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TOWARDS SAFEGUARDING THE FAST BREEDER REACTOR FUEL CYCLE

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EXECUTIVE SUMMARY

With increasing international interest in closed fuel cycles, it is highly probable that the technology for a closed fuel cycle will spread as the demand for it increases. However, there is another option open to countries that wish to have a closed fuel cycle but find construction of reprocessing and/or fuel fabrication facilities economically, technologically, or politically unsound. Such countries then be forced to have their spent thermal reactor fuel reprocessed externally in facilities run by other nations, and potentially fabricated into fuel as well. This carries several benefits for both the client nation and the nation providing the service.

The reduction of the number of reprocessing and fuel fabrication facilities in the world reduces overall risk of proliferation due to fewer sites to be monitored by the IAEA and fewer states having direct access to large-scale reprocessing facilities. However, there would still be risks associated with transport of fresh fuel containing plutonium (Pu) across the border of countries. From an economical standpoint facilities can be run at or near their capacity, ensuring for the processing nation that their financial investment in the facility is being maximized. For the client, delays associated with learning to operate a new facility with potentially inexperienced personnel are avoided, and in general fewer delays may be expected since the processing nation is under contract to provide fuel in a timely manner and will risk losing business if unable to keep their schedule. This is a system that already has precedent; Japan shipped spent fuel to France and the United Kingdom through 2001 and the United Arab Emirates signed a nuclear agreement that included outsourcing most of its fuel cycle.

The objective of this report is to analyze a closed fuel cycle portion in equilibrium, determine the facility most sensitive to diversion, and develop a safeguards approach for said facility. Particular attention will be paid to instrumentation as a method of reducing the uncertainties associated with safeguards measurements. Future reports should develop approaches for other facilities, to assist in developing effective and economical methods of enacting safeguards.

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1. INTRODUCTION

1.1. Motivation for this Study

The rising need for power for the world's growing population has increased the demand for reliable energy production. Nuclear energy has been a major provider of energy around the world, and with the proposed Generation IV designs seems poised to increase its output in the future. In particular, interest in fast breeder reactor (FBR) cycles has increased, with programs underway in India, Russia, France, and China[1].

India has actively pursued fast breeder reactor technology since 1954 as part of its three-stage nuclear program. The Fast Breeder Test Reactor (FBTR), a 40MWth research reactor achieved criticality in 1985, with a 500 Megawatt electric (MWe) Prototype Fast Breeder Reactor (PFBR) expected to come online in 2013. China has maintained consistent interest in FBRs and the China Experimental Fast Reactor (CEFR) began producing power in 2011. Current research is being conducted in the field of thorium molten-salt thermal breeder reactor technology. France, while having shut down three fast reactors previously, retains an interest in the technology. In 2010, the French government approved funding to complete the design of the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID), a 600 MWe Gen IV design. Construction is scheduled to begin in 2017. Russia's 600MWe BN-600 has been in operation since 1980, and a new 880MWe reactor based on the BN-600, the BN-800, is under construction with an estimated completion date of 2014[1].

1.2. Method

The specific steps in this report toward accomplishing this objective are to:

- Construct a material flow diagram for a FBR fuel cycle. Conceptually this cycle begins at the Fast Breeder Reactor, continues with the recovering of plutonium in a spent fuel reprocessing facility, which then is assembled into fresh MOX fuel assemblies in a fuel fabrication plant. This fuel is then shipped back to the FBR. A single equilibrium cycle portion is considered.
- Examine each facility and determine the most sensitive facility from a safeguards perspective, taking into account the flow of Pu through the facility, the forms in which the Pu is present in the processes in the facility, potential for holdup, and if the material is self-protecting.
- Develop a safeguards approach for the sensitive facility in the cycle, with regard to design verification, inspections, information and data to be reported by the operator, containment and surveillance, and nuclear material accountancy.

[1] World Nuclear Association (WNA), *Fast Reactor Information Library*, *http://www.world-nuclear.org/info/Current-and-Future-Generation/Fast-Neutron-Reactors*, *2013*

