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PEBBLE BED MODULAR REACTOR SAFEGUARDS: DEVELOPING NEW APPROACHES AND IMPLEMENTING SAFEGUARDS BY DESIGN

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ABSTRACT

The design of the Pebble Bed Modular Reactor (PBMR) does not fit or seem appropriate to the IAEA safeguards approach under the categories of light water reactor (LWR), on-load refueled reactor (OLR, i.e. CANDU), or Other (prismatic HTGR) because the fuel is in a bulk form, rather than discrete items. Because the nuclear fuel is a collection of nuclear material inserted in tennis-ball sized spheres containing structural and moderating material and a PBMR core will contain a bulk load on the order of 500,000 spheres, it could be classified as a "Bulk-Fuel Reactor." Hence, the IAEA should develop unique safeguards criteria. In a multi-lab DOE study, it was found that an optimized blend of i) developing techniques to verify the plutonium content in spent fuel pebbles, ii) improving burn-up computer codes for PBMR spent fuel to provide better understanding of the core and spent fuel makeup, and iii) utilizing bulk verification techniques for PBMR spent fuel storage bins should be combined with the historic IAEA and South African approaches of containment and surveillance to verify and maintain continuity of knowledge of PBMR fuel. For all of these techniques to work the design of the reactor will need to accommodate safeguards and material accountancy measures to a far greater extent than has thus far been the case. The implementation of Safeguards-by-Design as the PBMR design progresses provides an approach to meets these safeguards and accountancy needs.

Key Words: IAEA Safeguards, PBMR, Reactor Safeguards

INTRODUCTION

Since the 1960's, reactor designers created High Temperature Reactors (HTR) designs. A modern variant of high temperature reactors is the Pebble Bed Modular Reactor (PBMR), originally developed in Germany, but now being redesigned and marketed by the Republic of South Africa with other possible designs coming from China which has a prototype test reactor in operation. With the renewed interest in PBMRs, the U.S. Department of Energy/National Nuclear Security Administration under its Office of International Regimes & Agreements funded a study to investigate the safeguards issues inherent with such novel technology from which genesis of ideas put forth in this document occurred.[1]

The International Atomic Energy Agency (IAEA) that safeguards nuclear reactors worldwide considers a conventional LWR as an "item facility," because the fuel is discrete, integral and can be randomly identified and verified as a discrete item. The new PBMR and related reactors are more like a "bulk facility," in which the fuel is in bulk form since there are upwards of 500,000 fuel items that are not uniquely identifiable with a serial number or isotopic signature. Since this reactor design is unique and in flux, it provides an opportunity to attempt to incorporate the concepts of Safeguards-by-Design into the reactor layout since safeguarding of such and "on load reactor" will be more challenging than present Gen II and III designs. Regarding the South African PBMR, a 165 MWe (400 MWth) model is being considered.[2, 3] The reactor would be a high-temperature, helium gas cooled reactor, modularly pre-fabricated and erected on site, to permit easier licensing and expansion for increased power production. The fuel will consist of highly refractory 6 cm diameter spheres, made of a proprietary technology that uses high temperature carbide and pyrolytic carbon coated (TRISO), 0.5 mm diameter UO_2 fuel kernels.

The fuel will be fed into the reactor from a fresh fuel storage bin, circulate for a defined residence time to allow optimum fuel burn-up, and then be ejected out of the reactor into spent fuel storage bins.

The fuel would be more highly enriched than typical LWR fuel, being on the order of 9.6% ^{235}U, although the uranium content per sphere is a miniscule 9 grams. Prior to loading in the reactor, present designs project drums containing up to 1,000 pebbles storing the fresh fuel, although the size of these bins could easily be changed in the future. The fuel spheres are approximately the size and shape of tennis balls. In the current design, the reactor core would have approximately 452,000 fuel sphere "pebbles", containing approximately 5.5 significant quantities (SQ) of ^{235}U in the form of low-enriched uranium (LEU) and 5.3 SQ of Pu. On-line fueling of the pebbles occurs at the rate of approximately 500 pebbles per day. Each of the defueling chutes leads to a Core Unloading Device (CUD), where the CUD separates the spheres. The CUD removes spheres that are broken, damaged, or too small a diameter from the lines. Following discharge from the CUD, gross gamma activity measurements identify whether a sphere is a graphite or fuel sphere. This gross gamma measurement occurs mainly during the period when the core contains both fuel and graphite spheres (i.e. during reactor start-up). After the by the gross gamma activity count identifies the sphere type, a pneumatic tube transports the spheres to the top of the reactor, still part of KMP-2, where non-destructive assay (NDA) determines the burn-up of each fuel sphere. After determination of the burn-up, the fuel reenters the reactor (KMP-B) or discharges to the spent fuel tanks (KMP-C).

