FUEL PEBBLES THEFT ANALYSIS FOR PHYSICAL PROTECTION SYSTEM DEVELOPMENT

Dany Mulyana[1] and Sunil S. Chirayath[1,2]

[1]Department of Nuclear Engineering, Texas A&M University, College Station, TX-77843-3133
[2]Center for Nuclear Security Science and Policy Initiatives, Texas A&M University, College Station, TX-77843-3473

dmulyana@tamu.edu;sunilsc@tamu.edu

ABSTRACT

Pebble bed reactor (PBR) is not a new technological concept, but it is a relatively new marketable reactor option. As with the other reactor types, PBR requires its own safety, security, and safeguards approaches in place. With the unique pebble-type fuel design contained within a 6 cm-diameter sphere, the PBR fuel should be able to achieve a burnup of up to 90 GWd/MTU. A fuel pebble may consist of 8,000 to 15,000 tri-isotropic (TRISO) microspheres as fuel kernels, which can contain fission products during and after irradiation. A set of Monte Carlo n-Particle (MCNP) neutronic simulations on the PBR's fresh and spent fuel pebbles were completed to investigate the potential radiation risk to the personnel. This type of understanding is needed for safety, security, and safeguards analysis. With the amount of UO_2 per pebble being 5 g and enriched to 17 wt% of ^{235}U, the radiation dose rate from a fresh fuel pebble is only 0.38 μrem/h at 1 m. At the same distance, a bare spent fuel pebble with a burnup of 90 GWd/MTU and cooled for one year produces a gamma dose rate of about 1.0 rem/h. A lead sphere shielding (density of 11.34 g/cm^3) with a thickness of approx. 12.5 cm can reduce the gamma radiation dose rate to 0.33 μrem/h. This may or may not be detected by a radiation detector. However, the 12.5 cm thick lead is about 175.6 kg, while the pebble itself is only 200.2 g. This gives a significant security barrier against the theft of the irradiated fuel pebble. This study provides technical information on possible ways to minimize the probability of detection of the fresh and spent fuel by an adversary, which is useful for a physical protection system development, especially to prevent insider threat in a PBR system. This study is limited only to gamma radiation analysis.

INTRODUCTION

Pebble bed reactor (PBR) is one of the advanced nuclear reactor designs, which is prospective and marketable. Reactor safety is one of the main aspects that gets attention at the design stage. The PBR uses small-size (about 6-cm diameter) fuel pebbles made out of graphite and embedded with tri-isotropic (TRISO) coated microspheres of low enriched uranium (LEU). Instead of water being used as the coolant and neutron moderator in the current generation of reactors, the PBR uses helium as the coolant and graphite as neutron moderator. In addition to graphite in the pebble the some of the reactor structures are also made with graphite. The Chinese design of a PBR is the High Temperature Test Reactor (HTR-10) [1] and the South African design is the Pebble Bed Modular Reactor (PBMR-400) design [2].

The PBR falls under the category of generation IV [3] reactor designs with advanced safety features than the current generation of generation III and III+ reactors. However, there is a concern regarding the security of the fuel pebble because of their small size, numerous (in thousands) pebbles being used in the reactor core, and the associated online refueling feature. In generation III and III+ light water reactors (LWRs), the fuel is in the form of large assemblies about 200 in number, each weighing over 500 kg, with no online refueling feature. Hence, an investigation with regards to the feasibility of stealing these fuel pebbles for malicious act needs to be carried out, which is the focus of the study described in this paper. This study should throw light on the design of the physical protection system (PPS) that must be designed to minimize the risk of the theft of the pebble fuel. In this study, essential characteristics of the radiation emitted by a PBR fuel pebble is estimated. The estimation is carried out by a set of Monte Carlo radiation transport and fuel burnup simulations of HTR-10. The results of the simulations should guide us to understand the amount of intrinsic resistance that each irradiated fuel pebble will provide with respect to preventing it from stolen by an adversary. Methodology used in the study, the results of the study with discussion, and the conclusion of the study are presented in the next three sections.

