

Quantitative Assessment of Be-9 Photonuclear Contributions to TBM Shutdown Dose Rate

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1. Introduction

The ITER HCCP (Helium-Cooled Ceramic Pebble-bed) TBM, developed under the KODA-F4E collaboration, uses beryllium pebble beds as a neutron multiplier in the breeder blanket [1, 2]. Following shutdown, decay gamma rays with energies above the Be-9 photonuclear threshold can interact with the beryllium multiplier and produce secondary neutrons through the ${}^9\text{Be}(\gamma,n){}^8\text{Be}$ reaction [5, 6]. Because Be-9 has the lowest photoneutron threshold among stable nuclei ($Q = -1.665$ MeV), this physical reaction pathway raised concern regarding its potential contribution to the shutdown radiation field. The resulting photoneutrons can contribute directly to the neutron dose and can additionally generate prompt gamma rays through capture and scattering.

To quantify the contribution of this physical pathway, the present study modeled photonuclear transport with the D1S-UNED and MCNP transport systems [3, 4]. To evaluate the effect of this pathway on the HCCP TBM SDDR, the present study combined a reference D1S SDDR calculation, a photonuclear source-characterization calculation, and a dedicated fixed-neutron-source dose calculation.

The need for this assessment arises because previous ITER TBM SDDR studies focused on activation, shielding performance, and maintenance dose fields rather than on an explicit decomposition of the Be-9 photonuclear contribution [1, 2, 7, 8]. D1SUNED provides the computational framework for this assessment by implementing the Direct One-Step methodology in MCNP5 for the calculation of decay-photon fields and related quantities [3]. Within the D1S numerical treatment, each activation-producing neutron collision is coupled to the corresponding decay-photon emission, while the irradiation and cooling histories are represented by correction factors [3]. The photonuclear physics implemented in MCNP enables secondary-neutron production from photon interactions to be simulated using evaluated photonuclear data [4, 11]. In the present work, a numerical transport setting was used to include or exclude this pre-existing physical pathway in the transport calculation.

Pampin et al. investigated the radiation impact of delayed photoneutron production in ITER components [9]. Martínez-Albertos et al. used D1SUNED to assess remote-handling radiation fields and to calculate photoneutron-flux maps for beryllium first-wall panels [10]. These studies established the relevance of delayed

photoneutrons to ITER component handling and electronics protection [9, 10]. However, neither study quantified the photonuclear neutron and secondary prompt-gamma dose components relative to the D1S decay-gamma SDDR for the HCCP TBM [9, 10]. Accordingly, the present study quantifies the photonuclear neutron and secondary prompt-gamma dose components within the local TBM model and evaluates their contributions relative to the D1S decay-gamma SDDR.

2. Photonuclear Physics and Calculation Method

2.1. Be-9 photonuclear physics

In this study, the ${}^9\text{Be}(\gamma,n){}^8\text{Be}$ reaction was evaluated with a threshold energy of $E_{\text{th}} = 1.665$ MeV, the lowest photoneutron threshold among stable nuclei. The cross-section data were taken from the ENDF/B-VII.0 photonuclear evaluation, processed as MCNP ACE evaluation 4009.70u (MAT 425), and comprise 163 energy points from 1.665 to 30 MeV, as shown in Fig. 1.

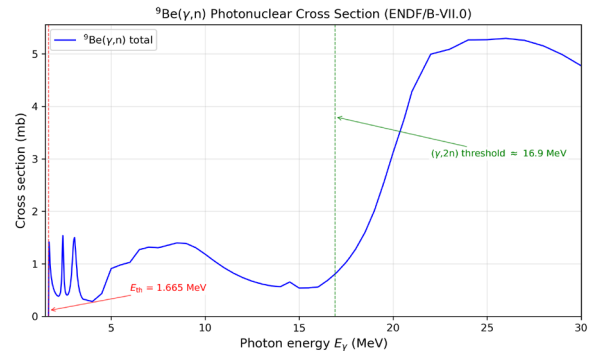


Fig. 1. Total ${}^9\text{Be}(\gamma,n)$ photonuclear cross section from ENDF/B-VII.0.

The cross section rises sharply above threshold, exhibits structure in the 1.6–4 MeV range including the Giant Dipole Resonance, and reaches millibarn-level magnitudes. The total photonuclear cross section was used for source-rate estimation by summing all neutron-producing channels. The available decay-gamma spectrum extends only to approximately 4 MeV; therefore, the $(\gamma,2n)$ channel above 16.9 MeV does not contribute.

