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A Preliminary Study on the Prompt Radiation Shielding Analysis for Target Rooms in the RAON ISOL Facility

Song Hyun KIM [a], Do Hyun KIM [a], Chang Ho SHIN [a,*], and SHIN Woo NAM [b]
[a]*Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seoungdong-gu, Seoul, 133-791, Korea*
[b]*Institute for Basic Science, 1689 Yuseong-daero, Yuseong-gu, Daejeon, 305-811, Korea*
[*]Corresponding author: gemini@hanyang.ac.kr

1. Introduction

RAON [1] is a specific-purpose accelerator approved by Korea government in 2009. The specific feature of the RAON is that both ISOL and IF facilities are utilized. The ISOL is a production method of the heavy ion beams generated from the light-ion imping on targets. EURISOL [2] and SPES [3] are the representative ISOL accelerators. In the target room of the RAON ISOL facilities, the accelerated proton beams with high intensity are induced to the UCx target, and thus strong neutron and photon radiations are generated by the proton-target reactions. Therefore, the radiation safety in ISOL target room and its related regions should be carefully analyzed. In this study, a preliminary study about the radiation shielding analysis on the proton-target reactions was performed to effectively analyze the prompt radiation safety.

2. Methods and Results

Fig. 1 is an overview of the ISOL target room and related facilities. A and B are the locations of UCx targets which is in the target rooms. Lines C and D are the proton beam line from the cyclotron.

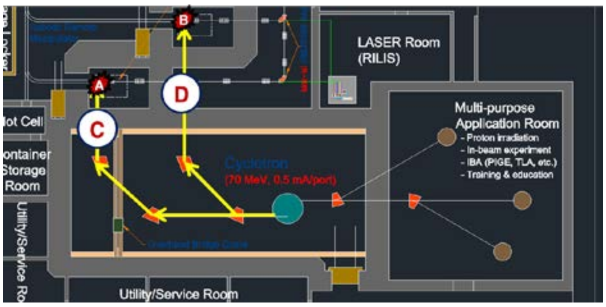


Fig. 1. Overview of the ISOL Target Room

The accelerated proton beam as given in Table I is induced to the targets, and the protons react with the target materials. The maximum intensity of proton accelerator is planned to 1 mA (6.24 x 10^{15} protons/sec). Also, the target material is the UCx target that lots of neutron is generated by the proton induced reaction. Hence, the intensity of the radiations is considerably higher than the other facilities. In this study, some characteristic analyses of the prompt radiations were pursued for the reliable and effective radiation shielding analysis in the facility. The evaluations were pursued as the following aspects: (1) stopping range for the target model decision, (2) prompt radiation generation, (3) neutron source term generation, and (4) variance reduction technique for the bulk shielding analysis. All evaluations were pursued with MCNPX 2.7 code [4] and JENDL-HE cross section library [5]. Also, for all dose estimations, ICRP 116 AP flux to dose conversion factor was used.

Table I: Specification of the Proton Beam

Classification	Value	Unit
Intensity	6.24 x 10^{15}	#/sec
Energy	70	MeV
Direction	Mono*	-

* Assumed as a mono-directional beam

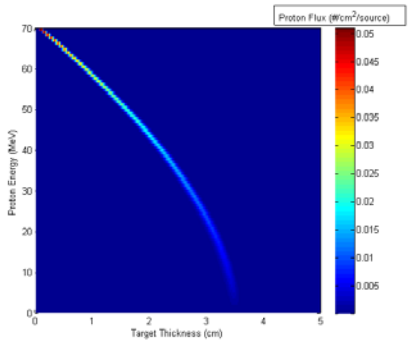
2.1 Stopping Range Analysis

In this research step, the details on the UCx target design for the generation of heavy ions in the ISOL facility are not specified. Also, it should be considered that the target model should be conservatively selected to secure expandability of the target design. It is well known that the proton-uranium reaction in the UCx target is the main cause of the prompt radiation generations. Therefore, if the target length is chosen to be longer than the proton stopping range (to react all protons in the target), the flexibility and expandability of the target design can be secured as well as good for increasing the reliability of the radiation safety analysis results. In this study, the stopping ranges of the proton beams were evaluated with the basic UCx models. The details of the targets are given in Table II.

