Estimation of the Radionuclide Inventory in Spent Fuels of VVER-1200 Using TRITON

Seyda Karadag [a.b*], Yong Ho Ryu [b*]
[a]*Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 3414, Korea*
[b]*Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon 305-338, Korea*
**Corresponding authors: karadag@kaist.ac.kr, ryh@kins.re.kr*

1. Introduction

Spent fuel is a byproduct of a nuclear fuel cycle and it must be managed effectively to ensure an optimum level of safety. Spent fuel is highly radioactive due to irradiation and thermally hot due to decay heat, therefore, it must be handled and stored carefully. For effective spent fuel management, assessment of radionuclide inventories is necessary. These inventories are used in choosing shielding design and size, as well as for safe transportation of the spent fuel.

VVER-1200 is a Generation III+ reactor and it is the latest design of VVERs. VVER-1200 is developed based on VVER-1000. The fuel assembly model of VVER-1000 is TVS-2 and VVER-1200 is TVS-AES-2006 [1]. Although the design of these two fuel assemblies is identical for both reactors, the VVER-1200 assembly is taller [1]. Also, VVER-1200 uses more enriched fuel (up to 4.95 ± 0.05%), larger pellet radius, and taller fuel rods. All these differences lead to a longer cycle length and a higher burn-up.

The Oak Ridge Isotope Generation code (ORIGEN) has a variety of reactor libraries including VVER-440 and VVER-1000. ORIGEN sequence uses these libraries to perform accurate depletion and decay calculations for spent nuclear fuel assemblies [2]. Currently, ORIGEN does not have a VVER-1200 library. Therefore, a VVER-1200 reactor library should be created by using Transport Rigor Implemented with Time-dependent Operation for Neutronic depletion code (TRITON) in order to get accurate results.

This paper details creating ORIGEN reactor library for VVER-1200 by using TRITON and estimating the radionuclide inventory for 1 MTU fuel. To calculate more accurate results, U-Gd fuel rods were also included as a second fuel material.

2. Methodology

In this study, in order to create an ORIGEN library for VVER-1200, TRITON was used. TRITON is included in SCALE6.2 and it is a SCALE control module for transport and depletion analysis. Normally using TRITON for calculating spent fuel inventories took more time compared to ORIGEN-ARP. But SCALE 6.2 can perform faster calculations with TRITON/NEWT compared to SCALE 6.1.

To model the assembly data about material compositions, temperatures, geometry, and irradiation history were required. The relevant data is given in Tables I, II and III.

Table I: Input data

Electric power (MWe)	1200
Specific power (MW/MTU)	40
Fuel enrichment (%)	4.95
Cycle length (effective days)	340
Gd2O3 content in U-Gd fuel (%)	8
U235 enrichment in U-Gd fuel (%)	2.4
Fuel pin outer radius (mm)	9.1
Cladding inside diameter (mm)	7.73
Fuel pellet outer radius (mm)	7.6
Fuel pellet central hole radius (mm)	1.2
Pitch (mm)	12.75
Height (mm)	3730
Fuel pellet density (g/cm^3)	8.8958
Cladding density (g/cm^3)	6.5500
Coolant density (g/cm^3)	0.7145

Table II: Chemical composition of alloy E-110

Element	Content (%)
Zr	98.97
Nb	1.00
Hf	0.03

Table III: Chemical composition of alloy E-365

Element	Content (%)
Zr	97.2
Nb	1.1
Sn	1.3
Fe	0.4

2D TRITON depletion sequence `T-DEPL` was used for generating the reactor library of VVER-1200. T-DEPL is the two-dimensional TRITON depletion sequence which uses NEWT for transport calculations and coupled with ORIGEN depletion calculations [3]. While T-DEPL sequence automates cross section processing, transport and depletion calculations, ORIGEN performs depletion and decay calculations and then isotopic concentrations are found [3].

Keyword “parm=” is used for cross-section processing. parm=(addnux=N) is the control parameter and it adds trace quantities of selected nuclides, which impact the cross-section processing and transport calculations [4]. By changing it N number nuclides are added to the fuel material. In this paper, N=3 depletion sequence is used which adds 231 nuclides to the fuel

material. TRITON has four options for N and N=0 and N=1 are not advised to be used for high burn-up fuels [4].

