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Preliminary Safeguards Assessment for the Pebble-Bed Fluoride High-Temperature Reactor (PB-FHR) Concept

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INTRODUCTION

This report provides an initial assessment of the international safeguards considerations for the pebble bed fluoride-salt-cooled high temperature reactor (PB-FHR) concept. Pebble bed reactors, such as the PB-FHR, do not lend themselves to traditional safeguards approaches since the fuel consists of a large number of fuel pebbles that flow through the reactor core instead of large fuel assemblies as in a PWR. In this respect, pebble bed reactors require a safeguards approach that is more in line with bulk handling facilities, such as enrichment or reprocessing facilities. This report indicates where enhancing PB-FHR safeguards may require facility design additions, which in turn could affect the physical protection and safety operation of the overall system. The qualitative analysis presented here will form the basis of more quantitative analysis to be conducted during the second year of this project.

The PB-FHR concept [1] is being developed by a collaboration that includes the University of California Berkeley, Oak Ridge National Laboratory, and the Massachusetts Institute of Technology. The PB-FHR reactor vessel design appears below in Figure 1.

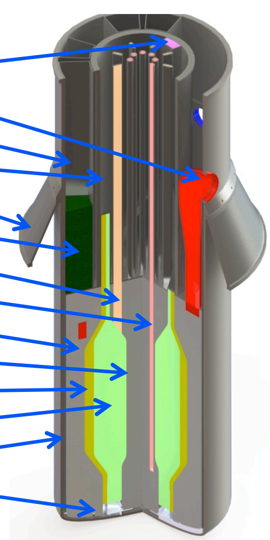

Fig. 1. PB-FHR reactor vessel conceptual design [1]

The PB-FHR was chosen as a test case for a quantitative application of the Safety, Safeguards, and Security by Design (3SBD) approach, since it is in the beginning stages of the design process. The insights gained from 3SBD analysis are expected to be relevant to other advanced reactor designs, namely the gas-cooled pebble modular reactor and potentially low-pressure coolant reactor designs such as the sodium cooled fast reactor (SFR).

Description of the Reactor System

The Technical Description of the Mark-1 PB-FHR by the University of California, Berkeley [1] was used as the basis for this work. The relevant parameters for the safeguards assessment are summarized below in Table 1.

Table 1. PB-FHR Key Parameters [1], [2]	
Number of fuel pebbles in core and defueling chute	470,000
Number of graphite pebbles in core and defueling chute	218,000
Pebble diameter	3.0 cm
Uranium enrichment	19.9%
Fresh fuel uranium mass	1.5 g
Fresh fuel U-235 mass	.2985 g
Burn-up at discharge	190 MWd/kg
Spent fuel plutonium mass	.09 g
Spent fuel U-235 mass	.035 g
Pebble consumption rate	920 pebbles/full power day

The pebbles are 3.0 cm in diameter with a core of low-density graphite surrounded by a layer of fuel, which is then covered by a high-density graphite surface. Each fuel element, in pebble form, contains 19.9% enriched uranium with a U-235 mass of 0.2985 grams. There are 29,440 pebbles in each storage cask. Fifteen casks are filled with fresh fuel in storage while two of the fresh fuel casks are in a transfer dock. The reactor has a flow path for graphite pebbles and a separate one for fuel. It also has removal process, along with a Pebble Burnup Measurement System (BUMS), to discharge damaged pebbles and Post Irradiation Examination (PIE) samples. The canisters used are assumed to store the pebbles are the same size at each point in the fuel flow.

BUMS was developed by the IAEA to measure pebble burn up in earlier PBMRs. Using a high purity germanium detector, BUMS measures the Cs-137 in each pebble. Cs-137 is a good basis for assessment because it has an approximately equal fission yield from U-235 and Pu-239 (6.3% and 6.5% respectively), a negligible cross section for thermal neutron capture, and a relatively long half-life of 30 years [1].

Pebbles are injected into the core through eight paths: four to the active fuel region and four for the inert graphite pebble reflector region on the outside. There are 440,000 fuel pebbles and 204,000 graphite pebbles in the core at one time. The consumption rate is 920 pebbles per full power day (FPD). The pebble circulation rate at full power operation is 450 pebbles per hour. Each pebble goes through the core approximately eight times for about 60 days in the core, with an average total residence time of 1.40 years [1].

The Pebble Handling and Storage System circulate fuel and graphite pebbles through the core via buoyancy and fluid drag forces of the primary coolant. They are exchanged for fresh fuel using the Pebble Canister Transfer System. Pebbles are removed through two Core Unloading Devices (CUDs) that lead to the defueling chute, where the pebble cools for four days. Then two CUDs remove pebbles from the top of the defueling transfer chute [1]. The spent fuel contains approximately 0.09 grams of U-235 and 0.035 grams of Pu based on an estimated burnup of 190 MWd/kg [2].

The pebbles are sorted such that fragments are removed then the rest are submitted to BUMS. Fresh fuel is added and mixed into flow of pebbles recirculating through the core. Fuel and graphite pebbles can be also be extracted from the BUMS system for PIE. A diagram of the system can be seen below in Figure 2.

