A Study on the Establishment of Radiation Dose Estimation Procedure for Accumulated Radioactive Ions for RAON ISOL System

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Abstract. For purposes of various experiments, RAON heavy ion accelerator facility has been designed in Korea. ISOL is one system of RAON accelerators to generate and separate rare isotopes. Radioactive ions generated from target-proton reactions are separated and accumulated at separation devices. The accumulated isotopes release the gamma radiations; therefore, the radiation safety must be clearly estimated. In this study, a process to evaluate radiations from the accumulated ions was proposed by modifying FISPACT code. The proposed process was validated by comparing a solution of single element decay problem. Using the process, a preliminary study for radiation doses were performed in a virtual separation devise.

1 Introduction

In Korea, RAON accelerator facility is under construction for various experiments using heavy ions. It includes the In-flight Fragment (IF) and Isotope Separation On-Line (ISOL) systems. In the ISOL system, 70 MeV proton beam, which was designed to have 70 kW maximum beam power, is induced into UCx target to generate rare isotopes. Lots of unstable isotopes are generated from the UCx-proton reactions. Specific isotopes of the generated isotopes are accumulated at various separation devices in ISOL system during operation. Radiations are generated from the accumulated radioactive ions. In previous study [1], a study using ^{132}Sn isotope was evaluated for ISOL system of SPIRAL 2 [2]. However, the radiation from various radioactive ions should be individually performed for shielding design and operation plan. As a preliminary study of the radiation safety, process to evaluate radiation doses generated from accumulated ions is proposed. In addition, a preliminary study of radiation doses according to individual mass number of accumulated ions was performed.

2 Method and results

2.1 Overview of ISOL system of RAON

Figure 1 is a schematic design of ISOL system for RAON accelerator. ISOL system has lots of devices for generating and separating radioactive ions as follows: (A) Cyclotron to accelerate protons (1 mA and 70 MeV); (B) ISOL target system to generate various secondary particles using UCx-proton reaction; (C) Pre-separator to separate ions extracted from UCx target (In pre-separator, specific isotopes having a mass number can be separated); (D) diagnostic device used to check beam information. (E) RF-cooler which is used to slow down the beam; (F) HRMS is a devise to further separate ions. (G) ECR-CB is used to breed charges of ions from the +1 to +n charge state; (H) RF-Cooler/Buncher is a devise to cool and bunch the ions; (I) EBIS-CB having similar function of ECR-CB; and, (J) A/q separator is a remover of contaminants from charge breeders.

In these beam line, ions have low energy about 50 keV. Therefore, it is impossible to generate secondary particles from ions and beam line reactions; however, they are accumulated at the specific locations. Hence, it is important to estimate the radiation safety from the accumulated ions in the beam line. Table 1 shows the maximum beam transport rate for each device. Also, the locations of the devices are given as shown in Figure 1.

Table 1. Transport rate of major devices to separate isotopes.

Location	Device Name	Maximum Transport Rate
A	Cyclotron	-
B	Target System	20 % (extraction rate)
C	Pre-separator	5 %
D	Diagnostic Device	0% (if use)
E	RF-Cooler	100 %
F	HRMS	15 % (only Z-1, Z,Z+1)
G	ECR-CB	60 %
H	RF-Cooler /Buncher	45 %
I	EBIS-CB	100 %
J	A/q separator	25 %

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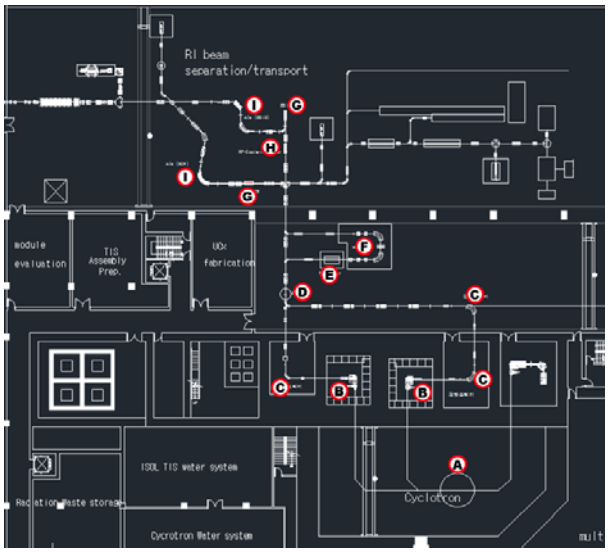

Figure 1. ISOL system and the device locations.

