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Shielding Evaluation and Activation Analysis of Facilities by Neutron Generator for the Development of 20 Feet Container Inspection System

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Abstract KAERI (Korea Atomic Energy Research Institute) is conducting research and development of large-scale radiation generators and the latest radiation measuring instruments. In particular, research and development of security screening equipment using an electron beam accelerator and a neutron generator is in progress recently. Globally, 20 ft containers are used to transport imports and exports, and electron beam accelerators are radiation sources to measure the shape of the material inside the container during customs inspections in each country. KAERI is developing a device that can use an electron beam accelerator and a neutron generator sequentially to grasp the shape of various materials as well as the location of the internal target material. In this study, when using the neutron generator, the radiation dose and the degree of activation by neutron for the facility and surrounding environment, facility equipment were simulated using MCNP and FISPACT code. As a result, the shielding structures inside and outside the radiation control area were satisfactory to the reference level established conservatively based on the Korean Nuclear Act.

Key words: Neutron generator, Radiation shielding, Activation, MCNP code, FISPACT code

1. INTRODUCTION

Only an electron accelerator commercially produced is being used for the radiation source of 20 ft container inspection to measure the location of a target material inside a container by using the internal radiation three-dimensional position detection technology and the miniaturization of security screening equipment. But, an electron accelerator and a neutron generator are used sequentially for a more precise container inspection in the developing system by research team of KAERI.

Accordingly, shielding analysis was performed on neutrons caused by the new installed D-T (Deuterium-Tritium) neutron generator to confirm whether structure of building satisfies the public exposure dose limit in the public area outside the building using MCNP code. In addition, activation analysis was done in the surrounding facilities around D-T neutron generator using FISPACT code.

2. MATERIALS AND METHODS

2.1. Neutron generator overview

The radiation source for this project is a Deuterium-Tritium neutron generator that produces single energy neutrons of 14.1 MeV. The average neutron production rate is 1×10^{10} (n/s/4πsr) (±10%) and the maximum operating time is 2,000 hours. Table 1 and Fig. 1 show the specifications and appearance of the neutron generator.

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The sealed tube type D-T (deuterium-tritium) neutron generator utilizes the nuclear reaction of deuterium and tritium to produce 14.1 MeV neutrons [1].

$$^{2}D + {}^{3}T \rightarrow {}^{4}He\,(3.6\,Mev) + n\,(14.1\,MeV)$$

The above nuclear reaction occurs in a sealed neutron tube inside the Neutron Emission Module, which is the core component of the generator. The Neutron Tube consists of a Target, Accelerating gap, Ion source, Replenisher and Pressure Gauge. The titanium target contains tritium (720 GBq) bonded to a solid metal hydride, and the reaction occurs inside the sealed tube, so tritium leakage is impossible or so limited [2].

The emergency shutdown output of the system is triggered by the interlock event shown in Fig. 2, which includes detailed events such as abnormal behavior inside the neutron generator and the occurrence of unexpected radiation leakage. In the case of an interlock event, the main controller blocks neutron generation by shutting off power supply for ion acceleration inside the neutron generator to cut off the acceleration energy in the accelerating gap in the neutron tube and prevent it from colliding with the target.

In the event of an interlock event, the emergency stop system control of the neutron generator is implemented through a hard-wired interlock circuit in the form of open/close, so that the above-described output function is blocked when an interlock event occurs in even one

Table 1. The specification of neutron generator

Division	Contents
Size (Diameter × Length)	Φ150 mm × 865 mm
Weight	27 kg
Energy	14.1 MeV (peak)
Generation rate	1×10^{10} n/s/4πsr (±10%)
Activity of tritium (3H)	720 GBq
Voltage of generator	160 kV
Cooling method	Water cooling
Operating hour (Max.)	2,000 hours

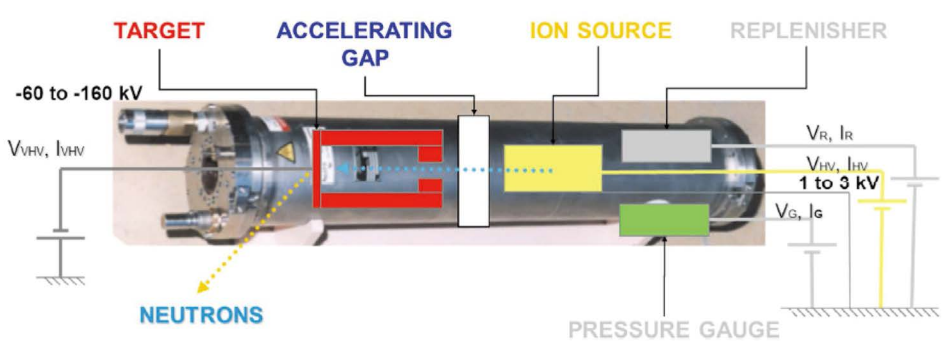

Fig. 1. Neutron emission module.

