Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

A Preliminary Study on the Radiation Damage to Safeguards Instruments in the Head-End Pyroprocess Based on Dose Rate Evaluation

JINHWAN KIM[a], SEONG-KYU AHN[b], CHANGYEOP LEE[a], SE-HWAN PARK[b], and GYUSEONG CHO[a]
[a] *Dept. of Nuclear & Quantum Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
[b] *Korea Atomic Energy Reserch Institute, KAER, 989-111 Daedeok-daero, Yuseong-gu, Daeheon 34057, Republic of Korea*
[*]Corresponding author: gscho@kaist.ac.kr

1. Introduction

Because of the international trend of reinforcement on the regulation of the greenhouse gas emission from fossil fuel consumptions, the rate of nuclear power generation is expected to regrow continuously in many countries. In 2015 nuclear power accounts for 30.0 percent of the total electric power generation in Korea. This rate has been continuously grown since 1977 when the first nuclear power plant started operation in Kori site. Under the circumstances, the national-level decision on the treatment policy of nuclear spent fuels (SFs) becomes an unavoidable and urgent issue to be made in due course. Recently the Korean government has decided to build a centralized interim storage of SFs for the period of more than 50 years. During this period, a decision on the final treatment policy of SFs will be made through studies of various options. A pyroprocess has been selected as a viable option of reprocessing SFs not only to reduce the volume and radiotoxicity of high– level radioactive wastes to be disposed permanently but also to reutilize transuranic elements (TRU) for the next generation nuclear reactors such as sodium-cooled fast reactors (SFR) [1].

The pyroprocess is a series of mechanical and chemical processes to convert PWR spent fuel assemblies (SFAs) into metallic pellets of uranium and TRU for reuse after dissembling the cladding. Also fission products will be extracted as melted salt forms. It is basically a dry process where there is no chance to separate the plutonium from the TRU in contrast to a typical wet reprocess. Therefore, it could be highly acceptable to the international society in the point of nuclear safeguards and nonproliferation with the installation of proper monitoring devices [2– 6].

In 2012, the Korea atomic energy research institute (KAERI) proposed a conceptual pyroprocess facility, so called the Reference Engineering-scale Pyroprocess Facility (REPF), where 10 tHM (ton Heavy Metal) of the SFAs per year shall be processed [7]. Currently KAERI is revising the REPF to a larger-scale facility which can treat 30 tHM per year. The new facility is mainly composed of three hot-cells in series. The 1st hot-cell is an air cell where the preprocess (or head-end pyroprocess) will be conducted. The preprocess is a serial combination of 25 unit processes including a de-cladding and pelletizing unit process. The other two hot-cells are argon cells where the electrical reduction and electrical recovery processes will be conducted respectively [1,8].

In the safeguards aspect, it is important to assure that there can be no chance of non-permissioned diversion of nuclear materials in these hot cells. As previous experience in the Rokkasho reprocessing plant (RRP) in Japan, the Integrated Head-End Verification System (IHVS) was defined in order to verify the flow of the SFAs within Material Balanced Areas (MBAs) [9]. This system consists of a number of Camera/Radiation Detector (CRDs), shown in Fig. 1, mounted in the cell walls with additional CCTV units installed near rod sectioning process.

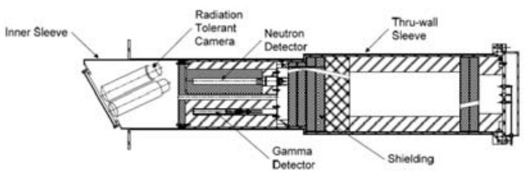

Fig. 1. The schematic of a camera-radiation detector (CRD), composed of a He-3 neutron detector, a gamma detector and two radiation-tolerant cameras, which has been applied in the head-end process of the Rokkasho reprocessing plant in Japan.