2. FBR FUEL CYCLE CHARACTERISTICS

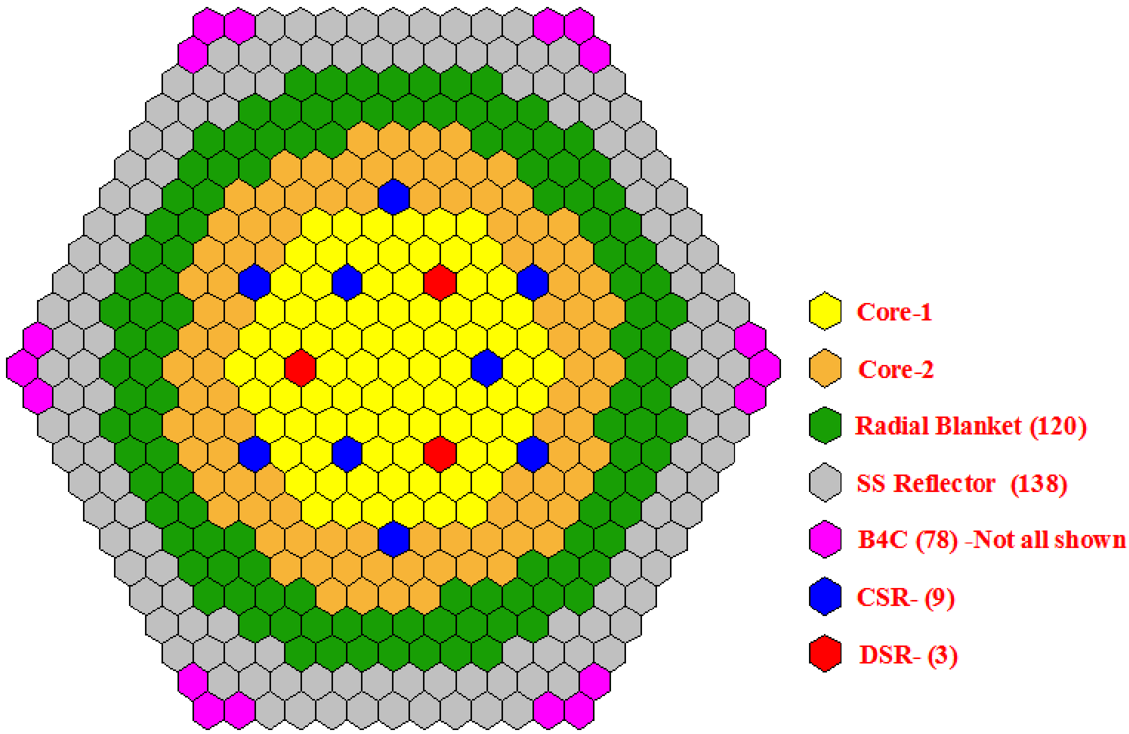

Fig. 1. Core configuration for 500MWe PFBR-style reactor.[2]

An equilibrium cycle is assumed. The design of the reactor follows the 500 MWe design (Fig. 1) of the Indian PFBR (Prototype Fast Breeder Reactor).[2] There are two types of assemblies in the core, 90 inner assemblies and 91 outer. The core fuel consists of PuO_2-UO_2 (MOX) powder mixed to concentrations of 21% and 28% for the inner and outer core, respectively. Each core assembly includes an axial blanket above and below the active fuel length; all Pu calculations for core assemblies include the axial blanket. There are 90 inner core assemblies and 91 outer. The initial core load is 2040 kilograms of plutonium. A single core fuel cycle lasts 180 full power days, at the end of which the core fuel assemblies are shuffled and 1/3 of the core removed. Each 1/3 of the core goes through 3 cycles before being removed, staying in the reactor a total of 540 fpd.

Outside the core there are 120 axial blanket assemblies consisting of depleted UO_2. The blanket assemblies are irradiated over 1000 calendar days before being reprocessed. This means the blankets stay in the core over approximately 5.5 cycles. An equilibrium core load contains 500 kg of Pu, including the axial blankets for that period.

After removal from the core, the core assemblies are moved to a position on the outer edge of the blanket, in storage rods to cool for 240 calendar days before being sent to the reprocessing facility. The reprocessing facility is assumed to maintain a concentration of 7 grams per liter in the process solution to

[2] "Development, Fabrication and Characterization of Fuels for Indian Fast Reactor Programme", *A. Kumar, International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13), Paris, March 4-7, 2013*

avoid accidental criticality. In order to account for time closed for inspections, cleaning, and maintenance it is assumed that the reprocessing plant operates for 250 days per year. As such, approximately 4 kg of plutonium will be processed by the facility per day. The fuel fabrication facility follows the same schedule.

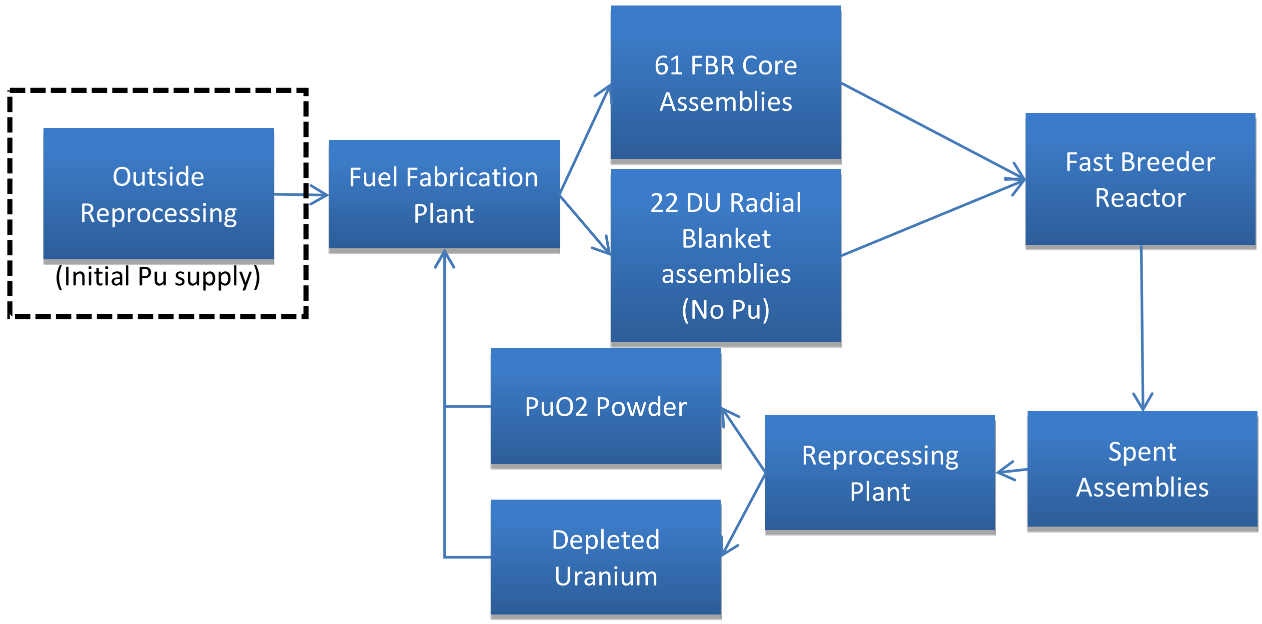

Fig. 2. Material flow for the cycle.