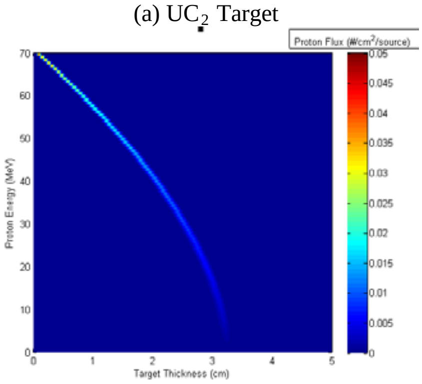
Table II: Details of UCx Target for the Stopping Range Analysis

Variable	Value
Chemical Composition	UC_2 / UC_4
Density	2.5 g/cm^3
Shape	Cylinder
Diameter	6 cm

Using the target conditions, 70 MeV proton beams were induced to the UC_2 and UC_4 targets, and the stopping ranges were evaluated with the MCNPX code. Fig. 2 is the results of the proton energy distributions as the particle track length in UC_2 and UC_4 targets, respectively. The result shows that the stopping ranges based on the results were 3.77 cm and 3.47 cm, respectively.



(a) UC_2 Target



(b) UC_4 Target

Fig.2. Proton Energy Distribution in the UC_2 and UC_4 Target

2.2 Analysis of Prompt Radiation Generation

From the proton beam reaction with nuclides, various particles are generated such as photon, neutron, proton, electron and the other heavy ions. As an aspect of the prompt radiation shielding, it is well known that the charged particles including proton and electron do not significantly affect the radiation safety analysis because they are easily shielded by the structural materials. Hence, the main radiations of the proton reaction for the radiation shielding aspect must be the neutron and photon. To study how the neutron and photon generated by the proton reactions affects the dose estimation result, Monte Carlo simulations were performed as the increase of the proton energy from 10 MeV to 1,000 MeV. The concrete shielding thickness was assumed to be 200 cm and the composition of the ORNL regular concrete [] with 2.3 g/cm^3 density was used. The protons were used as the radiation source, and both the neutron and photon were simulated and tallied at outside of the concrete shielding. Fig. 3 is the results of the dose contribution fraction to the total dose for the neutron and photon. The results show that the dose contribution fraction from the neutrons were dominant (> 95%) when the proton energy is over 70 MeV. The analysis shows that the neutron should be considered as a main source for the bulk shielding design.

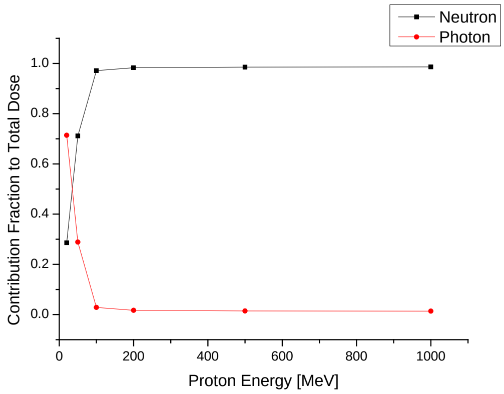


Fig. 3. Dose Contribution Fraction of the Neutron and Photon Generated by Proton Reactions

2.3 Neutron Source Term Generation

For the prompt radiation shielding analysis, it was analyzed that the neutron generated by proton-induced reaction is a dominant radiation. For increasing the efficiency of the Monte Carlo simulation, two step analysis method [6] is generally used: i) the neutron source term is estimated by the proton-nuclides reactions, and ii) the source term is used for the bulk shielding analysis without the proton simulation. Especially, the main radiation in the target room is the proton-target reactions; therefore, the two step approach in this case is adequate for the bulk shielding analysis. To generate the neutron source term, both UC_2 and UC_4 targets in Section 2.1 were used. Also, it is assumed that the target thickness is the stopping range for the each target. Using the target and proton information in Table I, the proton simulation was performed as shown in Fig. 4. The neutrons generated proton-target reactions were scored at the surface which has 400 cm. Then, the azimuthal angle and neutron energy were evenly divided to 100 sub-regions, respectively. For each simulation, 10^9 proton histories were used.