Since the IHVS is expected to be highly irradiated in hot cell, their designed values of radiation tolerance, expected dose rates at their installation positions and proper shielding on gamma-rays and neutrons should be considered for the estimation and extension of their life-times and for minimization of cost for their maintenance and replacement.

In this study, based on the proposed geometry and material balance of unit processes, radiation damage to the IHVS was evaluated. For this, only the radiation tolerant camera itself embedded in the CRD and CCTV were taken into account; shielding effect on degradation of detection efficiency for the detectors embedded in the CRD was neglected. In addition, the desired lifetimes and the cameras of the IHVS were assumed to be 10 years and 5 × 104 Gy respectively, considering the specification of commercially available camera. In case of excessive radiation exposure to the IHVS, the shielding effects with different thicknesses were evaluated to achieve its desired lifetimes. Furthermore, some selected combination of variance reduction techniques was applied to minimize the relative errors as well as the computation times for the shielding calculation.

2. Materials and Methods

2.1 Unit processes in the air cell

It is assumed that only the unit process chambers exist in the air cell for the simplicity of the simulation of radiation transport; that is, other devices or structures such as pipelines, product separators, and weight scales are ignored. In this regard, the preprocess in the air cell comprises 14 different but total 25 unit processes. The objective of the air cell is to convert the SFAs to a suitable feed material for the following electrolytic reduction process in the argon cell. The preprocess in the air cell comprises mainly three steps; disassembling, de-cladding and pelletizing. The first step is to disassemble the SFAs. They are mechanically chopped into rod-cuts in a proper size for the de-cladding process. In order to achieve a high de-cladding efficiency in the second step, a voloxidation and a powder mixing process are required [1]. The final step is the pelletizing, reduction and high-temperature treatment (H.T.

treatment) processes in sequence. The reduction process converts U3O8 powder into granular and porous UO2 pellets and it will later enhance the efficiency of electro-reduction process in the argon cell [8]. There are several WIPs (Work In Processes) where the nuclear materials are temporary stored before the next unit processes.

All unit processes are assumed to be conducted in separate solid cylindrical chambers made of stainless steel. They are filled with the air and nuclear materials that are the source terms for the simulation. However, the filters of a few unit processes are made of inconel and filled fully with a mixture of collected cesium gas and ceramic. The SFA is assumed to be a bundle with a half size of 16×16 array of PULS7 covered with a zirconium cladding [10]. The air cell size, the number of unit process and its batch size etc. are assumed for the scaled-up facility based on the process capability of 30 tHM (ton heavy metal) per year.

2.2 Simulation geometry of the air cell

The proposed air cell has a dimension of 12×71×9 m3, containing an air atmosphere, with 1 m thick boron frits-barite concrete shielding around the wall, the ceiling, and the floor [6]. All the unit processes are shown and listed in Fig. 2. It also indicates the position of the IHVS. The cameras embedded in the CRD and the CCTV were simply assumed to be filled with silicon covered by stainless steel.

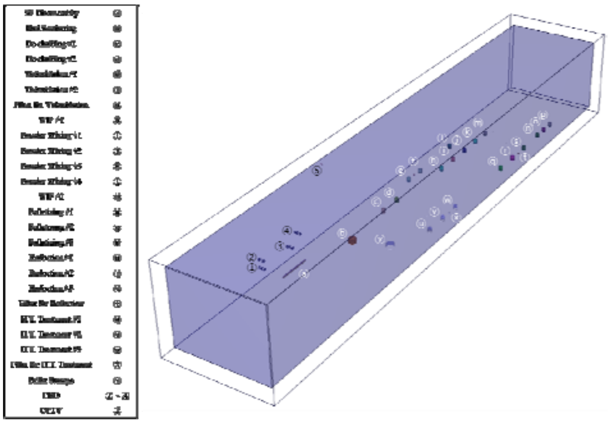

Fig. 2. The schematic of the air cell geometry and the positions of all the unit processes. A 3D display is visualized by MCNPX visual editor.