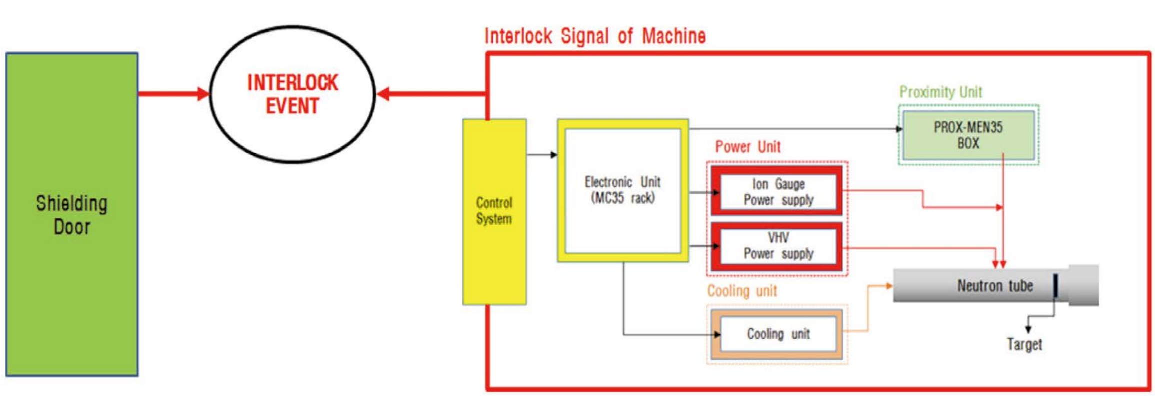

Fig. 2. Interlock system of neutron generator.

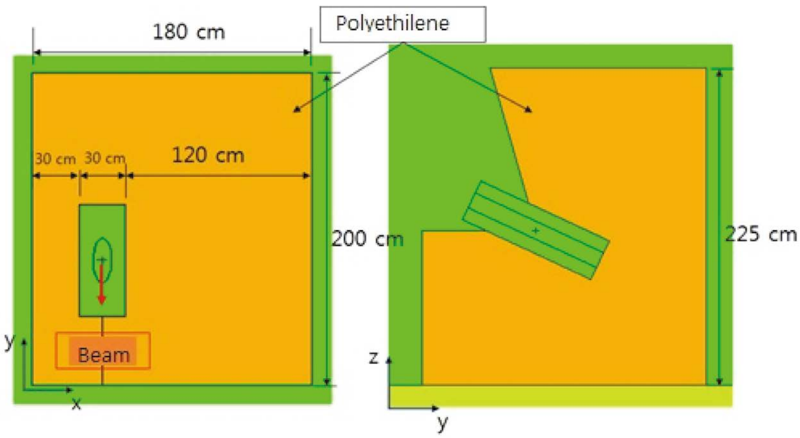

Fig. 3. Neutron generator source container.

Fig. 4. MCNP modeling for container inspection room of facilities.

device to prevent radiation generation. In addition, even if an interlock event does not occur internally, it is possible to artificially trigger an interlock event by authorizing an emergency stop switch by the operator.

In addition, the operation of the neutron generator is determined by a single on/off key switch installed in the rack, and the key can be used to start the device. In the off state, the generator power supply is cut off, such as when an interlock event occurs in the unit's emergency shutdown system. The on-off state change is accomplished by checking the device's system operation type signal (open/close circuit). The on/off key is kept in a separate key box for double security.

2.2. Evaluation of shielding using MCNP code

The neutron generator generates neutrons through the D-T reaction, and the maximum energy of the generated neutrons is 14.1 MeV. Since the facility plans to use a neutron intensity of 1×10^9 neutron s^{-1}, this calculation was performed conservatively by assuming a neutron intensity of 1.1×10^9 neutron s^{-1} with a 10% error in the neutron intensity, and we check whether the shielding thickness satisfactory to the reference radiation dose [3].