The secondary-neutron energy distribution was derived by weighting the cell-averaged photon spectrum

$\phi(E\gamma)$ in the Be multiplier region with the total photonuclear cross section $\sigma_{\text{tot}}(E\gamma)$. For each reacting gamma energy $E\gamma > E_{\text{th}}$, the emitted neutron energy follows the non-relativistic two-body kinematics in Eq. (1):

$$\begin{aligned} E_n &= (E\gamma - E_{\text{th}}) \cdot m_{\text{Be-8}} / (m_n + m_{\text{Be-8}}) \\ &= (E\gamma - 1.665) \times 8/9 \text{ MeV} \end{aligned} \quad (1)$$

Here, $m_{\text{Be-8}}$ is the mass of the residual Be-8 nucleus and m_n is the emitted-neutron mass. The non-relativistic two-body relation uses the mass-number approximation $m_{\text{Be-8}}/(m_n + m_{\text{Be-8}}) \approx 8/9$.

Emitted neutrons were sampled isotropically. Near the ^9Be photoneutron threshold, the angular distribution is approximately isotropic because the process is

dominated by E1 electric-dipole transitions [6]. In the evaluated reaction-rate distribution, 99.85% of the reaction rate originates within 0.3 MeV of threshold, which supports this approximation. The continuous E_n distribution was discretized into 19 energy bins.

2.2. Calculation framework and photonuclear source construction

The assessment consisted of three linked calculations, summarized in Table I: a reference D1S SDDR calculation, a photonuclear source-characterization calculation, and a dedicated photonuclear dose calculation. All three calculations used the same local TBM geometry to maintain consistency in source normalization and spatial comparison.

Table I: Summary of the calculation framework

Calculation role	Code	Physical treatment	Principal output
Reference decay-gamma SDDR	D1S-UNED 3.1.2	Decay-gamma transport without photoneutron production	Reference SDDR field and comparison denominator
Photonuclear source characterization	D1S-UNED 3.1.2	Be-9 photoneutron production using evaluated photonuclear data	Photoneutron source strength and energy distribution
Dedicated photonuclear dose	MCNP5 [13]	Fixed photoneutron source transport	Photoneutron and secondary prompt-gamma dose components

The reference calculation used D1S-UNED 3.1.2 to calculate the decay-gamma SDDR with photoneutron production excluded and with ICRP-74 photon dose conversion coefficients [3, 12]. The resulting SDDR provided the reference radiation field and the denominator used to evaluate the relative photonuclear dose contribution.

The source-characterization calculation used the same D1S model and irradiation and cooling conditions but included Be-9 photoneutron production based on evaluated photonuclear data [3, 4, 11]. The decay-gamma field in the Be multiplier was combined with the evaluated $^9\text{Be}(\gamma, n)$ cross section to determine the spatial reaction-rate distribution and total photoneutron source strength. The secondary-neutron energy distribution was constructed by weighting the cell-averaged photon spectrum in the Be multiplier with the total photonuclear cross section. The dedicated source was normalized to the total photoneutron source strength of 3.806×10^6 n/s obtained from the source-characterization calculation.

The dedicated fixed-neutron-source calculation was performed with MCNP5 [13] to calculate the photoneutron and secondary prompt-gamma dose components. These outputs represent photoneutron and secondary prompt-gamma dose rates in $\mu\text{Sv/h}$ and were evaluated relative to the reference decay-gamma SDDR. Separate fluence-to-dose conversion coefficients and a more specific dose-quantity designation for the dedicated outputs were not reported in the source documentation;

this limits reproducibility of their absolute dose interpretation.

2.3. Dedicated photonuclear dose calculation and model assumptions

The photonuclear dose calculation adopted the irradiation and reaction definitions of the reference D1S model, including the standard ITER DT-1 irradiation schedule and a cooling time of 7 days. A fusion neutron source strength of 1.5×10^{18} n/s was assumed for source normalization.

The dedicated photonuclear source was normalized to the total photoneutron source strength obtained from the source-characterization calculation, whereas its spatial distribution was approximated using a representative Be cell in the inner pebble-bed layer. Source particles were sampled uniformly within the bounding box of the representative cell, with cell-rejection sampling used to confine the particles to the Be region. This representative-cell treatment was a cell-average approximation and did not reproduce the exact spatial distribution of photonuclear reaction sites. Because the physical photoneutron source was assumed to be concentrated closer to the first wall, the spatial approximation was intended to avoid underestimating dose at the outer TBM boundary relevant to maintenance access. Its conservatism remains an unquantified modeling assumption because no spatial-source sensitivity bound was established.

