

RISK INFORMED SAFEGUARDS INTEGRATION STUDIES FOR A FAST REACTOR FUEL CYCLE

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ABSTRACT

Fast reactors with a closed fuel cycle (FRFC) are important for the sustainability, reliability, and security of the world's long-term energy supply because of its potential to extract more energy from the mined uranium than other fuel cycles and also due to its capability to incinerate transuranic elements. Knowing this vast potential, research activities on the FRFC technology have rejuvenated worldwide. Presence of three such systems among the six proposed by the GEN IV International Forum marks their importance for the future. However, Pu production and its use in large quantities in these systems is a major safeguards concern. Hence, it is prudent to assess the proliferation resistance (PR) of the FRFC facilities for finding weak links, so as to ensure adequate safeguards for Pu. Towards this objective, the Nuclear Security Science and Policy Institute at the Texas A&M University is carrying out pre-conceptual design studies for the integration of modern safeguards directly into the planning and building of FRFC facilities. A broad three step safeguards approach is adopted consisting of; (1) quantitative SNM flow diagram development for the FRFC, (2) PR assessment tool development for analyzing SNM diversion scenarios, and (3) design of a safeguards system based on the risk informed data obtained from the PR assessment. Accordingly, the SNM flow diagram for the FRFC was developed by employing MCNP/ORIGEN/MONTEBURNS computer codes choosing the Indian Proto-type FBR design details available from the open literature. The PR assessment software, PRAETOR (proliferation resistance analysis and evaluation tool for observed risk) based on the well established multi-attribute utility analysis decision methodology is developed and employed. A set of 21 SNM diversion scenarios for the three key FRFC facilities (fuel fabrication, fast breeder reactor and fuel reprocessing) and a PWR spent fuel diversion scenario (as a reference case) are analyzed using the PRAETOR tool. The details of setting up material balance areas (MBA), material balance periods (MBP), key measurement points (KMP), and the containment & surveillance program based on a classical safeguards approach are presented in addition to the risk informed safeguards approach employing the PRAETOR tool.

INTRODUCTION

Pre-conceptual studies carried out for the integration of modern safeguards directly into the planning and building of fast breeder reactor fuel cycle (FRFC) facilities are presented here. The studies focused on identifying a proliferation resistance (PR) assessment methodology, developing special nuclear material (SNM) flow diagram for a generic FRFC, performing PR assessment for various SNM diversion scenarios and proposing risk informed safeguards approach for the FRFC. The first two tasks were completed with their results made available by Metcalf [1], Chirayath et. al. [2,3]. In brief, first task was accomplished by selecting MAUA methodology (multi-attribute utility analysis) for the PR assessment and developing a software tool named PRAETOR [1] (proliferation resistance analysis and evaluation tool for observed risk). Second task objectives were

accomplished by developing the SNM flow diagram for the FBRFC by employing MCNP/ORIGEN/MONTEBURNS computer codes and by choosing the Indian Proto-type FBR design details available from the open literature. This paper describes the studies and results carried out for completing last two tasks aforementioned.

STUDIES ON SAFEGUARDS APPROACHES FOR FBRFC

Safeguards approach presented here is to set up material balance areas (MBA) for each facility and determine material balance period (MBP) for each MBA. The following subsections describe the safeguards studies for fuel fabrication, fast breeder reactor, and spent fuel reprocessing facility.

Fuel Fabrication Facility (FFF)

FFF MBAs

A schematic of the MBAs setup is shown in Figure 1. MBA-1 includes input material storage area for the FFF. MBA-2 accounts for the entire fuel fabrication process. All of the material going into the process must balance with the material going out into product storage. MBA-3 accounts for the product storage area.

Detection Mechanisms in FFF

Scales, surveillance methods, and onsite seals will be used in the storage area. Stored PuO₂ containers will be item accounted. A high level neutron coincidence counter (HLNC) will be used for Pu accounting. This, along with gravimetric measurements, can very accurately quantify the amount of Pu in MBA-1. In MBA-2, detector systems can be implemented for process monitoring to provide information on operation history, facility misuse and possibly detect SNM diversion. Gravimetric measurements for the fuel pellets (since they are stored in containers) and counting measurements for the fuel rods and assemblies can be used for these stored material and items. While these measurement types ensure there is material present, HLNC will quantify the amount of Pu material present in MBA-2. Item counting of fuel rods/assemblies and Pu quantification by HLNC are envisaged for the SNM accounting in MBA-3. The facility doors and perimeters would have detectors setup to detect any possibility of material being diverted. This facility will have key measurement points (KMPs) at the boundaries of each MBA.