In the composition block, UO2 composition was created using the density, the average temperature and the concentration of U isotopes. 20 important elements were added to the composition because they are required for the characterization of the spent fuel. E-110 composition was used as a cladding material. Then coolant and concentration of boron were added for fuel material. For U-Gd fuel rods, another composition was created and cladding and coolant compositions were supplied to the code for this fuel material.

```
uo2 1 den=8.8958 1 900
                    92235 4.95
                    92238 95.5 end
```

Fig. 1. Fuel material 1 - U fuel rods

```
uo2    11 den=8.8958 0.92 900 92235 2.4 92238 97.6   end
gd2o3   11 den=8.8958 0.08 900 end
```

Fig. 2. Fuel material 2- U-Gd fuel rods

VVER-1200 has a hexagonal core, therefore, it has a triangular pitch. In the cell data block, triangular pitch and fuel diameters were defined. Cell data that is used in this study is given in Fig. 3.

```
read celldata
latticecell triangpitch fuelr=0.386 1 cladr=0.455 2 hpitch=0.6375 3 end
latticecell triangpitch fuelr=0.386 11 cladr=0.455 12 hpitch=0.6375 13 end
```

Fig. 3. Cell data

For irradiation history, a power level of 40 MW/t with 12 time periods each of 85 days (3 cycles operation) was used. Also, different decay times were used in order to observe changes of radioactivity the number of years in Table IV.

```
read burndata
power=40 burn=1e-15 end
power=40 burn=85 end
power=40 burn=85 end
power=40 burn=85 decay 365 end
```

Fig. 4. Example of irradiation history for one year decay time

In the geometry block, the geometry of fuel cells and non-fuel cells was defined in terms of the assembly, instrumentation tube, and guide channels. For the fuel cell, the central hole is added to the gap for the simplicity calculation.

For the array block, hexagonal assembly was supplied. The instrumentation channel was placed in the middle of the assembly and 17 guide channels are placed triangularly to the center of the hexagonal assembly [1].

In this study, six U-Gd fuel rods were placed symmetrically in the assembly as seen in Fig. 5.

The input material was specified to 1MTU. Therefore, in this paper results are given for 1MTU fuel.

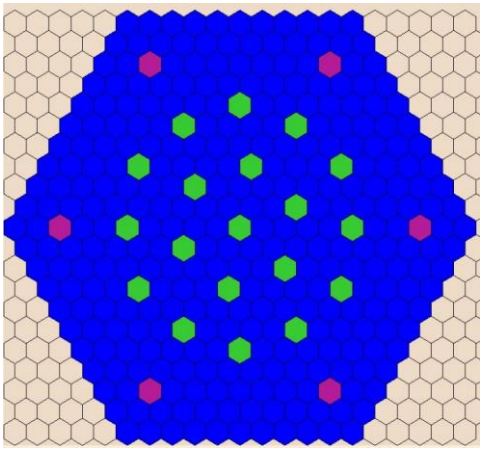

Fig. 5. VVER-1200 assembly model

3. Results and Discussion

The top ten nuclides which contribute to radioactivity in the short-term and the long-term are given in Table IV. Table IV also shows total radioactivity levels of actinides, fission products, and light elements as a function of time. Fig. 6, and 7 show the change in radioactivity over time.

Actinides, fission products, and light elements contribute to radioactivity in spent fuel. Table IV shows that after discharge, most of the radioactivity is due to actinides i.e. U-239 and Np-239. After one year, fission products cause most of the radioactivity as seen from Fig. 6, and 7. Before 500 years this contribution reduces because at larger time periods actinides contribute to radioactivity more than fission products due to Am-241 and Pu-239.

As seen in Table IV, the radioactivity immediately after discharge is due to U-239 and Np-239 actinides. U-238 captures a neutron so that U-239 is formed. U-239 has a half-life of 23.43 minutes. It emits β so that Np-239 is formed. Therefore, one day after the discharge Np-239 is the top contributor to radioactivity. Np-239 has a half-life of only 2.36 days so that after some time it disappears.