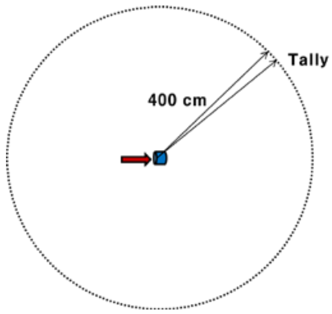
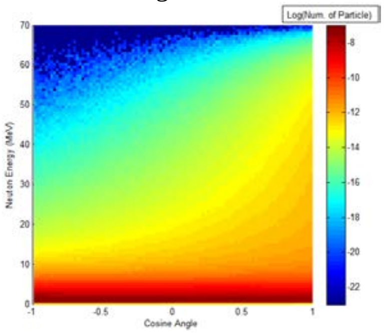
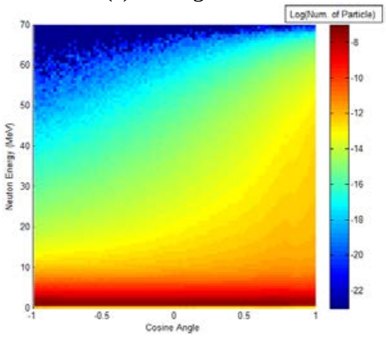


Fig. 4. Neutron Current Scoring Strategy for the Generation of Source Term

The neutron source term for each target was generated with the estimation results. In the source term generation, the discrete energy distribution was applied, which is the upper energy boundary of the each bin for the conservative radiation shielding analysis. For the verification, at first, the energy-angular neutron distribution was pursued. Fig. 5 and Fig. 6 are the results of the energy-angular distributions with the source term and direct-proton induced reaction. The results show that the source terms were accurately produced for the both target cases.

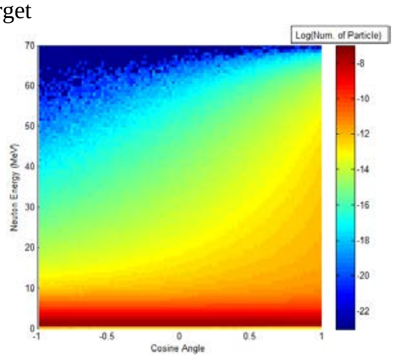


(a) Using Proton Beam

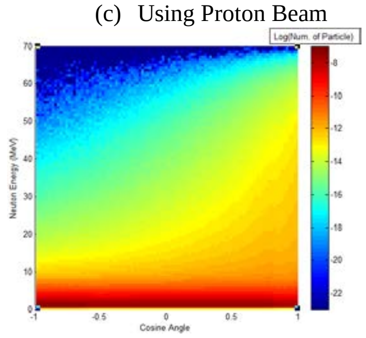


(b) Using Source Term

Fig. 5. Angular-energy Distribution of the Neutrons Using Proton-Target Reactions and Source Term for UC_2 Target



(c) Using Proton Beam



(d) Using Source Term

Fig. 6. Angular-energy Distribution of the Neutrons Using Proton-Target Reactions and Source Term for UC_4 Target

For the addition verification, the radiation dose analysis using both the proton beam and the generated source term was performed at the forward wall of the target room. Fig. 7 is the overview of the verification problem. At the tally region, the dose was evaluated for the both target cases using the direct proton beam and generated source term. Tables III and IV are the results dose estimations. Analysis shows that the two stem method using source terms gives a good agreement within 2 % relative difference giving conservative results.

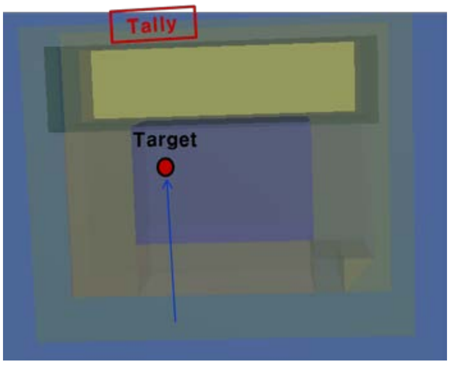


Fig. 7. MCNP Modeling Result of the Target Room

Table III: Dose Estimation Results Using Proton-Target Reactions and Source Term for UC_2 Target