Material Throughputs in FFF

The facility throughput is as given in Table 1. Equilibrium fuel cycle period is 240 days. The core will reload one third of its fuel every cycle. Depleted uranium involved has such a high significant quantity that any achievable SQ (>10 tons) of would be easily detected. One SQ being the approximate amount of nuclear material for which the possibility of manufacturing a nuclear

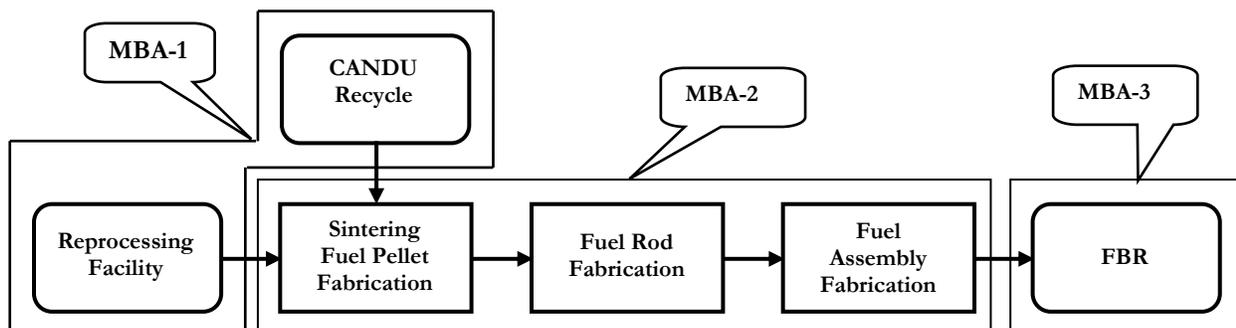


Figure 1. Schematic of Material Balance Areas for Fuel Fabrication Facility

explosive device cannot be excluded [4]. This model assumes that any waste material containing Pu is recycled in FFF. Fuel assemblies come in two Pu concentrations, 21% for inner core and 28% for outer core. Safeguards are designed around the equilibrium core fuel cycle. The facility was designed for two reactor cores.

Table 1: Fuel fabrication facility throughput

Unit in kg	Inner Core	Outer Core	Radial Blanket	Total/Cycle	Oxide/Year	HM/Year	HM/Day
PuO ₂	564.8	900.5	0.0	1465.3	2228.5	1961.1	5.4
UO ₂	2168.1	2349.4	0.0	4517.5	6870.4	6046.0	16.6
UO ₂ Blanket	1773.4	2101.8	11104.8	14979.9	22782.0	20048.1	54.9

To achieve a direct diversion, one would have to get hold of approximately 1.48 days worth of material. Since, it is very unlikely that the adversary would take 100% of throughput during this time period; diversion of a different kind would be more likely. The standard uncertainties in measurements for the FFF material throughput are computed employing international target values [5] and based on these the time needed to divert 1 SQ of Pu from FFF, buried in measurement uncertainty, is 133.3 days (PuO₂), 72.7 days (fuel pellets), 66.7 days (fuel rods) and 80 days (fuel assembly). The fuel rods diversion takes the least amount of time (66.7 days) to achieve 1 SQ. The timeliness goal of this direct use un-irradiated material is one month. Hence, to achieve the $3\sigma < 1SQ$ standard, the material balance period is set to be 22 days.

Fast Breeder Reactor (FBR)

Reactor core has an inner and outer region with varying Pu content in its fuel assemblies as well as radial blanket assemblies. Figure 2 shows the schematic of fuel assembly core loading. The CSR and DSR refer to control safety rod and diverse safety rod, respectively. In addition to the radial blanket assemblies, both inner and outer fuel assemblies will have axial blankets. The isotopics for the fresh and spent assemblies are tabulated elsewhere [3]. Reactor power is 500 MWe and is refueled every 240 days. Spent fuel is cooled at the periphery of core for one fuel cycle. This is to avoid damage to fuel transportation equipment from decay heat. After this cooling period, it is cleaned off for sodium coolant and is transported to the spent fuel storage pool. For an equilibrium cycle 27 inner core, 32 outer core and 42 radial blanket assemblies are replaced in every fuel cycle. A comprehensive list of FBR characteristics can be found elsewhere [3].

