RADIATION SAFETY EVALUATION OF THE HANARO RESEARCH REACTOR SPENT FUEL DISPOSAL SYSTEM

by

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HANARO is a multi-purpose Korean research reactor with a high neutron flux and unique fuel types. Recently, a new conceptual disposal system for HANARO spent fuel has been suggested as a solution to the current spent fuel accumulation problem in the near future. This paper investigates HANARO spent fuel characteristics, evaluates radiation intensity by generating its own cross-section library and, finally, estimates the radiation safety of its disposal system. By comparing the absorbed dose of the engineering barrier with the recommended value, it was concluded that the proposed disposal system has a large enough safety margin.

Key words: HANARO, research reactor, spent fuel, disposal system, dose

INTRODUCTION

The multi-purpose Korean research reactor HANARO has been in operation since the mid 1990's. All HANARO spent fuel has been stored in a storage pool and the pool's saturation time is estimated as being around 2025 for the two types of HANARO spent fuel, under certain operational conditions. If the operation time of HANARO is to be prolonged, an enlargement of spent fuel storage is inevitable and, in that sense, two possible methods applied simultaneously are likely: that of changing the design of the storage module and that of using the empty space of TRIGA spent fuel storage. These methods could expand the pool's capacity up to 1.6 times and extend its saturation time to around 2040 [1]. Table 1 shows the enhancement plan for the management of HANARO spent fuel.

Table 1. HANARO spent fuel management plan

Before enlargement			
Type of fuel	Storage capacity [rods]	Current amount [rods]	Expected limit [year]
18-element	432	217*	2027
36-element	600	120*	2024
TRIGA	315	–	–
After enlargement			
Type of fuel	Storage capacity [rods]	Enlarged ratio [%]	Expected limit [year]
18-element	720	166	2042
36-element	984	164	2038

*HANARO spent fuel storage amount as of July 2009 [2]

Upon the expiration of the extension period, the problem of HANARO spent fuel could be considered in the light of three alternative options: returning the spent fuel to the country of origin (USA, Russia) in the form of the 'take-back' TRIGA program for spent fuel [3], recycling the spent fuels by pyroprocessing, as was the case with PWR spent fuel (Korean national strategy), or disposing of it in a final, underground repository. The possibility for the first option is extremely low because of the recent international trend that the generator of radioactive waste has to solve its own high-level waste problems. The second option is as improbable because of the uncertainty of the pyroprocess method, as far as profitability and low feasibility of spent fuel enrichment go. The last of the three options could, therefore, prove to be the most likely one, as was the case in some other countries [4-7]. HANARO spent fuels are expected to be disposed of at a final complex repository, recently suggested as a repository for commercial PHWR spent fuels, high-level wastes produced by pyroprocessing of PWR spent fuel and research reactor spent fuels, combined [8]. The purpose of this article is to characterize HANARO spent fuel properties, evaluate radiation source intensity by generating its own cross-section library and to estimate the radiation safety of the proposed disposal system by comparing dose assessment results with the recommended values.

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HANARO SPENT FUEL CHARACTERISTICS

The core of the HANARO reactor is of an open pool-type, consisting of an inside and outside core with an effective diameter of 0.5 m and a height of 0.7 m. Both cores are cooled by light water, but the latter has a heavy water reflector, so as to increase neutron population. The two types of HANARO fuel in question are: that of the 20 assemblies of hexagonal 36-element (fuel rod) type with 2.2 kg of uranium and that of 12 assemblies of circular 18-element type with 1.2 kg of uranium at the core (fig. 1). The total uranium load in the cores amounts to 58 kg and 12 kg for ^{235}U, respectively. HANARO fuel material is made up of U_3Si and these high density U_3Si particles are dispersed in a high purity alumina matrix. High enriched (95 wt.%) fuel has been used in the past to raise the neutron flux by operating the reactor with a high specific power but, recently, low enriched (19.75 wt.%) fuel which has the maximum limit for low enrichment, is being loaded for non-proliferation reason. This high specific power operation leads to a high decay heat per unit of uranium mass and a high discharge burn-up of around 100,000 MWd/MtU.