Polyethylene was used as the shielding for the neutron generator, and the optimal shielding thickness was calculated for each direction. The beam irradiation angle of the neutron generator is 25° to the floor, and the beam height

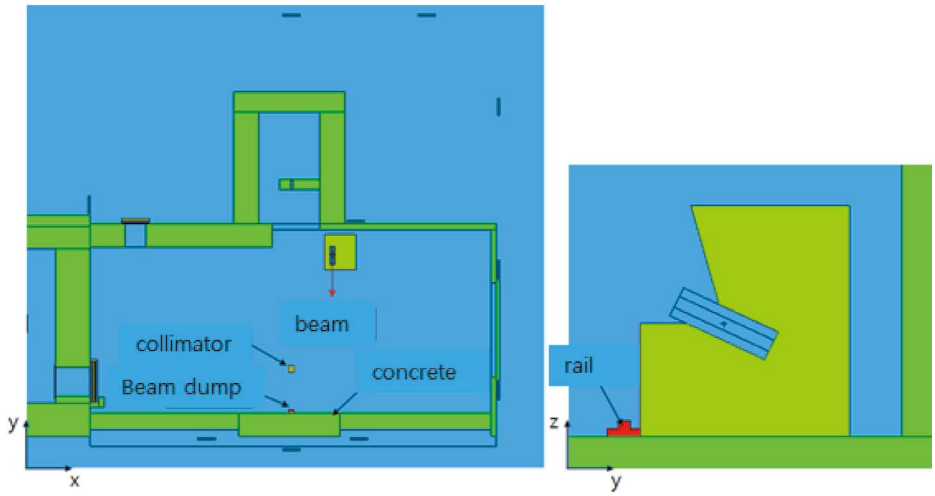

Fig. 5. Facilities component for activation analysis.

Table 2. Calculation results of radiation dose rate at location by the neutron generator

Location	Dose rate (μSv h^{-1})	R.E.*	Note
①	8.99×10^{-3}	6.03%	Figure 4
②	2.26×10^{-2}	3.61%	
③	2.91×10^{-2}	3.25%	
④	6.04×10^{-1}	1.00%	
⑤	2.53×10^{-1}	1.43%	
⑥	2.59×10^{-2}	4.89%	
⑦	1.90×10^{-2}	3.68%	
⑧	4.42×10^{-3}	8.01%	
⑨	6.09×10^{-1}	0.89%	
⑩	1.73×10^{-2}	4.36%	
⑪	9.62×10^{-3}	5.46%	Room 216 of Figure 4
⑫	1.55×10^{-2}	4.43%	Room 218 of Figure 4
Ⓐ	2.10×10^{-1}	0.79%	5 meters apart from EXIT
Ⓑ	1.06×10^{-1}	1.11%	10 meters apart from EXIT
Ceiling	1.21×10^{0}	0.65%	Ceiling

*R.E (Relative Error) = (Standard deviation/mean)

is 110 cm above the floor. The beam spread angle is 74.5° and the beam width is 7 mm. The beam spread angle and beam width were applied to the local shield to ensure that the beam was irradiated. The beam operation time is 0.5 hours day^{-1}, 5 days week^{-1}, and 50 weeks year^{-1}.

To calculate the radiation dose from neutrons, MCNP was modeled as shown in Fig. 4. The complex structure inside and outside the neutron generator can affect the neutron shielding, but to be conservative, it was not simulated, and a cylinder-shaped volumetric source with a radius of 6 cm and a length of 100 cm was applied. In addition, a space of 30 cm wide, 30 cm high, and 100 cm long was left empty for the accessories [4].

The MCNP6 (ver 1.0) computer code was used for radiation dose evaluation. ENDF/B-VII was used as the nuclear cross section library for neutrons from the neutron generator. The F4 tally, the default tally in MCNP, was used for radiation dose calculations. Since the F4 tally calculates the dose rate in space (particles cm^{-2}-sec^{-1}), a photon flux-to-dose conversion factor and a neutron flux-to-dose conversion factor are required to convert it to an effective dose. The photon flux-to-dose conversion factors and neutron flux-to-dose conversion factors used in this calculation are based on ICRP-74 [5].

2.3. Activation analysis

Since neutron from the neutron generator could activate the surrounding facilities and concrete of the building, an activation analysis was performed. The FISPACT code was used for analysis. This code was developed by the United Kingdom Atomic Energy Authority (UKAEA) and is specialized for radiation calculations and activation analysis, providing a library of nuclear cross sections for 65,565 reactions involving 816 nuclides reacting with neutron [6,7].