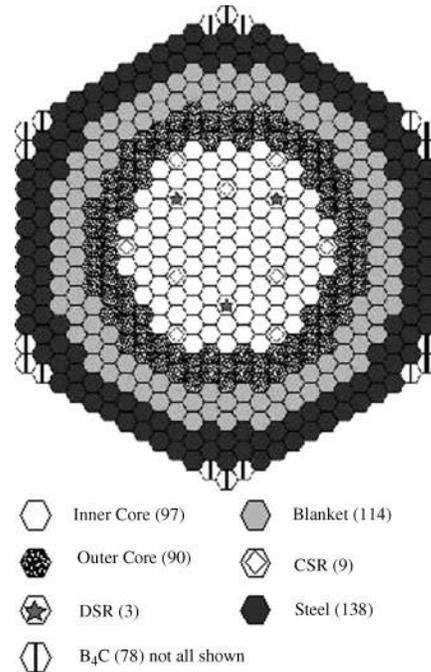


Figure 2. Equilibrium Cycle FBR Core loading

FBR MBAs

The FBR has direct use un-irradiated Pu requiring MBP to be one month [6]. Figure 3 shows the proposed MBAs and KMPs for the FBR. Each core operating with an equilibrium fuel cycle requires 647 kg of Pu in fresh fuel and the spent fuel contain 519 kg of Pu, both of which must be measured to an accuracy so that 3σ is less than one SQ (8 kg) of Pu. A HLNC will be used to measure the total Pu mass. The uncertainty of the HLNC measurement is 0.2% [5]. To find out whether 1 SQ of Pu can be diverted from MBA-4, buried within the measurement uncertainties, Equation (1) is employed. Equation (1) gives material balance in MBA-4. Net uncertainty associated with the measurements in MBA-4 is computed using the principle of propagation of errors [7] as $3\sigma_{ID} = 8.93$ kg of Pu per refuel of core. This mass is more than 8 kg (1 SQ), which means that quantitative measurements are not accurate enough and that item accounting must be used. It is also assumed in the MBA-4 computations that the Pu required to refuel an equilibrium cycle of FBR is always available in MBA-4.

$$ID = PB - PE + FF_1 + SF_1 - FF_2 - SF_2 \quad (1)$$

Where, ID is the net Pu inventory at the end of MBP; PB and PE are the physical inventories at the beginning and end of MBP respectively; FF_1 and FF_2 are respectively the fresh fuel Pu inventories entering and leaving MBA-4; SF_1 and SF_2 are respectively the spent fuel Pu inventories entering and leaving MBA-4.

The fuel assembly integrity verifying and item identifying methods proposed for accounting are: eddy current measurements, serial number readers (employing ultra sound for under sodium measurements [8]), radioactivity measurements, and containment and surveillance (C&S). Eddy current measurements can be done on the welds of each fuel assembly to uniquely identify it as well as ensure that no rods have been removed from the assembly. Reading the serial numbers on each assembly adds a secondary level of verification that no assemblies have been diverted.

Radioactivity measurements of spent fuel assembly can be done to determine burn-up. Under sodium ultra sound measurements are useful to verify whether the fuel assemblies were swapped within the core locations. C&S around the reactor and at each penetration through it could verify that no undeclared SNM is transported to or from the reactor core. This will ensure that for every fresh fuel assembly that enters the reactor containment, only one spent fuel assembly will exit it.

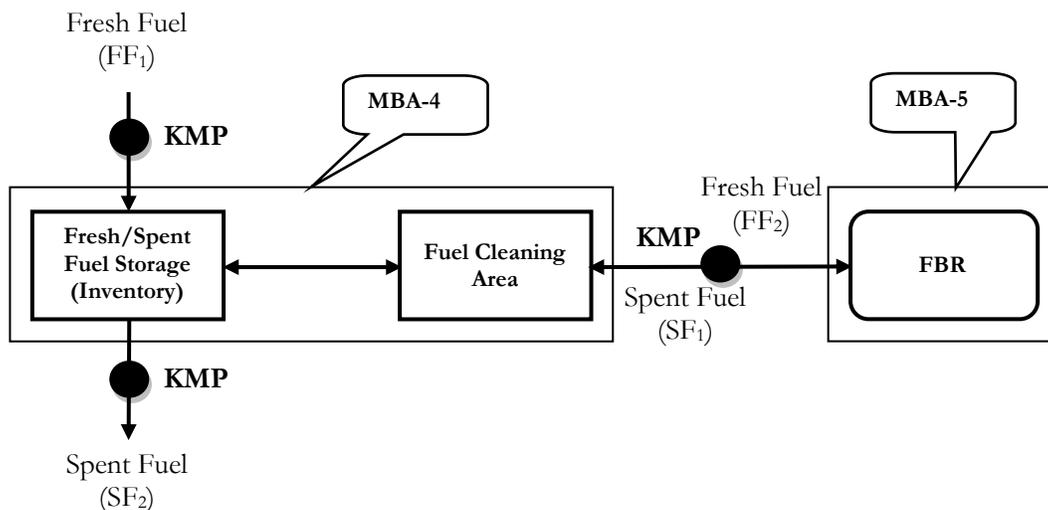


Figure 3. Schematic of the Material Balance Areas for the Fast Breeder Reactor

Fast Reactor Fuel Reprocessing Facility (FRFRF)