The fuel spheres circulate in this manner an average of 6 times to reach optimum burn-up. At the optimum burn-up, they collect in one of ten purpose-built spent fuel storage tanks (or bins). Each of these spent fuel storage bins can hold approximately 620,000 spent fuel pebbles. Each spent fuel pebble would contain approximately 0.12 gram plutonium. It should be noted, that it would take 66,700 spheres to equal one significant quantity (SQ) of plutonium. One can see at this early stage, that the diversion of one SQ of spent fuel would require a removal of a huge number of spent fuel pebbles and by effective and reliable containment and surveillance measures it should be easy to detect the diversion of such a massive number of pebbles.

DEFINING SAFEGUARDS GOALS FOR PBMR

The IAEA defines the timeliness goal for detecting a diversion of LEU or plutonium based on the time required to produce a crude atom bomb from either of these materials. These quantity and timeliness goals for detection are shown below in Tables 1 and 2:

Table 1: PBMR Fuel Safeguards Goals

Nuclear Material	Quantity Goal (1 SQ)	Timeliness Goal
Pu in core or spent fuel (Irradiated direct-use material)	8 kg (all isotopes)	3 Months
U containing <20% 235U (LEU)	75 kg of ^{235}U	1 Year

Note that these are the timeliness goals under traditional international safeguards Comprehensive Safeguards Agreements.[4] The detection probability for these materials will be 50%.

Table 2: PBMR Fuel Pebble Composition

PBMR Fuel Pebble Stratum	U-235 Enr. %	U-238 grams	U-235 grams	SQ of LEU	Pu grams	SQ of Pu	Pebbles per SQ - LEU	Pebbles per SQ -Pu
Fresh Fuel (FF)	9.6	8.134	0.864	$1.2x10^{-5}$	0	0	**86,800**	**N.A.**
Core Fuel* (CF) *(Assumes average of fresh and spent fuel)	6.23	7.887	0.530	$7.1x10^{-6}$	0.077	$9.7x10^{-6}$	**141,500**	**104,000**
Spent Fuel (SF)	2.50	7.835	0.196	$2.6x10^{-6}$	0.154	$1.9x10^{-5}$	**382,700**	**52,000**

An evaluation of the PBMR reactor fuel cycle shows that the most effective use of a proliferator's effort would be to take the plutonium diversion path rather than the uranium diversion path using the LEU and divert core or spent PBMR fuel. Table 2 shows how many pebbles would be needed to be diverted to a clandestine enrichment plant compared to a clandestine reprocessing plant, based on normal end-of-cycle PBMR fuel burn-up and isotopics.[5] Additionally, Herring, et al., calculated that if UO_2 target spheres were inserted into the PBMR to produce weapons grade plutonium, it would require 20,000 pebbles to produce 1 SQ of plutonium. However, these targets would be optimized for plutonium production.[6] In any event, a huge number of fuel pebbles would need to be diverted, although fewer in the case of the plutonium diversion path than in the case of the LEU diversion route.

The IAEA used the defined detection goals for timeliness, quantity, and probability and developed safeguards criteria for Other Types of Reactors, including high temperature gas reactors, and notionally PBMR. Since the nuclear material has a one year timeliness detection goal for LEU and a three-month timeliness goal for irradiated plutonium in the core and spent fuel, a yearly Physical Inventory Verification (PIV) will provide sufficient timeliness for detecting diversions of LEU but not for the plutonium in the spent fuel. Hence, interim inventory verifications (IIV) at a quarterly interval (every 3 months) will provide timeliness for detecting diversions of plutonium in the spent fuel storage and the core. Since the PBMR is basically an On-Load Reactor (OLR) in the same vein as the CANDU or RBMK, which the Agency has experience safeguarding, the Agency will have to grapple with the complication of receipts of pebbles and the constant feeding of fresh fuel, recirculating core fuel pebbles, and discharging the spent fuel pebbles from the reactor (see KMP-2 on Figure 1). Thus, the inspector has three major safeguards issues. They must: i) verify the transfers of fresh fuel received at the reactor, prior to introduction into the reactor, ii) verify transfers of spent fuel from the reactor core to spent fuel storage, and iii) verify the fresh fuel, reactor core fuel and spent fuel inventory. This is the major challenge of an OLR in general, and the PBMR in particular, because of its hybrid nature of being a hybrid between a true "item facility" and a true "bulk facility," in terms of IAEA safeguards. More will be said regarding the nuclear diversion pathways and the safeguards approach options for the nuclear material, but what is clear from the start is that this type of reactor does not fit the classic cases in the current IAEA Safeguards Criteria, under the categories of light-water reactor (LWR), on-load refueled reactor (OLR, i.e. CANDU), or other-types of reactor (prismatic HTGR).[7] To effectively safeguard these reactors under the current safeguards criteria the IAEA would need to uniquely identify the fuel items and randomly verify fresh fuel to confirm uranium and/or plutonium content, and verify that the spent fuel is highly irradiated. What is then clear from the outset of this discussion is that this is not practical, nor necessary, considering that the nuclear material in the case of the PBMR is dispersed among a huge number of fuel pebbles. Safeguarding the PBMR appears to be more similar to safeguarding an enriched uranium or MOX fuel fabrication plant, where the uranium, ^{235}U, and/or plutonium mass content of the bulk nuclear material is verified by NDA and destructive assay (DA).

