view of first array of 7 ^{3}He counters facing the Pu-Cu ball (Right).

4 TRIPOLI-4® calculation results

The TRIPOLI-4® calculated of neutron multiplicity counting rates of ^{3}He array detectors for subcritical reflected plutonium spheres Pu-W are presented in Fig. 12. A good agreement was observed between the TRIPOLI-4® results and benchmark ones (measurements and MCNP6 calculations).

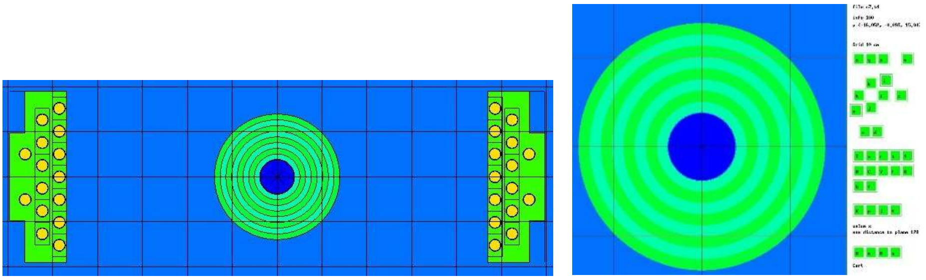

Fig. 10. Traditional manual made TRIPOLI-4® simplified calculation model for the Pu-Cu subcritical experiment 7 (see Fig. 3). Horizontal view including NoMAD ^{3}He tubes in polyethylene moderator (Left, grid 10 cm, 47 cm from the Pu ball center to the entrance surface of NoMAD detector, cf also Fig. 6) and vertical view of Pu ball in deep blue and 8 reflector layers: polyethylene layer followed by alternating layers of copper in green and polyethylene in light blue configuration (Right, grid 10 cm).

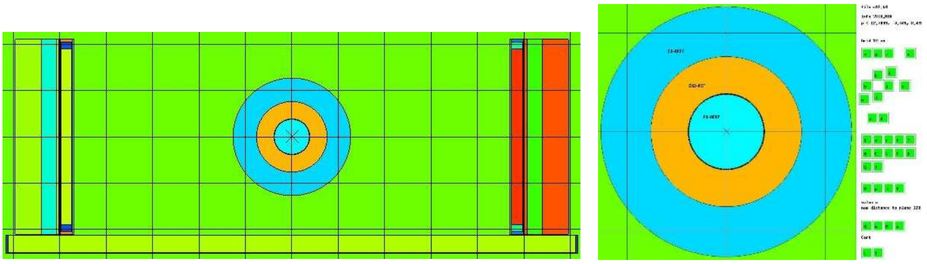

Fig. 11. Traditional manual made TRIPOLI-4® simplified calculation model for the Pu-Cu subcritical experiment 12 (see Fig. 4). Vertical view including NoMAD ^{3}He tubes in polyethylene moderator (Left, grid 10 cm, 47 cm from the Pu ball center to the entrance surface of NoMAD detector) and vertical view of Pu ball and 7 reflector layers: 3 polyethylene layers merged in orange color followed by 4 layers of copper merged in blue color (Right, grid 10 cm).

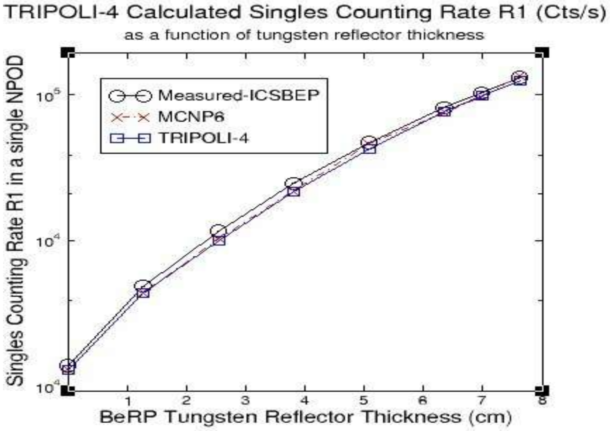

Fig. 12. TRIPOLI-4® calculated singles counting rates R1 (cts/s) in one NPOD detector for Pu-W cases.

For the Pu-Cu benchmark experiments, the TRIPOLI-4® calculated results are presented in the Figures 13 and 14.

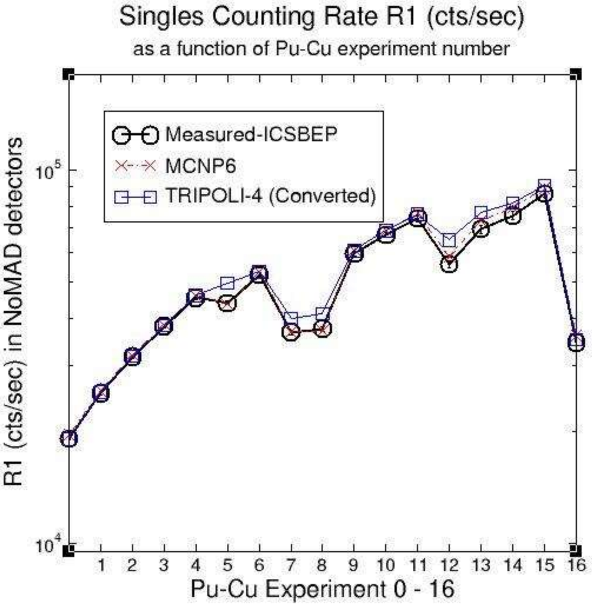

Fig. 13. TRIPOLI-4® calculated singles counting rates R1 (cts/s) in NoMAD detectors for Pu-Cu simplified models. (TRIPOLI-4® geometrical data and material compositions were obtained from the MCNP/TRIPOLI-4 conversion tool).