The objects irradiated are the collimator and beam dump located in the beam direction of the neutron accelerator, the rails located under the front of the neutron generator, and the air inside the container inspection room,

Table 3. Activity of nuclide by air activation

Nuclide	Activity (Bq m^{-3})				
	0.5 hours	2.5 hours	125 hours	250 hours	1000 hours
^{41}Ar	1.33×10^{2}	4.72×10^{2}	7.70×10^{2}	7.70×10^{2}	7.70×10^{2}
^{19}O	4.12×10^{-2}	4.12×10^{-2}	4.12×10^{-2}	4.12×10^{-2}	4.12×10^{-2}
^{37}Ar	8.13×10^{-3}	4.06×10^{-2}	1.93×10^{0}	3.67×10^{0}	1.11×10^{1}
^{14}C	6.87×10^{-3}	3.44×10^{-2}	1.72×10^{0}	3.44×10^{0}	1.37×10^{1}
^{39}Ar	8.98×10^{-8}	4.49×10^{-7}	2.25×10^{-5}	4.49×10^{-5}	1.80×10^{-4}

Table 4. Activity of nuclide by beam dump activation

Nuclide	Activity (Bq m^{-3})				
	0.5 hours	2.5 hours	125 hours	250 hours	1000 hours
^{56}Mn	2.34×10^{-3}	9.10×10^{-3}	1.86×10^{-2}	1.86×10^{-2}	1.86×10^{-2}
^{234}Th	1.48×10^{-5}	7.39×10^{-5}	3.44×10^{-3}	6.39×10^{-3}	1.72×10^{-2}
^{234m}Pa	–	–	–	–	1.72×10^{-2}
^{51}Cr	6.28×10^{-6}	3.14×10^{-5}	1.47×10^{-3}	2.76×10^{-3}	7.80×10^{-3}
^{60m}Co	3.59×10^{-3}	4.17×10^{-3}	4.17×10^{-3}	4.17×10^{-3}	4.17×10^{-3}
^{64}Cu	–	7.77×10^{-5}	7.50×10^{-4}	7.51×10^{-4}	7.51×10^{-4}
^{231}Th	–	6.01×10^{-5}	1.10×10^{-3}	1.14×10^{-3}	1.14×10^{-3}
^{55}Fe	1.18×10^{-7}	5.92×10^{-7}	2.95×10^{-5}	5.90×10^{-5}	2.33×10^{-4}
^{65}Ni	–	–	1.15×10^{-4}	1.15×10^{-4}	1.15×10^{-4}
^{60}Co	4.25×10^{-8}	2.65×10^{-7}	1.40×10^{-5}	2.80×10^{-5}	1.11×10^{-4}
^{59}Fe	–	–	1.57×10^{-5}	3.06×10^{-5}	9.81×10^{-5}
^{76}As	–	–	9.10×10^{-5}	9.45×10^{-5}	9.47×10^{-5}
^{187}W	–	–	7.24×10^{-5}	7.44×10^{-5}	7.45×10^{-5}

as shown in Fig. 5. The collimator is made of lead, and the beam dump and rails are stainless steel [8].

The activation calculation was performed using the FISPACT code, and the energy group structure was calculated using GAM-II nuclear cross section data. The beam operating hours are 0.5 hours day^{-1}, 2.5 hours week^{-1}, and 125 hours year^{-1}. Since the facility is expected to operate for 2~3 years, 250 hours and 1000 hours were added to perform radiation calculations. Radiation calculations were performed for a 30 cm wide, 200 cm long, and 30 cm deep section of concrete at the location of the direct impact of the neutron beam where the most activation is predicted to occur, 2 meter long section of rail at the point closest to the neutron generator, and the entire collimator and air [9].

3. RESULTS AND DISCUSSION

The radiation dose was evaluated at the locations ①~⑫ of container inspection room in Fig. 4. The radiation dose calculation was performed according to the distance of 1 meter to 10 meters outside the vehicle entrance and exit. The radiation dose calculation results of neutrons are shown in Table 2, including radiation dose calculation results of secondary particles of neutrons. The radiation dose according to the distance outside the vehicle entrance and exit are designated as Ⓐ and Ⓑ at the points of 5 m and 10 m. As shown in the table, considering the distance of 10 meters in the direction of the vehicle entrance and exit, all locations met 0.5 μSv per hour or less, which is the reference level of public area from the boundary of the radiation controlled area according to the internal reg-