Regarding the safeguards approach, it would need to consider the unique features of the PBMR, in addition to the usual safeguards issues posed by the storing and safeguarding of low-enriched uranium fresh fuel, successful containment and securing of core fuel, and safeguarding and securing spent fuel containing plutonium. Hence, linking the facility design using Safeguards-by-Design concepts to effective and efficient safeguards will be advantageous for the IAEA to facilitate safeguards and for the vendor to provide reduced safeguards effort for the customer in a non-nuclear weapons State. Of all the most mature new reactor concepts, the PBMR with its on line fueling and bin storage of spent fuel could be most improved by Safeguards-by-Design concepts changing the design at this early design stage.

The fresh fuel contains 9.6% ^{235}U, although the amount of ^{235}U per sphere is small. Regardless, it must be possible to verify the bulk mass or volume of the fresh fuel, take pebble samples or verify the enrichment of the fresh fuel using NDA, and positively verify from which drum or bin it comes. Considering the large bulk of fuel-bearing material in the core, in principle, it is possible to introduce, irradiate and discharge pebbles, for the undeclared irradiation and production of plutonium or ^{235}U. Unlike, LWRs, the core cannot be viewed during refueling outages over the 40-year life of the reactor, although the IAEA currently faces this same circumstance in safeguarding the CANDU reactor. Only bulk verification of the core and the spent fuel bins appears possible, although destructive and non-destructive assay (NDA) verification of sample materials from both would help confirm the absence of gross substitution of spent fuel with non-fuel items. It appears as though the spent fuel can only be verified by a combination of flow monitoring, spent fuel counting and NDA as noted. There will be storage bins or transfer routes for damaged pebbles, or those selected for post-irradiation examination (PIE) to evaluate performance of the new or redesigned fuel. These offer nuclear material diversion routes that have not been normally encountered in power production reactors, but which have been historically well addressed by the IAEA in safeguarding complex research reactors and reprocessing facilities.

From the aforementioned discussion, the nuclear material diversion scenarios can be summarized in general as:

- **Diversion and removal of spent fuel pebbles, containing irradiated plutonium**, from the spent fuel storage bins, or as redirected during transfer from the core,
- **Diversion and removal of partially-spent fuel pebbles, containing irradiated plutonium and ^{235}U, from the core** during continuous reactor operation,
- **Diversion and removal of fresh fuel pebbles**, containing unirradiated ^{235}U in the form of LEU, from feed drums or fresh fuel storage bins,
- **Misuse of the PBMR for undeclared feed, irradiation, and withdrawal** of spent fuel pebbles for producing plutonium (^{238}U target spheres) or ^{233}U (Possible PBMR thorium cycle or thorium targets).

While in principle, all of these scenarios are possible, the would-be diverter would need to remove a huge number of pebbles in all cases to come close to diverting an SQ of ^{235}U, plutonium, and/or thorium. These safeguards issues will be addressed in more detail in the following sections of this report.

The PBMR is a reactor type that defies the traditional item accountancy safeguards approach applied to LWRs.[8] Reactor types such as Fast Breeder Reactors (FBRs) and PBMRs that prohibit traditional item counting fall into a safeguards gap between item-counting facilities and bulk facilities. At FBRs and all the proposed PBMR variants, the difficulties associated with traditional item counting have given rise to safeguard approaches that rely upon maintaining continuity of knowledge (CofK) of containment and surveillance (C/S) data throughout the operational lifetime of the reactor that attempt to cover the frequency of inspection for timeliness. The reliance on CofK with layers of C/S represents an inherent vulnerability in the safeguards approach. If CofK is lost with C/S failures or anomalies and cannot be re-established, a facility will potentially not be able to attain IAEA timeliness detection goals for the duration of its operational lifetime. The IAEA probably never can recover the nuclear material detection quantity goals thereafter. In simple terms, the IAEA would not be able to confirm that nuclear material had not been diverted from the facility. This would be reflected in the safeguards conclusions drawn by the IAEA for the state and indicated in the IAEA annual Safeguards Implementation Report (SIR). With this in mind, it is clear that a new safeguards approach is required for the PBMR to mitigate the CofK vulnerability.

The most probable diversion scenarios for the PBMR would be: i) Diversion of undeclared irradiated target fuel pebbles for producing plutonium or ^{233}U, or ii) Diversion of spent fuel pebbles from the facility. In both cases, the would-be diverter would attempt to conceal this activity in a very hectic background involving the transfer and recirculation of hundreds and thousands of fuel pebbles to and from the reactor. This would be especially challenging during the initial start-up when the reactor is half filled with moderating graphite spent fuel dummies, which would be gradually drawn down and replaced by fuel pebbles, as the reactor reaches operating power and equilibrium. However, as noted above, a diversion would take between 50,000 to over 100,000 fuel pebbles, or the order of 10% of a PBMR reactor core fuel inventory. The hybrid bulk handling approach for the PBMR makes sense, especially considering the small amount of nuclear material per fuel pebble (9 g initial uranium) and the fact that an SQ of nuclear material would involve 50,000 to over 100,000 fuel pebbles. In many ways, the safeguards issues for a PBMR more closely resemble those of an enriched uranium fuel fabrication plant, rather than a conventional nuclear reactor.