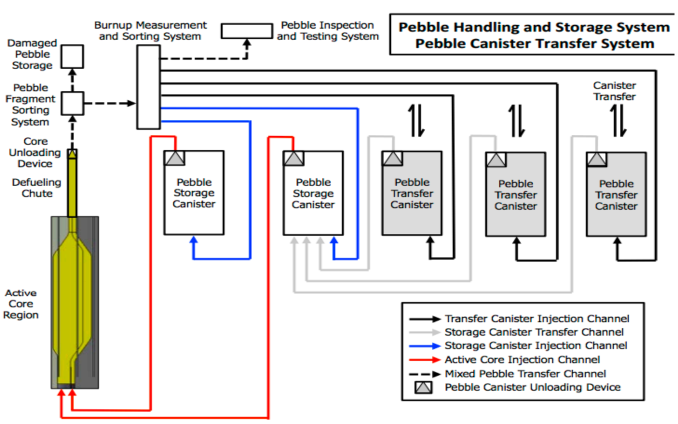

Fig. 2. PB-FHR Fuel and Graphite Flow [1]

DESCRIPTION OF THE ACTUAL WORK

In order to evaluate the safeguards significance of the PB-FHR a nuclear material accountancy analysis was performed by using the projected material flows through the reactor system and the published uncertainties for existing instrumentation. Three facility misuse scenarios were also examined. In conducting this analysis an emphasis was placed on simplifying the system such that the relative sensitivities of each area could be seen. Therefore there are a number of simplifying assumptions made during this initial analysis.

Nuclear Material Accountancy

In order to perform the preliminary nuclear material uncertainty analysis the reactor system was first broken into material balance areas (MBAs) with key measurement points (KMPs), which can be seen below in Figure 3.

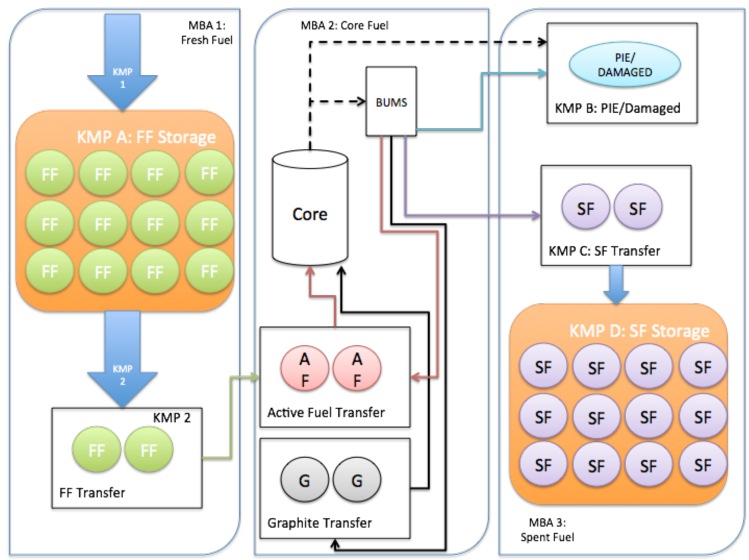

Fig. 3. PB-FHR MBA Structure

Next a spreadsheet was constructed to calculate the uncertainty at each KMP. The following simplifying assumptions were made to perform the analysis.

1. The fresh fuel storage area contains one core load of fresh fuel that was verified by the IAEA at the fuel fabrication facility.
2. The spent fuel storage area contains one core load of spent fuel.
3. 1% of the pebbles are sent to the PIE/Damaged pebble storage area each day
4. The reactor is running at full power for one year before the physical inventory verification (PIV) by the IAEA.

The IAEA's International Target Values 2010 was used for the relative and systematic uncertainties for existing instrumentation that could feasibly be used during the PIV. However, it is noted that when measuring many pebbles within a container these uncertainties may not be representative of in-field measurement errors.

SMC 3 "Other Types of Reactors" from the IAEA safeguards manual was used for the PIV verification procedure. Definition 10.8 from the IAEA Safeguards Glossary was used to determine the sample size the inspector takes during the PIV. And the International Target Value worksheets were used to determine standard uncertainties of relative difference between the inspector and operator measurement systems at the two RSD level.

Once the operator-inspector difference was determined this was multiplied by the throughput of the KMP to determine the uncertainty in number of pebbles. In order to count individual pebbles a notional pebble counting system was used in the calculations with an assumed uncertainty of 5%. The uncertainties used can be seen below in Table 2.

Table 2. Instrument Uncertainties [3]		
Instrument	u(r) (%rel.)	u(s) (%rel.)
Mini-Multichannel Analyzer with Ge Detector (MMCG)	3	2
High Level Neutron Coincidence Counter (HLNC)	2	1
Titration (TITR)	0.2	0.2
Electronic Balance (EBAL)	0.05	0.05
Pebble Counting System (PCS)	5	5

Facility Misuse

The facility misuse scenarios that were examined were:

1. Replacement or modification of graphite shield pebbles, specifically by modifying the graphite sphere to include uranium, while generally maintaining the geometry and buoyancy of an unmodified shield pebble.
2. Diversion of 19.9 % enriched fuel pebbles that were then used, after uranium recovery as feedstock for a clandestine enrichment facility.
3. Diversion of spent fuel pebbles with subsequent recovery of plutonium.

