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ARTICLE

Activation analyses of air by deuteron beam at 5-9 MeV

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A construction of accelerator-based neutron irradiation facility is required to develop materials for a demonstration fusion reactor. To obtain a 14 MeV neutron energy using the neutron-generating D-Li stripping reaction, an injection into liquid lithium flow by a 40 MeV deuteron beam is employed in IFMIF design concept. In the acceleration of deuteron beam, the activation due to the beam loss is a critical issue. The activation analyses for the air in an accelerator vault are performed by PHITS code and DCHAIN code in the first step, using the experimental data for deuteron induced thick target neutron yield at 5 MeV and 9 MeV as source term and a simple model of the 1 m-long beam duct. For the 9 MeV-1 μA beam loss, ^{41}Ar and ^{16}N are dominant for isotope production, it is evaluated to be 2.95×10^{-1} and 1.04×10^{-1} Bq/cm^3, respectively. It is found that the amount of ^{41}Ar reaches the permissible air concentration of 0.1 Bq/cm^3 after an 8-hour CW operation.

Keywords: accelerator; deuteron; isotope production; activation analysis; PHITS code; DCHAIN code

1. Introduction

International Fusion Materials Irradiation Facility (IFMIF) is an accelerator-driven neutron irradiation facility to develop materials for DEMO, a demonstration fusion reactor next to ITER [1]. In IFMIF design, an accelerator-based neutron irradiation facility is needed. And, to obtain the simulated neutron spectra produced by D-T reaction and the neutron flux of 10^{18} n/m^2/s or more, the neutron-generating D-Li stripping reaction is adopted and a 40 MeV deuteron beam with a current of 250 mA has to be injected into liquid lithium flow.

On the accelerator system for deuteron beam, activation for the air and accelerator components due to deuteron beam loss is a critical issue. For the air activation, ^{14}N(n,2n)^{13}N, ^{16}O(n,2n)^{15}O, ^{16}O(n,p)^{16}N, ^{40}Ar(n,α)^{37}S and ^{40}Ar(n,γ)^{41}Ar have to be evaluated at least. In the first step for order estimation, these isotope productions are calculated by PHITS code and DCHAIN code using the experimental data for source term.

2. Background

There is literature on the experimental data of Cu+d thick target neutron yield (TTNY) in the range of deuteron energy for 4 and 10 MeV, but there is no experimental data for 5-9 MeV. Therefore, we measured thick target neutron yields at 5 and 9 MeV in collaboration with Kyushu University [2][3].

A 0.2 mm thick copper was used as a target, and the average beam current of 10 nA was injected into the target. For the neutron distribution in all directions, the measured energy spectra at angles, 0°, 15°, 30°, 45°, 60°, 75°, 90°, 120° and 140° are used for a source term, and

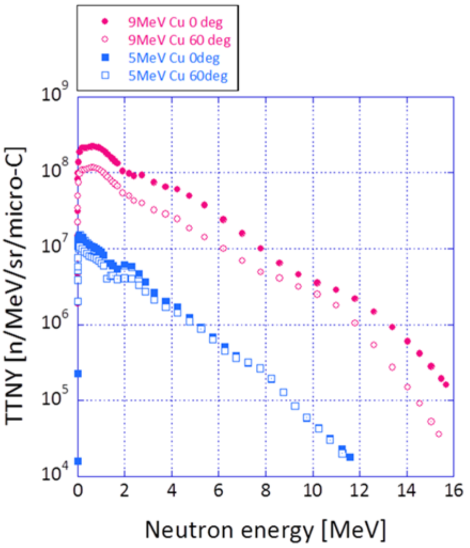

Figure 1. Neutron energy distributions produced at the angles of 0°, 60° with 9 MeV and 5 MeV deuteron beam bombardment on a copper target.

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*Corresponding author. Email: takahashi.hiroki@jaea.go.jp this source term is set for a surface source in the inside of 1 m-long beam duct. For example, the neutron energy distributions at angles of 0° and 60° for 9 MeV and 5 MeV deuteron beams are shown in **Figure 1**.

3. Analysis

3.1. Model

A simplified cylindrical model for beam duct and an outer cylindrical air region around the beam duct with a common center axis are used in these analyses. The model parameters are shown in **Figure 2**. A beam duct is 5 cm internal radius, 0.5 cm thickness and 1 m-long. Air area is 305.5 cm radius which means the thickness of air area is 300 cm. This radius (r2 in Figure 2) is defined with the assumption that the required minimum size of accelerator vault will be about 30 m^2 (about 6 m-width × 5 m-high).

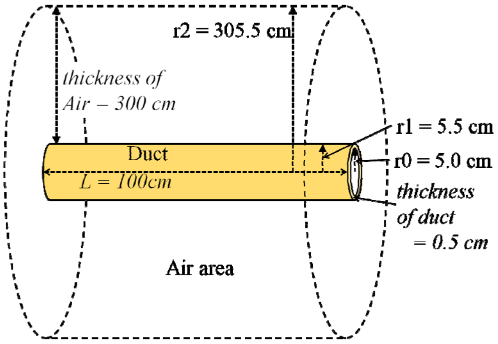

Figure 2. Analysis Model.