2.3 Source term of the air cell

The energy spectra of gamma-rays and neutrons emitted from the SF material were calculated, as shown in Fig. 3, by using ORIGEN-ARP code [11]. To make conservative and simple approaches, we established a number of assumptions and simulation strategies as described below.

- In order to estimate the radionuclide inventory of SFs, the initial enrichment of 235U was assumed to be 4.5%. The average burn-up and the cooling time were also assumed to be 55 GWD/MTU and 10 years respectively.
- Bremsstrahlung x-rays by the medium of UO2 were included in the energy spectra of gamma-ray.
- The (α , n) reactions were included in the energy spectra of neutron.
- The material composition of each unit process was obtained by applying to the yield of each unit process.
- Although the material compositions of each unit process are a little different, all

unit processes were classified into three groups of the same material compositions: the group 1 for the SF disassembly, rod sectioning and de-cladding processes, the group 2 for the WIPs, voloxidation, powder mixing, pelletizing and reduction processes, and the group 3 for the H.T. treatment process, and the pellet storage; Nevertheless, the energy spectra of emitted radiation in all unit process varied depending on the batch size of each unit process.

- Every unit process was assumed to contain one batch of the nuclear material. But, the voloxidation, the reduction, and H.T. treatment processes were assumed to contain five cumulated batches of gaseous cesium, which contributes the emission of gamma-ray.
- The source term was assumed to be homogenized in the nuclear material.

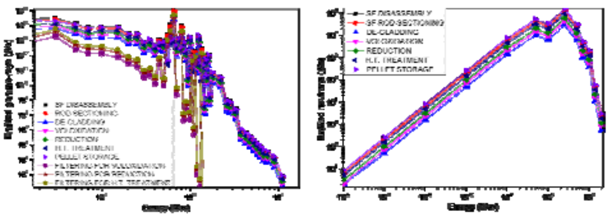

Fig. 3. The energy spectra of gamma-rays (left) and neutrons (right) from the materials of unit processes.

2.4 Tally and particle histories of Monte Carlo Simulation

Results were obtained using the F6 track length estimate of energy deposition tally to obtain the cumulative dose of the IHVS during 10 years.

MATLAB, which is compatible to MCNP6, was used to conduct iterative re-simulations at once. Particle histories automatically increased with 1×10^5 intervals from 1×10^5 until the tallies passed 10 statistical checks and the relative errors became below 10% as suggested generally [12]. If these conditions were satisfied, the simulation was terminated and another input file was automatically activated for the next simulation in the MATLAB program aforementioned.

3. Result and discussion

3.1 Cumulative dose of the IHVS

Cumulative dose of the IHVS during 10 years was evaluated. Fig. 4 shows that the CCTV and the CRD #4 satisfy their desired lifetimes. Whereas, additional shielding for the CRD #1, #2 and #3 is required in order to extend the use.

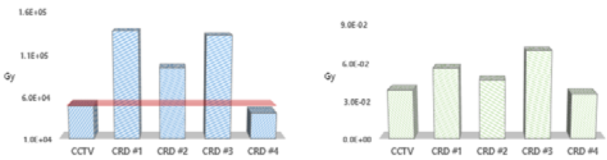

Fig. 4. Gamma-rays (left) and neutrons (right) cumulative dose of the IHVS during 10 years

3.2 Selection of variance reduction technuqes for shielding calucation

Some selected combination of variance reduction techniques such as the source biasing, the exponential transform, the weight windows, the forced collision, and the DXTRAN were applied to minimize the relative errors and the computation times for the shielding calculation of the photon transport for the case of a CRD #1 [13]. Two kinds of combination method were compared for the better efficiency of the simulations: one was the DXTRAN with the forced collision (the method A) and the other was the weight windows with the exponential transform (the method B). The source biasing was basically applied to both methods. These calculations are now progressing and the result will be presented in the student poster session.

