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RESEARCH ON SAFEGUARDS APPROACHES AND METHODS

Risk Informed Safeguards Approaches for Fast Reactor Fuel Cycle Utilizing MAUA based Proliferation Resistance Assessment

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EXECUTIVE SUMMARY

Fast breeder reactors with a closed fuel cycle (FBRFC) are important for the sustainability, reliability, and security of the world's long-term energy supply. Fast reactors have a hundred-fold energy extraction potential from the same amount of mined uranium compared to thermal reactors and have the possibility of incinerating all long-lived heavy elements during reactor cycle. Knowing this vast potential, research activities on the FBRFC technology have rejuvenated worldwide. Presence of three such nuclear systems among the total six systems proposed by GEN IV International Forum further marks the importance of fast reactor fuel cycle systems in the future. However, the breeding of high purity ^{239}Pu isotope and its envisaged use in large quantities in FBRFC by design is a major safeguards concern because of the vulnerability of special nuclear material (SNM) diversion from peaceful uses to destructive ones. Hence, it is prudent to assess the proliferation resistance (PR) of the FBRFC facilities for finding weak links, so as to ensure enhanced safeguards for the SNM.

Towards meeting this objective, the Nuclear Security Science and Policy Institute (NSSPI) 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 FBRFC facilities. A broad three step safeguards approach is adopted consisting of the following tasks; (1) to develop a quantitative flow diagram of SNM present at each of the FBRFC facilities, (2) develop a tool for the quantitative PR assessment of intrinsic and extrinsic barriers for a set of SNM diversion scenarios and (3) design a safeguards system by arriving at optimized material balance areas (MBA), material balance period (MBP), key measurement points (KMP) and the containment & surveillance program based on the risk informed data obtained from the PR assessment.

Accordingly, the SNM flow diagram for the FBRFC was developed by employing MCNP/ORIGEN/MONTEBURNS computer codes choosing the Indian Proto-type FBR design details available from the open literature.

PR assessment software, PRAETOR (proliferation resistance analysis and evaluation tool for observed risk) developed based on the well established multi-attribute utility analysis decision methodology as part of this research program is selected for the present study. A set of 21 SNM diversion scenarios for the FBRFC facilities (fuel fabrication, fast breeder reactor and fuel reprocessing) and a PWR spent fuel diversion scenario (for reference case) are analyzed using PRAETOR tool and the relative PR for these scenarios presented.

The details of setting up of MBAs, MBP, KMPs based on a classical safeguards approach for the three key facilities (fuel fabrication, fast breeder reactor and fuel reprocessing) of the FBRFC are presented. Risk informed safeguards approach employing the results of quantitative PR assessments provided by the PRAETOR tool is demonstrated for the fuel reprocessing facility and is compared with the classical safeguards approach.

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1. INTRODUCTION

1.1. Motivation for this Study

The Nuclear Security Science and Policy Institute (NSSPI) 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 fast breeder reactor fuel cycle (FBRFC) facilities. The results of the project study should lead to high-priority tradeoff studies, identify weak links (proliferation paths) in the FBRFC, and suggest specific ways to strengthen them by the integration of modern safeguards. The results obtained should also aid the International Atomic Energy Agency (IAEA) or the domestic inspecting entity to effectively and efficiently monitor and verify special nuclear material (SNM) in a manner that provides minimal intrusion into the normal facility operations. This research project is taken up under the sponsorship of USDOE National Nuclear Security Administration's office of Non -proliferation and International Security. The project tasks are; (a) to identify a suitable proliferation resistance (PR) assessment methodology from the available methodologies through literature survey, (b) develop SNM flow diagram of a generic FBRFC by computational efforts, (c) perform PR assessment for different diversion or misuse scenarios with the assumption that IAEA safeguards procedures along with additional protocol are in place at these facilities, and (d) to propose safeguards approaches for the FBRFC. Tasks (a) and (b) have been completed with their results made available by Metcalf [1], Chirayath et. al.[2, 3]. In brief, task (a) was accomplished by selecting MAUA methodology (multi-attribute utility analysis) for the PR assessment and developing a software tool called PRAETOR [1] (proliferation resistance analysis and evaluation tool for observed risk). In order to achieve the objectives of task (b), SNM flow diagram for the FBRFC was developed by employing MCNP/ORIGEN/MONTEBURNS computer codes choosing the Indian Proto-type FBR design details available from the open literature. This paper describes the studies and results carried out for completing tasks (c) and (d). The FBRFC facilities were essentially divided into three; fuel fabrication, fast breeder reactor, and spent fuel reprocessing to carry out the studies on safeguards approaches. Safeguards approaches proposed for these three facilities are discussed in Section 2. Section 3 presents the PR assessments carried out for 21 scenarios within the FBRFC and one scenario for the PWR spent fuel, which would result in the diversion of one significant quantity (SQ) of SNM, one SQ being the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded [4]. Demonstration of risk informed safeguards approach for the fast reactor fuel reprocessing facility in comparison with the classical safeguards approach is presented in Section 4 and the conclusions of the study are presented in Section 5.

2. 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.

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[1] Metcalf Richard R., "New Tool for Proliferation Resistance Evaluation Applied to Uranium and Thorium Fueled Fast Reactor Fuel Cycles", MS Thesis, Texas A&M University, 2009.

[2] Chirayath Sunil, Richard Metcalf, Jean Ragusa and Paul Nelson, "Assessment of Proliferation Resistance Requirements for Fast-reactor Fuel-cycle Facilities", Proceedings of the 8th International Conference on Facility Operations – Safeguards Interface, Portland, Oregon, USA, March 30 to April 4, 2008.

[3] Chirayath Sunil Sunny, Gordon Hollenbeck, Jean Ragusa, and Paul Nelson, "Neutronic and Nonproliferation Characteristics of (PuO_2-UO_2) and (PuO_2-ThO_2) as Fast Reactor Fuels." Nuclear Engineering and Design, Vol. 239, Issue 10, Pages 1916-1924, October, 2009.

[4] IAEA, "Safeguards Glossary Edition", International Verification Series No.3, 2001.

2.1. Fuel Fabrication Facility (FFF)

2.1.1 FFF MBAs

The MBAs are to be set up into three separate zones. The schematic of three MBAs planned for the FFF are shown in Figure 1. The MBA-1 will include input material storage accounting received from CANDU recycled material (operation mode 1) as well as directly from the fast reactor fuel reprocessing facility (operation mode 2). This will be the storage area for the FFF materials separated by operation mode. The measurement method envisaged for MBA-1 is to weigh the input material at the entry point and then perform item counting depending on the storage method such as sealed containers. The MBA-2 shown in Figure 1 will account for the entire fuel fabrication process. All of the material going into the process must balance with the material going out into product storage. All of the material going into the fuel fabrication process must be measured by weight and the material exiting in the form of fuel assemblies must be counted and plutonium content accounted for. Since both operation modes produce same product and the input materials vary with respect to plutonium/uranium vectors, there is potential for excess depleted uranium, which must be stored. This will be in the same MBA as the product after the fuel fabrication process. The MBA-3 shown in Figure 1 will account for the product storage area. This will consists of strictly counting fuel assemblies and verification processes that all assemblies contain the correct amount of material.

