Preliminary Dose Analyses for the Transformational Challenge Reactor Facility*

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INTRODUCTION

The nuclear industry is impaired by high costs and lengthy design timeline. The Transformational Challenge Reactor (TCR) has been conceived at the Oak Ridge National Laboratory (ORNL) to accelerate the design, manufacturing, qualification, and deployment and to lower the cost of new nuclear energy power plants through the use of 3D printing technology [1]. This technology also allows to design any shape for the fuel, coolant channels, and moderator components; whereas, most traditional reactor designs use conventional manufacturing techniques. The design of the TCR facility has not been yet finalized and is under continuous optimization; within this context, this study contributes to the efforts in exploring different design configurations.

The TCR is fueled by TRISO particles containing uranium nitride. The TRISO particles are dispersed in holed hexagonal silicon carbide (SiC) blocks that are cooled by Y-shaped helium channels. The SiC blocks are manufactured by 3D printers. Eight silicon carbide blocks are stacked one after another in the axial direction. The core is moderated by yttrium hydride holed cylinders positioned at the center and corners of the silicon carbide blocks. Yttrium hydride is encapsulated in stainless steel type 316. Helium flows inside the central hole of the yttrium hydride cylinders. A stainless steel type 304L vessel encloses the silicon carbide blocks and the yttrium hydride holed cylinders. The TCR facility power is 3 MW_{th}. About 2.6% of the thermal power is deposited outside the vessel. The helium inlet and outlet temperatures are 350 and 550 °C, respectively, and pressure is 7MPa. The coolant flows inside the core from top to bottom; both inlet and outlet are positioned at the bottom of the vessel. A shutdown rod is located at the top of the vessel and penetrates the center of the core; a control shroud, made of enriched boron, is located around the vessel. The control shroud is surrounded first by an annular-shaped stainless steel reflector and then by a concrete biological shielding (bio-shield). The latter may or may not have a cover-head. A design without the bio-shield cover-head simplifies the refueling operation. This study focuses on the neutron and photon doses in the TCR facility for the configurations with and without the concrete bio-shield cover-head [2].

CALCULATION METHODOLOGY

The neutron and photon doses have been calculated by MCNP software [3] using a FMESH tally and energy dependent flux-to-dose conversion factors for the configurations with and without bio-shield cover-head, as illustrated in the top plots Fig. 1. The (FMESH) mesh tally extends from -1342, -458, and -102 up to 1342, 458, and 1220 cm on the x, y, and z axes, respectively. The spatial intervals of the mesh along the x, y, and x axes are 335, 114, and 165. For the configuration with no bio-shield cover-head, 200 batches (k-code cycles) of 4 million neutron were simulated; for the configuration with the cover-head, the number of batches has been increased up to 800. The latter simulation completed in 8 hours on a computer node with 80 cores, 2.4 GHz CPU frequency, and 250 Gb RAM memory.

The flux-to-dose conversion factors F have been taken from Table 10 of Ref. [4]. These factors are in [(mrem/h)/(particles/s/cm2)] units, consequently the FMESH tally results have been normalized according to Eq. 1.

$$dose\left[\frac{mrem}{h}\right] = FMESH\left[\frac{1}{neutrons \cdot cm^2}\right] \cdot F\left[\frac{\frac{mrem}{h}}{\frac{1}{s \cdot cm^2}}\right] \cdot Power\left[\frac{MeV}{s}\right] \cdot \frac{1}{Qvalue[MeV]} \frac{\nu[neutrons]}{k_{eff}} \quad (1)$$

In Eq. 1, it has been assumed that the facility power is 3 MW, the fission Q-value is 202.04 MeV, the number of neutrons per fission ν is 2.436, and k_{eff} is about 1.04659. The last two parameters have been taken from the MCNP output of the FMESH calculation, whereas the Q-value has been calculated by previous analyses that included neutron and photon energy deposition [5].

The total dose includes both neutron and photon contributions. For U-235, the number of photons per fission is 8.13 and the number of photons per neutron in a fission reaction is 3.33. The latter number takes into account 2.436 neutrons emerge from a fission reaction. The value of photons per neutron is 5.52 and it is than 3.33 because the former value takes into account both photons born from fission and from neutron capture.

RESULTS

The bottom plots of Fig. 1 and the top plots of Fig. 2 show the neutron and photon doses, respectively, calculated by MCNP and normalized by Eq. 1. From these plots, it is possible to draw a few conclusions:

1) the peak of neutron dose is two order of magnitudes larger than the one of the photon dose;
2) the bio-shield cover-head significantly reduces the dose in the environment surrounding the reactor core, especially for neutrons.

In the configuration without the bio-shield cover-head, some of the particles leaking out of the core in the vertical direction are scattered back by the environment surrounding the core, which enhances both the neutron and photon doses outside the bio-shield. This effect is less for photons, relative to neutrons.