3. Determination of Critical Facility

In order to determine the facility that poses the greatest proliferation risk, the ability to address the potential vulnerabilities in the processes of the cycle must be determined. Of particular interest are the accuracy and precision of the measuring equipment, the quantity of Pu present in the process, the type of accountancy being employed, the potential for holdup (materials to be deposited in and around equipment during operation), and whether the material is self-protecting at that stage.

3.1. Fast Breeder Reactor Processes and Vulnerabilities

Fresh fuel assemblies, which contain direct use material in the form of Pu, arrive and are put in a storage area. The assemblies remain here until they are needed to replace spent assemblies in the core. Assemblies are moved from storage to the reactor vessel. Every 180 full power days, the assemblies are shuffled[3], and 1/3 of the core is removed and stored within the reactor vessel for initial cooling. During this time, the assemblies are under liquid sodium and are not visible. At the end of the 540 full power days, the assemblies are considered irradiated direct use material. After cooling for 240 calendar days, the

[3] "Approach to equilibrium fuelling scheme of 500MWe PFBR based on 3-D core burnup modeling", *K. Devan, A. Riyas, P. Mohanakrishnan, Nuclear Engineering and Design 241, pp. 1596-1605 2011*

spent assemblies are cleaned, inspected, and moved to spent fuel storage under water, where they are kept until transported to the reprocessing facility.

The form of the plutonium in this facility is a mixed oxide of UO_2 and PuO_2, contained in fuel assemblies that allow for item accountancy. As fresh fuel, it is considered a direct use material. Core characteristics for a 600MWe reactor were extrapolated from an existing 500MWe design. Using these characteristics, a fresh inner core assembly would contain approximately 10 kg of plutonium while a fresh outer core assembly would contain 13 kg. Therefore, diversion of even a single assembly would constitute a Significant Quantity[4] (SQ) of plutonium.

Detection of diversion of a fresh assembly before it is loaded into the reactor core depends on the location of the assembly in the facility when the diversion takes place. While in transport to any portion of the facility, cameras and radiation monitors can be utilized to ensure the material is not diverted. The most attractive location for diversion would be the fresh fuel storage. Item accountancy would track each assembly in the inventory via serial number. Cameras, radiation monitoring systems, and seals could provide near real-time accountancy. The sodium of the core would obscure visual monitoring devices such as cameras; however radiation detectors and ultrasound techniques would still be able to track assembly movement. Ultrasound can be employed to read serial numbers under sodium. While cooling, the assembly presents a technical challenge in transport due to its self-protecting nature. Although decay power drops sharply (from 463.5 kW to 34.7 kW in the first two days of cooling[5]) initially, the decay is still great enough throughout the cooling period to make transport hazardous. In addition, the fission products in the assembly would have to be separated in order to obtain useable material. The last stage an assembly could be diverted from within the reactor is the underwater spent fuel storage. Transport is less problematic at this stage, but water transparency allows for easy reading of serial numbers and visual monitoring of the assemblies.

In order to overcome item accountancy and spoof radiation monitors, it is possible for assemblies to be replaced with substitute materials. In this case, cameras or ultrasound would provide an avenue for detection. Additionally, gamma measurements of the assemblies can be taken to verify content.

There exists the potential for removal of pins from fresh assemblies, either from multiple assemblies in a short time (abrupt diversion scenario) or from a few assemblies over time (protracted diversion scenario). An inner assembly pin would contain 45 grams of Pu, while an outer assembly pin would contain 60 grams. Thus, at least 135 pins worth of material is needed to achieve 8 kg of Pu (one SQ). Each core assembly would contain 217 pins total.

Item accountancy would not track pin removal. However, the containment and surveillance system above would detect undocumented access to assemblies in fresh fuel storage, and radiation monitors would detect any material being moved in the facility. Specialized equipment would be needed to access and remove pins in the core, and would risk detection by ultrasound or radiation monitors. Removing pins from spent assemblies within the reactor facility itself would pose a significant obstacle, and the highly active pins would emit amounts of gamma and neutron radiation that would require significant shielding to obscure from detectors.

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[4] Defined as "The approximate amount of nuclear material for which the possibility of building a nuclear device cannot be excluded." International Atomic Energy Agency*, IAEA Safeguards Glossary 2001 Edition*, http://www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/PDF/NVS3_prn.pdf, 2001

[5] "Storage and Management of Spent Fuel of Fast Reactors in India," 11. S.C. Chetal, Intl Conf for Spent Fuel Management from Nuclear Power Plants, 31st May to 4th June, Vienna, 2010

While in the core, it would be possible to insert undeclared breeder material. As such material would be depleted uranium; detection via neutron detectors would not be very difficult at insertion. Further, the Pu-239 bred by the process would emit enough neutrons to have a reasonable chance of detection. Ultrasound could also potentially be employed to detect undocumented under-sodium[6] activity.