2.1.2 Detection Mechanisms in FFF

In order to provide an achievable probability of detection, detection systems must be implemented in a facility of this type. There will be scales and surveillance mechanisms in the material storage areas. A system of onsite seals can also be implemented for the case of long term storage. This will provide direct proof for the material on site. Due to criticality restrictions, plutonium oxide must be stored in containers of small quantities. While these are item accounted, a high level neutron coincidence counter (HLNC) can be used for verification of materials still being there. This, along with gravimetric measurements, can very accurately quantify the amount of plutonium in MBA-1. In MBA-2, detector systems can be implemented to provide a time scale of operations. This type of process monitoring will provide proof of operation history about the site and possibly detect a diversion between the detection points. This would provide a detection mechanism for a more complicated diversion involving facility misuse. After fuel pellets and rods have been produced, they sometimes are not used in the next process step immediately and are stored instead. For measurement purposes in these smaller storage sections, gravimetric measurements for the fuel pellets (since they are stored in containers) and counting measurements for the fuel rods and assemblies are used. While these measurement types ensure there is material present, it does not quantify the plutonium content at this point. The implementation of HLNC will quantify and ensure that appropriate amount of plutonium material is present in MBA-2. Item counting of fuel rods/assemblies and plutonium 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. The facility will have limited and restricted access. This would provide a detection mechanism for

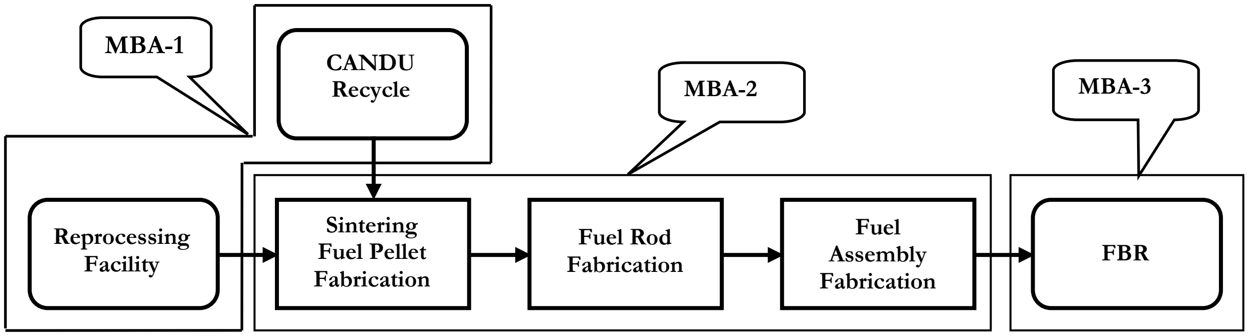

Figure 1: Schematic of Material Balance Areas for Fuel Fabrication Facility

material being simply fetched by personnel walking out of the facility.

This facility will have key measurement points (KMPs) at the boundaries of each MBA and a measurement of plutonium oxide going into the storage, then into the facility and measurements of the product assemblies for plutonium content. Other than measurements at KMPs, measurements can be performed at other points to quantify fuel pellets and fuel rods.

2.1.3 Material Throughputs in FFF

2.1.3.1. Measurement Uncertainties

The plutonium throughput is measured at each point with various types of measurements. Plutonium oxide is measured using HLNC and gravimetric measurements, also item accounted while still in containers. Fuel pellets are gravimetric measured and measured with HLNC. Fuel assemblies and fuel rods are item accounted and scrutinized with HLNC. The standard uncertainties for these types of measurements are shown in Table 1 [5].

Table 1: Plutonium Measurement Uncertainties from ITV-2000

High Level Neutron Coincidence Counting (HLNC) Error		
Material	**Random**	**Systematic**
Pu Oxide Powder	1.0%	0.5%
FBR MOX	2.0%	0.5%
MOX Fuel Rods	2.0%	1.0%
MOX Fuel Assemblies	1.5%	1.0%
Gravimetric Measurement Error		
Pu Oxide Powder	0.5%	0.5%

Since the material has various quantities of plutonium, simple gravimetric measurements on the pellets are not directly used for measuring the plutonium content but for pellet counting. The same problem is at hand with fuel rods and assemblies, simple counting techniques ensure there is material present, but does not quantify the plutonium content. The HLNC can be used for plutonium quantity measurements.

2.1.3.2. Throughputs for two reactor cores

The fuel cycle is for 240 days (8 months). The core will reload one third of its fuel every cycle. Assuming the fuel fabrication is a continuous process this would be equivalent to 2.68642 kg of plutonium per day per core throughput. Depleted uranium involved has such a high significant quantity that any achievable SQ (>10 tons) of would be easily detected. This model also assumes any material from machine process scrap, rejected fuel pins, and rejected fuel rods is put back into the fabrication process and still used. There is no waste in the form of plutonium produced here.

The fuel assemblies come in two plutonium enrichments, 21% for inner core and 28% for outer core. The safeguards are designed around the equilibrium core fuel cycle. The facility was designed for two reactor cores, so the throughputs were doubled making the total plutonium throughput per day as 5.3728 kg. The throughput and according uncertainties for PuO_2 for gravimetric measurements are shown in Table 2.

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[5] H. Aigner, R. Binner, E. Kuhn, "International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Materials", IAEA, 2000.

Table 2: Throughput and Uncertainties of PuO_2 Using Gravimetric Measurements

Unit in kg	**Inner Core**	**Outer Core**	**Radial Blanket**	**Total/ Cycle**	**Oxide/ Year**	**HM/ Year**	**Error**	**Error /Day**	**HM /Day**
PuO_2	564.84	900.48	0.00	1465.32	2228.51	1961.09	13.87	0.04	5.37
UO_2	2168.10	2349.44	0.00	4517.54	6870.43	6045.97	42.75	0.12	16.56
UO_2 Blanket	1773.36	2101.76	11104.80	14979.92	22781.96	20048.13	141.76	0.39	54.93

While gravimetric measurements are very accurate, another method must be used to ensure this material is actually plutonium. This is where HLNC will be effective for PuO_2 and these measurements and according uncertainties are shown in Table 3.

Table 3: Throughput and Uncertainties of PuO_2 Using High Level Neutron Counter (HLNC)

Unit in kg	**Inner Core**	**Outer Core**	**Radial Blanket**	**Total/ Cycle**	**Oxide/ Year**	**HM/ Year**	**Error**	**Error /Day**	**HM /Day**
PuO_2	564.84	900.48	0.00	1465.32	2228.51	1961.09	21.92	0.06	5.37
UO_2	2168.10	2349.44	0.00	4517.54	6870.43	6045.97	67.59	0.19	16.56
UO_2 Blanket	1773.36	2101.76	11104.80	14979.92	22781.96	20048.13	224.14	0.61	54.93

The next stage of measurements is after the material has been mixed with uranium oxide and formed into pellets. These pellets are measured in batches using HLNC for plutonium quantity measurements and the pellet throughput and measurement uncertainties are shown in Table 4.

Table 4: Throughput and Uncertainties of MOX Pellets Using High Level Neutron Counter (HLNC)

Unit in kg	**Inner Core**	**Outer Core**	**Radial Blanket**	**Total/ Cycle**	**Oxide/ Year**	**HM/ Year**	**Error**	**Error /Day**	**HM /Day**
PuO_2	564.84	900.48	0.00	1465.32	2228.51	1961.09	40.43	0.11	5.37
UO_2	2168.10	2349.44	0.00	4517.54	6870.43	6045.97	124.64	0.34	16.56
UO_2 Blanket	1773.36	2101.76	11104.80	14979.92	22781.96	20048.13	413.31	1.13	54.93

The next stage of measurements is when the pellets have been put into fuel rods. While these fuel rods can be item counted for ensuring they are present, HLNC is performed to ensure they are MOX fuel rods and not replaced with something else. The HLNC for plutonium quantity measurements for fuel rod throughput is shown in Table 5.