METHDOLOGY DESCRIPTION

The pebble characterization was completed through Monte Carlo radiation transport modeling and simulation using Monte Carlo n-Particle (MCNP) code version 6.1 [4]. There are two simulations carried out for this study. First simulation is to estimate the isotopic composition of the irradiated fuel pebble at a burnup of 90 GWd/MTU (the intended average burnup of a PBR fuel pebble at when discharged as spent fuel). The simulation was carried out by using three million neutron life histories for the HTR-10 model to yield a stochastic error of less than 0.05 % in the value of the reactor's estimated effective neutron multiplication factor (k_{eff}). An infinite lattice simulation technique using MCNP code was used instead of modeling the whole reactor core [5]. The second simulation was to estimate the radiation dose rate from a one-year cooled spent fuel pebble at 1 m using the isotopic composition estimated from the first simulation. The second simulation used 500 million gamma radiation life histories representing the fission product and actinide gamma radiation emitted from a spent fuel pebble. The objective was to calculate the gamma radiation dose rate with a stochastic error of less than 1%.

The HTR-10 is a pebble bed fueled high temperature gas-cooled reactor (HTGR) of the PBR type, which is designed to produce a thermal power of 10 MW. It is a test reactor intended to demonstrate the functionality and safety features of a PBR. The used fuel is in the form of pebbles containing TRISO coated LEU microspheres. Each fuel pebble contains 5 g of uranium dioxide (UO_2) with the amount of uranium being 4.4 g with a ^{235}U enrichment of 17 wt %. These characteristics of the fuel pebble, with more details provided in the IAEA-TECDOC-1382 [6] document, were used as input for the Monte Carlo fuel burnup modeling and simulation by MCNP 6.1 code.

The pebble is a sphere with a diameter of 6 cm made from graphite with a density of 1.73 g/cm^3. Its inner diameter is 5 cm, which is filled by the TRISO coated LEU microspheres (ref. Fig. 1). There are approximately 7,223 TRISO coated microspheres of LEU in a fuel pebble. These TRISO coated LEU microspheres, for simulation purposes, were modeled as placed within the pebble using a single cube lattice structure with the side of cube equal to 0.1958 cm. The infinite lattice in the first simulation used a body centered cubic (BCC) lattice configuration containing two pebbles with a packing fraction of 61% with a reflective boundary condition on its six surfaces. The space between the pebbles is filled with helium (gaseous coolant) with a density of 0.00016 g/cm^3. Within the model, the fuel was set at a temperature of 1200 K, while the temperature of the helium coolant was 600 K.

The TRISO coated LEU microspheres have an outer diameter of about 0.91 mm containing several layers (ref. Fig. 1) in the lattice structure. The UO_2 kernel in the TRISO coated microsphere has a radius of 0.025 cm with a density of 10.4 g/cm^3. The kernel is coated by a 0.009 mm thick graphite buffer layer with a density of 1.1 g/cm^3, which is further coated by an inner pyrolitic carbon (PyC) with a thickness of 0.004 mm having a density of 1.9 g/cm^3. It is further coated by a 0.0035 mm thick silicon carbide (SiC) with a density of 3.18 g/cm^3. As an outermost layer, another PyC layer with thickness of 0.004 mm is applied with the same density aforementioned.