3.3 Shielding effects on life-teims of IHVS

These calculations are also now progressing and the result will be presented in the student poster session.

REFERENCES

[1] H. Lee, G. Il Park, J.W. Lee, K.H. Kang, J.M. Hur, J.G. Kim, S. Paek, I.T. Kim, I.J. Cho, Current status of pyroprocessing development at KAERI, Sci. Technol. Nucl. Install. 2013 (2013). doi:10.1155/2013/343492.

[2] R.A. Borrelli, Use of curium spontaneous fission neutrons for safeguardability of remotely-handled nuclear facilities: Fuel fabrication in pyroprocessing, Nucl. Eng. Des. 260 (2013) 64– 77. doi:10.1016/j.nucengdes.2013.03.025.

[3] R.A. Borrelli, Use of curium neutron flux from head-end pyroprocessing subsystems for the High Reliability Safeguards methodology, Nucl. Eng. Des. 277 (2014) 166– 172. doi:10.1016/j.nucengdes.2014.06.028.

[4] R.A. Borrelli, Functional components for a design strategy: Hot cell shielding in the high reliability safeguards methodology, Nucl. Eng. Des. 305 (2016) 18– 27. doi:10.1016/j.nucengdes.2016.05.010.

[5] S.I. Moon, S.J. Seo, W.M. Chong, G.S. You, J.H. Ku, H.D. Kim, Identification of safety controls for engineering-scale pyroprocess facility, Nucl. Eng. Technol. 47 (2015) 915– 923. doi:10.1016/j.net.2015.08.005.

[6] S.I. Moon, W.M. Chong, G.S. You, J.H. Ku, H.D. Kim, Y.K. Lim, H.S. Chang, Preliminary safety study of engineering-scale pyroprocess facility, Nucl. Eng. Technol. 46 (2014) 63– 72. doi:10.5516/NET.06.2013.018.

[7] H.D. Kim, H.S. Shin, D.Y. Song, T.H. Lee, B.Y. Han, S.K. Ahn, S.H. Park, Application of Safeguards-By-Design for the Pyroprocessing Facilities in ROK, X (2012) 24– 31.

[8] H. Lee, G. Il Park, K.H. Kang, J.M. Hur, J.G. Kim, D.H. Ahn, Y.Z. Cho, E.H. Kim, Pyroprocessing technology development at KAERI, Nucl. Eng. Technol. 43 (2011) 317– 328. doi:10.5516/NET.2011.43.4.317.

[9] S.J. Johnson, C. Pearsall, K. Hiruta, C. Creusot, M. Ehinger, E. Kuhn, B. Chesnay, N. Robson, H. Higuchi, S. Takeda, K. Fujimaki, H. Ai, S. Uehara, H. Amano, K. Hoshi, Development of the Safeguards Approach for the Rokkasho Reprocessing Plant, (n.d.).

[10] K.-T. Kim, Y.-K. Jang, J.-I. Kim, In-Reactor Performance of an Advanced PWR Fuel, PLUS7, for OPR1000s in Korea, J. Nucl. Sci. Technol. J. J. Nucl. Sci. Technol. 458 (2008) 22– 3131. doi:10.1080/18811248.2008.9711485.

[11] S. M. Bowman, OrigenArp Primer□ : How to Perform Isotopic Depletion and Decay Calculations with SCALE / ORIGEN, 2010.

[12] J.T. Goorley, M.R. James, T.E. Booth, F.B. Brown, J.S. Bull, L.J. Cox, J.W. Durkee, J.S. Elson, M.L. Fensin, R.A. Forster, J.S. Hendricks, H.G. Hughes, R.C. Johns, B.C. Kiedrowski, S.G. Mashnik, MCNP6 User's Manual, Version 1.0, LA-CP-13-00634, (2013) 765.

[13] M.R. Hill, Los Alamos, Scr. Mater. 836 (2002) 0– 6.