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Fission Product Releases from a Core into a Coolant of a Prismatic 350-MW$_{th}$ HTR

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1. Introduction

A prismatic 350-MW$_{th}$ high temperature reactor (HTR) is a means to generate electricity and process heat for hydrogen production. The HTR will be operated for an extended fuel burnup of more than 150 GWd/MTU. Korea Atomic Energy Research Institute (KAERI) is performing a point design for the HTR which is a pre-conceptual design for the analysis and assessment of engineering feasibility of the reactor.

In a prismatic HTR, metallic and gaseous fission products (FPs) are produced in the fuel, moved through fuel materials, and released into a primary coolant. The FPs released into the coolant are deposited on the various helium-wetted surfaces in the primary circuit, or they are sorbed on particulate matters in the primary coolant. The deposited or sorbed FPs are released into the environment through the leakage or venting of the primary coolant. It is necessary to rigorously estimate such radioactivity releases into the environment for securing the health and safety of the occupational personnel and the public.

This study treats the FP releases from a core into a coolant of a prismatic 350-MW$_{th}$ HTR. These results can be utilized as input data for the estimation of FP migration from a coolant into the environment.

2. Design and operation of a prismatic 350-MW$_{th}$ HTR

2.1. A coated fuel particle

The coated fuel particle (CFP) considered in this study is a tri-structural isotropic particle (TRISO) which consists of a kernel, a low-density pyrocarbon layer called a buffer, an inner high-density pyrocarbon (IPyC) layer, a silicon carbide (SiC) layer, and an outer high-density pyrocarbon (OPyC) layer. The kernel material is $UC_{0.5}O_{1.5}$ with a ^{235}U enrichment of 15.5 w/o which is a mixture of 75 % UO_2 and 25 % UC_2. Table I shows the average thicknesses and densities of the layers of the TRISO.

Table I: Thicknesses and Densities of Layers in a TRISO

Layers	Thickness, μm	Density, g/cm^3
OPyC	40	1.9
SiC	35	3.2
IPyC	40	1.9
Buffer	100	1.0
UCO kernel	425$^{1)}$	10.5

1) This figure means kernel diameter.

2.2. A fuel compact and a fuel block

The fuel block is a right hexagonal prism in which a large number of vertical holes are machined for flowing down a coolant, enclosing fuel and burnable poison compacts, handling the fuel block, and tying together to a upper or lower fuel block. A channel for a reserved shutdown control rod is machined in some fuel blocks, which is explained in the next section. The fuel compact is a cylindrical mixture of a carbon matrix and a very large number of CFPs and graphite shim particles. Table II shows the design parameters of a fuel block and a compact of a prismatic HTR fuel.

Table II: Design parameters of a fuel block and a fuel compact of an HTR fuel

Fuel block material	H-451/PCEA
Fuel block density (g/cm^3)	1.83
Number of fuel block layers in a core	9
Number of fuel compact holes per fuel block	
- Fuel block without a reserved shutdown channel	54
- Fuel block with a reserved shutdown channel	12
Number of fuel compacts per fuel hole	16
Fuel compact matrix material	Carbon
Matrix density (g/cm^3)	1.83
Shim particle density (g/cm^3)	1.83
Shim particle material	H-451/PCEA
Packing fraction of CFPs in a compact (%)	25/30/35
Fuel compact diameter (cm)	1.245
Fuel compact length (cm)	5.2
Number of CFPs per compact	930
Fuel hole diameter (cm)	1.27
Large coolant hole diameter (cm)	1.588
Pitch (cm)	1.88

2.3. A prismatic HTR

The prismatic 350-MWth HTR core has 3 fuel rings with 66 fuel columns, 9 axial layers and a three-ring central reflector. There are 6 startup control rod holes in the third ring of the central reflector, 12 reserved shutdown channels in the third ring of the fuel blocks and 24 operating control rod holes in the side reflector, respectively. The cooling system of the HTR is composed of the reactor cooling system (RCS), the vessel cooling system (VCS) and the air-cooled reactor cavity cooling system (RCCS). Table III shows the design parameters of a prismatic HTR.