Table 5: Throughput and Uncertainties of MOX Fuel Rods Using High Level Neutron Counter (HLNC)

Unit in kg	**Inner Core**	**Outer Core**	**Radial Blanket**	**Total/ Cycle**	**Oxide/ Year**	**HM/ Year**	**Error**	**Error /Day**	**HM /Day**
PuO_2	564.84	900.48	0.00	1465.32	2228.51	1961.09	43.85	0.12	5.37
UO_2	2168.10	2349.44	0.00	4517.54	6870.43	6045.97	135.19	0.37	16.56
UO_2 Blanket	1773.36	2101.76	11104.80	14979.92	22781.96	20048.13	448.30	1.23	54.93

The final stage of measurements is when the fuel rods have been put into fuel assemblies. These fuel assemblies can be item counted, but just as in the case of the fuel rods another measurement must be performed to ensure no material is missing. The HLNC is an excellent measurement method in this phase again and the fuel assembly throughput and uncertainties are shown in Table 6.

Table 6: Throughput and Uncertainties of MOX Fuel Rods Using High Level Neutron Counter (HLNC)

Unit in kg	**Inner Core**	**Outer Core**	**Radial Blanket**	**Total/ Cycle**	**Oxide/ Year**	**HM/ Year**	**Error**	**Error /Day**	**HM /Day**
PuO_2	564.84	900.48	0.00	1465.32	2228.51	1961.09	35.35	0.10	5.37
UO_2	2168.10	2349.44	0.00	4517.54	6870.43	6045.97	109.00	0.30	16.56
UO_2 Blanket	1773.36	2101.76	11104.80	14979.92	22781.96	20048.13	361.43	0.99	54.93

To achieve a direct diversion, one would have to get a hold of approximately 1.48 days worth of material. Since it is very unlikely that the adversary would take 100% of the throughput for this amount of time and diversion of a different kind would be more likely. The amount of time needed for the adversary to achieve a diversion buried in the uncertainties at each stage is shown in Table 7. From Table 7, it can be inferred that 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.

Table 7: Time needed to divert 1 SQ of Pu from Fuel Fabrication Facility buried in measurement uncertainty

Stage	**Time**
PuO_2	133.3 days
Fuel Pellets	72.7 days
Fuel Rods	66.7 days
Fuel Assembly	80 days

2.2. Fast Breeder Reactor (FBR)

The FBR analyzed for this report is the Indian proto-type fast breeder reactor (PFBR) design. The reactor core has an inner and outer core with varying plutonium content in its fuel assemblies as well as radial blanket assemblies. Figure 2 shows a schematic of the fuel assembly loading for the reactor. 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 core assemblies will have axial blankets. The isotopics for the fresh and spent assemblies is tabulated in Appendix A. The power output of the reactor is 500 MWe and is refueled every 240 days. Due to the high average burn-up of ~70 GWD/MTHM, the spent fuel must be moved to a nearby location next to the core, while still being cooled by the sodium coolant inside the reactor containment, and allowed to thermally cool for one fuel cycle. If the fuel assemblies were removed before being allowed to cool, the thermal heat from the assembly would damage the fuel transportation equipment. After the spent fuel has been allowed to cool for one fuel cycle before it is transported to a fuel cleaning facility, where the coolant sodium is cleaned off the assembly. Once the cleaning process is complete, the assembly is transported to the fuel storage pool. For an equilibrium cycle 27 inner core, 32 outer core and 42 radial blanket assemblies are replaced in every fuel cycle. For a complete list of FBR characteristics see Appendix B [3].

2.2.1 FBR MBAs

The FBR has direct use nuclear material, un-irradiated plutonium, which requires a MBP of one month [6].The safeguards approach for this reactor has two separate MBAs, one around the reactor containment and the other around the spent fuel cleaning and fuel storage area. There are KMPs at the fresh fuel arrival, spent fuel departure, and between fuel storage / cleaning area and the reactor containment. Figure 3 shows the diagram of the MBAs and the KMPs for the FBR.

Each core operating with an equilibrium fuel cycle requires 647 kg of plutonium in fresh fuel and the spent fuel contain 519 kg of plutonium, both of which must be measured to accuracy such that, three times the cumulative uncertainty in the plutonium measurement is less than 1 SQ (8 kg) of plutonium. A HLNC will be used to measure the total plutonium mass. The uncertainty of the HLNC measurement is 0.2% [5]. To find out whether 1 SQ of plutonium can be diverted from MBA-4, buried within the measurement

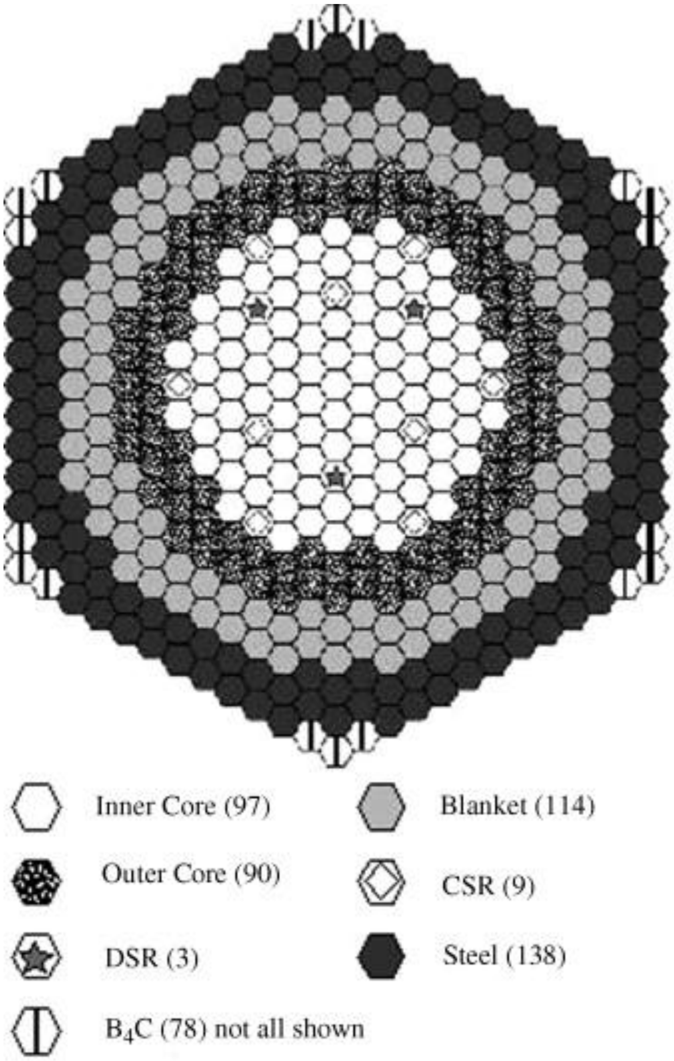

Figure 2: Schematic of the Fuel Assembly loading for the Equilibrium Cycle of the FBR