Secondary neutrons were emitted isotropically according to the energy distribution defined in Section 2.1. The assessment was restricted to the local TBM model at a cooling time of 7 days and was not intended to represent an absolute plant-wide shutdown dose-rate field.

3. Results and Discussion

The reference D1S calculation produced an SDDR of approximately 2.5×10^7 $\mu\text{Sv/h}$ in the Be multiplier region and approximately 4×10^6 $\mu\text{Sv/h}$ at the TBM lateral boundary. The dedicated photonuclear dose results are summarized in Table II, and their relative contributions at characteristic locations are compared in Table III. Figures 2–13 compare the spatial distributions of the reference decay-gamma SDDR, photoneutron dose rate, and secondary prompt-gamma dose rate at matched planes through the TBM.

Table II: Representative results of the dedicated photonuclear dose calculation

Property	Photoneutron	Secondary prompt-gamma
Maximum	8.14 $\mu\text{Sv/h}$	0.240 $\mu\text{Sv/h}$
Median	2.85×10^{-2} $\mu\text{Sv/h}$	2.62×10^{-3} $\mu\text{Sv/h}$
Relative error of median	0.057	0.156
Relative error at peak	0.003	0.017
Peak location	Be multiplier center	TBM lateral boundary

The maximum photoneutron dose rate was 8.14 $\mu\text{Sv/h}$ at the center of the Be multiplier, whereas the maximum secondary prompt-gamma dose rate was 0.240 $\mu\text{Sv/h}$ at the TBM lateral boundary. The different peak locations reflect the concentration of photoneutron production in the Be multiplier and the accumulation of secondary photons near the TBM boundary.

Table III: Quantitative comparison of the three dose-rate components at characteristic locations

Location	Reference decay-gamma SDDR ($\mu\text{Sv/h}$)	Photoneutron dose rate ($\mu\text{Sv/h}$)	Secondary prompt-gamma dose rate ($\mu\text{Sv/h}$)	Photoneutron/reference	Secondary prompt-gamma/reference
Be multiplier center	1.67×10^7	8.14	$\sim 1.2 \times 10^{-2}$	4.9×10^{-7}	$\sim 7 \times 10^{-10}$
TBM lateral boundary	4.09×10^6	~ 3	0.240	$\sim 7 \times 10^{-7}$	5.9×10^{-8}

At the center of the Be multiplier, the reference SDDR, photoneutron dose rate, and secondary prompt-gamma dose rate were 1.67×10^7 , 8.14, and approximately 1.2×10^{-2} $\mu\text{Sv/h}$, respectively. At this location, the photoneutron and secondary prompt-gamma contributions relative to the reference SDDR were 4.9×10^{-7} and approximately 7×10^{-10} , respectively. At the TBM lateral boundary, the corresponding dose rates were 4.09×10^6 $\mu\text{Sv/h}$ for the reference SDDR, approximately 3 $\mu\text{Sv/h}$ for photoneutrons, and 0.240 $\mu\text{Sv/h}$ for secondary prompt gamma rays. The corresponding photoneutron and secondary prompt-gamma contributions were approximately 7×10^{-7} and 5.9×10^{-8} of the reference SDDR, respectively. Together, these values place the photonuclear dose contribution at the 10^{-7} scale relative to the reference decay-gamma SDDR.

The dose-rate distributions presented in this section correspond to the local TBM model at a cooling time of 7 days. One of the principal above-threshold decay-gamma emitters at this cooling time was ^{24}Na , with $t_{1/2}=14.96$ h and $E_\gamma=2.754$ MeV. The other principal emitter was ^{56}Mn , with $t_{1/2}=2.58$ h and $E_\gamma=1.811$ MeV. At 7 days, the activity of ^{24}Na was reduced by a factor of approximately 2,000, whereas that of ^{56}Mn was reduced

by about 10^{19} and was effectively extinct. The residual above-threshold decay-gamma field at 7 days was therefore governed primarily by ^{24}Na .

Figures 2–4 present the reference decay-gamma SDDR, photoneutron dose rate, and secondary prompt-gamma dose rate, respectively, in the X–Y plane at the TBM center position.