The reprocessing facility employs Pu uranium extraction (PUREX) process. Every 240 days a new shipment of spent fuel (one third of the core) is received from the FBR. These are reprocessed to retrieve PuO₂ and UO₂ within the next 240 days and shipped to the FFF for fuel pellet fabrication. The total inventory at the facility and number of assemblies discharged from FBR heading to FRFRF is given in Table 2. Pu inventory has approximately 130 SQs (one SQ is 8kg of Pu) and safeguards approach is presented only for Pu. The average throughput per day in the reprocessing cycle was calculated by dividing the total amount of Pu (1037.5 kg) from two FBRs by the length of one reprocessing cycle (240 days). The total Pu loss for this facility is assumed to be 1%.

Table 2 Pu and ²³⁵U Inventory

	Pu total g/SA	²³⁵U total g/SA	Assemblies Per core of Equilibrium Fuel Cycle
Inner Core	4125.54	91.42	27
Outer Core	11427.33	102.93	32
Radial Blanket	991.95	265.43	42
Total 2 Cores	1037452	33820	

FRFRF MBAs

The material considered for the classic safeguards approach is Pu in spent fuel, separated Pu solution, and PuO₂. The highest risk category is direct use material, PuO₂ with a timeliness detection goal of one month and hence the maximum MBP will be one month. Three standard deviation uncertainty in material unaccounted for calculations over each MBA for the considered MBP must be less than 8 kg Pu. Using this classic safeguards approach, MBAs were established for the reprocessing facility based on where the material form could be accounted for by item accounting or bulk measurement accounting. The chosen MBAs are shown in Figure 4. MBA-7 is set up around the spent fuel storage, and it employs item accounting of the assemblies and containment & surveillance (C&S). C&S will ensure that there is only one path in and out of the facility and also monitor movement of fuel assemblies. The MBA-8, where in the fuel is changed from item to bulk form, C&S will be relied upon because front end measurements are not accurate enough. A conservative 25% uncertainty was assumed for the estimation of Pu in spent fuel declared by the reactor operator. Hybrid k-edge densitometer (HKED) and dip tube (DIPT) measurements are used in the input accountability tank (IAT), with a combined measurement uncertainty of 0.7%. The HKED measures the elemental concentrations in spent fuel solution, and DIPT measures the volume of the IAT. The clad hulls to the waste have negligible amounts of Pu (limit 100nCi); however Pu scrap multiplicity counter (PSMC) measurements of the clad hulls are taken to detect the possible diversion of Pu through the clad hull waste. With the assumed uncertainty 25% and the IAT measurements, the calculated combined uncertainty (1σ) in Pu measurements based on MBA-8 using Equation (2) and propagation of errors is 259.46 kg, which then is equal to 1.08 kg/day and the 3σ will be 3.24 kg/day. That is to avoid diversion of 1 SQ of Pu the MBP needs to be restricted to 2.5 days.