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[6] Doyle, James E. Nuclear Safeguards, Security and Nonproliferation: Achieving Security with Technology and Policy. Burlington: Butterworth-Heinemann, 2008.

uncertainties, Equations 1 and 2 are employed. Equation 1 is for the material balance in MBA-4 and Equation 2 calculates the net uncertainty associated with the measurements in MBA-4 using the principle of propagation of errors [7].

$$ID = PB - PE + FF_1 + SF_1 - FF_2 - SF_2 \tag{1}$$

$$\sigma_{ID}^2 = \sigma_{PB}^2 + \sigma_{PE}^2 + \sigma_{FF_1}^2 + \sigma_{SF_1}^2 + \sigma_{FF_2}^2 + \sigma_{SF_2}^2 \tag{2}$$

Where, ID, net inventory of plutonium at the end of MBP; PB, the physical inventory at the beginning of MBP; PE, the physical inventory at the end of MBP; FF_1, fresh fuel plutonium inventory entering into MBA-4; FF_2, fresh fuel plutonium inventory leaving from MBA-4 to MBA-2; SF_1, spent fuel plutonium inventory entering into MBA-4 from MBA-2; SF_2, spent fuel plutonium inventory leaving from MBA-4. The respective uncertainties in the plutonium inventory measurements using HLNC are denoted as σ (standard deviation) in Equation 2; the σ value per unit mass of measurement for HLNC being 0.002. Equation 2 can be also written as shown in Equation 3 for easy substitutions.

$$\begin{aligned}\sigma_{ID}^2 &= \left(\frac{\sigma_{PB}}{PB}\right)^2 PB^2 + \left(\frac{\sigma_{PE}}{PE}\right)^2 PE^2 + \left(\frac{\sigma_{FF_1}}{FF_1}\right)^2 FF_1^2 + \left(\frac{\sigma_{SF_1}}{SF_1}\right)^2 SF_1^2 + \left(\frac{\sigma_{FF_2}}{FF_2}\right)^2 FF_2^2 + \left(\frac{\sigma_{SF_2}}{SF_2}\right)^2 SF_2^2 \\ &= 0.002^2\ 647^2 + 0.002^2\ 647^2 + 0.002^2\ 647^2 + 0.002^2\ 519^2 + 0.002^2\ 647^2 + 0.002^2\ 519^2 \\ &= 8.852632\end{aligned} \tag{3}$$

Equation 3 gives $3\sigma_{ID} = 8.93$ kg of plutonium per refuel of core equilibrium cycle. This mass is greater than 8 kg (1 SQ), which means that quantitative measurements are not accurate enough and that item accounting must be used. It is assumed in the above computations that an amount equivalent to plutonium required to refuel an equilibrium cycle of FBR in the form of fresh fuel assemblies is always available in MBA-4.

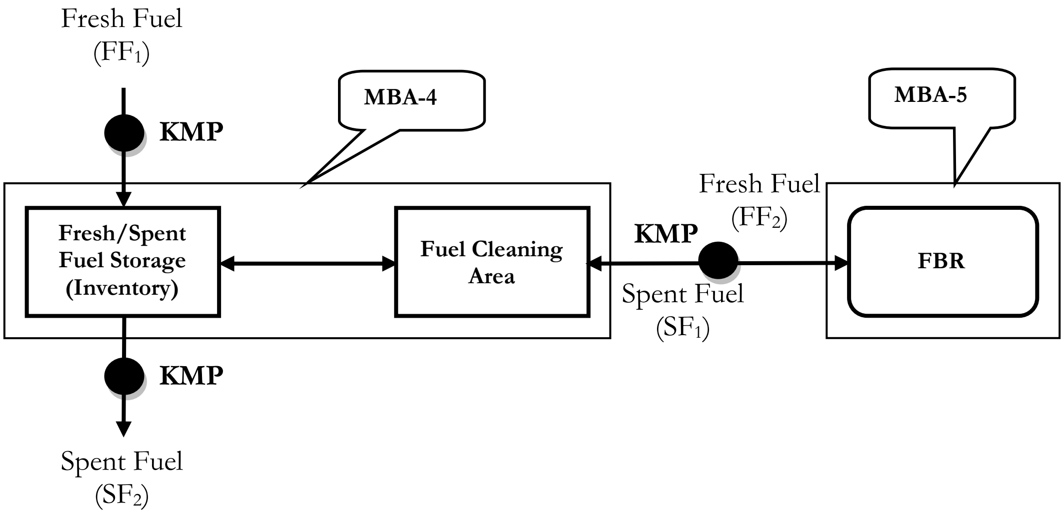

Figure 3: Schematic of the Material Balance Areas for the Fast Breeder Reactor

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[7] Knoll, Glenn F., Radiation detection and measurement, New York: Wiley, 2000.

In order for item accounting to work there must be a method to verify that the fuel assemblies counted at the beginning of the MBP are the same as the ones counted at the end of the MBP. There are some available methods, which can be used to achieve this goal, but the ones proposed in this report are the following: eddy current measurements, serial number readers (employing ultra sound for under sodium measurements) **[8]**, radioactivity measurements, and containment surveillance. Eddy current measurements can be done on the welds of each fuel assembly immediately upon arrival to the reactor facility 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 stolen and replaced. After the fuel assemblies have been used in the reactor core, radioactivity measurements can be done on each fuel assembly to determine their burn-up. Under sodium ultra sound measurements are useful to verify the fuel assemblies are not swapped while inside the core. Containment surveillance will be used around the reactor containment and at each penetration through it to verify that no undeclared nuclear material is transported to or from the reactor core. This will insure that for every fresh fuel assembly that enters the reactor containment dome, one and only one spent fuel assembly will exit it.

2.3. Fast Reactor Fuel Reprocessing Facility (FRFRF)

The reprocessing facility in this FBR fuel cycle employs plutonium uranium extraction (PUREX) process. The PUREX process uses tri-*n*-butyl phosphate (TBP) diluted in a hydrocarbon as the extraction solvent for more efficient extraction of plutonium. This reprocessing cycle operates on a 240 days cycle. Every 240 days a new shipment of spent fuel (one third of the core) is received from the FBR. These are reprocessed into PuO_2 and UO_2 powders within the next 240 days period and then shipped to the fuel fabrication facility for storage until taken up for the fuel pellet fabrication.

The isotopic data content of the spent fuel received by the reprocessing facility is displayed in Table 8. The data is tabulated for each of the three assembly types used in the FBR. The total inventory of the facility was determined using Table 8 and the number of assemblies of each type, inner core region, outer core region, or radial blanket (Table 9), from two reactor cores of the equilibrium cycle for the FBR.

Table 8 Isotopic Mass at Discharge from the FBR

	Isotopic Mass at Discharge (grams/subassembly)		
Assembly	Inner Core	Outer Core	Radial Blanket
^{235}U	91.42	102.93	265.43
^{238}U	59057.00	57606.00	115070.00
^{238}Pu	3.17	1.98	0.08
^{239}Pu	963.54	7433.02	979.29
^{240}Pu	2556.80	3220.00	12.47
^{241}Pu	446.10	579.45	0.12
^{242}Pu	155.94	192.87	0.00

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[8] Beddingfield, D.H., Kawakubo, Y., and Gerhart, J.J., "Under -Sodium Viewing Technology for Improvement of Fast-Reactor Safeguards", LA-UR-09-03685, Proceedings of the 50th INMM (the Institute of Nuclear Materials Management) annual meeting, July 12-16, 2009, Tucson, Arizona, USA.