The verification of spent fuel pebbles is complicated by the storing of PBMR spent fuel in one of ten spent fuel storage bins that nominally could contain over 600,000 spent fuel pebbles. These bins would be a high radiation area and human access would be prevented, which also precludes direct verification of the spent fuel in storage, one of the main safeguards issues with the PBMR. Traditional item counting, random item identification and gross attribute verification as has been applied to spent fuel at other types of reactors, including CANDU-type on-load refueled reactors is not practical or possible in this case. However, Slabber of PBMR Ltd. has proposed an elaborate and redundant fuel flow monitoring and containment/surveillance safeguards approach that would help address these issues.[9] However, it should also be noted for the record that this kind of issue is not unlike the verification of ^{235}U bearing nuclear material or plutonium bearing nuclear material in a MOX fuel fabrication plant, which has been successfully addressed by the IAEA. As long as the IAEA has the ability to verify the bulk of the spent fuel in storage, through the use of radiation-based volume or fill-height measuring devices, the accumulation and inventory of spent fuel pebbles could be effectively monitored over the course of the reactor's life.

MATERIAL BALANCE STRUCTURE AND KEY MEASUREMENT POINTS

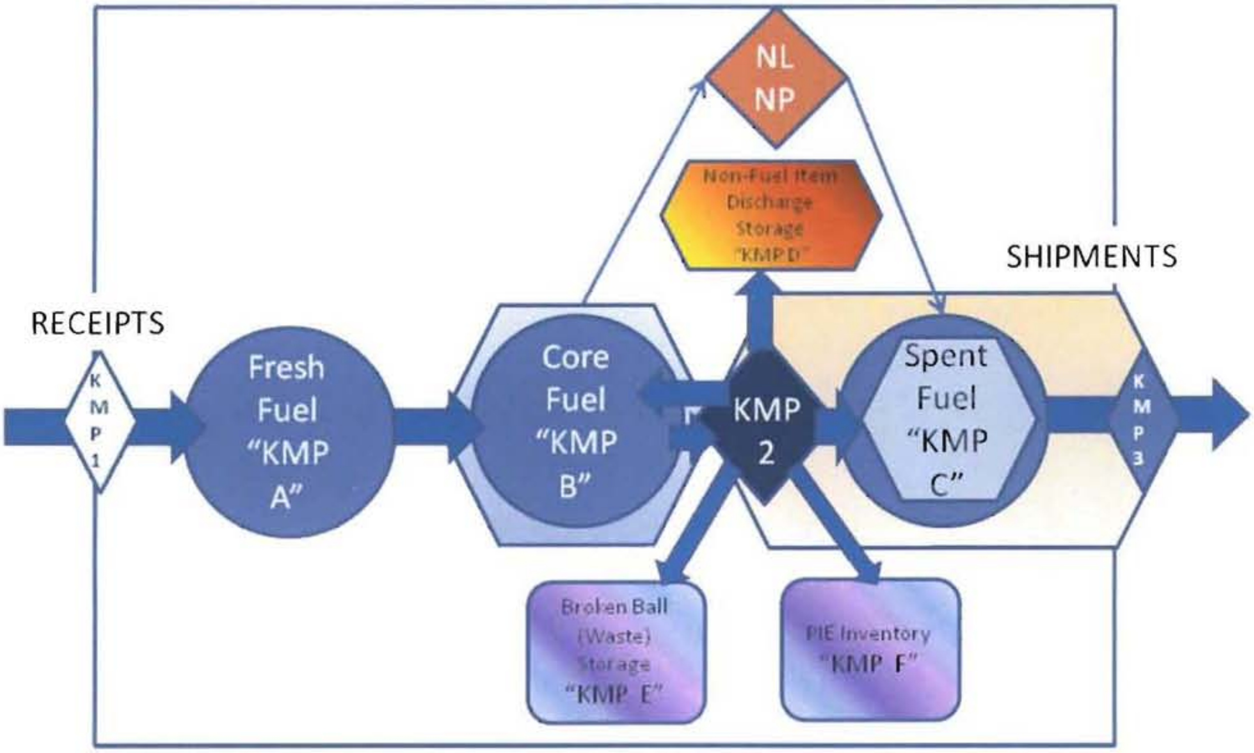

Figure 1: Proposed Nuclear Material Balance Area (MBA) and Key Measurement Points (KMP) for the PBMR (NL=Nuclear Decay (Loss), NP = Nuclear Production, PIE = Post Irradiation Examination)