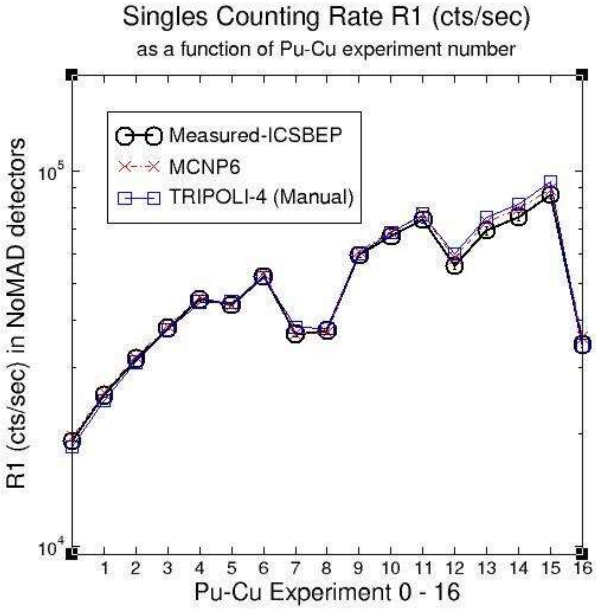

Fig. 14. TRIPOLI-4® calculated singles counting rates R1 (cts/s) in NoMAD detectors for Pu-Cu simplified models. (TRIPOLI-4® geometrical data and material compositions were manually prepared according to the ICSBEP handbook).

For the R1 counting rates presented in figures 13 and 14, when the reflector polyethylene related cases are excluded (see Fig. 5), generally a good agreement between TRIPOLI-4 (Converted) and TRIPOLI-4 (Manual) calculations can be obtained. It is also the case for benchmark TRIPOLI-4®, MCNP6, and ICSBEP measured ones. The TRIPOLI-4® calculation uncertainties for R1 were lower than 0.4 %. The total uncertainties of experiments for R1 were up to 2.6 % (cf Tables 144 and 145 of reference [3]).

A difference from 5 to 16 % for R1 was observed between TRIPOLI-4® (Converted) and the ICSBEP measured ones when the polyethylene reflector was introduced into the Pu-Cu cases. To explain the difference of R1 results for Pu-Cu experiments using polyethylene reflectors (experiments 5, 7, 8, 12, 13, 14, 15, and 16, see Fig. 5), some possible causes are listed below for advanced analyses in the next steps of future study:

- Different methods were used to obtain R1 counting rates for MCNP6 code and TRIPOLI-4® code. The NoMAD list-mode data were generated by MCNP6 and the post-processing results depend on the detector gate-width for experimental R1 [7]. TRIPOLI-4® directly calculated the R1 under the fixed-source criticality mode. Future TRIPOLI-4 calculations using the FREYA fission model may be helpful to improve these cases [8].
- For experiments 12, 13, 14, and 15, the difference between TRIPOLI-4 (Converted) and ICSBEP reported results decreases when polyethylene thickness decreases. The R1 decreases from case 10 to 12 and from case 15 to 16 are primary due to the softer leaking neutron energy.
- Some differences exist in polyethylene cross sections and polyethylene cross sections processing tools for data libraries ENDF/B-VIII.0 (used by MCNP6) and ENDF/B-VIII.1 beta version (used by TRIPOLI-4) in this study.
- Some approximations in geometrical modelling were made in TRIPOLI-4 (Manual) model (see Figures 10 and 11).
- More tests are needed for the recent developed MCNP/TRIPOLI-4® conversion tool.
- Detailed verification may be helpful for the MCNP6 input files of ICSBEP handbook for polyethylene reflector cases of Pu-Cu experiments.

5 Conclusions

Nuclear criticality safety calculations and nuclear instrumentation applications are basic functions of the TRIPOLI-4® Monte Carlo radiation transport code. Fixed-sources criticality mode of TRIPOLI-4® was successfully used in this work to study the neutron multiplication of Pu-W and Pu-Cu subcritical experiments of the 2020 ICSBEP handbook. The neutron multiplicity counting rates R1 were calculated for the ^{3}He array detectors NPOD (Pu-W experiments) and NoMAD (Pu-Cu experiments). Using the manual prepared TRIPOLI-4® input files and those generated by the MCNP/TRIPOLI-4® geometrical conversion program, several Pu-W and Pu-Cu subcritical experiments were interpreted. Generally, a good agreement of singles counting rates R1 between TRIPOLI-4® and ICSBEP reported results was obtained. When using polyethylene reflector layers in Pu-Cu cases, a difference of 5 to 16 % for R1 was observed between TRIPOLI-4 (Converted) and the ICSBEP measured ones. The MCNP/TRIPOLI-4 geometrical conversion program, t4_geom_convert, is a convenient tool to perform the verification and validation study of these two Monte Carlo transport codes but more tests of the recently developed conversion tool are needed. Verification of polyethylene cross sections of nuclear data libraries are also necessary. In the next step, the leaking multiplication factor (M_L) and doubles count rate (R2) of Pu-Cu experiments will be tested and reported using the event based FREYA fission model in TRIPOLI-4® calculations.

ACKNOWLEDGEMENTS

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