Xe-133 and I-131 contribute to radioactivity after discharge. These nuclides have short half-lives 2.19 days and 8.02 days, respectively. Nuclides that have short half-lives can be problematic under accident conditions while handling the fuel since they tend to emit gamma rays.

Table IV: Nuclides contribution to radioactivity from the total 1 MTU discharged U fuel for various time periods

After discharge	
U-239	7.6795E+17
Np-239	7.6588E+17
I-134	9.1563E+16
I-133	8.1718E+16
Xe-133	7.8610E+16
I-135	7.7931E+16
Cs-138	7.5872E+16
La-140	7.4998E+16
Mo-99	7.4196E+16
Xe-137	7.3306E+16
Subtotals	2.1620E+18
Total	8.6244E+18

1 day	
Np-239	5.7465E+17
Xe-133	7.6054E+16
La-140	7.2529E+16
Nb-95	6.7246E+16
Zr-95	6.6134E+16
Ba-140	6.5999E+16
Ce-141	6.4456E+16
Ru-103	6.1319E+16
Rh-103m	6.0660E+16
Pr-143	5.8813E+16
Subtotals	1.1679E+18
Total	2.0797E+18

1 year	
Pr-144	2.2032E+16
Ce-144	2.2032E+16
Rh-106	1.0759E+16
Ru-106	1.0759E+16
Pm-147	6.4908E+15
Pu-241	5.3995E+15
Cs-134	5.1394E+15
Cs-137	4.7095E+15
Ba-137m	4.4598E+15
Y-90	3.5323E+15
Subtotals	9.5313E+16
Total	1.0624E+17

5 years	
Pu-241	4.4478E+15
Cs-137	4.2951E+15
Ba-137m	4.0674E+15
Y-90	3.2082E+15
Sr-90	3.2074E+15
Pm-147	2.2574E+15
Cs-134	1.3435E+15
Rh-106	7.0730E+14
Ru-106	7.0730E+14
Pr-144	6.3160E+14
Subtotals	2.4873E+16
Total	2.6551E+16

10 years	
Cs-137	3.8279E+15
Ba-137m	3.6250E+15
Pu-241	3.4905E+15
Y-90	2.8445E+15
Sr-90	2.8438E+15
Pm-147	6.0291E+14
Cs-134	2.5114E+14
Kr-85	2.4400E+14
Eu-154	1.2832E+14
Pu-238	1.0901E+14
Subtotals	1.7967E+16
Total	1.8302E+16

50 years	
Cs-137	1.5238E+15
Ba-137m	1.4430E+15
Y-90	1.0865E+15
Sr-90	1.0863E+15
Pu-241	5.0214E+14
Am-241	1.6682E+14
Pu-238	7.9529E+13
Pu-240	1.9547E+13
Kr-85	1.8563E+13
Pu-239	1.4445E+13
Subtotals	5.9406E+15
Total	5.9727E+15

100 years	
Cs-137	4.8181E+14
Ba-137m	4.5627E+14
Y-90	3.2628E+14
Sr-90	3.2620E+14
Am-241	1.6830E+14
Pu-238	5.3627E+13
Pu-241	4.4495E+13
Pu-240	1.9471E+13
Pu-239	1.4426E+13
Sm-151	6.6953E+12
Subtotals	1.8976E+15
Total	1.9035E+15

500 years	
Am-241	8.9504E+13
Pu-240	1.8671E+13
Pu-239	1.4269E+13
Pu-238	2.3092E+12
Np-239	6.6466E+11
Am-243	6.6465E+11
Tc-99	6.2546E+11
Sm-151	3.0814E+11
U-234	1.0127E+11
Zr-93	8.4549E+10
Subtotals	1.2720E+14
Total	1.2776E+14

1,000 years	
Am-241	4.0197E+13
Pu-240	1.7711E+13
Pu-239	1.4075E+13
Np-239	6.3414E+11
Am-243	6.3414E+11
Tc-99	6.2443E+11
U-234	1.0196E+11
Zr-93	8.4530E+10
Nb-93m	8.2418E+10
Pu-242	6.9150E+10
Subtotals	7.4213E+13
Total	7.4500E+13