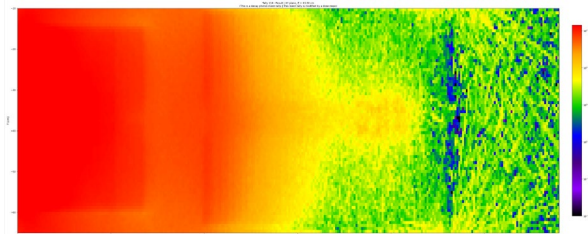


Fig. 2. Reference decay-gamma SDDR ($\mu\text{Sv/h}$) in the X–Y plane at the TBM center position.

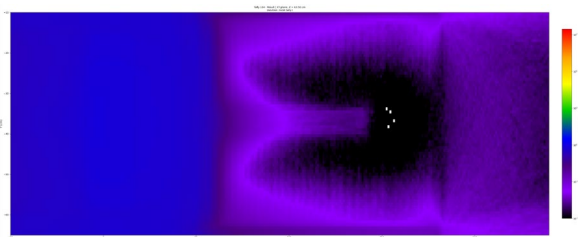


Fig. 3. Photoneutron dose rate ($\mu\text{Sv/h}$) in the X-Y plane at the TBM center position.

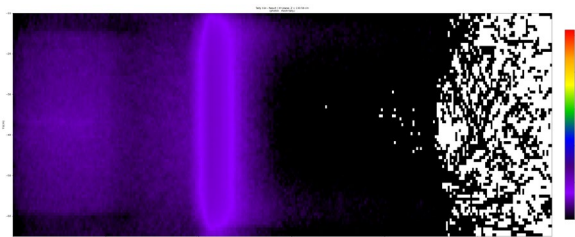


Fig. 7. Secondary prompt-gamma dose rate ($\mu\text{Sv/h}$) in the X-Y plane at the TBM peripheral position.

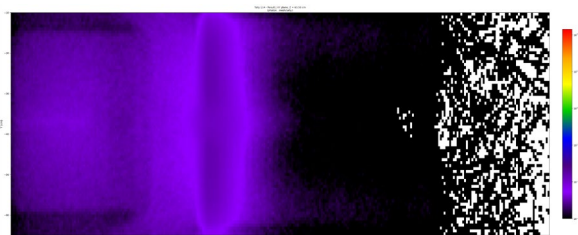


Fig. 4. Secondary prompt-gamma dose rate ($\mu\text{Sv/h}$) in the X-Y plane at the TBM center position.

Figures 5–7 present the same three dose-rate components in the X-Y plane at the TBM peripheral position.

Figures 8–10 present the three components in the X-Z plane at the TBM center position.

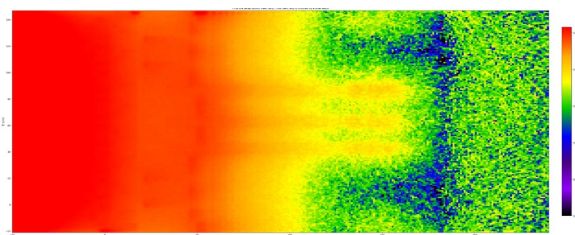


Fig. 8. Reference decay-gamma SDDR ($\mu\text{Sv/h}$) in the X-Z plane at the TBM center position.

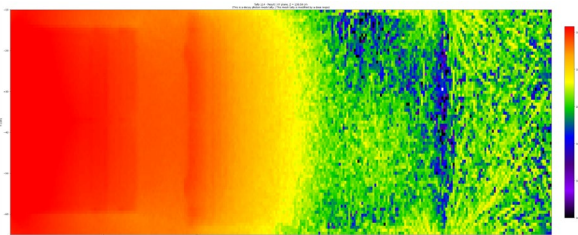


Fig. 5. Reference decay-gamma SDDR ($\mu\text{Sv/h}$) in the X-Y plane at the TBM peripheral position.

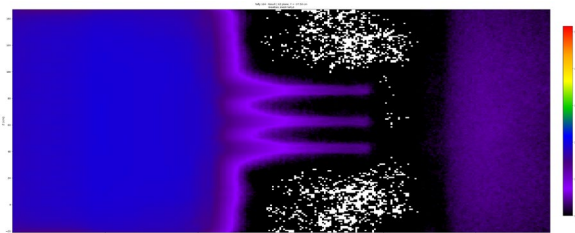


Fig. 9. Photoneutron dose rate ($\mu\text{Sv/h}$) in the X-Z plane at the TBM center position.