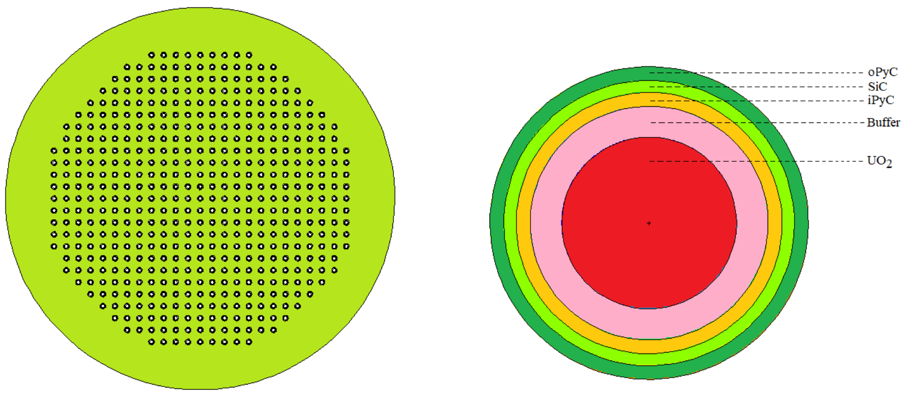

Figure 1. A fuel pebble with a diameter of 6 cm (left) and a TRISO with a diameter of 0.91 mm (right)

RESULTS AND DISCUSSION

The mass of ^{235}U in a fresh fuel pebble is 749 mg. The MCNP neutronic code simulation results showed that the gamma radiation dose rate from a fresh fuel pebble is only 0.38 μrem/h at 1-m distance. A theft actor is very likely to steal the fresh fuel pebble only if they have the capability to retrieve the uranium (17 wt% ^{235}U) and further enrich it for use in a nuclear explosive device (NED). On the other hand, the dose rate from a spent fuel pebble irradiated to a discharge burnup of 90 GWd/MTU and cooled for one year was estimated using MCNP as 0.98 rem/h at 1-m distance. The irradiated fuel contains 316 mg of leftover ^{235}U, 69 mg of total Pu, and 55 mg of the fissile Pu isotopes. The information regarding the radioactivity content of actinides and fission products obtained from the MCNP simulation for a fuel burnup of 90 GWd/MTU is listed in Table 1. If we assume that the adversary is a terrorist group, it would be an enormous task for them to target the small amount of Pu contained in a single irradiated fuel pebble to assimilate the needed Pu for a NED. It is less than 100 mg of Pu per pebble, so they will need to steal ten to hundred thousand pebbles to obtain the needed Pu to be used in a NED. Nevertheless, for terrorism purposes, a single irradiated fuel pebble emitting a radiation dose rate of 0.98 rem/h can be utilized in a radioactive dispersal device (RDD).

The next question to answer is what it takes to make the spent fuel handling as safe as the fresh fuel pebble. To answer this question, another MCNP radiation transport simulation with lead shield (density=11.34 g/cm^3) surrounding the fuel pebble was carried out. The results of the simulation showed that a 12.5 cm thick lead (about 175.6 kg) will be needed to bring the radiation dose rate down to a similar dose rate like that of a fresh fuel pebble, which is a challenge for any adversary because it has to be carried out by penetrating the physical barriers of a PPS at the facility.

Table 1. Actinide and fission product activities per irradiated fuel pebble at 90 GWd/MTU with an initial ^{235}U enrichment of 17wt%.