The plutonium and ^{235}U inventories are displayed in Table 9. Table 9 shows that the total ^{235}U inventory is less than one significant quantity (SQ), 75kg ^{235}U for depleted uranium, while the plutonium inventory has approximately 130 SQs (one SQ is 8kg of plutonium). The safeguards analysis was performed for both the depleted uranium and plutonium. However, due to the low relative value of the depleted uranium, the safeguards approach presented for this facility is only for the plutonium content. The average throughput per day in the reprocessing cycle was calculated by dividing the total amount of plutonium (1037.5 kg) from two FBRs by the length of one reprocessing cycle (240 days). The total plutonium loss for this facility is assumed to be 1%, with half of the plutonium loss being extracted with the fission product solution and the remainder being equally extracted with the uranium separation stream and the low level waste stream.

Table 9 Pu and ^{235}U Inventory

	Pu total g/SA	**^{235}U 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	

2.3.1 FRFRF MBAs

The material considered for the classic safeguards approach is plutonium in spent fuel, separated plutonium solution, and PuO_2. The highest risk category of material is direct use material (PuO_2), which has a detection timeliness goal of one month; therefore the maximum MBP will be one month. Also, the nuclear material being considered is plutonium, so the SQ is 8 kg of plutonium and the uncertainties (one standard deviation) in material unaccounted for calculations over each MBA for the considered MBP must be less than 2.67 kg plutonium. 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. In addition, the MBAs and KMPs were chosen based on diversion pathway analysis. The chosen MBAs are shown in Figure 4.

The first MBA for the FRFRF (MBA-7) is set up around the spent fuel storage, and it employs item accounting of the assemblies and containment surveillance. The goals of the containment and surveillance are to ensure that there is only one path in and out of the facility, monitor movement of fuel assemblies, and monitor movements within the facility. The second one (MBA-8) encompasses the mechanical shearing, de-cladding and fuel dissolution processes, where the fuel is changed from item to bulk form. Here, the lack of accurate front end measurements does not allow for sufficient material accountancy to be employed. Therefore, the containment and surveillance system will be relied upon to prevent and detect diversion of nuclear material. A conservative 25% uncertainty was assumed for the estimation of the plutonium content of the spent fuel declared by the reactor operator, the MBA input. 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 plutonium (limit 100nCi); however plutonium scrap multiplicity counter (PSMC) measurements of the clad hulls are taken to detect the possible diversion of plutonium through the clad hull waste. With the assumed uncertainty 25% and the IAT measurements, the calculated combined uncertainty (one standard deviation) in measurements based on MBA-8 using Equations (4), (5), and (6) is 259.46 kg. This amount is for the entire period of 240 days (one core fuel cycle time), which then is equivalent to 1.08 kg per day and the 3 times the standard deviation will be 3.24 kg/day. That is to avoid diversion of 1 SQ of plutonium the MBP needs to be restricted to 2.5 days.

$$ID = PB - PE \tag{4}$$

$$\sigma_{ID}^2 = \sigma_{PB}^2 + \sigma_{PE}^2 \tag{5}$$

$$\sigma_{ID}^2 = \left(\frac{\sigma_{PB}}{PB}\right)^2 PB^2 + \left(\frac{\sigma_{PE}}{PE}\right)^2 PE^2 = 0.25^2\ 1037.452^2 + 0.007^2\ 1037.452^2 = 67321.9 \tag{6}$$

This is operationally impractical and therefore relies on containment and surveillance to safeguard the material. The goals of containment and surveillance 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 plutonium in the IAT (a specific diversion pathway). In order to obtain a MBP equal to the IAEA timeliness goal for plutonium 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 plutonium conversion. The KMPs is depicted in Figure 4. This MBA analysis is shown in Table 10.

The input stream measurements are from the IAT of the previous MBA. The fission product output stream contains very small amounts of plutonium (assume 0.5%); however the high radioactivity of the fission products will cause nondestructive assay detection methods to be insufficient for plutonium detection. The low level waste output stream contains the waste solution for the uranium and plutonium partitioning, uranium purification, and plutonium purification stages. The low level waste does contain trace amounts of plutonium, but in this case the low radioactivity will allow for effective nondestructive assay methods for the detection of plutonium. A high purity germanium (HPGe) detector is used to obtain a gamma spectrum of

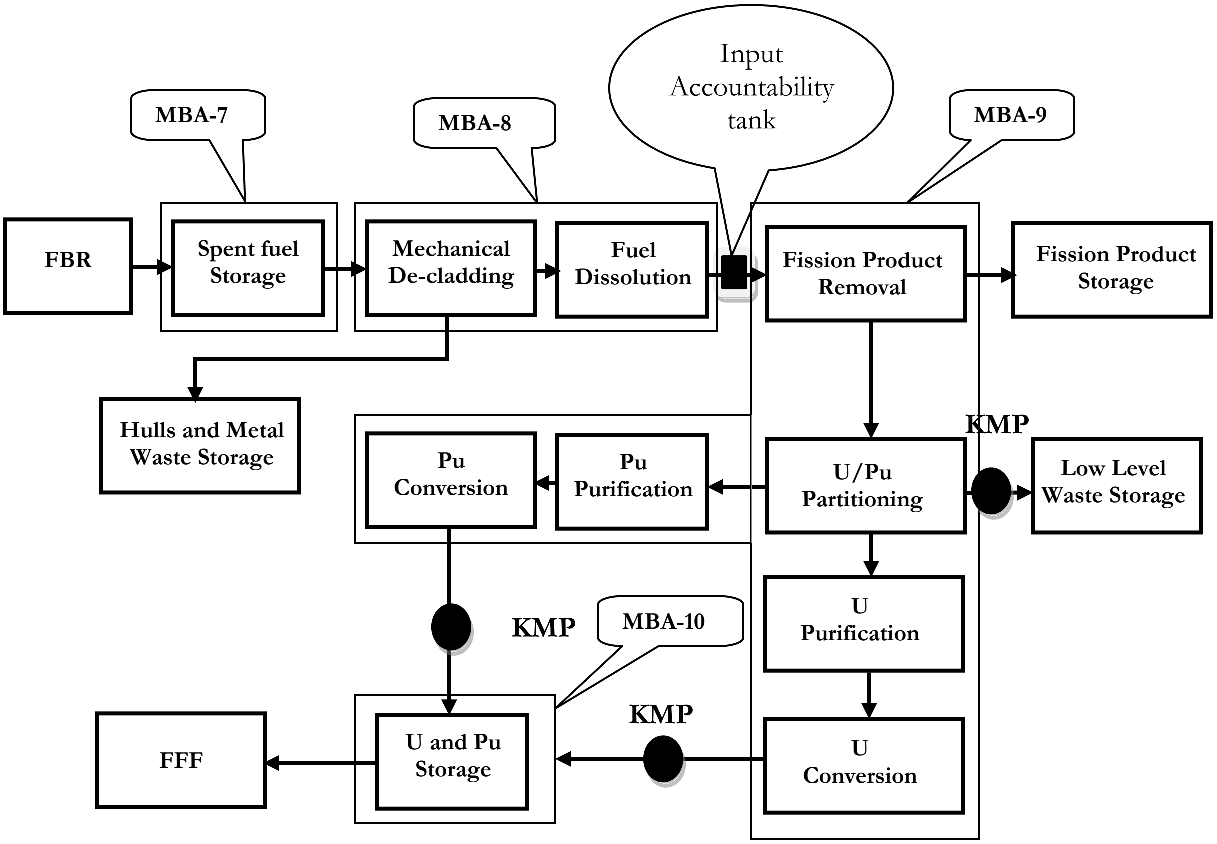

Figure 4: Schematic of the Material Balance Areas for the Fast Reactor Fuel Reprocessing Facility