$$ID = PB - PE \quad (2)$$

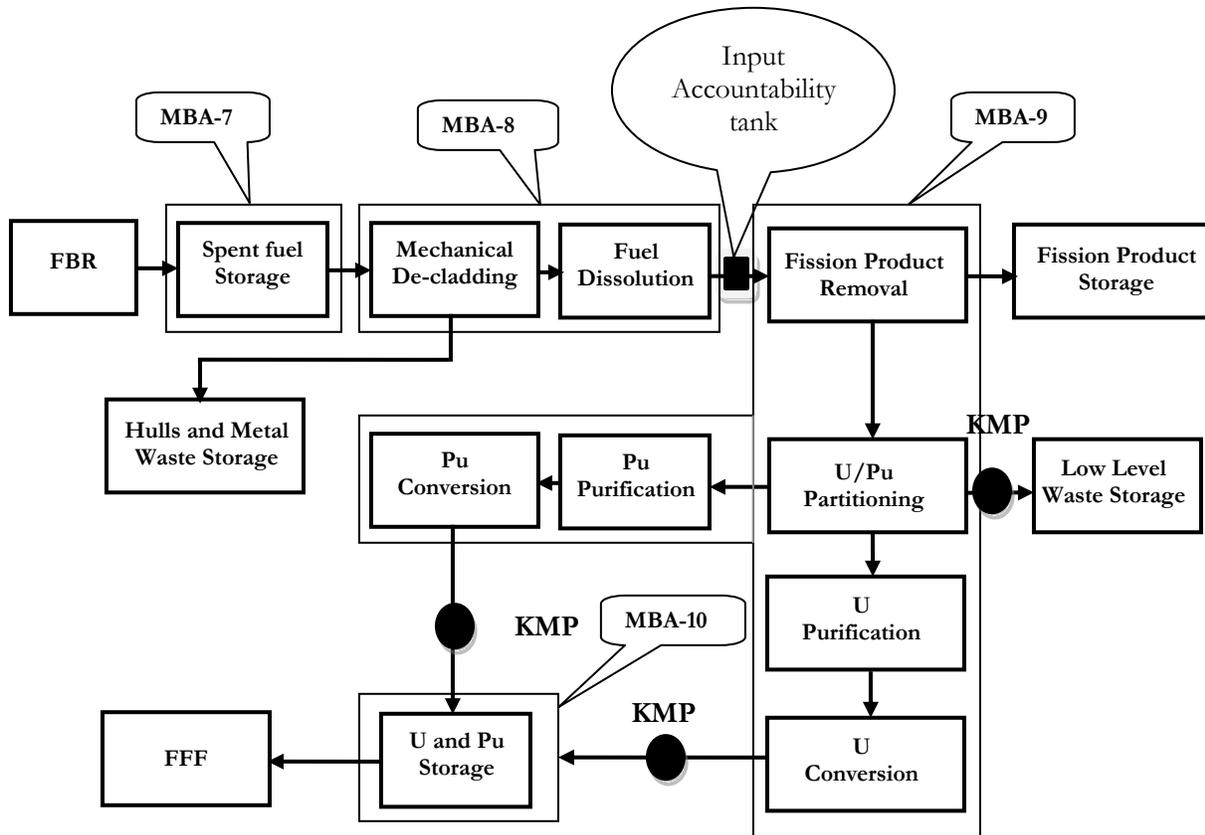


Figure 4. Schematic of the Material Balance Areas for the Fast Reactor Fuel Reprocessing

This is operationally impractical and therefore relies on C&S to safeguard the material. The goals of C&S in this MBA-8 are to ensure there is one path in and one path out to waste and the IAT, ensure fuel pieces and fuel rods are not removed during mechanical de-cladding and during fuel dissolution process, prevent diversion of material from fuel dissolution process and IAT and prevent precipitation of Pu in the IAT (a specific diversion pathway). In order to obtain a MBP equal to the IAEA timeliness goal for Pu of 1 month for this facility, the front end measurement would need to have 1.9% accuracy.

The MBA-9 encompasses the IAT till the uranium and Pu conversion. The KMPs are depicted in Figure 4. This MBA analysis is shown in Table 3.

Input stream measurements are from the IAT of the previous MBA. Fission product output stream contains very small amounts of Pu (assume 0.5%); however high radioactivity of the fission products will cause nondestructive assay detection methods to be insufficient for Pu detection. The low level waste output stream contains the waste solution from the uranium and Pu partitioning, uranium purification, and Pu purification stages. The low level waste does contain trace amounts of Pu, but in this case the low radioactivity will allow for effective nondestructive assay methods for the detection of Pu. A high purity germanium (HPGe) detector is used to obtain a gamma spectrum of the low level waste to look for possible diversions of Pu. Also, a flow meter is used to monitor the material flow of low level waste to waste storage. Inside this MBA, the nuclear materials are converted into oxide forms. After conversion, the nuclear materials are sealed containers of specific sizes to prevent criticality. Each container undergoes gravimetric (GRAV) measurements to verify the amount of PuO_2 or UO_2 added to the specific containers. The HLNC measurements are taken of

a random sampling of the PuO₂ containers to verify the Pu content. HPGe measurements are taken to obtain the gamma spectra for random sampling of the UO₂ containers; the presence of Pu would be obvious in the gamma spectra. Therefore, the UO₂ container measurements provide a method to detect the diversion of Pu through the uranium output line. The total σ_{MUF} for this MBA is 0.0352 kg Pu/day. The calculated MBP for this MBA is 75.7 days, which is much longer than the IAEA's required one month timeliness goal for Pu. This result implies the safeguards for this MBA could be relaxed, thus less accurate and less expensive detection methods.