RADIATION SOURCE EVALUATION

To evaluate the HANARO spent fuel radiation source, this research used the ORIGEN-ARP 5.0 code [9]. A cross-section library is of utmost importance for this purpose, but ORIGEN-ARP did not serve the HANARO library, so that this research produced its own cross-section library with SAS2 in the SCALE code system. As the first step, a simplification of the fuel rod shape was performed based on data from tab. 2 [10].

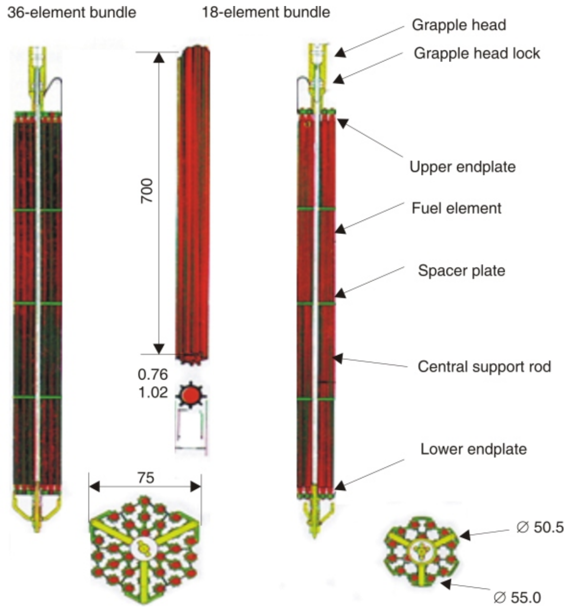

Figure 1. HANARO fuel types

Table 2. Major information on 36-element type fuel bundle and fuel rod

Fuel bundle data	
Bundle type	Hexagonal array
Bundle length [m]	0.96
Number of fuel rods	36
Mass of bundle [kg]	6.784
Mass of uranium [kg]	2.193
Mass of ^{235}U [kg]	0.433
Fuel rod (element) data	
Fuel composition [wt.%]	U: 58.3, Si: 2.2, Al: 39.5
Fuel enrichment [wt.% ^{235}U]	19.75
Fuel density [kgUm^{-3}]	3150
Fuel out-diameter [m]	0.00635
Rod length [m]	0.7
Rod pitch [m]	0.012
Clad material	Al-type AA1060
Clad out-diameter without fins [m]	0.00787
Clad thickness [m]	0.00076

This modification produced a hexagonal flow tube with two main output data: inside flat-to-flat diameter as 0.00744 m and outer diameter as 0.0076 m. A real fuel rod configuration and a simplified model to produce the cross-section library of the 36-element fuel assembly are shown in fig. 2.

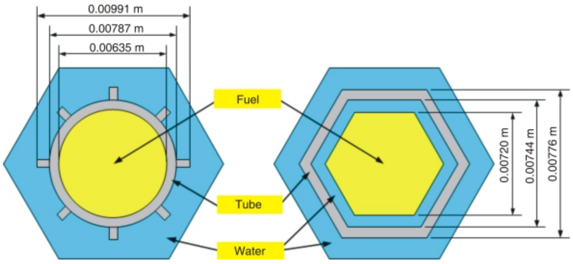

Figure 2. Fuel rod configuration and its homogenized shape

Contrary to the commercial power reactor library which usually needs 5 initial enrichment cases (1.5, 2, 3, 4, and 5 wt.%) with various burn-up levels, the HANARO library only needs one initial enrichment case (19.75 wt.%) with various burn-up levels of up to 100,000 MWd/MtU. By using the ARPLIB module, a total of 12 library sets with 0, 4637.5, 13912.4, 23187.4, 32462.4, 41737.3, 51012.3, 60287.3, 69562.2, 78837.2, 88112.2, and 97387.1 MWd/MtU burn-ups were produced for the 36-element fuel assembly [11]. For simplicity and conservatism, only the 36-element type was considered in the creation of the library and radiation calculations. The irradiation history of the fuel assembly consisted of 7 cycles which include an irradiation time of 28 days with 510200 W/kgU specific power and a downtime of 7 days. This irradiation history could reach

Table 3. Basic information for cross-section library generation

Item	Value	Irradiation history	Value
Fuel type	HANARO 36-element	Power/basis [$W(kgU)^{-1}$]	510200
Initial enrichment	19.75 wt.%	1 cycle time [d]	28
Final burn-up	100000 MWd/MtU	Cycle burn-up [$MWd(MtU)^{-1}$]	14285.7
Cooling time	30 years		

up to 100,000 MWd/MtU for each fuel assembly. Table 3 lists the basic information used in the creation of the libraries.