the low level waste to look for possible diversions of plutonium. 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 in stainless steel containers of specific sizes to prevent criticality. Each stainless steel 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 PuO_2 containers to verify the plutonium content. The HPGe measurements are taken to obtain the gamma spectra for random sampling of the UO_2 containers; the presence of plutonium would be obvious in the gamma spectra. Therefore, the UO_2 container measurements provide a method to detect the diversion of plutonium 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 plutonium. This result implies the safeguards for this MBA could be relaxed, thus less accurate and less expensive detection methods.

Table 10 MBA-9 Analysis

	Measurements	**Uncertainty (%)**	**Pu Throughput (kg/day)**	**Uncertainty (kg Pu / day)**
In - Input Accountability Tank	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

The MBA-10 encompasses the PuO_2 and UO_2 of the product storage. Here, the containers of PuO_2 and UO_2 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 plutonium in the waste for this facility within the MBP.

3. PROLIFERATION RISK ANALYSIS USING PRAETOR

In order to analyze the proliferation resistance 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 twenty two different diversion scenarios were analyzed using PRAETOR. The listing of those 22 diversion scenarios analysed each to divert 1 SQ of plutonium is as follows: (1) PuO_2 powder, (2) outer core MOX pellets, (3) outer core MOX rods and (4) inner core MOX fuel assembly diversions from FFF; (5) fresh radial balnket assembly, (6) fresh inner core fuel assembly and (7) fresh outer core fuel assembly from storage area; (8) spent radial blanket, (9) spent inner core fuel assembly and (10) spent outer core fuel assembly from FBR core; (11) spent radial blanket, (12) spent inner core fuel assembly and (13) spent outer core fuel assembly from spent pool; (14) spent radial blanket after decladding, (15) spent radial blanket after decladding, (16) spent blanket after dissolution, (17) spent fuel after dissolution, (18) dissolved spent blanket after fission product removal, (19) dissolved spent fuel after fission product removal, (20) after U-Pu partitioning of spent blanket and (21) after U-Pu partitioning of spent blanket from FRFRF and finally (22) a one year cooled pressurized water reactor (PWR) spent fuel diversion from core. Values for the spent PWR fuel were obtained from the Lawrence Livermore National Laboratories report on Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air and by running ORIGEN ARP [9]. The PWR case is analysed as a reference case. The PRAETOR analyses presented here assumes two cases for each diversion scenario, that is, with and without IAEA safeguards.

The PRAETOR tool output (Metcalf [1] or Donald Giannangeli's thesis [10]) contains computed U-values running between zero and unity, which represent the relative proliferation resistance (PR) against diversion associated with the SNM present in a facility. Closer to unity represent higher PR. The U-values are broken into 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

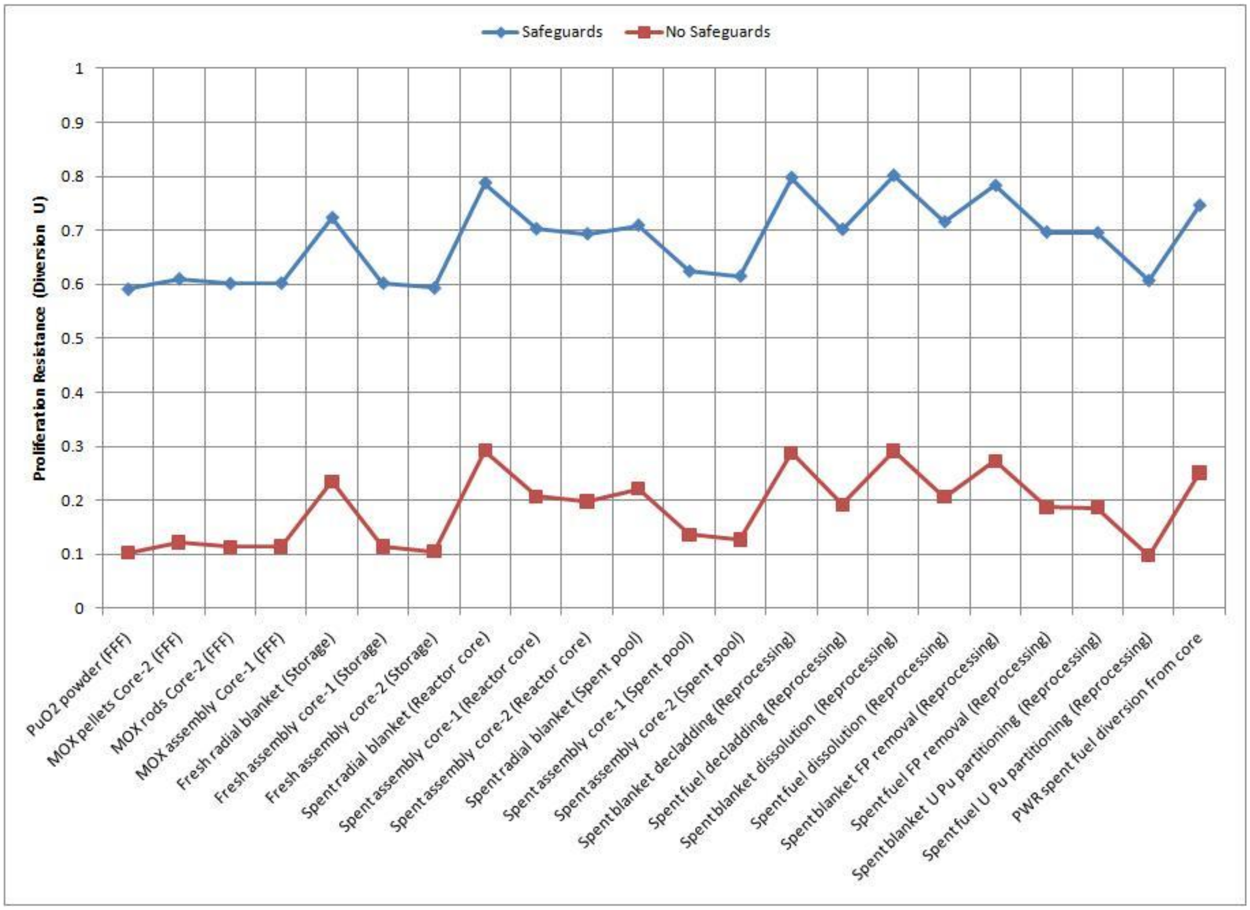

Figure 5: PRAETOR results obtained for PR of the diversion sub-step with different SNM diversion scenarios within the FBRFC facilities with and without safeguards

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[9] Llooyd W. R., Sheaffer M. K., and Sutcliffe W. G., "Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air", Lawrence Livermore National Laboratory, January 31, 1994.