3.2. Analysis condition

The beam loss is distributed uniformly over the inside wall area of beam duct, and the total beam loss of 1 μA for the beam duct of 1 m-long (1 μA/m) is assumed. During an operation time of 8-hour CW, the amount of each isotope productions is analyzed. **Table 1** shows the material components of the air.

Table 1. Mass ratio of constituent gas in air.

Components	Mass ratio
N_2	0.7551
O_2	0.2301
Ar	0.01286
CO_2	0.000314

3.3. Calculation of neutron spectra

In the realistic system of accelerator, neutron flux is produced not only a beam duct of the limited area (“Air area” in Figure 1) but also the other ducts where exist upstream and downstream. Therefore, 10 m-long cylindrical air area which is ten times longer than the beam duct length define to avoid the underestimate of neutron flux in “Air area”. Neutrons generated from 1 m-long beam duct located in the center of the 10 m-long cylindrical air area is considered as neutrons in “Air area”.

With the assumption that deuteron beam operation of each 9 MeV and 5 MeV cases, the neutron spectra of “Air area” around a beam duct are calculated by PHITS code, which uses the JENDL 4.0 for nuclear cross-section library. These parameters for calculation of neutron spectra are shown in **Table 2**.

Table 2. Parameters for the calculation of neutron spectra.

Beam Duct	Length (L)	100 cm
	Internal radius (r0)	5.0 cm
	External radius (r1)	5.5 cm
	Thickness of duct	0.5 cm
	Materials	copper, Stainless Steel(*)
Air	Length for calculation of neutron spectra (same as Figure 2.)	100 cm
	Length for calculation of neutrons (first calculation)	1000 cm
	Radius (r2)	305.5 cm
	Thickness of air area	300 cm

*) Copper data are used as a neutron source term.

In **Figure 3**, the neutron flux from beam duct due to deuteron beam loss of 9 MeV-1 μA is indicated. The air around the beam duct is irradiated by neutron flux from 10^{-7} to 10^{-4} order [$1/cm^2$/source-particle].

Finally, the radioactivity of “Air area” after an 8-hour CW operation is calculated by DCHAIN using the neutron spectra for under 20 MeV which are results by PHITS code.

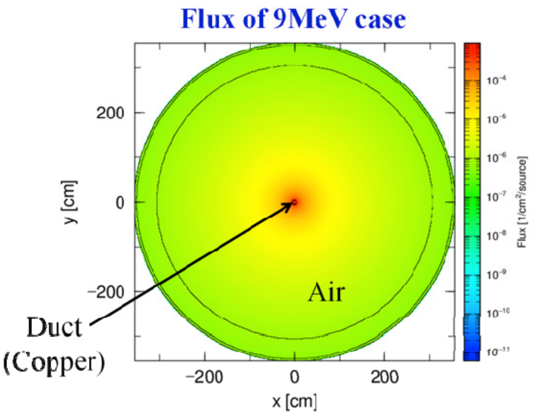

Figure 3. Neutron flux of 9 MeV case.

3.4. Results

The calculation results for deuteron beam loss of 9 MeV-1 μA and 5 MeV-1 μA case are shown in **Table 3**. The value in table shows the radioactivity after an 8-hour CW operation. And, the time-decay of radioisotopes for 9 MeV case is shown in **Figure 4**.

It is found that the isotope productions of the two cases of the beam ducts of copper (Cu) and stainless steel (SS) are almost same.

In the 9 MeV-1 μA beam loss case, ^{41}Ar, ^{16}N, ^{13}N and

^{37}S are dominant after 8-hour CW beam operation, and the results of their concentrations are 2.95 × 10^{-1}, 1.04 × 10^{-1}, 1.48 × 10^{-2} and 4.80 × 10^{-3} Bq/cm^3, respectively. The total radioisotope production is 4.23 × 10^{-1} Bq/cm^3, and the ^{41}Ar occupies 70% of the total production. This total production of 4.23 × 10^{-1} Bq/cm^3 exceeds the permissible air concentration in a radiation controlled area (for example, 0.1 Bq/cm^3 for ^{41}Ar).

In the beam loss of 5 MeV-1 μA, it is found that only ^{41}Ar is dominant and the amount of ^{16}N, ^{13}N and ^{37}S can be neglected. Because ^{16}N, ^{13}N and ^{37}S are produced by (n,p), (n,2n) and (n,α) reactions, and it is strongly dependent on neutron energy of more than 5 MeV. The ^{41}Ar production is 3.14 × 10^{-2} Bq/cm^3, and it is about one tenth of the 9 MeV-1 μA case. This difference can be explained by the difference of low energy neutron flux, since ^{41}Ar is produced by (n,γ) reaction.

As shown in Figure 4, the decay of ^{16}N, ^{13}N and ^{37}S is very fast, since these half-lives are 7.13 sec, 9.97 min and 5.05 min, respectively. The half-life of ^{41}Ar is 1.82 hour, and it takes about 3 hours to fall below the permissible air concentration of 0.1 Bq/cm^3 for ^{41}Ar.