The safeguards approach for a PBMR would have the following Material Balance Area (MBA) structure, with probable inventory and flow key measurement points (KMP), is shown in Figure 1. In this very typical arrangement for a nuclear reactor under IAEA safeguards, KMP-A contains the fresh fuel inventory, KMP-B holds the core, and KMP-C is the spent fuel storage. KMP-D holds stored non-fuel and would be subject to inspection to confirm the declared absence of nuclear material. KMP-E will hold and segregate the broken balls which contain nuclear material. KMP-F will have the post-irradiation examination (PIE) hot-cells where destructive assay can be done to the spent balls which contain nuclear material by the operator for quality assurance and monitoring of fuel performance as part of normal PBMR operations. KMP-1, -2, and -3 are the fuel receipt, fuel transfer from core to spent fuel storage, and fuel shipment KMPs, respectively. It should be noted that material flowing into KMP-2 has 5 paths it could take (KMP-B, KMP-C, KMP-D, KMP-E, and KMP-F) including return to the reactor. Hence, because of the number of paths for moving core and spent fuel pebbles, there are more flow and inventory key measurement points than one would find in an LWR, but comparable to large test reactors with PIE hot-cells where experimental examination of spent fuel and irradiated items is part of the research program.

FRESH FUEL

As noted in Table 2, the fresh fuel (FF) contains approximately 1 x10^{-5} SQs of ^{235}U showing the diversion of a single PBMR item has little value or meaning for proliferation. Hence, this table gives us an overview of the value to a proliferator of a pebble of PBMR fuel and provides perspective for the effort needed to safeguard a Pebble Bed Modular Reactor.

The fresh fuel needs to be verified upon receipt from the fuel vendor, prior to loading in the reactor at KMP-1. The inspectors would verify the fresh fuel by counting the fresh fuel drums, weighing selected drums to confirm bulk pebble weight, and verifying uranium and ^{235}U content in samples of pebbles, by non-destructive and/or destructive assay (NDA and DA). The operator will store the fresh fuel in a storage room, which will be KMP-A, after receipt in shipping barrels, which may also have been verified at the fuel fabrication plant and placed under seal. The inspectors would verify the seals on the drum (if shipped sealed) and verify the barrels at the PIV by item counting the barrels and re-measuring the pebbles in the drums with a 10% detection probability (random low-low) for gross defects. The pebbles would be verified in randomly selected drums to confirm total uranium and isotopic ^{235}U mass content. The IAEA's random sampling plan and algorithm would determine the number and random selection of the drums.[10] The gross defect verification of the fresh fuel in drums should be possible using the IAEA HM-5 detector or mini multi-channel analyzer (MMCA) coupled with a cadmium-telluride, sodium, or germanium detector.[11]

CORE FUEL

The core fuel in an OLR-style Reactor poses the safeguards challenge of being inaccessible to visual or NDA verification once it is in the core. The operator loads the fresh fuel pebbles into the PBMR fueling machine. The PBMR loads the fresh fuel into the core, which is designated KMP-B, to the proper fresh fuel position. The pebbles circulate in the pebble bed until they drop out of the bottom and are checked by operator NDA for either being fuel item or non-fuel item and for burn-up by fission product content at KMP-2 in Figure 1. Non-fuel items (start-up graphite moderating pebbles) are removed as the core reaches equilibrium, while fuel pebbles move through the core and are recirculated to achieve a pre-determined burn-up – predicted to be achieved by recirculating the fuel pebbles six times on average.

Depending on the burn-up, the pebbles are routed to the proper loading position in the core or ejected as spent fuel. If damage is detected here at KMP-2, the pebbles are sent to the broken ball waste storage (KMP-E). In principle, individual fuel transfers could be declared by the operator: i) 500 pebbles loaded per day (about 1 every 3 minutes) and ii) 2900 recirculated per day (1 every 30 seconds) and verified by a spent fuel pebble counting system (flow monitor- FM). But the declaration and accounting of such large numbers of fuel pebbles individually would be onerous. The direct observation of the pebbles would seem out of the question. To put into perspective PBMR core fuel safeguards, the core average burn-up of ~45,000 MWd/t[12] gives uranium and plutonium masses equal to about 4 SQs of LEU and 5 SQs of plutonium – contained in 450,000 pebbles. The Safeguards Criteria for such a difficult-to-access core requires dual C/S measures to ensure no unrecorded removal of fuel. Dual C/S, as defined by the IAEA, is a C/S system where "each plausible diversion path is covered by two C/S devices that are functionally independent and are not subject to a common tampering or failure mode, e.g. two different types of seal, or seals plus surveillance."[13]

The PBMR will present the IAEA with enormous numbers of SF pebbles. At equilibrium, 500 spent fuel pebbles will leave the reactor and transfer to one of ten spent fuel storage bins (KMP-F), which can contain 620,000 pebbles each. The operator will transfer broken or damaged fuel pebbles to a separate storage area. Consequently, there are two more diversion pathways in a PBMR than normally encountered in an LWR. Since a waste stream similar to that in a bulk handling facility exists, the idea of a hybridized item/bulk facility safeguards approach would appear appropriate and sensible.

SPENT FUEL

PBMR spent fuel pebbles would contain more highly burned or lower grade plutonium, called MOX-grade in the reference noted, compared to plutonium in spent LWR fuel assemblies.[14] As noted above in Table 2, it would take ~52 000 PBMR spent fuel pebbles to make one SQ of plutonium. The goal in safeguarding the plutonium in the spent fuel is to maintain the CofK after it leaves the reactor and arrives in the spent fuel storage. Surveillance of the spent fuel storage helps provide assurance that no spent fuel has been diverted. During the PIV and interim inspections, the inspectors would verify that the C/S systems have been effective and continuity of knowledge has been maintained on the spent fuel, or would randomly verify the fill height (volume) and radiation attributes of the spent fuel bins by NDA.