[10] Giannangeli III, Donald D., "Development of the Fundamental Attributes and Inputs for Proliferation Resistance Assessments of Nuclear Fuel Cycles", Thesis, Texas A&M University, 2007.

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 are shown in Figures 5, and 6. Figure 5 depicts the U-values obtained for the diversion sub-step and Figure 6 shows the overall U-value considering four sub-steps leading to a nuclear explosive.

It can be inferred from Figures 5, and 6 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. Also, implementing safeguards had an improved proliferation resistance significantly for every case, as would be expected. 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. Another observation is that the spent blanket assemblies have the largest proliferation resistance of all the assemblies analyzed even marginally higher than that of fresh blanket assemblies. Marginally lower U-value of fresh blanket assemblies compared to the spent blanket assembly may be due to the weighting scheme used in PRAETOR for attributes like radiation field associated with the handling difficulty for proliferation. The proliferation risk for plutonium increased (from the point of view of safeguarding nuclear material, not the adversary) significantly once the fission products were removed, and the area most susceptible to proliferation is the PuO_2 product storage. The PRAETOR results show there need to be safeguards improvements from the fission product removal to the uranium and plutonium partitioning. The decrease in value can be solved by implementing an accurate measurement method for plutonium content after fission product removal, thus changing the MBAs. The HKED provides

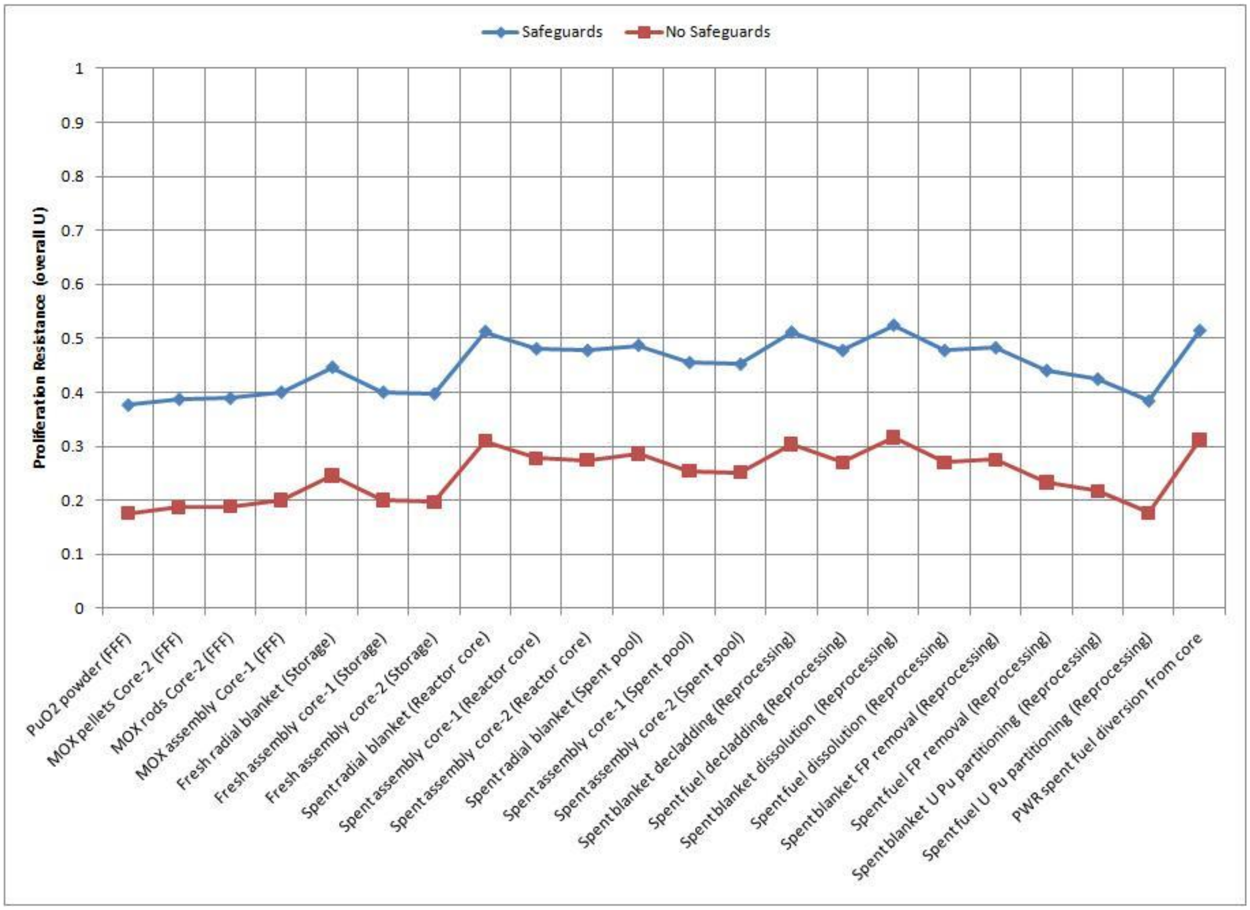

Figure 6: PRAETOR results overall PR for diversion, transportation, transformation and weaponization with SNM diverted from FBRFC facilities with and without safeguards

the first accurate plutonium 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 plutonium content. PRAETOR tool is found to reasonably predict relative PR among FBRFC.

4. 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 and hence intrinsically safe due to the high level of radioactivity associated and heat generation rate, which complicates each of the four stages of proliferation. Now safeguards will be focused to the areas, which have fewer radio-activities and where there is pure plutonium product, which poses a greater proliferation risk. The MBAs for the risk informed safeguards approach are shown below in Figure 7. 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 plutonium content measurement is a titration (TITR) measurement, more accurate than HKED and could be used on the uranium and plutonium nitrate stream. Since there would be an accurate plutonium 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.