2.2 Calculation Method

To calculate residual radiation, BATEMAN equation is used as follows:

$$\frac{dN_m(t)}{dt} = -\beta_m N_m(t) + \sum_{k\neq m} N_k(t)\gamma_{k\to m} \quad (1.1)$$

$$\beta_m = \lambda_m + \Phi\sigma_a^m \; and \; \gamma_{k\to m} = \lambda_{k\to m} + \Phi\sigma_{k\to m} \quad (1.2)$$

where N_m = number of 'm' nuclide, λ_m is decay constant of 'm' nuclide, Φ is neutron flux, σ_a^m is absorption cross section of 'm' nuclide, $\lambda_{k\to m}$ is decay constant from 'k' to 'm' nuclide and $\sigma_{k\to m}$ is reaction cross section from 'k' to 'm'. In our case, the neutron flux is not considered. Also, addtional term, which is ion generation rate accumulated at each device, is required. The general procedure of FISPACT code is briefly reviewed in section 2.2.1. To estimate our case, a process was proposed in section 2.2.2 using modified FISPACT 2010 [3-4] code.

2.2.1 Review of procedure for FISPACT code

To solve the Eq. (1) in FISPACT code, 3 steps are performed as shown in Figure 2. The first step is to produce a collapsed library called 'COLLAPX'. In the process, EAF-2010 reaction cross section library is weighted by neutron fluxes and the 'COLLAPX' is generated. The secondary step is to produce a library called as 'ARRAYX' condensed from collapsed library and decay library. Last step is a standard running module to solve the Eq. (1) with interest time.

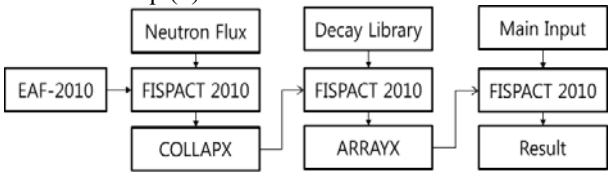

Figure 2. Diagram of FISPACT code process.

2.2.2 Proposed process for calculating accumulated ions

In FISPACT procedure, it is impossible to directly apply the production term caused by accumulations of the ions. To apply the production rate of accumulated ions, virtual condition, which is that all accumulated ions are produced to stable nuclides, was assumed as follows: ^{1}H is fully filled in an activation system with 1 cm^3 volume. The density is set to 1×10^{50} atoms/cm^3 to assume an enough amount to prevent the change of the number of ^{1}H atoms. Then, virtual reaction was used by modification of 'COLLAPX' file.

To verify the result using this modification, a simple test was performed by using ^{67}Ni with following conditions:

- Production Rate (K): 1.754×10^{9} atoms/s
- Decay Constant of ^{67}Ni: 0.033 s^{-1}
- Period: production time = 400 sec and decay time = 400 sec.

This case is solved by following equation.

$$\frac{\partial N}{\partial t} = -\lambda N + K \quad (2)$$

where N is the number of ^{67}Ni, λ is decay constant of ^{67}Ni and K is production rate of ^{67}Ni. The solution of Eq. (2) is given by using Eq. (3).

$$\begin{cases} N = \frac{K}{\lambda}(1-e^{-\lambda t}), & (if < 400\,s) \\ N = Ce^{-\lambda(t-400)}, & (if > 400\,s) \end{cases} \quad (3)$$

Where $C = \frac{K}{\lambda}(1-e^{-\lambda 400})$. Table 2 and Figure 3 are results of the simple test using exact solution and proposed process. The result shows that the proposed process can accurately estimate the number of accumulated ions.