Fresh radial blanket pins consist of depleted uranium approximately 0.2% ^{235}U content. The amount of material needed to achieve 75 kg of ^{235}U (one SQ for low-enriched uranium) assuming an enrichment of 0.2% is 37.500 tons, which makes a diversion of this material highly impractical. Every 1000 calendar days, the axial blanket as a whole is removed for reprocessing. These assemblies are subject to item accountancy, and similar containment and surveillance methods applied to fresh core fuel assemblies can be applied to irradiated blanket assemblies. Table 1 displays the relative attractiveness of the materials in an FBR.

Table 1. Relative attractiveness for materials in the Fast Breeder Reactor.

Material in	Fresh Fuel Storage	Core	Cooling	Spent Fuel Storage
Assembly/Pin	Attractive	Possible	Unattractive	Unattractive
Blanket Pin	Unattractive	Unattractive	-	Attractive

3.2. Reprocessing Plant Processes and Vulnerabilities

Spent fuel assemblies arrive from the reactor roughly every 180 calendar days and are contained in spent fuel storage. The spent fuel is moved to shearing by laser process, where the assemblies are chopped into 1-2 cm pieces and sent to the dissolution stage to be dissolved in nitric acid. After dissolution, the undissolved cladding materials (hulls) are discarded with a very small amount (assumed to be 0.1%) of undissolved Pu attached to the hulls being discarded as well. When the material reaches the input accountability tank (IAT), the Pu content of the material is measured. This is the first point at which the estimates of Pu content based on reactor physics can be verified. The solution is then sent for fission product removal. A small portion of undissolved Pu remains in the fission product waste stream, approximately 0.5%, and the high activity of this stream makes verifying the quantity of Pu difficult via Non-Destructive Analysis (NDA), allowing a potential pathway for diversion. The U + Pu product stream is then put through a partitioning process to separate the uranium from the plutonium, and both the U and Pu streams undergo purification. The waste from separation and purification processes contains a small amount of Pu (again estimated at 0.5%) which exits from all streams. Once purified, both U and Pu streams are converted into oxide powder. As a measure against allowing too much material to be concentrated and cause a criticality accident, the powder is stored in canisters. From this stage, the canisters are then moved to storage in preparation for shipping to the fuel fabrication plant.

The spent fuel storage facility of the reprocessing plant maintains the same item form as in the storage facility of the reactor. However, the calculations made by reactor physicists to quantitatively estimate the

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

amount of Pu in each assembly have a large uncertainty associated with them (25% is a conservative estimate) that renders material accountancy unwieldy at this stage. Emphasis is instead placed on containment and surveillance to ensure that no material is diverted.

Once through the chopper, item accountancy gives way to bulk accountancy. Surveillance is maintained. Theoretically, the chopped pieces could be diverted via modifying the trays dumping the pieces into the dissolver. This could be addressed by the continued surveillance of camera and radiation monitors and design verification.

In the dissolver, the material is in aqueous form. As the fission products remain, it is still self-protecting. Design verification would ensure that there is only one stream from the dissolver to the IAT.

Precipitation in the IAT can pose both a safeguards risk due to material being unaccounted for as holdup and a safety risk due to criticality concerns. Monitoring the flow out of this tank and ensuring that this matches the measurements made in the tank will reduce these risks.

Once the fission products have been separated from the U + Pu mix, the material shifts from irradiated direct use to direct use and is no longer self protecting. Careful bulk accountancy using precise measurements is necessary to reduce uncertainties that could mask a prolonged diversion.

There are several waste streams in this facility, which account for an estimated total loss of 1.1% of Pu: 0.1% with the hulls, 0.5% with the fission products, 0.25% with the low level waste from the U/Pu partitioning, and 0.25% remaining with the U after separation. There is potential to divert Pu through these streams, requiring monitoring of both volume and content. Gamma and neutron detectors can be used to verify the hulls and low level waste content, but the fission products present a challenge due to their high activity.

The PuO_2 powder is stored in canisters. This allows for item accountancy, provided one trusts seals, radiation monitors, and cameras as elements that provide containment and surveillance. Measurements to verify the content and quantity of material in each container can deter attempts at prolonged diversion of powder. Table 2 provides the relative attractiveness of materials in the reprocessing plan

Table 2. Attractiveness of materials in the reprocessing plant.

Material inside	Spent Storage	Dissolution/IAT	FP Removal	Pu Purification	Oxide Storage
Assembly/Canister	Unattractive	-	-	-	Attractive
Solution/Oxide	-	Unattractive	Possible	Attractive	-

3.3. Fuel Fabrication Plant Processes and Vulnerabilities

After the PuO_2 canisters arrive from the reprocessing plant, they are stored until the Plutonium dioxide can be mixed with uranium oxide powder. It is assumed that the supply of depleted UO_2 is not constrained. The MOX powder is mixed to two concentrations of Pu, 21% and 28%. It is assumed that there is no waste in the process and all Pu is used. The powder is compacted into a pellet shape, sintered at high temperature, and the center hole ground out of the pellet. The pellets are inspected, and rejects sent for thermal processing to be made into oxide for the fabrication of new pellets. The stack is assembled, consisting of non-fuel pin elements such as the spring and axial blanket materials. Once the stack is confirmed to be satisfactory, the pellets are loaded into the stack and the pin is welded shut. The pins are then combined into fuel assemblies, with 217 pins per assembly. At this point bulk accountancy ends, and item accountancy begins. As with previous steps in the process, fuel assemblies are inspected and rejects utilized in making new fuel. The pins are removed and decladded, and the Pu content reused. The finished assemblies are placed into storage until ready to be shipped to the reactor.