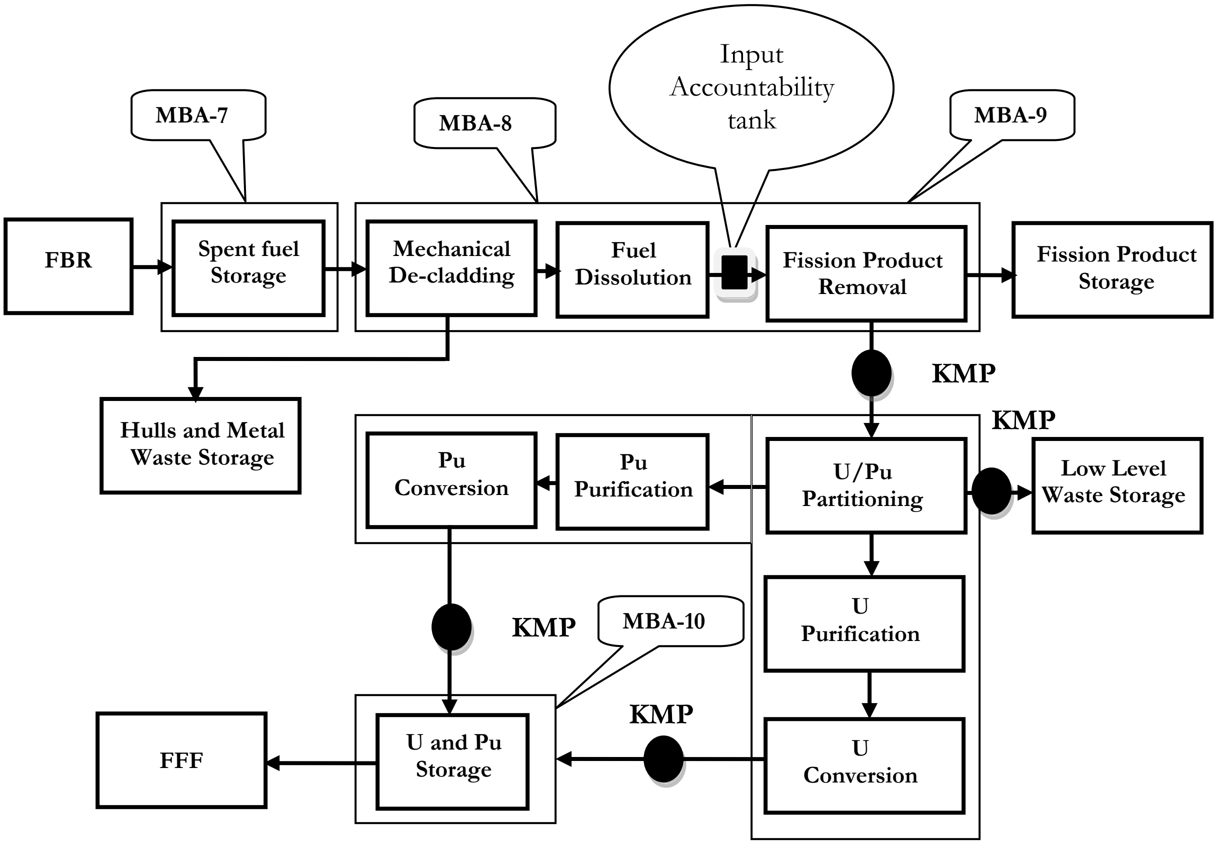

Figure 7: Schematic of MBAs for the FRFRF using PRAETOR Risk Informed Safeguards Approach

5. CONCLUSIONS

An attempt is made to quantify and compare the proliferation resistance of various steps of fast breeder reactor and its fuel cycle facilities. Multi attribute utility analysis methodology is employed to assess the relative proliferation resistance of each step. Special nuclear material inventory and its flow through a typical set of fast breeder reactor fuel cycle facilities are computed in order to facilitate a semi-quantitative proliferation resistance assessment. A computational tool, namely PRAETOR, based on the multi attribute utility analysis methodology is developed to perform proliferation resistance assessment for different special nuclear material diversion or misuse scenarios with the assumption that IAEA safeguards procedures along with additional protocol are in place at these facilities. The PRAETOR analysis carried out for different diversion scenarios of fast breeder reactor fuel cycle facilities could show significant improvements in proliferation resistance 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 of material balance areas and material balance period 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 was developed by modifying the material balance areas, key measurement points and measurement methods for the spent fuel reprocessing facility.

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APPENDIX A: ISOTOPICS FOR THE FRESH AND SPENT ASSEMBLIES

Isotopes	**Core-1**				**Core-2**				**Radial Blanket**	
	Fuel		**Axial Blanket**		**Fuel**		**Axial Blanket**		**Zero Burn-up**	**Discharge (1 GWd/t)**
	Zero Burn-up	**Discharge (80 GWd/t)**	**Zero Burn-up**	**Discharge**	**Zero Burn-up**	**Discharge (70 GWd/t)**	**Zero Burn-up**	**Discharge**		
^{234}U	0.00E+00	3.00E-02	0.00E+00	4.06E-03	0.00E+00	2.16E-02	0.00E+00	2.33E-03	0.00E+00	3.89E-03
^{235}U	8.63E+01	4.18E+01	7.05E+01	4.96E+01	7.89E+01	4.88E+01	7.08E+01	5.42E+01	2.88E+02	2.65E+02
^{236}U	0.00E+00	9.06E+00	0.00E+00	5.19E+00	0.00E+00	6.21E+00	0.00E+00	4.15E+00	0.00E+00	5.41E+00
^{237}Np	0.00E+00	1.12E+01	0.00E+00	1.55E+00	0.00E+00	9.03E+00	0.00E+00	1.21E+00	0.00E+00	2.19E+00
^{238}U	3.49E+04	3.16E+04	2.81E+04	2.75E+04	3.19E+04	2.99E+04	2.86E+04	2.78E+04	1.16E+05	1.15E+05
^{238}Pu	0.00E+00	2.97E+00	0.00E+00	1.97E-01	0.00E+00	1.87E+00	0.00E+00	1.07E-01	0.00E+00	7.65E-02
^{239}Pu	6.27E+03	5.22E+01	0.00E+00	9.11E+02	8.42E+03	6.71E+03	0.00E+00	7.20E+02	0.00E+00	9.79E+02
^{240}Pu	2.25E+03	2.51E+03	0.00E+00	5.09E+01	3.02E+03	3.19E+03	0.00E+00	2.69E+01	0.00E+00	1.25E+01
^{241}Pu	4.83E+02	4.44E+02	0.00E+00	2.53E+00	6.49E+02	5.79E+02	0.00E+00	9.53E-01	0.00E+00	1.22E-01
^{242}Pu	1.25E+02	1.56E+02	0.00E+00	5.89E-02	1.67E+02	1.93E+02	0.00E+00	1.31E-02	0.00E+00	5.73E-04
^{241}Am	0.00E+00	2.84E+01	0.00E+00	1.32E-01	0.00E+00	3.74E+01	0.00E+00	2.33E-02	0.00E+00	1.92E-03
^{242}Am	0.00E+00	8.71E-01	0.00E+00	1.22E-03	0.00E+00	7.66E-01	0.00E+00	1.39E-04	0.00E+00	4.57E-06
Total	4.41E+04	4.00E+04	2.82E+04	2.85E+04	4.42E+04	4.06E+04	2.87E+04	2.86E+04	1.17E+05	1.16E+05

APPENDIX B: FAST BREEDER REACTOR CHARACTERISTICS

Core parameter	Value
Reactor power (MWe)	500
Efficiency (%)	40
Maximum linear hear rating (W/cm)	450
Fuel pin clad O.D./I.D. (cm)	0.66/0.57
Fuel pellet diameter (cm)	0.555
Fuel pins per sub-assembly	217
Fuel pin triangular pitch (cm)	0.825
Assembly pitch (cm)	13.5
Radial blanket pin clad O.D./I.D (cm)	1.433/1.323
Radial blanket pellet diameter (cm)	1.29
Pins per radial blanket sub-assembly	61
Radial blanket pin triangular pitch (cm)	1.553
Fuel assembly sheath thickness & subassembly size (cm)	0.32/13.13
Active core height (cm)	100
Axial blanket height top + bottom (cm)	30 + 30
Radial blanket height (cm)	160
Fuel-Density of fuel (g/cc)	PuO_2-UO_2* (11.0)
Axial/radial blanket material	Dep. UO_2
Fuel clad material	20% CW D9 steel
Core Pu enrichments, Inner Core and Outer Core (%)	20.7/27.7
Plutonium isotope ratios in fuel: ^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu (%)	68.8/24.6/5.3/1.3
Plutonium inventory (tons)	1.99
Primary coolant	Liquid sodium
Primary inlet/outlet temperature (°C)	397/547
Fuel average temperature (°C)	1289
Fuel Cycle (Effective full power days)	180