Table III: Design parameters for a prismatic HTR

Active core height (cm)	792.99
Core radius (cm)	325
Top/bottom reflector thickness (cm)	118.94/198.4
Number of fuel columns	66

- Fuel columns without reserved shutdown channel	54
- Fuel columns with reserved shutdown channel	12
Number of axial layers	9
Number of control rods	
- Operating control rod	24
- Startup control rod	6
- Reserved shutdown rod	12
Graphite block density (g/cm^3)	1.83
Thermal power (MW)	350
Average power density (W/cm^3)	5.958
Inlet/outlet temperature (°C)	290 or 490/750 or 950
Coolant mass flow rate (kg/s)	146.2~258.5 for T_{outlet} = 750 ºC 120.0~186.4 for T_{outlet} = 850 ºC
Primary coolant pressure (MPa)	
- Normal operation	7.0

3. FP Releases from a Core into a Coolant of a prismatic 350-MW$_{th}$ HTR

The FP release analysis is applied to the unit cell of a prismatic HTR fuel block shown in Fig. 1. The failure fractions of TRISOs are assumed to have values presented in an INL report [1]. Then, the analysis of FP releases from a core in to a coolant of a prismatic HTR requires the estimation of fuel burnup and depletion, and the thermal analyses on a fuel component and a TRISO. McCARD [2] was used to generate the burnup and depletion data, and COPA [3,4] was used to perform the thermal and FP release analyses.

The unit cell of a prismatic HTR fuel block is approximated to be an equivalent cylinder in Fig. 2 in order to apply the FP release analysis more easily to the unit cell [5]. The compact region in an equivalent cylinder is equivalent to two original compacts. The areas of the structural graphite in a unit cell and an equivalent cylinder are the same.

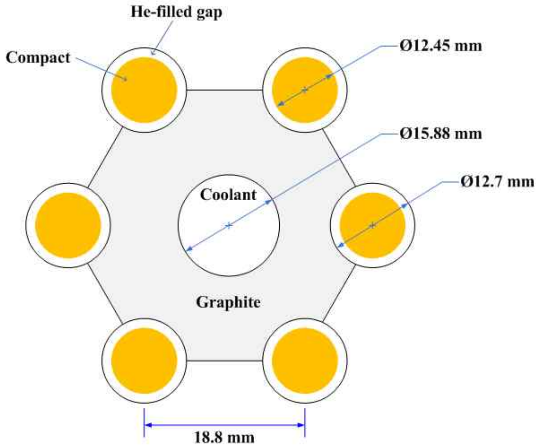

Fig. 1. A unit cell in a prismatic HTR fuel block.

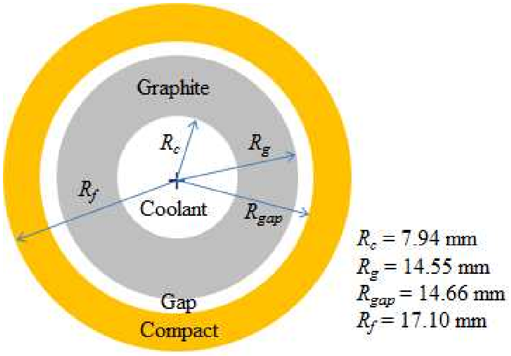

Fig. 2. Equivalent cylinder for a unit cell.

3.1. Fuel burnup and depletion

Fig. 3 displays the burnup and fast fluence histories of the HTR fuel throughout 1500 effective full power days (EFPDs). The final burnups are 152 GWd/tHM at packing fraction (PF) of 25 %. The final fast fluence approaches to 8×10^{21} n/cm^2, E_n > 0.1 MeV.

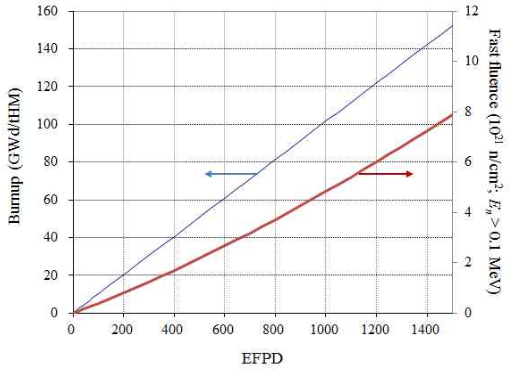

Fig. 3. Fuel burnup and fluence.

Table IV shows radionuclides within a FP class which are assumed to have the same release and attenuation factors based on physical and chemical properties, with the exception of silver where the two representative isotopes have much different half-lives [1]. Each FP class contains the key radionuclides that are expected to account for the majority of the offsite dose. Fig. 4 represents the radioactivity of some hazardous FPs, which are listed in Table IV, in a prismatic 350-MW$_{th}$ HTR core.