While in storage, PuO_2 powder could be diverted from the canisters. Similar safeguards methods used in the storage of PuO_2 at the reprocessing plant can be employed here. Item accountancy is in effect. Once the material is removed, accountancy switches back to bulk. Care must be taken to avoid or assess small quantities of PuO_2 left behind in canisters so that this does not affect the material unaccounted for (MUF) in this facility.

While mixing the PuO_2 with UO_2, mixing lower concentrations than planned could allow the excess Pu to be diverted. Element concentration sampling would verify the concentration of the powder in the case of an abrupt diversion using this method. While slow, sending regular samples for destructive analysis would provide the precision needed.

Rejects from the compacting process could be inaccurately reported as a method for proliferation. This risk can be decreased by mass measurements to verify the declared quantity and NDA measurements to verify the material is not a substitute. Material can be accumulated in the equipment and process piping, which is is known as holdup. Holdup should be carefully assayed to ensure it does not faction into the MUF figure.

During stack making, pins could be incompletely filled or filled with substitute material. NDA of the pin would assist in detecting missing or substituted material. Rejected stacks should be checked via NDA to ensure that no undocumented Pu is present. Again, holdup is a concern that must be accounted for.

In the fresh fuel assembly storage portion of the facility, item accounting can be used. As previously noted, diversion of a single assembly of either Pu concentration would constitute more than one SQ of material. Accepted assemblies are given a serial number to assist in accounting, and full containment and surveillance is in effect. Table 3 contains the breakdown of relative materials attractiveness in the facility.

Table 3. Attractiveness of materials in the fuel fabrication facility.

Material inside	Oxide Storage	Pellet Manufacturing	Stack Assembly	Fresh Fuel Storage
Assembly/Pin	-	-	Attractive	Attractive
PuO_2/MOX	Attractive	Attractive	Attractive	-
UO_2	Unattractive	Unattractive	Unattractive	Unattractive

3.4. Analysis of Vulnerabilities

Contrasting the process vulnerabilities between different facilities begins with previously noted basic trends. Throughout the entire FBR, the material is always in item form, which eliminates the allowance of MUF. In the case of item accounting, missing items are always of interest. Protracted diversions are addressed by the containment and surveillance systems. Unirradiated direct use material is present only in the fresh assemblies and bred axial assemblies, while material in the core is challenging to access and spent fuel contains fission products that complicate transportation and needs to be separated before the plutonium can be diverted.

In the case of the reprocessing plant, the high uncertainty of the actual Pu content vs. theoretical renders material accountancy difficult. This difficulty is offset by the emphasis placed on continuity of knowledge and surveillance, along with the item form of the material. The switch to bulk accountancy during the process can be addressed by highly precise measurements using DA techniques. Holdup poses a safety risk as well as proliferation risk, given the high concentration of Pu compared to thermal reprocessing facilities.

For the fuel fabrication facility, because of the lack of fission products, there is no point where the material is self-protecting, which increases its attractiveness throughout the facility. Additionally, the majority of the processes in this facility involve Pu in bulk form, which increases the overall uncertainty. Gravimetric measurements and NDA techniques have overall lower precision than DA techniques used in the processing plant. Additionally, the flow in the reprocessing plant is in a single direction (unless the plant recycles its organic solution), while the fuel fabrication facility must allow for rejected MOX, pellets, and rods to be recycled to minimize loss of Pu. Holdup is a factor in both cases.

From this comparison, it appears that the fuel fabrication facility will be of greatest concern, due to sharing many issues with the reprocessing facility while possessing unique traits that make it more vulnerable. To confirm this, the amount of uncertainty in the process area for each facility (from the accountancy tank up to U/Pu storage for reprocessing, pellet fabrication to assembly storage for fabrication) was evaluated using the methods in Section 4.2 below. For the reprocessing plant, the process area had a total uncertainty of total of 0.058 kg of Pu per day, while the fuel fabrication plant process area had an uncertainty of 0.097 kg of Pu per day. This differs from a typical (non-MOX) thermal fuel cycle, in which the most sensitive facility is the reprocessing plant because it is the only facility to have separated plutonium in its process streams.

4. Development of Safeguards Approach

4.1. Design Verification

It is assumed for the purposes of this report that safeguards are being designed into the facility from the beginning. This principle of "safeguards by design" (SBD) is a topic of ongoing research, including in thorium-based fuel cycles[7] and many suggested techniques of SBD such as integrated radiation portal monitors are implemented in this approach. In the field of design verification, SBD allows for the inspecting agency to quickly and efficiently verify that the plant has not deviated from its original design by virtue of not requiring extensive modifications to be made to complement safeguards. The value of this practice increases with the size of the facility. As the process becomes larger scale and more equipment is needed to handle the increase, the ability to carry out design verification becomes much more difficult.[8]

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[7] "Safeguards-by-Design Concepts for Thorium-based Fuel Fabrication Facilities," *S. Gangotra, R. B. Grover, K.L. Ramakumar, et al., Journal of Nuclear Materials Management, Vol. XLI No. 1, Fall 2012*

[8] "Lessons Learned in International Safeguards—Implementation of Safeguards at the Rokkasho Reprocessing Plant," *M.H. Ehinger, S. J. Johnson, Oak Ridge Natl Laboratory, ORNL/TM-2010/23, December 2009*

For the purposes of this report, the cycle contains a single reactor, reprocessing facility, and fuel fabrication facility all contained within a single complex. Thus, the hub-and-spoke model[9] cannot be implemented in this instance. In addition, it is unlikely that its size will pose a large problem for design verification. However, the possibility of difficult-to-access areas that may need to be inspected does potentially pose a challenge, and would most efficiently be addressed by designing with safeguards in mind.