By applying our cross-section library to ORIGEN-ARP, radiation time changes were obtained for a period of a million years (fig. 3), as of recently, considered to be an important time boundary for final disposal [12]. As is commonly the case with radioactive nuclides' decay, high heat generating nuclides like cesium and strontium disappear in a thousand years, but technetium and actinides keep generating radiations even beyond a period of ten thousand years.

Table 4 shows photon and neutron intensity of the 44 energy groups. The neutron source is not active because there will be a cooling time gap of more than 30 years between the discharge from the core and final disposal.

DOSE EVALUATION

Disposal system

The HANARO disposal system consists of spent fuel, basket, canister, and an engineering barrier system (EBS). The basket could hold 60 assemblies of 36-element fuel type and is made of stainless steel. A canister with a cast iron inside wall and copper outside wall could hold the basket and serve as a radiation shield. Cast iron of a thickness of 0.18 m and 0.095 m was used for structural material at the top and bottom and at the lateral sides, respectively. This difference in thickness is meant to prevent structural distortion by vertical compression and to allow for the fitting of the diametric limitation of the size of the disposal hole. A copper coating with a thickness of 0.03 m at the top and bottom and 0.01 m in the lateral region was added in order to prevent corrosion within the disposal environment. The engineering barrier system is similar to the KRS-V1 disposal barrier system [13]. It consists of bentonite blocks as a buffer around the disposal canister, a vertical disposal hole, disposal tunnel, and bedrock in the outer region. The engineering barrier, that is, the buffer, serves as a barrier preventing ground water intrusion and radionuclide release in case of accidents. The height of the tunnel was set to 4.1 m and its width to 3.9 m, taking into account the work space needed for the equipment. Figure 4 shows the comprehensive conceptual design of the HANARO spent fuel disposal system.

MCNP modeling

For radiation dose assessment of the disposal system, all disposal system components (fuel, basket, canister, and engineering barrier) were modeled and analyzed by the MCNP code [14].

In fuel component modeling, density and the composition fraction of the radiation source material is important for MCNP modeling and, therefore, a homogenized model of a fuel bundle (36 fuel rods and air) was generated in a cylinder shape, in following steps:

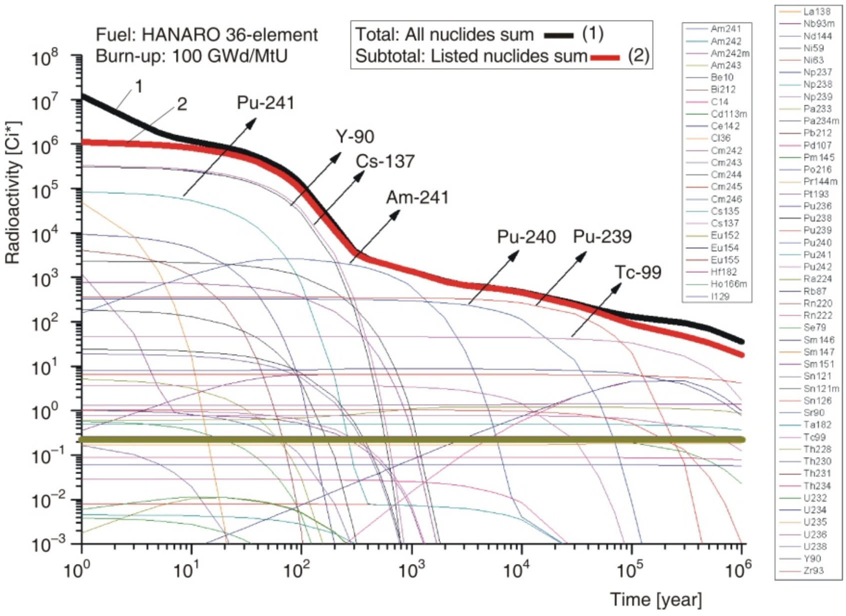

Figure 3. Radioactivity changes along time, up to 1 milion years

^{*1} Ci = 3.7 10^{10} Bq

Table 4. Radiation source intensity for 1 MtU

Energy group	Photon			Neutron		
	Energy range		Radiation intensity [s^{-1}]	Energy range		Radiation intensity [s^{-1}]
	Low [MeV]	High [MeV]		Low [MeV]	High [MeV]	
1	1.00E-02*	2.00E-02	1.8221E+15	1.00E-11	3.00E-09	1.09E-06
2	2.00E-02	3.00E-02	8.7269E+14	3.00E-09	7.50E-09	2.22E-06
3	3.00E-02	4.50E-02	1.0563E+15	7.50E-09	1.00E-08	1.53E-06
4	4.50E-02	6.00E-02	5.3373E+14	1.00E-08	2.53E-08	1.27E-05
5	6.00E-02	7.00E-02	2.3529E+14	2.53E-08	3.00E-08	4.87E-06
6	7.00E-02	7.50E-02	1.0055E+14	3.00E-08	4.00E-08	1.16E-05
7	7.50E-02	1.00E-01	3.9318E+14	4.00E-08	5.00E-08	1.31E-05
8	1.00E-01	1.50E-01	4.0781E+14	5.00E-08	7.00E-08	3.01E-05
9	1.50E-01	2.00E-01	2.6061E+14	7.00E-08	1.00E-07	5.36E-05
10	2.00E-01	3.00E-01	2.0341E+14	1.00E-07	1.50E-07	1.08E-04
11	3.00E-01	4.00E-01	1.4396E+14	1.50E-07	2.00E-07	1.54E-04
12	4.00E-01	4.50E-01	4.2813E+13	2.00E-07	2.25E-07	8.42E-05
13	4.50E-01	5.10E-01	4.1371E+13	2.25E-07	2.50E-07	8.82E-05
14	5.10E-01	5.12E-01	4.9663E+11	2.50E-07	2.75E-07	9.20E-05
15	5.12E-01	6.00E-01	2.0715E+13	2.75E-07	3.25E-07	1.95E-04
16	6.00E-01	7.00E-01	5.3683E+15	3.25E-07	3.50E-07	1.02E-04
17	7.00E-01	8.00E-01	2.5454E+13	3.50E-07	3.75E-07	1.06E-04
18	8.00E-01	1.00E+00	2.8226E+13	3.75E-07	4.00E-07	1.09E-04
19	1.00E+00	1.20E+00	1.2681E+13	4.00E-07	6.25E-07	1.10E-03