A NEW BULK-FUEL REACTOR APPROACH

As noted in the PBMR design, the elements are sufficiently small and numerous that the facility has many of the attributes associated with a bulk facility. Because the pebbles are indistinguishable by visual identification, or destructive and non-destructive assay (DA and NDA), the facility appears even more like a bulk facility. Counting errors will result in material unaccounted for (MUF) at PBMRs just as measurement errors give rise to MUF at traditional bulk facilities. Hence, we propose that the IAEA and operators consider a hybridized and novel bulk-handling approach to the PBMR, placing it in a new category of "Bulk-Fuel Reactors," which could encompass PBMR and perhaps other Gen-IV Reactors that might use bulk-fuel. We can utilize pebble counting to perform a number balance, but accept that this has uncertainty and give rise to MUF in the form of +/- some number of pebbles because of counting discrepancies, broken balls, and C/S failures.

This approach includes:

- Verifying ^{235}U and uranium in fresh fuel using an AWCC-style of measurement. Using an accounting unit larger than the pebble, perhaps Bueker's "drum/barrel unit" proposed for the German THTR.[15] Recognize that this give some MUF in the form of mass ^{235}U error from counting statistics and account for uranium and ^{235}U in the same statistical manner as at an enrichment, fuel fabrication, or reprocessing plant.
- Utilizing a layered safeguards approach integrating spectral data on fuel as it moves through the Key Measurement Points, verifying fuel at origin and destination.
- Measuring spent fuel to verify fuel burn-up and associated Pu inventory. Because existing spent fuel assay techniques cannot determine Pu and uranium directly, there is reliance on depletion codes in combination with verifying attribute measurement.
- Drawing a balance from number balance and from bulk material inventory and fold the uncertainties into a facility MUF.
- Determining total MUF by statistical analysis with counting MUF and Bulk MUF in quadrature. This arrives at a lower MUF than either individual technique and allows a longer operating interval before MUF becomes large enough that additional safeguards verification activities would be required.

Such an approach would include the elements of the containment and surveillance PBMR approach but would allow for a recovery of the verification of inventory if the containment and surveillance elements failed in some fashion.

RAMIFICATIONS OF THE BULK APPROACH

At some point the MUF will approach an SQ of Pu (or some other agreed operational limit) and a shut-down and clean out of the core may be required. This activity could potentially be coordinated with special reactor maintenance. Counting activities can be repeated to reduce errors and counting MUF. More precise spent fuel measurements can be done on longer cooled pebbles, which could reduce the bulk MUF, using active interrogation techniques, lead-slowing down time spectrometry, destructive analysis, and other techniques under development.[16] A statistical analysis of the approach would be required to determine the period of reactor operation to arrive at a particular MUF limit. Potentially, the safeguards verification at this time could be reduced to gross defect verification (for characteristic radiation), based on a random medium detection probability (50%) that would involve verification of randomly selected fresh fuel drums and spent fuel storage bins. In this case, we presume that the reactor core would have been discharged to the spent fuel storage bins. It is understood that this would be an extraordinary case, and would have to be coordinated with the national authorities and the facility operator. However, even in the worst case, this re-verification approach would be superior to the tedious accounting of every PBMR fuel sphere – which is simply not practical.

Regarding the bulk approach, another important aspect to consider is the need to independently verify the volume or fill height of each spent fuel storage bin. A Safeguards-by-Design feature for the PBMR is a proposed tube that would traverse the height of the spent fuel storage bin. The operator and inspectors could place a non-destructive assay (NDA) instrument in the tube to measure the spent fuel fill height for both operational and safeguards concerns. This would be extremely useful for confirming the fill-height and, hence, volume of the spent fuel pebbles that have been accumulated to date. Confirmation would most likely be needed during the annual PIV or during the clean-out re-verification activity noted above. This is analogous to the use of highly accurate volume or mass measuring devices on safeguarded vessels at other facilities handling nuclear material in bulk form.

With existing state-of-the-art spent fuel measurement and existing spent fuel composition data from depletion codes, the MUF from a PBMR bulk approach will be larger than the MUF from the number balance approach. However the bulk approach in combination with the number-balance CofK approach provides two independent measures of the facility MUF. This corroboration obtained by the two techniques cross-checking each other provides safeguards assurance that neither technique can provide alone and is a style of safeguards approach that the IAEA is looking into more and more to handle the bulk handling facilities.[17]