The reference data is obtained by the result applied the simple model. By using this result, the air activation of the deuteron accelerator of 100 mA class is studied. In this case, a 10 μA beam loss is assumed and the air activation is estimated. The air concentration for ^{41}Ar after the 8-hour CW operation is to be 10 times higher than the above calculation. And, for the ^{16}N, it is calculated to be 1.04 × 10^{0} Bq/cm^3 for the 9 MeV case. In order to reduce the ^{41}Ar and ^{16}N, the (n, γ) reaction in the neutron energy range from thermal level to less than 1 MeV and the (n,p) reaction in the neutron energy of more than 5 MeV have to be suppressed. For this purpose, local shielding using polyethylene or water layer is a good candidate, and an optimized design for the thickness and configuration is indispensable. For the next step, the local shielding designs are in progress.

Table 3. Isotope production in the air by calculations.

Isotope	9 MeV		5 MeV	
	Cu [Bq/cm^3]	SS [Bq/cm^3]	Cu [Bq/cm^3]	SS [Bq/cm^3]
Total	4.23 × 10^{-1}	4.14 × 10^{-1}	3.18 × 10^{-2}	3.12 × 10^{-2}
^{3}H	1.32 × 10^{-4}	1.34 × 10^{-4}	4.95 × 10^{-6}	5.07 × 10^{-6}
^{12}B	2.59 × 10^{-3}	2.61 × 10^{-3}	1.98 × 10^{-5}	1.99 × 10^{-5}
^{14}C	1.63 × 10^{-5}	1.60 × 10^{-5}	1.44 × 10^{-6}	1.43 × 10^{-6}
^{15}C	7.21 × 10^{-4}	7.27 × 10^{-4}	4.84 × 10^{-6}	4.89 × 10^{-6}
^{13}N	1.48 × 10^{-2}	1.49 × 10^{-2}	1.25 × 10^{-6}	1.25 × 10^{-6}
^{16}N	1.04 × 10^{-1}	1.05 × 10^{-1}	2.77 × 10^{-4}	2.78 × 10^{-4}
^{37}S	4.80 × 10^{-3}	4.85 × 10^{-3}	1.10 × 10^{-4}	1.12 × 10^{-4}
^{37}Ar	5.07 × 10^{-5}	4.89 × 10^{-5}	5.44 × 10^{-6}	5.33 × 10^{-6}
^{41}Ar	2.95 × 10^{-1}	2.85 × 10^{-1}	3.14 × 10^{-2}	3.07 × 10^{-2}

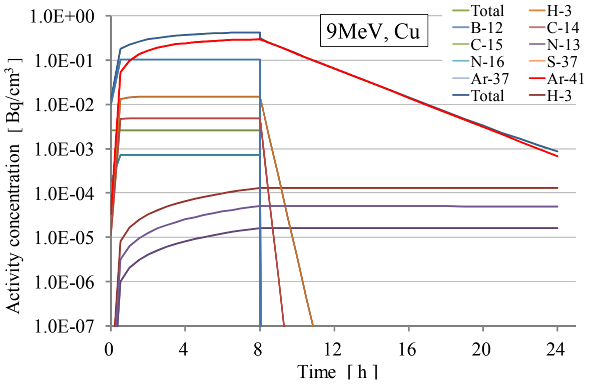

Figure 4. Time-decay of isotopes for 9 MeV case.

4. Conclusion

An evaluation for the air activation was performed by assuming the deuteron beam loss of 1 μA per meter for the beam energy of 5 and 9 MeV by PHITS code and DCHAIN code using the experimental data of deuteron induced thick target neutron yield as a source term.

It is found that the amount of ^{41}Ar exceeds the permissible air concentration (1.0 × 10^{-1} Bq/cm^3) after an 8-hour CW operation for the 9 MeV-1 μA beam loss. In consideration of the half-life of ^{41}Ar, 1.82 hour, about 3 hours are necessary to fall below 1.0 × 10^{-1} Bq/cm^3.

On the other hand, at the present accelerator technology, for the accelerated current of 100 mA class, the 10 μA order beam loss is caused at least. Therefore, further study is necessary on the local shielding design, accelerator operation pattern and the air exhaust system to realize the final target, that is, 10-month CW operation per every year. Then, for the next step, the local shielding design, accelerator operation pattern and the air exhaust system will be studied.

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References

[1] IFMIF-CDA team (edited by M. Martone), *IFMIF International Fusion Materials Irradiation Facility Conceptual Design Activity Final Report*, ENEA Frascati Report, RT/ERG/FUS/96/11, December 1996.

[2] N. Shigyo, Y. Watanabe, K. Hidaka, Y. Nakamura, D. Moriguchi, M. Kumabe, S. Hirayama, Y. Naitou, C. Motooka, K. Sagara, C. Lan and T. Watanabe, Measurement of deuteron induced thick target neutron yields at 9 MeV, *Journal of the Korean Physical Society* 59(2) (2011), pp. 1725-1728.

[3] K. Hirabayashi, T. Nishizawa, H. Uehara et al., *Measurement of Deuteron Induced Thick Target Neutron Yields at 5MeV and 9MeV*, JAEA-Conf 2011-2, pp. 113-118.