20	1.20E+00	1.33E+00	1.5212E+13	6.25E-07	1.00E-06	2.26E-03
21	1.33E+00	1.44E+00	1.1133E+12	1.00E-06	1.77E-06	5.93E-03
22	1.44E+00	1.50E+00	5.5259E+11	1.77E-06	3.00E-06	1.22E-02
23	1.50E+00	1.57E+00	3.3796E+11	3.00E-06	4.75E-06	2.19E-02
24	1.57E+00	1.66E+00	1.3150E+12	4.75E-06	6.00E-06	1.83E-02
25	1.66E+00	1.80E+00	2.6020E+11	6.00E-06	8.10E-06	3.51E-02
26	1.80E+00	2.00E+00	1.1851E+11	8.10E-06	1.00E-05	3.58E-02
27	2.00E+00	2.15E+00	2.0282E+10	1.00E-05	3.00E-05	5.51E-01
28	2.15E+00	2.35E+00	7.8137E+07	3.00E-05	1.00E-04	3.92E+00
29	2.35E+00	2.50E+00	7.6975E+07	1.00E-04	5.50E-04	5.48E+01
30	2.50E+00	3.00E+00	1.2999E+08	5.50E-04	3.00E-03	6.19E+02
31	3.00E+00	3.50E+00	7.6808E+05	3.00E-03	1.70E-02	9.48E+03
32	3.50E+00	4.00E+00	4.4302E+05	1.70E-02	2.50E-02	8.06E+03
33	4.00E+00	4.50E+00	2.5603E+05	2.50E-02	1.00E-01	1.24E+05
34	4.50E+00	5.00E+00	1.4803E+05	1.00E-01	4.00E-01	8.78E+05
35	5.00E+00	5.50E+00	8.5619E+04	4.00E-01	9.00E-01	1.90E+06
36	5.50E+00	6.00E+00	4.9539E+04	9.00E-01	1.40E+00	1.95E+06
37	6.00E+00	6.50E+00	2.8671E+04	1.40E+00	1.85E+00	1.75E+06
38	6.50E+00	7.00E+00	1.6597E+04	1.85E+00	2.35E+00	1.98E+06
39	7.00E+00	7.50E+00	9.6104E+03	2.35E+00	2.48E+00	4.81E+05
40	7.50E+00	8.00E+00	5.5658E+03	2.48E+00	3.00E+00	1.80E+06
41	8.00E+00	1.00E+01	6.5623E+03	3.00E+00	4.80E+00	2.61E+06
42	1.00E+01	1.20E+01	3.3858E+02	4.80E+00	6.43E+00	4.93E+05
43	1.20E+01	1.40E+01	0.0000E+00	6.43E+00	8.19E+00	1.51E+05
44	1.40E+01	2.00E+01	0.0000E+00	8.19E+00	2.00E+01	5.07E+04
	Totals		1.16E+16	Totals		1.42E+07