Table 5. Activity of nuclide by rail activation

Nuclide	Activity (Bq m^{-3})				
	0.5 hours	2.5 hours	125 hours	250 hours	1000 hours
^{56}Mn	6.32×10^{-3}	2.46×10^{-2}	5.03×10^{-2}	5.03×10^{-2}	5.03×10^{-2}
^{51}Cr	1.70×10^{-5}	8.47×10^{-5}	3.98×10^{-3}	7.47×10^{-3}	2.11×10^{-2}
^{60m}Co	9.71×10^{-3}	1.13×10^{-2}	1.13×10^{-2}	1.13×10^{-2}	1.13×10^{-2}
^{234}Th	1.48×10^{-5}	7.39×10^{-5}	3.44×10^{-3}	6.39×10^{-3}	1.72×10^{-2}
^{234m}Pa	–	–	–	–	1.72×10^{-2}
^{64}Cu	–	2.10×10^{-4}	2.03×10^{-3}	2.03×10^{-3}	2.03×10^{-3}
^{55}Fe	3.20×10^{-7}	1.60×10^{-6}	7.98×10^{-5}	1.59×10^{-4}	6.31×10^{-4}
^{231}Th	–	6.01×10^{-5}	1.10×10^{-3}	1.14×10^{-3}	1.14×10^{-3}
^{65}Ni	–	–	3.11×10^{-4}	3.11×10^{-4}	3.11×10^{-4}
^{60}Co	1.15×10^{-7}	7.15×10^{-7}	3.78×10^{-5}	7.56×10^{-5}	3.01×10^{-4}
^{59}Fe	–	–	4.25×10^{-5}	8.26×10^{-5}	2.65×10^{-4}
^{76}As	–	–	2.46×10^{-4}	2.56×10^{-4}	2.56×10^{-4}
^{187}W	–	–	1.96×10^{-4}	2.01×10^{-4}	2.01×10^{-4}
^{72}Ga	–	–	5.48×10^{-5}	5.49×10^{-5}	5.49×10^{-5}

Table 6. Activity of nuclide by concrete activation

Nuclide	Activity (Bq m^{-3})				
	0.5 hours	2.5 hours	125 hours	250 hours	1000 hours
^{24}Na	–	2.21×10^{-4}	2.49×10^{-3}	2.50×10^{-3}	2.50×10^{-3}
^{31}Si	–	–	4.18×10^{-4}	4.18×10^{-4}	4.18×10^{-4}
^{42}K	–	–	3.96×10^{-4}	3.97×10^{-4}	3.97×10^{-4}
^{152m}Eu	–	–	1.44×10^{-4}	1.44×10^{-4}	1.44×10^{-4}
^{3}H	5.27×10^{-8}	2.63×10^{-7}	1.32×10^{-5}	2.63×10^{-5}	1.05×10^{-4}
^{45}Ca	–	–	6.56×10^{-6}	1.31×10^{-5}	4.95×10^{-5}
^{37}Ar	–	–	3.70×10^{-6}	7.11×10^{-6}	2.16×10^{-5}
^{60}Co	–	–	8.12×10^{-7}	1.64×10^{-6}	6.57×10^{-6}
^{55}Fe	–	–	8.00×10^{-7}	1.61×10^{-6}	6.43×10^{-6}
^{59}Fe	–	–	–	–	2.19×10^{-6}
^{152}Eu	–	–	1.96×10^{-7}	3.96×10^{-7}	1.59×10^{-6}
^{35}S	–	–	–	–	5.15×10^{-7}
^{154}Eu	–	–	2.05×10^{-8}	4.14×10^{-8}	1.66×10^{-7}
^{134}Cs	–	–	–	–	1.10×10^{-7}
^{41}Ca	2.52×10^{-12}	1.26×10^{-11}	6.30×10^{-10}	1.26×10^{-9}	5.04×10^{-9}
^{14}C	–	–	3.81×10^{-11}	7.69×10^{-11}	3.10×10^{-10}
^{59}Ni	–	–	1.64×10^{-12}	3.31×10^{-12}	1.33×10^{-11}

ulations of KAERI [2,10].

The calculated radioactivity by nuclide over time is shown in Tables 3 through Tables 6. For air activation, the radioactivity of ^{41}Ar was calculated to be 1.33×10^{-2} Bq m^{-3} after 0.5 hours of operation. This is below the emission control standard of 5×10^{2} Bq m^{-3} because the beam is operated for 0.5 hours per day according to the operation plan. The emission standard was met even if the beam was operated continuously for 2.5 hours [11,12].

In addition, we could confirm that the activated radioactivity of lead of collimator, stainless steel of beam dump, rails, and concrete were also insignificant below the permissible concentration below clearance level [13].

4. CONCLUSIONS

KAERI uses a D-T neutron generator for research and development of 20 ft container inspection. In this study, The shielding evaluation based on the structure of container inspection room indicates that radiation dose rate at the public area outside the building are satisfactory. The activation of beam dump, rail, and concrete by neutron generator could be confirmed below the clearance level. With above simulations, KAERI got the radiation generator usage permission from the Korean government. And, R&D is being done after the inspection of nuclear regulatory body.

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