A layered approach beyond the normal C/S measures would bolster the safeguards posture for bulk, on-load refueling reactors like the PBMR. These efforts may not ensure CofK in the event of a failure of either mode due to the unique nature of the fuel movements. The variability of the expected (and acceptable) fission product inventory of the fuel during recycle and eventual routing to spent fuel storage further complicates matters as it i) opens the door to diversion by substitution and ii) makes verification that fuel moved from point A is the same fuel that arrives at point B difficult. One thing to consider that might augment the safeguards plan would be integration of an automated detector system with good spectral resolution, such as the new mechanically-cooled High Resolution High Purity Germanium (HPGe) systems on the market, as part of the fuel movement systems. Integration into the key measurement points allow verification (via a spectral fingerprint) that the pebble passing point A had arrived at point B by virtue of spectrum comparison. This could be done quickly and efficiently as part of an automated system. Additionally, it provides an orthogonal method of CofK in case of a C/S failure (e.g. if a seal/gross sensor failure occurs spectral data and verification can still be used along with surveillance systems to regain balance) that would also potentially be able to detect anomalies such as substitution and irradiation of a depleted uranium target item by virtue of detecting the difference in expected and measured isotopics. The on-line measurement of isotopics is also useful for maintaining peak core efficiency since it can also be used to more accurately measure burn-up of the pebbles as well as the additional safeguards benefit of being able to ratio multiple isotope peaks to accurately characterize the fuel at loading, during movement for recycle, storage as spent fuel, and movement for PIE.

One can see the need for Safeguards-by-Design considering the proposed safeguards approach prepared by Slabber, effective Design Information Examination (DIE)/ Design Information Verification (DIV) of the PBMR should consider the verification of the design, placement and performance of:

- Fresh Fuel (FF) bulk measuring devices (for verifying the mass or volume of stored fresh fuel)
- Flow monitors (FM) for the fresh fuel (FF) feed, discharged core fuel (CF), recirculated core fuel, spent fuel (SF), and fuel samples taken for post-irradiation examination (PIE)
- The addition of High Resolution automated assay systems (such as mechanically cooled HPGe detector systems) in line with the fuel movement systems to augment flow monitoring, gross counting, and C/S systems
- The Core Unloading Device (CUD)
- Spent fuel (SF) non-destructive assay (NDA) bin volume measuring system
- Digital Surveillance systems covering the Fresh Fuel (FF) store, access to reactor service hatch and core fuel (CF), the spent fuel (SF) discharge route - including the core unloading device, access to the spent fuel storage vaults, access to the post irradiation examination (PIE) sample hatch, access to the high-level waste store (with damaged fuel), and potentially the IAEA instrument room
- Electronic and mechanical sealing systems and tamper indicators on the fresh fuel (FF) storage drums, the reactor access hatch, access to the spent fuel storage bins (SF), the spent fuel bin removal line and valve, access to the high level waste storage (HLW), access to the PIE sample hatch (PIE), and potentially access to the IAEA instrument room

The authentication of the aforementioned systems would need to be confirmed, and where appropriate, the safeguards data may need to be encrypted from the safeguards sensor to the data collection computer to prevent possible interception and manipulation. An important aspect of DIE/DIV is ensuring that the safeguards instruments and equipment, instrument signals, and data collection computers have been properly secured to prevent tampering. In this regard, safeguards date authentication and where needed, encryption, are important issues and can only be easily confirmed during the DIE/DIV of the facility. Incorporating these systems into the PBMR will need to be part of Safeguards-by-Design since retrofitting such instruments or fuel storage concepts in the PBMR could prove to be costly and less effective than designing them into the original plant design.

Slabber's original safeguards approach would provide redundant containment and surveillance coverage of all fuel storage and flows. It is considerably more elaborate than what is currently done to safeguard an LWR and even on-load refueled (OLR, CANDU-type) reactors. This level of conservatism however, may be appropriate considering the IAEA's lack of experience in safeguarding this type of reactor. Over time, this approach could most likely be optimized. The IAEA is currently developing next generation surveillance and electronic sealing systems that would have a very prominent role in the PBMR.[18] Additionally, all of the aforementioned fuel monitors, surveillance, and electronic sealing systems are amenable to remote data transmission and monitoring (RM), as has been demonstrated by the IAEA at a number of safeguarded nuclear facilities around the world, particularly in Japan.

ANTI-NEUTRINO DETECTORS: POSSIBLE SAFEGUARDS TOOL FOR THE FUTURE?