The MBA-10 encompasses the PuO₂ and UO₂ of the product storage. Here, the containers of PuO₂ and UO₂ powder are stored and are safeguarded using item accounting and containment/surveillance. The goals of containment and surveillance are to monitor the movements within the storage area, monitor the movement of product containers, and ensure that there is only one path in from conversion and packing stage and one path out to fuel fabrication, and prevent and detect diversion of the nuclear material.

Also, not shown in the Figure 4, is the MBA which store metal waste, clad hulls, fission product waste, and low level waste. This MBA employs containment and surveillance to meet safeguards requirements. For this particular scenario, it is assumed that the waste is shipped off the facility; thus not needing to account for the trace amounts of Pu in the waste for this facility within the MBP.

Table 3 MBA-9 Analysis

	Measurements	Uncertainty (%)	Pu (kg/day)	σ_{MUF} (kg Pu / day)
In - IAT	HKED + DIPT	0.762	4.32	0.033
Out - To fission product storage	Flow meter with no NDA	100	0.0216	0.00022
Out - To low level waste	HPGe + Flow meter	2.83	0.0108	0.0003
Out - to U/Pu storage (Pu line)	ANCC + GRAV	0.292	4.280	0.0125
Out - to U/Pu storage (U line)	HPGe + GRAV	2.83	0.0108	0.0003
Total σ_{MUF}				0.0352

PROLIFERATION RISK ANALYSIS USING PRAETOR

In order to analyze the PR against SNM diversion from FBRFC, the Texas A&M University proliferation resistance analysis and evaluation tool for observed risk (PRAETOR) [1] was used. A total of 22 various diversion scenarios were analyzed using PRAETOR and are listed in Figure 5. One reference scenario of a PWR spent fuel assembly diversion is analysed using data from the LLNL report on dose rate estimates from irradiated LWR fuel assemblies in air and by running ORIGEN ARP [9]. The PRAETOR analyses are performed for each diversion scenario, with and without IAEA safeguards. The PRAETOR tool output (Metcalf [1] or Donald Giannangeli's thesis [10]) contains computed U-values running between 0 and 1, which represent the relative PR against diversion associated with the SNM present in a facility. Closer the U values to one higher the PR. The U-values are computed for four different sub-steps, vis-à-vis Diversion, Transportation, Transformation, and Weaponization leading to the manufacture of a nuclear explosive device, each sub-step having further sub-steps and corresponding utility functions and its attribute values. The

PRAETOR tool computes the U-value for each of the four sub-steps using MAUA methodology and also one final U-value combining all four categories. The results obtained for the aforementioned 22 diversion scenarios for the diversion sub-step are shown in Figures 5.