RESULTS

Nuclear Material Accountancy

The measurements taken and the combined uncertainties at the 2 RSD level at each KMP for MBAs 1 and 2 can be seen below in Table 3.

Table 3. Simulated Measurements			
KMP	Operator	Inspector	2*u(d)
A	MMCG, EBAL	MMCG, EBAL	6.86%
2	PCS	PCS	14.14%
B	EBAL, TITR	EBAL, HLNC	3.49%
C	EBAL	PCS	12.25%
D	-	HLNC, EBAL	3.47%

Due to the small amount of nuclear material in each pebble there are relatively only a small amount of nuclear material for each strata even though the number of pebbles may be large. For instance, it would take over 251,000 pebbles of fresh fuel to make a significant quantity (SQ) of U-235 and over 228,000 pebbles of spent fuel to make an SQ of Pu. Therefore, even though many thousands of pebbles could be missing in a given KMP due to measurement uncertainty, the relative amount of nuclear material that could be diverted is still small. The uncertainties for each KMP in pebbles and SQs are given in Table 4 below.

Table 4. Uncertainties in Pebbles and SQs		
KMP	Pebbles	SQs
A	24,226	0.096 (U)
2	99,923	0.398 (U)
B	115	0.0005 (Pu)
C	40,727	0.178(Pu)
D	12,246	0.049 (Pu)

However, as stated in the Description of Work, the uncertainties for MMCG and HLNC are not valid for measuring the amount of nuclear material in a container that stores thousands of pebbles. If the uncertainties for these instruments were increased three fold, then the uncertainties in KMP A and D, where whole containers are being measured, would increase to:

Table 5. Uncertainties in Pebbles and SQs for 3x MMCG/HLNC Uncertainties		
KMP	Pebbles	SQs
A	72,662	0.289 (U)
D	36,717	0.146 (Pu)

Facility Misuse

Results from the misuse scenarios are summarized below:

1. Modification of approximately of 25% of the shield pebbles to include uranium 238 for plutonium breeding could produce up to 30 grams of Pu-239 per module per reactor year;
2. Diversion of about 10% of a module's total fuel pebbles, in the form of unirradiated or low irradiated pebbles, could serve as input to a clandestine 450 SWU enrichment facility to produce 1 SQ of HEU
3. Diversion of a large fraction (approximately 40%) of spent fuel pebbles per module could produce 1 SQ of plutonium although the resulting plutonium isotopics from the high burnup PB-FHR fuel plus the need to utilize a large fraction of spent pebbles make this an unlikely pathway for a covert material source.

CONCLUSIONS

The amount of 19.9 % uranium to meet or exceed IAEA SQ for enriched uranium would require massive diversion of fuel pebbles that would affect reactor output and would be readily detectable. Likewise the misuse scenarios produced relatively small amounts of nuclear material for an individual PB-FHR module.

However if a full 12 module PB-FHR were implemented and if such a facility had a common fresh fuel and spent fuel storage facilities, then the overall system non-detection probability may be called into question. At this point the safeguards system could benefit from individual pebble tracking methods such as those proposed in [4].

Further sensitivity analysis and refinement of the model needs to be completed before a complete assessment of the nuclear material accountancy implications can be made. However, from this preliminary analysis the most sensitive areas of the plant in regards to measurement uncertainty are fresh fuel storage (KMP A) and spent fuel storage (KMP D) where the inspector and operator are going to be making measurements on large containers, containing thousands of pebbles in order to determine the mass of nuclear material inside.

In addition, safeguards by design will need to begin to be considered for the PB-FHR. Since this reactor operates more like a bulk facility rather than a traditional item facility the reactor design will need to provide areas for independent IAEA verification instrumentation. Consideration should also be given to joint use equipment in difficult to access areas such as the BUMS system. The IAEA could use this data in its safeguards calculations if it is verified to be authentic data that maintains the IAEA's "independence."

Further development of uranium and plutonium measurement systems will have to take place in order to minimize the uncertainties associated with measuring large containers of pebbles. Depending on further sensitivity analysis the size of the containers could be scaled down to provide more accurate measurements while still meeting safety requirements.

REFERENCES

1. C. Charalampos, "Technical Description of the 'Mark 1' Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (PB-FHR)," UCBTH-14-002, University of California, Berkeley (2014).
2. Zhiwen Xu, Mujid S. Kazimi, Michael J. Driscoll, "Impact of High Burnup PWR Spent Fuel Characteristics", Nuc. Sci. Eng. **151**, 261(2005).
3. IAEA, "International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials," STR-368, IAEA, 2010.
4. E. TRAVIS GITAU AND WILLIAM S. CHARLTON, " Use of a Microsphere Fingerprint for Identity Verification of Pebbles in a Pebble-fueled HTGR," *Journal of Nuclear Materials Management",* **XL**, p. 19, (2012)