10,000 years	
Pu-239	1.0963E+13
Pu-240	6.8481E+12
Tc-99	6.0626E+11
Np-239	2.7216E+11
Am-243	2.7216E+11
U-234	9.9706E+10
Zr-93	8.4186E+10
Nb-93m	8.2083E+10
Pu-242	6.8015E+10
Pa-233	5.3444E+10
Subtotals	1.9350E+13
Total	1.9608E+13

100,000 years	
Pu-239	8.3500E+11
Tc-99	4.5124E+11
Zr-93	8.0825E+10
U-234	7.9925E+10
Nb-93m	7.8805E+10
Pu-242	5.7563E+10
Po-210	5.3705E+10
Bi-210	5.3705E+10
Pb-210	5.3705E+10
Ra-226	5.3705E+10
Subtotals	1.7982E+12
Total	2.4950E+12

1,000,000 years	
Zr-93	5.3776E+10
Nb-93m	5.2432E+10
Pb-209	4.1295E+10
Ac-225	4.1295E+10
Th-229	4.1295E+10
At-217	4.1295E+10
Fr-221	4.1295E+10
Ra-225	4.1295E+10
Bi-213	4.1292E+10
U-233	4.1193E+10
Subtotals	4.3646E+11
Total	8.9506E+11

Pr-144 and Ce-144 are largest contributors to radioactivity in the first year after discharge. Ce-144 has a half-life of 284.89 days and is the parent nuclide Pr-144. Pr-144 has a half-life of 17.28 minutes and disappears after a short period of time.

10 years, 50 years, and 100 years after discharge, Cs-137 is the largest contributor to radioactivity. Cs-137 is one of the most important fission products since it is chemically reactive and also radioactive. It has a half-life of 30 years. Although it has an intermediate half-life, it contributes to radioactivity more than other elements at 100 years. Because fission of U as well as Pu and Th yields about % 6 Cs-137 [5].

Tc-99 is formed by fission of U-235 and Pu-239. It is one of few fission products that contribute to radioactivity even at larger time periods.

Pu-239 has a long half-life of 24,110 years so it becomes the largest contributor to radioactivity at larger time periods. Nuclides that have a half-life more than thousand years such as Tc-99 (211,100 years), Ra-226 (1,600 years), U-234 (245,500 years), are still present at larger times and contribute to radioactivity.

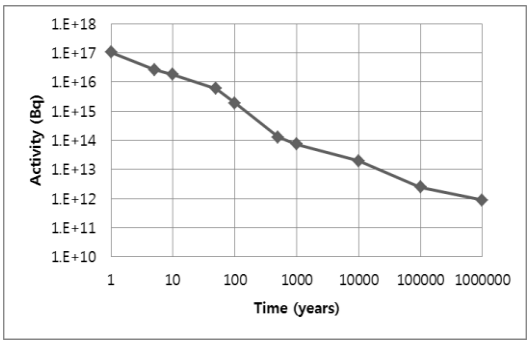

Fig. 6. The radioactivity due to actinides, fission products, and light elements

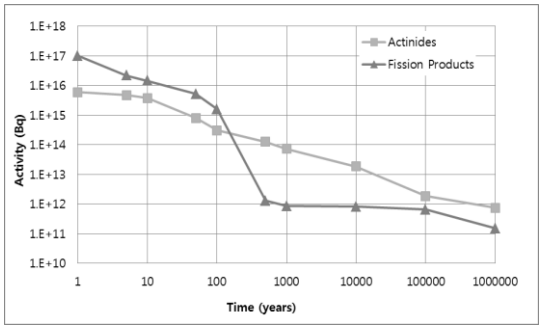

Fig. 7. The radioactivity due to actinides and fission products

4. Conclusions

The purpose of this study was to estimate the radionuclide inventory in spent fuels of the VVER-1200. TRITON was used to create the reactor library for VVER-1200. Nuclides contribution to radioactivity from the total 1 MTU discharged U fuel for various time periods are presented. In addition, radioactivity due to actinides and fission products are successfully examined. The radionuclide inventory of VVER-1200 spent fuels is useful for countries planning to build VVER-1200 to develop their national waste management strategies.

Acknowledgements

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