Table IV: Fission product classes

Fission Product Class	Characteristic Nuclide
Noble gases	Kr-85, Kr-88, Xe-133
I, Br, Te, Se	I-131, I-133, Te-132
Cs, Rb	Cs-134, Cs-137
Sr, Ba, Eu	Sr-90
Ag, Pd	Ag-110m, Ag-111
Sb	Sb-125
Mo, Ru, Rh, Tc	Ru-103
La, Ce	La-140, Ce-144
Pu, actinides	Pu-239

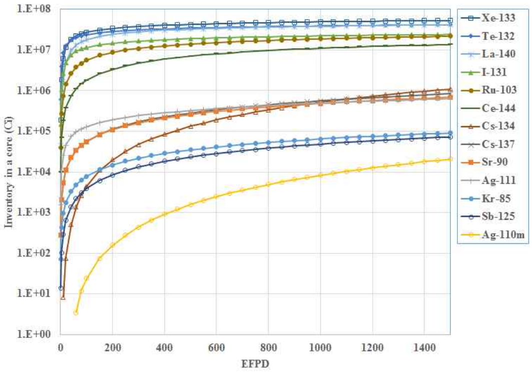

Fig. 4. Radioactivity of some hazardous fission products in a prismatic 350-MW_{th} HTR core.

3.2. Thermal analysis for a TRISO and a fuel block

Fig. 5 represents the temperature distribution in an equivalent cylinder when the coolant temperature is 850 ºC. The temperature jumps down at the gap between compact and structural graphite due to the relatively low thermal conductivity of helium in the gap. Fig. 6 displays the temperature distribution in a TRISO. The thermal conductivity of the buffer was assumed to be 0.5 W m^{-1} K^{-1}. A relatively large temperature drop occurs across the buffer because its thermal conductivity is much lower than those of other layers.

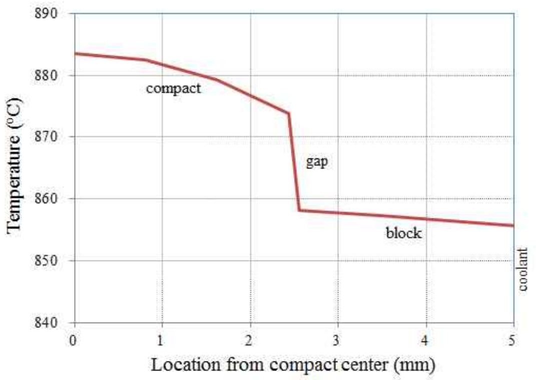

Fig. 5. Temperature profile in an equivalent cylinder.

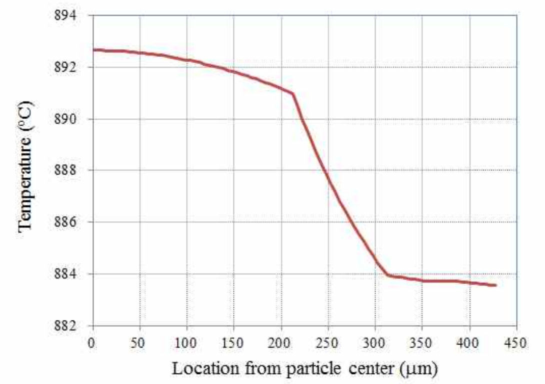

Fig. 6. Temperature profile in a TRISO located at the center of compact.

3.3. FP releases

Table V shows three cases of TRISO failure and heavy metal contamination fractions extracted from an INL report [1]. Fig. 7 through Fig. 9 display the radioactivity of some hazardous FPs released from a 350-MW_{th} HTR core into a coolant under three cases of Table V. In this study, the releases of ^{88}Kr, ^{133}I, ^{125}Sb, ^{239}Pu were not calculated because their depletion, diffusivity and sorption data are not known. In a coolant of a prismatic HTR with no TRISO failure and heavy metal contamination, silver is the most radioactive species. Its radioactivity is about 10 mCi. Xenon is the most radioactive fission product in a coolant of a prismatic HTR with broken TRISOs and heavy metal contamination. The radioactivity of xenon are 5.5 and 11.1 kCi at Case 2 and 3, respectively. For metallic FPs, the radioactivity are large, of the order of cesium, silver, strontium and tellurium.