* Read as 1.00 10^{-2}

- analyzing nuclides and its composition fraction in fuel with a 3150 kg/m^3 density; uranium 58.3, silicon 2.2, and aluminum 39.5 wt.%,
- analyzing nuclides and its composition fraction in cladding (Al AA1060) with a 2700 kg/m^3 density; iron 0.35, manganese 0.03, silicon 0.25, copper 0.05, zinc 0.05, aluminum 99.27 wt.%,
- volumetric calculation for fuel and cladding result in 65% occupation of fuel material. This has updated the homogenized composition fraction of each nuclide, and
- volumetric calculation for bundle (fuel and cladding) and open space (air) results in 42% of fuel bundle.

The final source material density and composition fractions for each nuclide are shown in tab. 5.

In basket modeling, the CANDU spent fuel basket was applied for HANARO spent fuel fixing in the

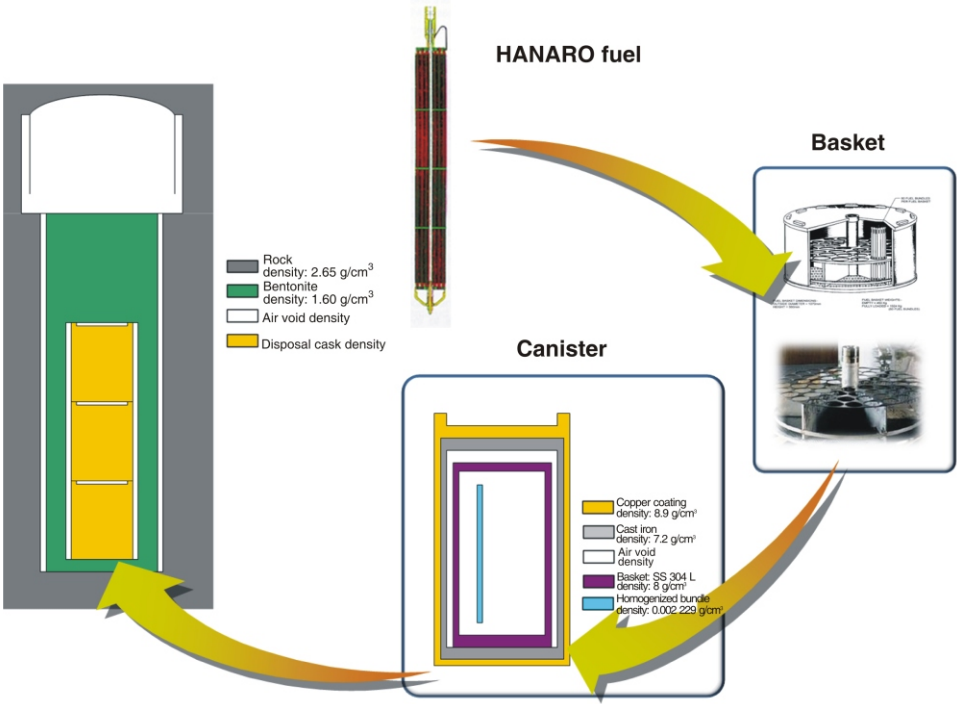

Figure 4. Conceptual diagram of HANARO spent fuel disposal system

Table 5. Homogenized material composition of HANARO fuel

Homogenized fuel			2.2229 kg/m³	Total = 1
Fuel area	Fuel		3 150 kg/m³	
42%	65%	Nuclide	Value unit	
		U	58.3%	0.04517769
		Si	2.2%	0.01120309
		Al	39.5%	0.21661922
	Clad		2 700 kg/m³	
	35%	Nuclid	Value unit	
		Fe	0.35%	0.00025789
		Mg	0.03%	0.00004789
		Si	0.25%	0.00034209
		Cu	0.05%	0.00003303
		Zn	0.05%	0.00003193
		Al	99.27%	0.14628717
Empty space	Air		1.293 kg/m³	
58%	100%	Nuclide	Value	
		N	78	0.45240000
		O	22	0.12760000

vertical direction [15]. The top view of the basket and the position of the hole are shown in fig. 5.

In canister modeling, one basket containing 60 spent fuel bundles was loaded into a canister as in fig. 6. The shoulder of the canister was intentionally omitted because this part could not significantly affect the whole tally results. Cast iron and copper shields were properly modeled. In order to monitor radiation particle tracking in detail, a 0.01 m thickness mesh approach was applied to the cast iron shield because of its thickness.

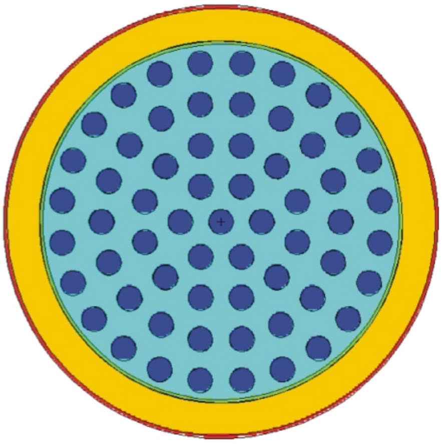

Figure 5. Basket configuration of 60 HANARO 36-element fuel bundles

In engineering barrier modeling, 3 canisters were installed into a disposal hole surrounded by a wet bentonite buffer (engineering barrier). Figure 7 shows vertically installed canisters in a disposal hole and tunnel, conceptually. Major properties of the disposal components are listed in tab. 6.

Dose assessment

The total photon and neutron rates for one canister have been calculated for the 44 energy groups by using ORIGEN-ARP 5.0: for photons as 1.508 10^{15} s^{-1}