The bottom plots of Fig. 2 show the relative error of the neutron dose for the configurations with and without the bio-shield cover head. For the first configuration, the relative error outside the core is generally below 10 to 20%; variance reduction techniques are needed to reduce this error. For the latter configuration, the relative error outside the core significantly grows because of the smaller values of the neutron dose. The relative error previously discussed is defined as the ratio between the standard deviation and the average value, as calculated by MCNP.

CONCLUSIONS

This study analyzed the neutron and photon doses for the TCR configurations with and without the concrete bio-shield cover-head. The neutron dose in the core is 2 order of magnitude higher than the photon dose. The back-scattering of the particles vertically leaking the core significantly enhances the dose outside the bio-shield. This effect is attenuated for photons, relative to neutrons, due to their higher penetration in matter.

According to this study, the TCR facility should be equipped with a bio-shield cover-head. However, the inclusion of this reactor component may require a more complex system to allow fuel loading/unloading operations.

ACKNOWLEDGMENTS

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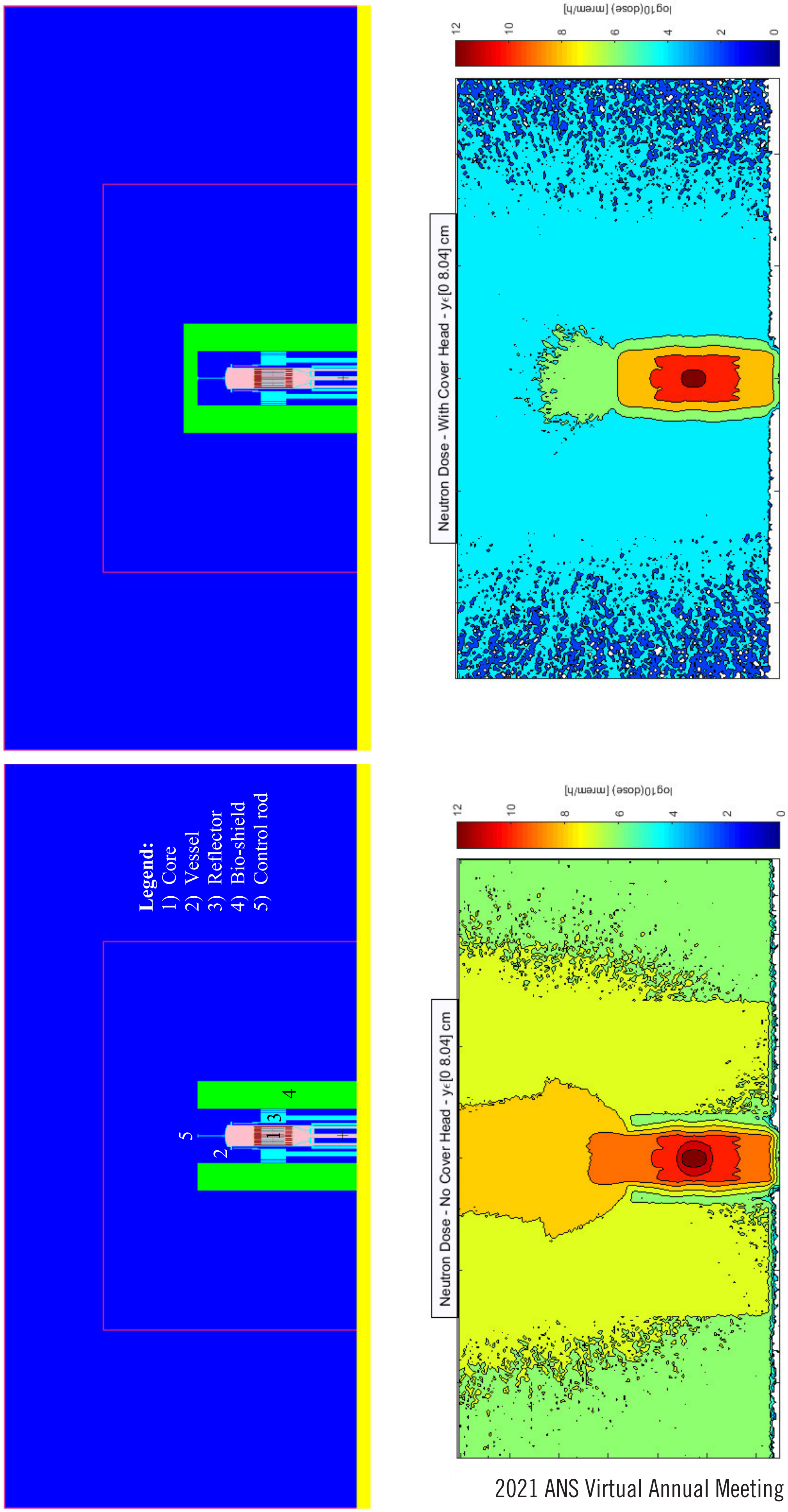

Fig. 1. Top-left plot: MCNP model of the TCR facility without bio-shield cover-head. Top-right plot: MCNP model of the TCR facility with bio-shield cover-head. Bottom-left plot: neutron dose for y between 0 and 8.04 cm without bio-shield cover-head. Bottom-right plot: neutron dose for y between 0 and 8.04 cm without bio-shield cover-head.