Anti-neutrino detectors have been proposed to enhance the safeguarding of research reactors and nuclear power plants by the IAEA, including the PBMR. Researchers have demonstrated that anti-neutrino particle detectors buried beneath a nuclear reactor would record and indicate whether the reactor was operating, and proper evaluation of this data can even indicate the relative reactor power output and hence, plutonium production in the reactor. [19,20] Having said this, this safeguards measure is in a very early stage of consideration and it is not entirely clear what the added benefit would be, in connection with the established safeguards approach for research reactors and nuclear power plants in general, and the PBMR specifically. It should be noted that the IAEA has reviewed the concept and has seen improved performance, smaller instrument footprint, and cheaper costs for such a detector over the past decade.[21] The prospective safeguards approach appears very straightforward and similar to the application of safeguards at an on-load refueled rector (OLR, CANDU-type), provided continuity of knowledge is maintained over the core fuel and spent fuel. At this stage, the containment/surveillance system configuration proposed by Slabber et al. of PBMR Ltd. appears to be more than adequate, and consistent with IAEA practice for safeguarding comparable nuclear materials and facilities. With this equipment in place under current IAEA safeguards criteria, the IAEA would conduct the annual physical inventory verification (PIV), together with periodic re-verification of the facility and updated design information. If the installed safeguards equipment is set up in an unattended remote-monitoring (RM) mode, as is envisioned, inspectors should be able to conduct infrequent short-notice random inspections (SNRI) to confirm that the safeguards systems are operational and that the reactor remains properly safeguarded. With this straight-forward approach in mind, it is difficult to imagine what is to be gained with expensive anti-neutrino detectors installed at great cost beneath more than 440 nuclear power plants and hundreds of research reactors operating worldwide. Regardless, the IAEA is seriously considering the use of anti-neutrino detectors in selected cases, with the PBMR as one of those cases. More cannot be said in this regard, until additional data concerning the cost and safeguards benefit of this safeguards measure are better known. This is also an area for further consideration, once the design of the PBMR becomes better known and the specific safeguards approach can be optimized. For the anti-neutrino detector to operate most effectively a Safeguards-by-Design approach by the designer and is essential to enable optimal placement in the PBMR.

SAFEGUARDS SYSTEM DESIGN CHALLENGES

With the PBMR being a design that is in flux it can be possible to influence design layout to accommodate the safeguards concepts described within this paper. Realistic simulation and modeling of the PBMR system to determine the composition of spent pebbles is a significant challenge. Each pebble is subjected to a unique time-varying neutron flux depending upon the path followed through the reactor vessel. This reality of the PBMR system adds considerable complexity (and uncertainty) to the modeling process and defining the safeguards parameters and credible diversion threats from SF removal to UO_2 target insertion and removal to the PBMR system. However, estimates of the fissile content of the core and spent fuel are available in the literature and are the basis for this subsequent safeguards analysis. Despite not knowing the exact fissile content of the core and spent fuel, the safeguards challenge remains keeping track of a large number of small fuel spheres.

CONCLUSIONS

The Pebble Bed Modular Reactor type does not fit the models as described by the IAEA Safeguards Criteria, light water reactor (LWR), on-load refueled reactor (OLR, i.e. CANDU), or Other (prismatic HTGR). Because the nuclear fuel is dispersed across such a large bulk of material, it could be classified as a "Bulk-Fuel Reactor" and unique safeguards criteria should be developed for this reactor type by the IAEA, in cooperation with affected IAEA Member States, and international safeguards partners, such as U.S. DOE.

In developing the new safeguards criteria, the IAEA should consider the bulk nature of the fuel. The historical requirements to identify discrete fuel assemblies in the LWR, OLR or Other-type reactors and verify those randomly for uranium, ^{235}U, plutonium, and/or thorium content, does not seem feasible or relevant in the case of the PBMR reactor design. Verification of the fresh, core, and spent fuel are more akin to ^{235}U or plutonium verification in a uranium or MOX fuel fabrication plant. That is, the uranium or plutonium bearing material can be verified, but sphere identification is irrelevant, only the verification of the mass of uranium, plutonium, thorium and fissile isotopes on a sample and bulk basis to detect diversion of nuclear material. We believe that the bulk approach has merit, and that undue emphasis not be placed on the unique verification of fuel pebbles. The ideal safeguards approach appears to be a hybridized approach employing fuel flow-monitoring, redundant containment and surveillance for nuclear material, and bulk-handling facility accountancy and verification techniques combined in a layered safeguards approach to adequately address the unique nature of bulk fuel.

The IAEA originally recommended considered whether nuclear material in spent PBMR fuel was irrecoverable, because of the highly refractory nature of the fuel. However, reprocessing of similar HTGR fuel has been demonstrated in the United States at the Idaho Chemical Processing Plant (ICPP). Consequently, we consider that the recovery of plutonium, uranium and thorium from PBMR spent fuel is possible, although technically challenging.

As the PBMR design matures towards commercial deployment, we need to revisit this issue to see if the safeguards considerations change. It is unlikely that the overarching issues will change, since they are generic to the bulk nature of the PBMR fresh, core and spent fuel. However, the IAEA is currently developing next generation surveillance and electronic sealing systems, and the optimization of the safeguards approach may depend on the readiness of these safeguards measures, since containment and surveillance measures figure prominently in the safeguards approach. Close cooperation by the U.S. lab experts, IAEA, U.S. government experts, and reactor designers and operators to develop a safeguards regime that is integrated with the overall Safeguards-by-Design process is essential to effectively addressing the hybrid nature of the PBMR.

We recognize the need to support development or optimization of: i) techniques to verify the plutonium content in spent fuel pebbles, ii) burn-up computer codes for PBMR spent fuel, and iii) bulk verification techniques for PBMR spent fuel storage bins. The need to re-verify the spent fuel storage bins at some point in the future looms as a likely possibility in the case of containment and surveillance failure and the IAEA will need the tools to perform this task – which they do not presently have.

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