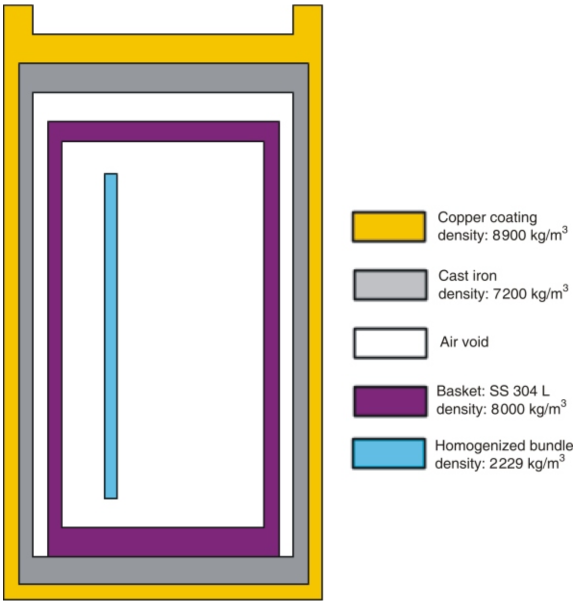

Figure 6. Canister configuration with a basket

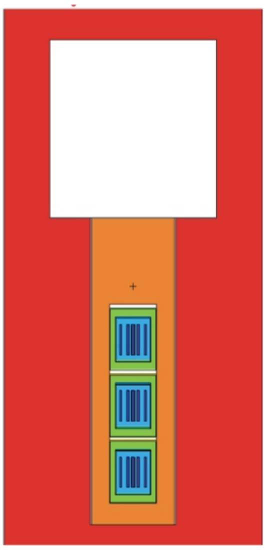

Figure 7. Conceptual design of a disposal hole

and for neutrons as 1.85 10^6 s^{-1}. The flux-to-dose conversion factor of ICRP-74 recommendation was used in the conversion [16]. Tallies were set at the top, bottom, and lateral side of the canister at a 0.1 m distance. Dose calculation results for each of the said directions are shown in tab. 7. For gamma radiation, the tally relative error was 2.54% for 10^6 number of particles. For neutron radiatin, the tally relative error was 0.15% for 10^6 number of particles.

Table 7. Dose result for the HANARO disposal system

Item	Location	Dose			Unit
		Gamma	Neutron	Total	
Canister	Top	1.06E+00*	4.54E-03	1.06E+00	mSvh^{-1}
	Side	3.58E+02	1.40E-02	3.58E+02	
	Bottom	1.13E+04	2.98E-02	1.13E+04	
EBS		0.59E+00	5.56E-07	0.60E+00	Gyh^{-1}

* Read as 1.06 10^0

The dose result for the bottom of the canister was higher than the one for the top and this is probably due to the 0.1 m thickness of the copper in the bottom area, compared to that of 0.3 m in the top area. Contrary to canister dose calculation, the absorbed dose is usually used for engineering barriers such as bentonite or bedrock, so as to estimate how the barrier could, instead of enhancing, absorb the radiation energy from the waste. Usually, 1 Gy/h value is the recommended limit for the bentonite engineering barrier, because the higher the radiation energy, the higher the possibility for the radiolysis of bentonite [17]. The absorbed dose of the engineering barrier system from the 3 canisters has been conservatively calculated for most of the inner (0.01 m) bentonite layer. The absorbed dose result in tab. 7 shows that the engineering barrier system of the HANARO spent fuel disposal system has a wide enough margin to accommodate the radiolysis threshold limit. This result is expected to be very useful in assessing the performances of engineering barrier systems in general.

CONCLUSIONS

This article has reviewed the major characteristics of the HANARO research reactor spent fuel, suggested its disposal system conceptually, made a MCNP-based model of it, and presented radiation safety evaluations of the disposal system, quantitatively. For this purpose, a unique cross-section library of HANARO was created and successfully applied to ORIGEN-ARP and MCNP calculation techniques. It was concluded that the recently proposed HANARO disposal system has a wide enough margin for radia-

Table 6. Dimensions and material properties of disposal components

Components	Material	Density [kgm^{-3}]	Diameter [m]	Height [m]	Thickness [m]		
					Top	Side	Bottom
Basket	SA240 Type 304 L	8000	1.0670	1.0220	0.0085	0.0085	0.0191
Canister	Cast iron	7200	1.2600	1.4050	0.1800	0.0950	0.1800
	Copper	8900	1.2800	1.4450	0.0300	0.0100	0.0300
Buffer	Bentonite	2150	2.0200	7.0900	–	0.3600	–

tion safety, based on the absorbed dose assessment of the disposal system engineering barrier.

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ОЦЕНА РАДИЈАЦИОНЕ СИГУРНОСТИ НАЧИНА ОДЛАГАЊА ИСЛУЖЕНОГ ГОРИВА ХАНАРО ИСТРАЖИВАЧКОГ РЕАКТОРА

ХАНАРО је корејски вишенаменски истраживачки реактор, са високим флуксом неутрона и јединственим врстама нуклеарног горива. Недавно, као решење актуелног проблема нагомилавања искоришћених горивних елемената у блиској будућности, предложен је нови концепт одлагања. У раду су приказани резултати истраживања карактеристика искоришћених горивних елемената реактора ХАНАРО, израчунавања интензитета зрачења помоћу генерисаних сопствених библиотека пресека и, најзад, оцене радијационе сигурности предложеног система одлагања. Упоређивањем апсорбоване дозе кроз предвиђење баријере предложеног система одлагања закључено је да су знатно испод препоручених вредности.

Кључне речи: ХАНАРО, истраживачки реактор, ислужено гориво, систем одлагања, доза