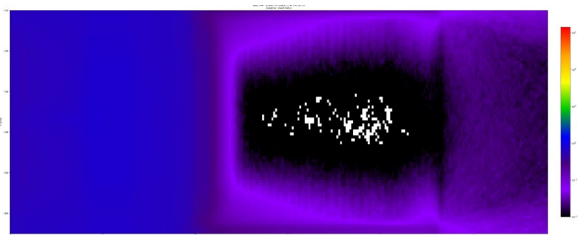


Fig. 6. Photoneutron dose rate ($\mu\text{Sv/h}$) in the X-Y plane at the TBM peripheral position.

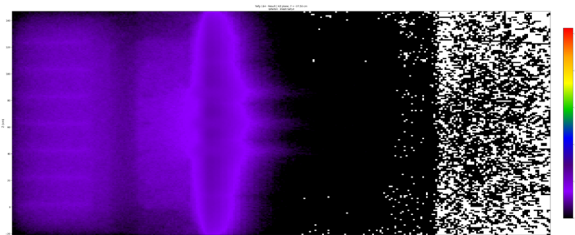


Fig. 10. Secondary prompt-gamma dose rate ($\mu\text{Sv/h}$) in the X-Z plane at the TBM center position.

Figures 11–13 present the corresponding distributions in the X-Z plane at the TBM peripheral position.

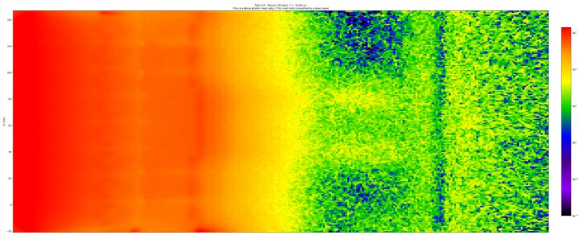


Fig. 11. Reference decay-gamma SDDR ($\mu\text{Sv/h}$) in the X-Z plane at the TBM peripheral position.

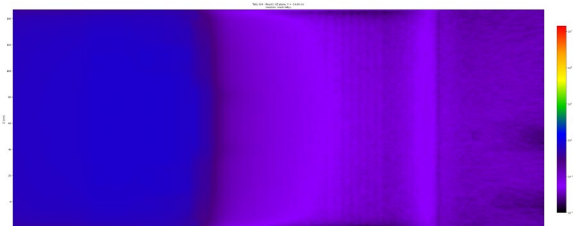


Fig. 12. Photoneutron dose rate ($\mu\text{Sv/h}$) in the X-Z plane at the TBM peripheral position.

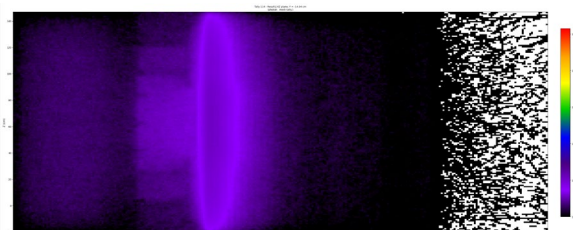


Fig. 13. Secondary prompt-gamma dose rate ($\mu\text{Sv/h}$) in the X-Z plane at the TBM peripheral position.

Together, the matched X-Y and X-Z views provide a direct spatial comparison between the reference SDDR and the two photonuclear dose components.

The statistical confidence interpretation and propagated uncertainty of the Table III ratios were not established. Sensitivity to the representative-cell and source treatments was not quantified, and the complete local photonuclear source-to-dose chain was not externally benchmarked. These limitations bound the conclusion to a screening assessment of the local TBM model at a cooling time of 7 days.

4. Conclusions

This study quantified the photoneutron and secondary prompt-gamma contributions relative to the DIS decay-gamma SDDR for the local HCCP TBM model at a cooling time of 7 days. The following quantitative conclusions were obtained.

1. The dedicated dose calculation used a photoneutron source strength of 3.806×10^6 n/s obtained from the source-characterization calculation. The

photoneutron component peaked at the center of the Be multiplier, whereas the secondary prompt-gamma component peaked at the TBM lateral boundary.

2. The photoneutron dose rate was the dominant photonuclear dose component at both characteristic locations, while both photonuclear components remained negligible relative to the reference decay-gamma SDDR.
3. Overall, the photonuclear dose contribution was at the 10^{-7} scale relative to the reference decay-gamma SDDR. These results indicate that an explicit photonuclear correction is not required for the DIS-UNED SDDR evaluation under the assessed conditions.

Acknowledgments

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