4.2. Nuclear Material Accountancy

Nuclear Material Accountancy (NMA) is the principal method of verification of a facility's inventory. The establishment of a NMA system gives the inspecting agency a method of verifying the operator's accounting information. Typically, a facility is divided into one or more Material Balance Areas (MBAs). The size of an MBA is determined by the accuracy of the measurement systems in the area. Inside an MBA, Inventory Key Measurement Points (IKMPs) may be established to track the inventory within an MBA, while Flow Key Measurement Points (FKMPs) will track material as it transitions between each MBA.

It is useful to divide a fuel fabrication facility into three MBAs, as seen in Figure 3. MBA 1 consists of the PuO_2 powder storage, MBA 2 covers the process area, and MBA 3 is the finished assembly storage. This takes account of the item nature of the storage areas, and the bulk nature of the process area. By keeping the storage areas separate from the processes, the MUF from the process area is not included in either of the storage areas. As stated above, FKMPs are established between each MBA, as well as where the depleted UO_2 enters the process area. Between each step in the fabrication process, an IKMP is established to track the progress and losses of the material through MBA 2. Further MBA could be established around process steps that contain commercially sensitive information upon operator request.

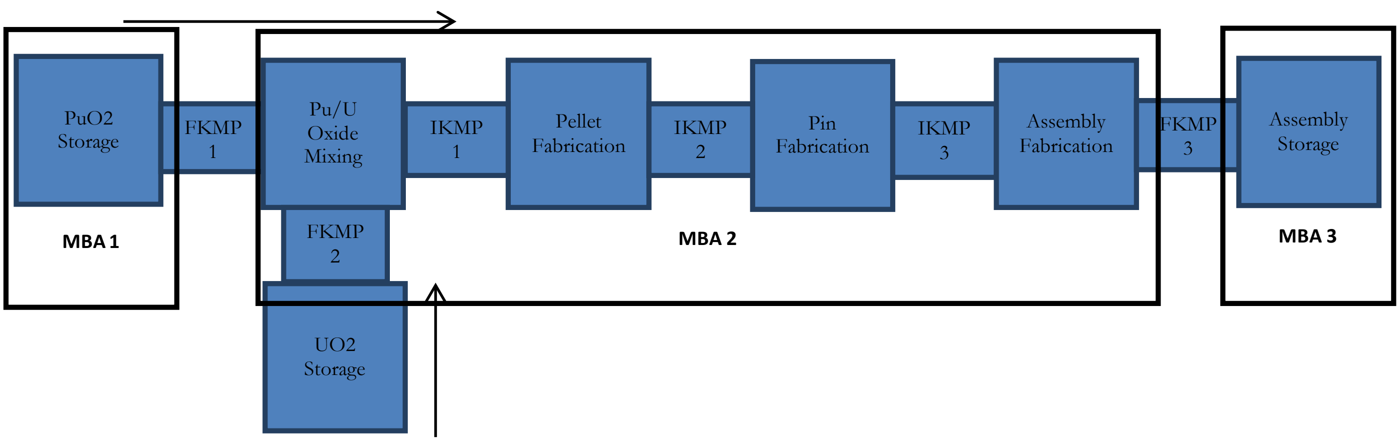

Fig. 3: MBA plan for the fuel fabrication facility.

[9] "Comparison for thorium fuel cycle facilities of two different capacities for implementation of safeguards," *S. Gangotra, R.B. Grover, K.L. Ramakumar, Nuclear Engineering and Design, Vol. 262 pp. 535 – 543, 2013*

In MBA 1, PuO_2 powder is stored in canisters to prevent accidental criticality. The PuO_2 powder is shipped in from the reprocessing plant, stored, and then shipped out to MBA 2 as needed. Each canister has a unique ID, which allows for item tracking and accountancy. The balance equation, for any MBA, is:

$$ID = PB - PE + X - Y \qquad (1)$$

Here *ID* is the net change in inventory, *PB* is the starting inventory, *PE* is the ending inventory, X is the amount of material received during the MBP, and *Y* is the amount of materials leaving the MBA during the MBP. For the case of MBA 1, there is no uncertainty in this value: it should always equal zero, which indicates that there is no unexplained missing or gained plutonium inventory. In order to meet the IAEA minimum standard criteria of the ability to detect the diversion of 1 SQ of materials within a month, the maximum MBP for this area is 30 days.

MBA 2 is where most of the facility processes occur. PuO_2 is received from MBA 1, and finished fuel assemblies are sent to MBA 3. Note that depleted UO_2 is received into this MBA for the purposes of mixing MOX fuel. While this material goes through a Key Measurement Point (KMP) in order to verify its composition, its uncertainties were not calculated due to the large quantity of material needed to obtain a single SQ.

To calculate the MUF in MBA 2, the uncertainties of the variables in Equation 1 are found and via propagation of error, the total uncertainty for the MBA can be calculated (Equation 2):

$$\sigma_{total}^2 = \sigma_{PB}^2 + \sigma_{PE}^2 + \sigma_X^2 + \sigma_Y^2 + \sigma_{hold}^2$$

(2)

For the sake of simplicity, it is assumed that in MBA 2 the amount of material at the beginning and end of each MBP is zero, which sets the first two terms of Eq. 2 to zero. This means that all uncertainty comes from the systems measuring material entering, leaving, and holdup.