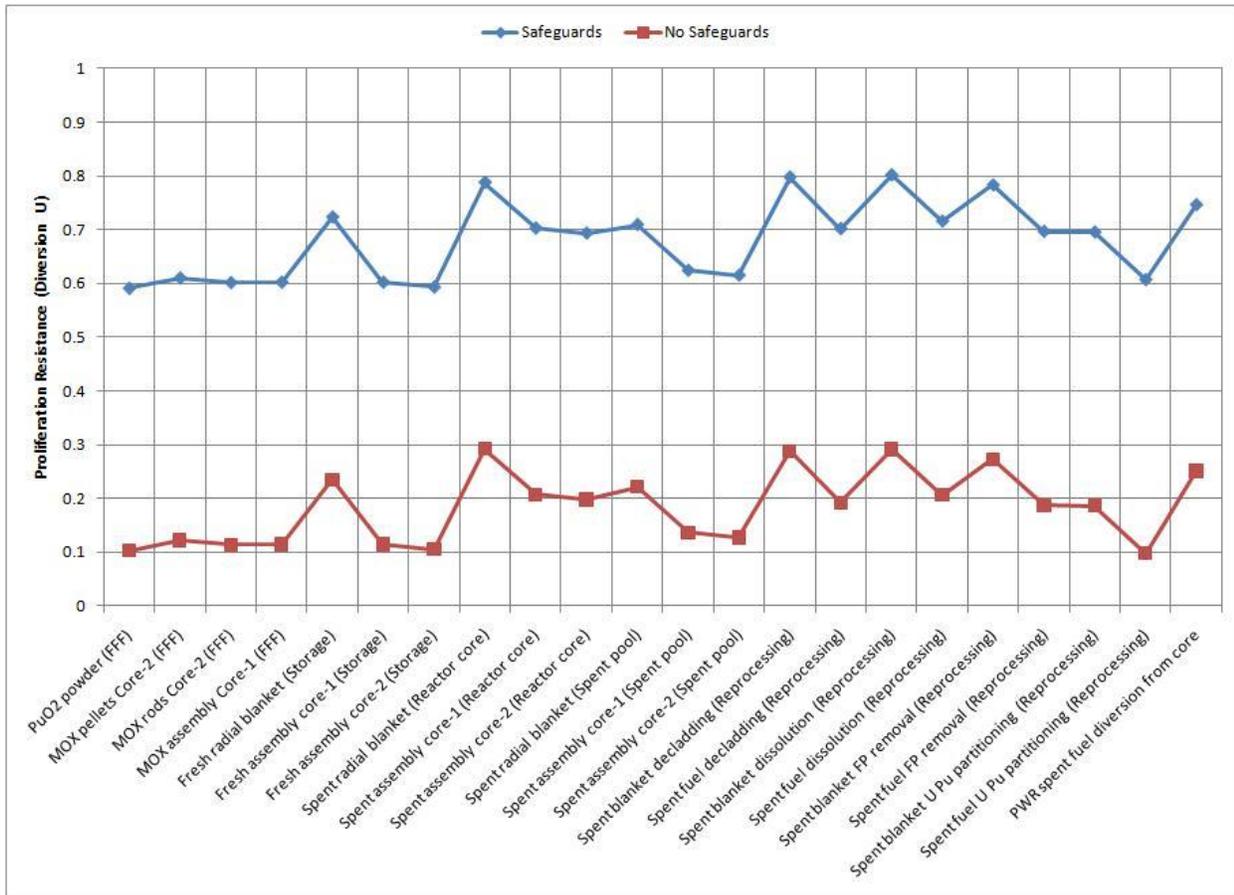


Figure 5. PRAETOR results obtained for PR of the diversion sub-step with different SNM diversion scenarios within the FBRFC facilities with and without safeguards

It can be inferred from Figures 5 that the results of the PRAETOR tool are in general logical with spent core fuel being more proliferation resistant than fresh fuel due to its high radioactivity. As expected, implementing safeguards had an improved proliferation resistance in every case. The comparison case of spent PWR fuel decayed for one year had U-values lower than spent FBR radial blanket but higher the spent FBR fuel assembly. Spent blanket assemblies have the largest proliferation resistance among all the assemblies analyzed. Marginally lower U-value of fresh blanket assemblies compared to the spent blanket assembly may be due to the weighting scheme used in PRAETOR. Proliferation risk for Pu increased significantly once the fission products were removed, and the area most susceptible to proliferation is the PuO₂ product storage. The PRAETOR results showed there need to be safeguards improvements from the fission product removal to the uranium and Pu partitioning. The decrease in value can be solved by implementing an accurate measurement method for Pu content after fission product removal, thus changing the MBAs. The HKED provides the first accurate Pu content measurement at the reprocessing facility; the disadvantage of this measurement is the need for a homogeneous sample while still containing many fission products. A measurement after fission products are removed and at the beginning of

U-Pu partitioning will probably provide a more homogeneous sample to analyze for the Pu content. PRAETOR tool is found to reasonably predict relative PR among FBRFC.

RISK INFORMED SAFEGUARDS APPROACH

The PRAETOR analysis of FBRFC indicates that a risk informed safeguards approach may be more effective compared to the classical safeguards approach. To illustrate this consider the example of the FRFRF discussed in section; steps up to and including the fission product removal are found to have high PR. Now safeguards will be focused to the areas, which have fewer radio-activities and where there is pure Pu product, which poses a greater proliferation risk. The MBAs for the risk informed safeguards approach are shown below in Figure 6. The major changes from the classical safeguards approach (see Figure 4) are the inclusion of the fission product removal state with the MBA-8 and the addition of a new KMP between the fission product removal and uranium and partitioning stages. A possible Pu content measurement is a titration (TITR) measurement, more accurate than HKED and could be used on the uranium and Pu nitrate stream. Since there would be an accurate Pu content measurement and the total mass output to the next MBA is less, the proliferation risk increase from fission products to no fission products should be less than that of the previous plan.