Table 2. Results from exact solution and proposed process.

Time [sec]	1	200	400	600	800
Proposed Process [atoms]	1.06 ×10^9	3.25 ×10^{10}	3.26 ×10^{10}	4.43 ×10^7	6.01 ×10^4
Solution [atoms]	1.06 ×10^9	3.25 ×10^{10}	3.26 ×10^{10}	4.43 ×10^7	6.03 ×10^4

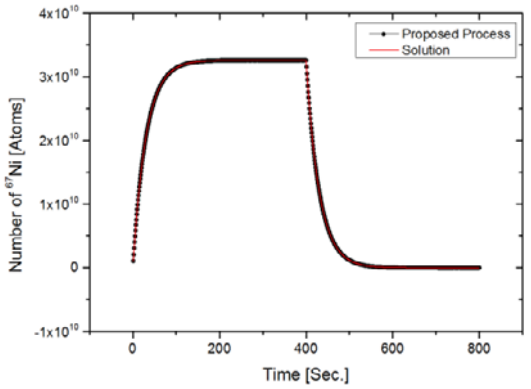

Figure 3. Results from exact solution and proposed process during all time periods.

2.3 Calculation results

2.3.1 Results of ion production rate

The ion production rates in the ISOL system were calculated by rigorous-two-step (R2S) method [5] with following step:
- MCNPX 2.7 [6] code simulation is pursued to get neutron spectra using JENDL/HE 2007 cross sections and HISTP option [7].
- Amounts of radioactive nuclides are estimated by modified FISPACT 2010 code [4].

The UCx target was assumed as Table 3, which generate a largest number of radioactive nuclides, to get secure result for radiation safety.

Table 3. Target information to calculate production rate of ions.

Element	Value
Composition	UC_2 (Natural abundance)
Length	3.77 cm (stopping length of proton)
Density	2.5 g/cm^3
Diameter	6 cm
Shape	Cylinder

Production rates using results of activation were calculated by Eq. (4) from solution of Eq. (2).

$$K = \frac{N\lambda}{1 - e^{(-\lambda t)}} \quad (4)$$

Figure 4 shows results of the ions production rates depend on mass number. The ^{235}U and ^{238}U nuclides were excepted because those are target material. Total 153 kind of isobar were estimated.

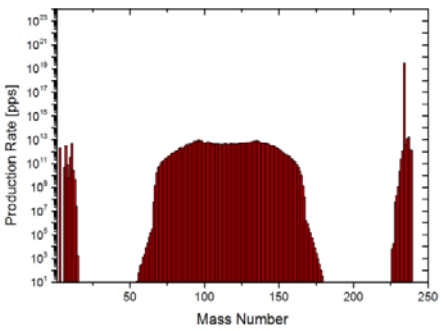

Figure 4. Production rates of ISOL system.

2.3.2 Results of radiation doses from accumulated ions

ISOL system is planned to use a single target for 14 days. After that, the target is cooled for 14 days. In this study, the operation time was assumed as 14 day, 1 year, 10 year, and 30 year with 0 second, 1 minute, 1 hour, 30 day, 180 day, and 1 year decay time for each operation time. To perform a preliminary study, the accumulation rate of the ions was assumed to 1 % (20 % × 5 %) for a virtual device after passing through pre-separator.

After passing the pre-separator, lots of isobar nuclides excepting target ions can be accumulated in the separation devise. It cannot be predicted to use which ions will be used as a target ions in experiments, and thus, some conservative assumption is necessary. Therefore, in this study, radiation doses of the isobars were estimated to confirm ions having maximum radiation dose. And, it was assumed that the isobar showing maximum radiation dose is accumulated in the devise. To evaluate the radiation doses, a simple model, as shown figure 4 was used with ICRP-116 [8] dose conversion factor for Antero-posterior.