For both entry and exit points, High Level Neutron Coincidence (HLNC) counting is utilized, with gravimetric measurements used in tandem at the entry point. This allows for quick movement of the material through the processes. The holdup is assumed to be 1% of the total throughput, and is assayed by the proposed Glove box Unattended Assay and Monitoring system, which is in development for the planned J-MOX facility in Japan. This system has an error of 8%.[10] The International Target Values (ITVs) for uncertainties for these systems, determined by the IAEA, are given in Table 4.[11]

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[10] "Safeguards Approaches: MOX fuel Fabrication Plants" *J.B. Marlowe, M. T. Swinhoe, H. O. Menlove, Next Generation Safeguards Initiative Human Capital Development Workshop, Santa Fe and Los Alamos, N.M., August 10-13 2009*

[11] "International Target Values 2010 for Measuring Uncertainties in Safeguarding Nuclear Materials", K. Zhoa, M. Penkin, C. Norman, et al, International Atomic Energy Agency, Vienna, November, 2010

Table 4. The uncertainties associated with measurement systems in MBA 2.

Method	Material	Random Error (%)	Systematic Error (%)	ITV (%)
HLNC[1]	Pu Oxide	1	0.5	1.1
	MOX (>10% Pu)	2	0.5	2.1
	MOX Pins	2	1	2.2
	FBR Assemblies	2	1	2.2
Gravimetric[1]	Pu Oxide	0.05	0.05	0.07

The total uncertainty for the entry point FKMP 1 (HLNC and GRAV measurements) is 1.12%, while the exiting point FKMP3 is 2.2%. The quantity of Pu being received Equation 2 can thus be expressed in the form of Equations 3 and 4:

$$\sigma_{total}^2 = \frac{\sigma_X^2}{X}X + \frac{\sigma_Y^2}{Y}Y + \frac{\sigma_{hold}^2}{hold}hold \quad (3)$$

$$\sigma_{total}^2 = 0.0112^2 * 3.95^2 + 0.022^2 * 3.91^2 + 0.08^2 * 0.0395^2 \quad (4)$$

Equation 4 yields a value of 0.0968 kg of plutonium per day for σ_{total}. Taking the value of 3σ to include the maximum statistically significant amount of unaccounted material gives 0.29 kg of materials that can be unaccounted for in the period of a day. To acquire 8kg of Pu (one SQ) would therefore require 8/0.29 days, or approximately 27 days. In practice this number would be rounded to a lower value to get a value of Pu that results in an integral number of finished assemblies.

It is important to determine if there is a single process within the MBA that has a higher associated uncertainty. If so, the MBP would be based on this process as the most sensitive process within MBA 2, and would be lower than the previously found 27 days. Referring to Table 4, the measurements of highest uncertainties are the HLNC measurements of the MOX pins and FBR assemblies which share a total uncertainty of 2.2%. Taking the 3.95 kg throughput per day, the uncertainty for the measurement of the pins or assembly stages is 0.087, for a maximum potential error of 0.26 kg. This gives an MBP of 30.77 days, so the earlier value of 27 days represents the minimum MBP for MBA 2.

In MBA 3, finished fuel assemblies are received from MBA 2, and shipped to the reactor in MBA 3. The balance equation used is Equation 1, and as in MBA 1, the value of *ID* should be zero. Similar to the canisters, each assembly has a unique ID that allows for item tracking and accounting. Eddy current measurements can also be taken on the weld of each fuel pin in the assembly, allowing for another form of unique tracking through the cycle up to reprocessing as well as verification that the pin has not be re-welded.

In addition to measurements taken to determine Pu mass, measurements could also be made to verify the Pu content and isotopic concentration in the MOX, so that diversion via substituted materials is not feasible. To this end, random samples of material in every MBA would be analyzed through a destructive analysis method such as titration.

4.3. Containment and Surveillance

Measurements for accountancy require time to collect enough counts to achieve the target uncertainties shown above. Due to this fact, it is not possible to be constantly accounting material through these methods as it proceeds through the fabrication process. Surveillance methods bridge this gap by providing monitoring of activities in the facility and ensuring that the processes match what is declared by the operator. This can be provided by a number of methods, with redundancy improving the ability of the system to detect diversion of material.

Optical surveillance systems, such as cameras and motion trackers, track movement within each MBA, with 2 or more cameras used to ensure that there are no "blind spots" within the area. They are generally employed in a "dual surveillance" system with another system, such as radiation monitors. In this method, access and movement of materials can be documented. Remote monitoring surveillance systems send data directly back to the inspecting agency where they can be reviewed directly. In the two storage MBAs where there is no process occurring, these cameras may be motion-triggered.

In MBA 1, video surveillance may be used to verify canister ID and that the seals applied at the reprocessing plant have not been tampered with, while radiation monitors could verify empty or full canisters upon receipt. These cameras would also monitor the arrival and departure of the canisters, and provide a deterrent by maintaining visual confirmation of the integrity of the canisters. In MBA 2, video surveillance becomes more difficult due to the gloveboxes required for handling the material. These gloveboxes are enclosed when in use and visual monitoring of the materials inside may not be feasible. For this reason, radiation monitoring equipment is used to track the progress of the MOX powder through the MBA. Video surveillance may be used to observe complete construction of fuel assemblies and the assignment of serial numbers to finished assemblies prior to leaving the MBA. In MBA 3, video surveillance is used to verify the serial numbers on received assemblies as well as the eddy currents of the welds. Similar to MBA 1, video surveillance would also be used to verify departure of the assemblies and record all access to the assemblies during storage.