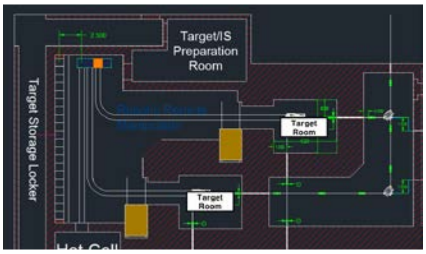
Source	Dose	Relative Error.
Direct Proton	13.0257 μSv/h	3.56%
Source Term	14.0889 μSv/h	3.86%

Table IV: Dose Estimation Results Using Proton-Target Reactions and Source Term for UC_4 Target

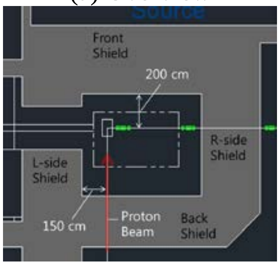
Source	Dose	Relative Error.
Direct Proton	12.0408 μSv/h	1.67 %
Source Term	12.2795 μSv/h	1.69 %

2.4 Variance Reductions and Bulk Shielding Analysis

Fig. 8 shows a temporal floor plan of the target rooms. The facilities around of the target rooms are also restricted area during the operation of the ISOL accelerators. However, to secure the radiation safety in any accident situations, it was decided that the concrete shielding thickness is designed to keep 5 μSv/h dose limit without considering the streaming effect. For the effective analysis of the bulk shielding design, the UC_2 source term generated from Section 2.3 was used. Also, to increase the simulation efficiency, two kinds of the variance reduction techniques were introduced, which are the geometry splitting and source energy biasing [4]. The importance map for the cylindrical geometry splitting is shown in Fig. 9. Also, the source energy biasing used in this study is given in Fig. 10.

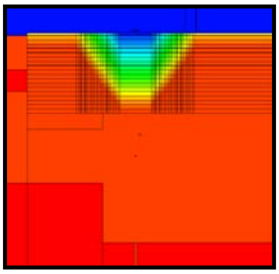


(a) Overview

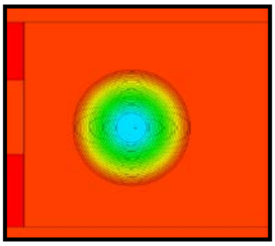


(b) ISOL-bunker (Target Room)

Fig. 8. Overview of the Target Rooms of ISOL Facilities



(a) Radial View



(b) Axial View

Fig. 9. Importance Mapping for the Cylindrical Geometry Splitting Strategy Used in This Study

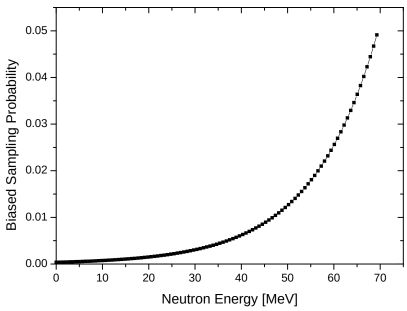


Fig. 10. Biased Source Sampling Probability for the Bulk Shielding Analysis

Using the variance reduction techniques and the source term, the bulk shielding calculations were pursed without considering any streaming effects. The concrete composition and density is equal to the concrete used in Section 2.2. Table V is the results of the concrete shielding thicknesses and doses. The thicknesses are the temporally designed values based on the 5 μSv/h dose limit; thus, the design value can be revised in the future.

Table V: Temporal Bulk Shielding Results for the Six Sides of the Target Room

Parameter	Front	R-side	L-side	Back	Roof	Bottom
Thickness [cm]	405	300	345	270	325	345
Dose [μSv/h]	4.426	3.358	3.772	2.683	4.024	4.528
Relative Error	1.98%	2.27%	4.42%	3.07%	3.20%	2.24%

3. Conclusions

In this study, a preliminary study for the prompt radiation shielding analysis in the target rooms of the RAON ISOL facility was performed. Therefore, the purpose in this study is to establish and optimize the radiation shielding analysis procedure. The evaluations were pursued as the following aspects; stopping range for the target model decision; prompt radiation generation; neutron source term generation; and variance reduction technique for the bulk shielding analysis. As a result, the optimization method and estimation procedure were derived as well as a temporal shielding design. It is expected that the method can be contributed for increasing the efficiency and accuracy on the ISOL facility safety analysis.

Acknowledgement

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