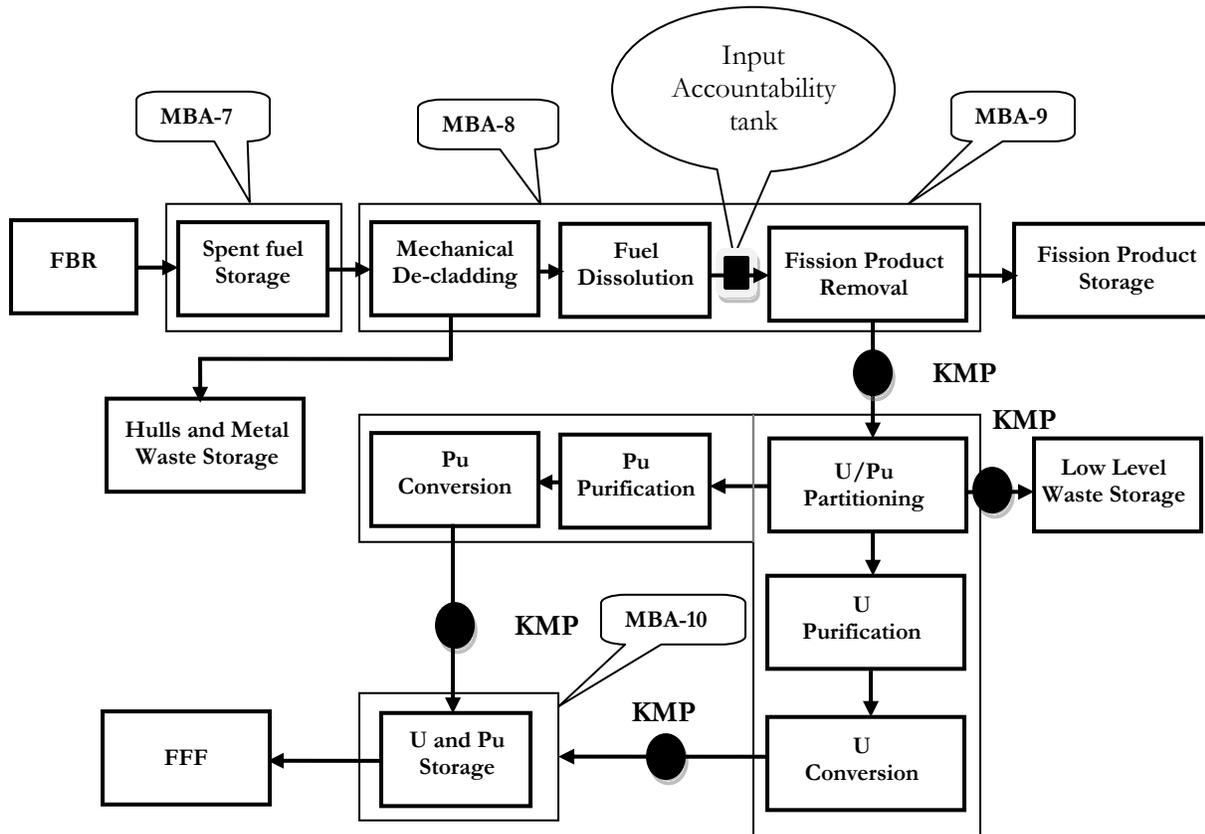


Figure 6. Schematic of MBAs for the FRFRF using PRAETOR Risk Informed Safeguards

CONCLUSIONS

An attempt is made to quantify and compare the PR of various steps of FBRFC facilities. MAUA methodology is employed to assess the relative PR of each step. SNM inventory and its flow

through a typical set of FBRFC are computed in order to facilitate a semi-quantitative PR assessment. A computational tool, namely PRAETOR, based on the MAUA methodology is developed to perform PR assessment for various SNM diversion scenarios with the assumption that IAEA safeguards procedures along with additional protocol are in place at these facilities. The PRAETOR analysis carried out for these diversion scenarios for FBRFC facilities could show significant improvements in PR when safeguards are enforced at the facility. These facilities were essentially divided into three groups, such as fuel fabrication facility, fast breeder reactor and fuel reprocessing facility. Safeguards approaches to be employed at each of these facilities in terms MBAs and MBPs are clearly brought out in this study. As a capability demonstration of PRAETOR tool, classical safeguards approach and risk informed safeguards approach were studied for the fuel reprocessing facility. Based on the weak links (proliferation risk areas) within the fuel cycle predicted by the PRAETOR tool, a risk informed safeguards approach is developed by modifying the MBAs, KMPs and measurement methods for the spent fuel reprocessing facility.

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