Containment methods are used to verify the integrity of contained material in conjunction with surveillance. They are designed to prevent undocumented access to containers in a separate supplementary system to surveillance. Two primary methods of containment that can be employed are containment areas and seals. A containment area is simply a place where nuclear material can be stored that is physically protected and easily isolated from normal traffic. Minimizing the number of entry points and ensuring that there is no operational activity unrelated to the nuclear materials stored in that area allows for easier monitoring and surveillance. Seals are used to indicate when an area or container has been accessed. Seals do not restrict access, but they are a valuable tool for inspectors. A Tamper Indicating Enclosure, or TIE, is an area designed specifically for containment with safeguards in mind. It applies the concept of a seal to cover an area, and provides a non-erasable record of entry into the enclosed area.

MBAs 1 and 3 are storage areas, and will therefore make use of containment storage methods. The canisters arriving in MBA 1 would be already sealed after being shipped from the reprocessing plant. The integrity of these seals would be visually confirmed by video surveillance simultaneously with canister IDs to verify that no containers were accessed during transport. Wire-loop and cable seals are most commonly used, but fiber optic seals such as COBRA can provide a higher degree of identity as well as integrity. Active seals continuously test their integrity and send the results remotely to the investigating agency. Unlike passives seals, these seals are generally reusable. However, they are often much more expensive.

In MBA 3, the larger fuel assemblies would be stored in TIEs until ready to be shipped to the reactor. Before shipping, confirmation of the eddy currents in the welds along with the serial number would serve to verify the integrity and identity of the assemblies.

4.4. Reports and Inspections

Reports from the operator are vital sources of information to the inspecting agency in verifying the declared activities of the facility in question. Reports are the method by which the operator provides nuclear accountancy data from each MBA, which can then be verified by the IAEA. The type of information being reported is similar but not identical for each MBA.

In MBA 1, as previously noted, upon receiving PuO_2 canisters, the date and time are noted, canister IDs are logged, and the integrity of the seal is checked. In the case of damaged or broken seals, the operator is expected to report this to the inspecting agency as quickly as possible in order to jointly verify the mass and composition of the seal via gamma and neutron spectrometry. The amount of canisters and individual weights are logged and compared with the weights previously registered at the reprocessing plant. MBA 2, as it involves the process of fabrication, has a large amount of data to be reported. Estimates of holdup, the quantity and Pu content of rejected powder, pellets, rods, and assemblies, isotopic results from DA, and current operating uncertainties for measuring equipment are all information used to verify the facility's activities. MBA 1 would report the serial numbers of the new assemblies, the visual record of eddy currents, and whether the TIE had been accessed for any reason outside of expected operations. This information needs to be reported regularly. Information such as canister ID and seal integrity should be reported in near real time, while accountancy reports would follow the MBP for that area.

Inspections allow the IAEA to independently verify the reported information provided by the operator. Ideally, the efficiency of scheduled inspections should be maximized through the efficient use of remote monitoring devices, allowing for fewer inspections while maintaining confidence in verification ability. Regular inspections would be carried out one per month, while random inspections could be carried out a set number of times a year at short notice to the operator. Examples of inspection goals would be to independently confirm inventory reports, perform NDA on randomly selected process materials, corroborate equipment uncertainties, and other verification of reported activities. Once a year, a Physical Inventory Verification (PIV) would be carried out. During this time, facility operation would be stopped while the materials balance is evaluated, book inventory taken, and samples tested with DA. It has been proposed for other MOX fabrication plants [12] that increasing automation of both the fabrication process and safeguards measurements taken throughout the process could allow for elimination of the monthly inspections while relying entirely on real-time accountancy data provided remotely and on random inspections. This would have the effect of reducing safeguard costs for the inspecting agency and lessening the downtime of the plant for the operator. While this may be a

[12] "Integrated Safeguards (IS) for MOX Fuel Facilities - Development of Approach and Applications" T. Asano, S. Takahashi, S. Fujiwara, T. Nagatani, JAEA-IAEA Workshop on Advanced Safeguards Technology for the Future Nuclear Fuel Cycle, Japan, 13-16 November 2007

possibility, it is assumed that such a level of automation is currently not in place and as such, monthly inspections would be necessary.

5. Conclusions

A closed FBR fuel cycle portion is defined and a material flow chart for the portion developed. A safeguards evaluation covering the reactor, reprocessing, and fuel fabrication facilities of a fast breeder reactor cycle is carried out based on the processes contained in each relevant facility and associated vulnerabilities. Each facility is evaluated based on the state of the plutonium throughout the facility, the quantity of material, the sensitivity of measurement equipment, holdup, and the self-protecting nature of the material. By these criteria, the fuel fabrication facility was determined to be the primary facility of interest in the cycle portion. This differs from the thermal reactor cycle, where the reprocessing plant is the most vulnerable facility. A safeguards approach was outlined including concepts of design verification, containment and surveillance, nuclear material accountancy, reports and inspections.

Future work could focus on the effects of different FBR fuels on safeguards, such as metallic or carbide fuels. In the case of metallic, other methods of reprocessing besides PUREX may be explored as well. Pyroprocessing, while not yet utilized on a commercial level, is of particular interest for reprocessing FBR fuel. Optimization of inspections in a facility that uses a minimum of automation is also an area that could be further explored.

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