Serial No.	Element	Mass Number	Activity (Ci)	Serial No.	Element	Mass Number	Activity (Ci)	Serial No.	Element	Mass Number	Activity (Ci)
Actinide				*Non-actinide*				*Non-actinide*			
1	Th	232	3.91E-16	29	Mo	99	1.72E+01	58	La	138	2.07E-15
2	U	234	2.85E-08	30	Tc	99	1.74E-04	59		140	1.74E+01
3		235	6.84E-07	31	Ru	103	1.13E+01	60	Ce	139	1.36E-05
4		236	4.56E-06	32		105	6.02E+00	61		141	1.60E+01
5		237	4.36E+00	33		106	2.80E+00	62		142	7.36E-16
6		238	1.19E-06	34	Rh	105	5.68E+00	63		143	1.56E+01
7		239	9.53E+01	35	Pd	107	5.58E-07	64		144	1.39E+01
8	Np	238	1.92E-06	36	Ag	111	2.70E-01	65	Pr	142	3.86E-01
9		238	9.57E-01	37	Cd	113	3.45E-19	66		143	1.58E+01
10		239	9.52E+01	38	In	115	1.16E-16	67	Nd	144	1.45E-14
11	Pu	238	7.14E-03	39	Sn	123	8.81E-03	68		145	3.82E-16
12		239	2.97E-03	40		125	5.65E-02	69		147	6.18E+00
13		240	2.85E-03	41		126	4.73E-06	70	Pm	147	2.65E+00
14		241	7.04E-01	42	Sb	124	2.07E-03	71		148	1.28E+00
15		242	5.64E-06	43		125	7.06E-02	72		149	3.76E+00
Non-actinide				44		126	4.91E-03	73		151	1.43E+00
16	Se	79	8.26E-06	45	Te	123	1.08E-18	74	Sm	147	3.20E-11
17		82	1.43E-20	46		132	1.27E+01	75		148	2.86E-16
18	Kr	85	1.36E-01	47	I	129	2.54E-07	76		149	3.03E-17
19	Rb	86	8.31E-03	48		130	9.72E-02	77		151	2.73E-03
20		87	3.17E-10	49		131	8.79E+00	78		153	2.48E+00
21	Sr	89	1.14E+01	50		135	1.79E+01	79	Eu	152	1.91E-05
22		90	1.16E+00	51	Xe	133	1.92E+01	80		154	4.05E-02
23	Y	90	1.19E+00	52		135	5.44E+00	81		155	2.83E-02
24		91	1.41E+01	53	Cs	134	9.61E-01	82		156	7.99E-01
25	Zr	93	2.51E-05	54		135	6.54E-06	83		157	7.99E-02
26		95	1.73E+01	55		136	2.69E-01	84	Gd	152	8.50E-18
27	Nb	94	8.09E-10	56		137	1.29E+00	85		153	7.06E-05
28		95	1.73E+01	57	Ba	140	1.70E+01	86	Tb	160	1.29E-03

Based on the results of this study, the external threat from a terrorist group is potentially to steal a large number of fresh fuel pebbles. However, they are unlikely to steal so many fresh fuel pebbles, if there is no intention to build a NED. A terrorist group is unlikely to steal spent fuel pebbles in a large number, due to its high radiation dose rate, instead could steal a few of them to use them in RDDs. The possibility of spent fuel pebble theft would be higher, if the actor is in collusion with an insider or the actor is the insider itself.

The insider will have access and capability to transport the stolen pebble safely, as well as to defeat the physical barriers, if the PPS is not adequate. And from a nuclear safeguards perspective, this event may also lead to a protracted diversion made by the host state. The intrinsic security features of the fuel pebbles with a quite large weight due to the number of spent fuel pebbles needed may raise the difficulties for the actor to steal it. However, it should be noted that there are several scenarios that might occur to both the fresh and the spent fuel pebbles, based on the threat perspective. The intrinsic features are possible to be engineered, but the extrinsic barriers are the most likely to be designed to mitigate the security risk through an efficient PPS.

CONCLUSION

With the mass of UO_2 as 5 g per fuel pebble, which is enriched in ^{235}U to 17 wt%, the radiation dose rate from this fresh fuel pebble is only 0.38 μrem/h at 1 m. At the same distance, the gamma radiation dose rate from a bare spent fuel pebble discharged with a target burnup of 90 GWd/MTU and cooled for one year is about 0.98 rem/h. A lead shielding (density of 11.34 g/cm^3) with a thickness of approximately 12.5 cm can reduce this dose rate to 0.33 μrem/h, similar to that of a fresh fuel pebble. This may or may not be detected by a radiation detector. However, the 12.5 cm thick lead will weigh about 175.6 kg, while the mass of the pebble itself is only 200.2 g.

The fresh fuel is unlikely to be the target of theft for RDD development purpose, while it keeps its attractiveness to be the target only if the actor has the capability for ^{235}U enrichment for NED development. The spent fuel pebble is very likely to be a target for RDD development purpose, however, the additional weight to carry the pebble safely adds an important intrinsic security barrier that will significantly characterize the needed PPS. Nevertheless, an insider may increase the probability of success for the adversary to defeat the PPS.

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