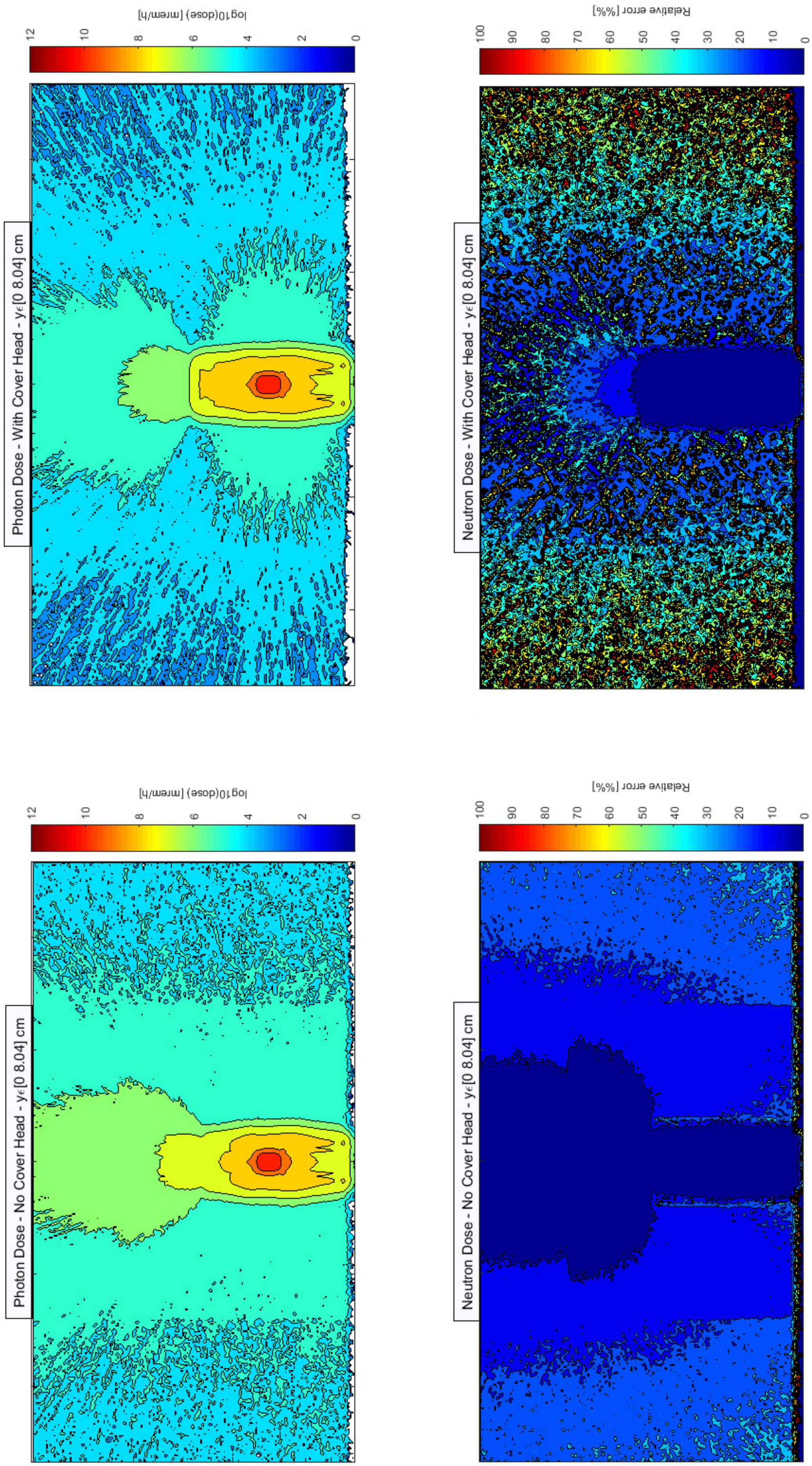

Fig. 2. Top-left plot: photon dose for y between 0 and 8.04 cm without bio-shield cover-head. Top-right plot: photon dose for y between 0 and 8.04 cm with bio-shield cover-head. Bottom-left plot: relative error of the neutron dose for y between 0 and 8.04 cm without bio-shield cover-head. Bottom-right plot: relative error of the neutron dose for y between 0 and 8.04 cm without bio-shield cover-head.