Table V: Fuel failure and heavy metal contamination

		IPyC	SiC	OPyC	Matrix graphite
Case 1	Defect fraction	0	0	0	
	Failure fraction		0		
	HM[1] contamination fraction	0	0	0	0
Case 2	Defect fraction	1×10^{-5}	1×10^{-5}	1×10^{-5}	
	Failure fraction		7×10^{-6}		
	HM contamination fraction	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}
Case 3	Defect fraction	3×10^{-5}	3×10^{-5}	3×10^{-5}	
	Failure fraction		2×10^{-5}		
	HM contamination fraction	2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}

1) Heavy metal.

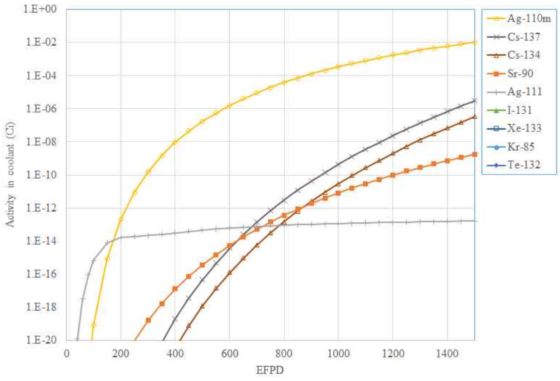

Fig. 7. Radioactivity in a coolant of a prismatic 350-MW_{th} HTR (Case 1).

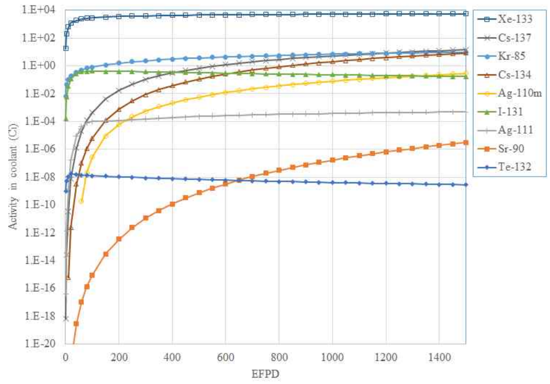

Fig. 8. Radioactivity in a coolant of a prismatic 350-MW$_{th}$ HTR (Case 2).

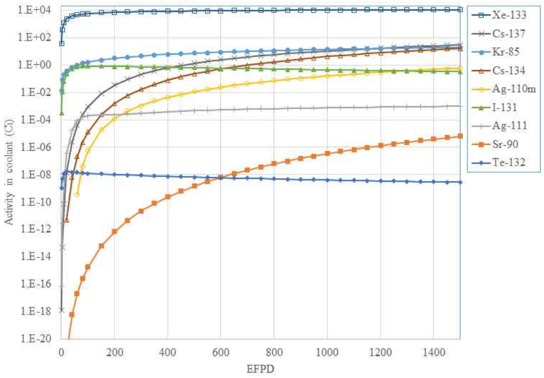

Fig. 9. Radioactivity in a coolant of a prismatic 350-MW$_{th}$ HTR (Case 3).

4. Summary

The analysis of fission product release within a prismatic 350-MW$_{th}$ HTR has been done. It was assumed that the HTR was operated at constant temperature and power for 1500 EFPDs.

- The final burnup is 152 GWd/tHM at packing fraction of 25 %, and the final fast fluence is about 8×10^{21} n/cm^2, $E_n > 0.1$ MeV.

- The temperatures at the compact center and at the center of a kernel located at the compact center are 884 and 893 ^{o}C, respectively, when the packing fraction is 25 % and the coolant temperature is 850 ^{o}C.

- Xenon is the most radioactive fission product in a coolant of a prismatic HTR when there are broken TRISOs and fuel component contaminated with heavy metals. For metallic fission products, the radioactivity are large, of the order of cesium, silver, strontium and tellurium.

- The releases of ^{88}Kr, ^{133}I, ^{125}Sb, ^{239}Pu must be also estimated for public and operational safety even if the related calculation method is very conservative.

- The calculated radioactivity of FPs in a coolant can be utilized as input data for estimating the radioactivity released from a coolant into an environment, and then it will be judged how much hazardous they are.

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