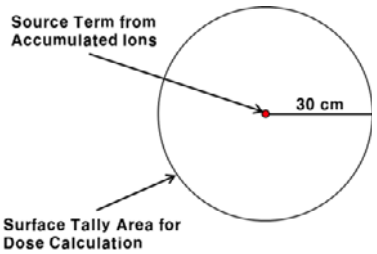

Figure 5. Model for dose estimation of each accumulated isobar.

Figure 6-7 are the results of decay gamma doses. The results show that doses for 0 decay time have similar dose distributions in cases of 2 week and 30 year operation periods. However, doses after 1 year decay time gives a considerable differences. It was analysed that the differences is caused by the differences of the decay constants. Thus, for the radiation safety, an additional study to select the isobar having maximum radiation dose should be performed as the decay times.

Figure 8 shows maximum gamma doses among various selected isobars for each decay time. The analysis of the results shows that following phenomenon should be considered for the radiation safety analysis: i) at each decay time, the isobar which shows maximum radiation dose is different; ii) for the conservative analysis of the radiation safety, it is recommended to select maximum accumulation time of the isobars.

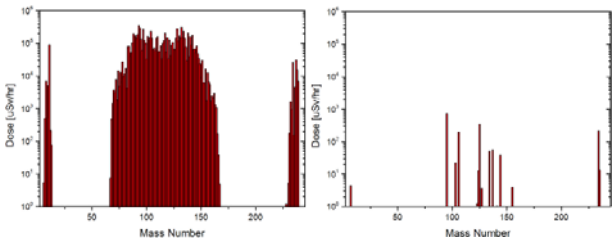

Figure 6. decay gamma dose with 2 week operation and 0 (left) 1 year (right) decay time.

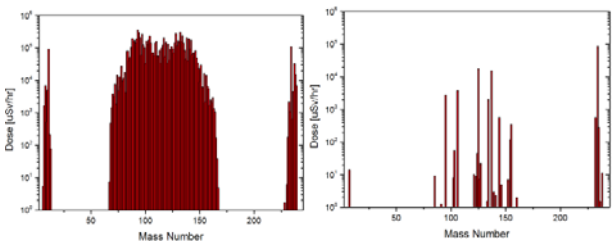

Figure 7. decay gamma dose with 30 year operation and 0 (left) 1 year (right) decay time.

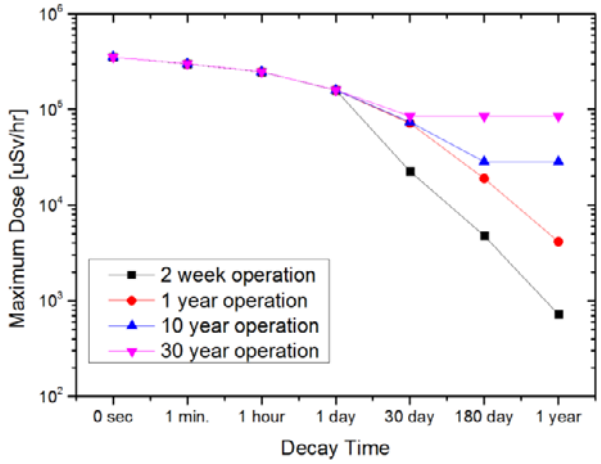

Figure 8. Maximum decay gamma dose according to operation and decay times for all accumulated isobars.

3 Conclusion

In the ISOL system, lots of separation systems are installed to select specific ion beam. Lots of ions generated by proton-target reactions are unstable nuclides. In this study, an estimation procedure for the radiation safety near the separation devises was proposed. First, modification of 'COLLAPX' file of FISPACT code was performed. This process was validated by solving a test problem, and the results estimated with the proposed method were compared with an exact solution. Second, the properties on the radiation doses of the isobars separated by ion separation devices were analysed. It is planned that the proposed method and procedure will be used for the radiation safety analysis in ISOL system.

References

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