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Safeguards Inventory and Process Monitoring Regulatory Comparison

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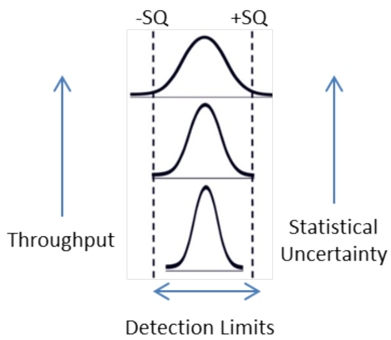
Contents

List of Acronyms

ACRONYM	DEFINITITION
ATR	Advanced Thermal Reactor
BI	Beginning Inventory
BWR	Boiling Water Reactor
DOE	Department of Energy
EI	Ending Inventory
FBR	Fast Breeder Reactor
HEU	Highly Enriched Uranium
IAEA	International Atomic Energy Agency
ID	Inventory Difference
ITDB	Incident and Trafficking Database
Kg	Kilogram
LEU	Low Enriched Uranium
LWR	Light Water Reactor
MA	Material Accounting
MBA	Material Balance Area
MEU	Medium Enriched Uranium
MOX	Mixed Oxide
NM	Nuclear Material
NMA	Nuclear Material Accounting
NRC	Nuclear Regulatory Commission
NRTA	Near Real Time Accounting
PIT	Physical Inventory Taking
PM	Process Monitoring
Pu	Plutonium
PuO2	Plutonium Oxide
PWR	Pressurized Water Reactor
SEID	Standard Error of Inventory Difference
SNM	Special Nuclear Material
SQ	Significant Quantity
SSNM	Strategic Special Nuclear Material
U	Uranium
U233	Uranium-233
U235	Uranium-235
UF6	Hexafloride
UO2	Uranium Oxide

Executive Summary



Detecting the theft or diversion of the relatively small amount of fissile material needed to make a nuclear weapon given the normal operating capacity of many of today's running nuclear production facilities is a difficult task. As throughput increases, the ability of the Material Control and Accountability (MC&A) Program to detect the material loss decreases because the statistical measurement uncertainty also increases.

The challenge faced is the ability of current accounting, measurement, and material control programs to detect small yet significant losses under some regulatory approaches can decrease to the point where it is extremely low if not practically non-existent at normal operating capacities. Adding concern to this topic is that there are variations among regulatory bodies as far as what is considered a Significant Quantity (SQ). Some research suggests that thresholds should be lower than those found in any current regulation which if adopted would make meeting detection goals even more difficult.

This paper reviews and compares the current regulatory requirements for the MA elements related to physical inventory, uncertainty of the Inventory Difference (ID), and Process Monitoring (PM) in the United States Department of Energy (DOE) and Nuclear Regulatory Commission (NRC), Rosatom of the Russian Federation and the Chinese Atomic Energy Agency (CAEA) of China. The comparison looks at how the regulatory requirements for the implementation of various MA elements perform across a range of operating capacities in example facilities. More specifically, the comparison identifies at what simulated operating throughputs of these facilities the MA elements stop contributing to detection capability due to statistical measurement uncertainty. While the concept of protracted theft is discussed, the models found that at normal operating capacities the systems were not effective against abrupt theft of SQs therefore the systems were assumed even less effective against protracted theft.

To accomplish the comparison model facility material balances and Standard Error of the Inventory Differences (SEIDs) were developed to illustrate the impact of the regulatory requirements on the maximum allowable loss limits. All of the regulations reviewed put a limit on the SEID as a percentage of the facility's annual throughput. When these percentage based limits are applied to realistic accounting systems and facilities, they were generally found to only be effective at detecting a SQ at small throughputs which was well below what would be considered the normal operating capacity. Only the DOE and NRC had additional regulatory controls to manage the size of the SEID itself.

The paper found that integrating a concept called Process Monitoring as a MA element into a safeguards system has shown improved detection capabilities and timeliness. PM involves completing more frequent evaluations around smaller units of throughput to manage the statistical measurement uncertainty. While PM could enhance safeguards, the research found a lack of regulatory performance criteria so it is currently not possible to fully quantify its costs and benefits. Of the regulating bodies examined which mention PM, none other than the NRC has set performance goals ("unit process detection capability" in the NRC MC&A regulations).

In summary, the analysis and application of the regulatory requirements found that current MA elements ability to provide timely detection of losses of a SQ was not effective at normal operating capacities of the example facilities. The historical approach of setting regulatory performance criteria for the MA elements as a percentage of throughput based on inventory cycles does not yield timely loss detection in line with what is considered a SQ as defined in any regulation reviewed. An approach call Process Monitoring logically is able to address many of the observed issues, however it wasn't found in all the regulations reviewed and where it was performance criteria was only defined by the NRC.

In conclusion, more clearly defined regulatory performance criteria with respect to fixed, not relative (e.g., percentage), loss detection thresholds and timelines are needed if MA elements are to be able to be an effective and active tool for theft detection. If protracted theft is to be meaningfully addressed, these criteria must also re-examine and lower the amounts for what is considered a SQ.

Analytical Approach

For the comparison this paper performed pseudo material balances on the process Material Balance Areas (MBA) for three different model nuclear fuel facilities. The material balances did not consider hypothetical IDs, but instead focused on propagating measurement error to determine the MBAs' Standard Error of Inventory Difference (SEID or one sigma limit) for a range of possible material throughputs. The SEIDs were then analyzed to determine the accounting systems' effectiveness at detecting the loss of one Significant Quantity (SQ) as defined by the International Atomic Energy Agency (IAEA). In addition to SEIDs, the paper discussed the concept of Process Monitoring (PM) and what role it could play in improving the ability of the accounting system to detect credible opportunities of theft or loss scenarios.

The hypothetical facilities used to evaluate the regulations were a Mixed Oxide (MOX) fuel fabrication facility, a Low Enriched Uranium (LEU) conversion and fuel fabrication facility, and a spent fuel reprocessing facility. A range of design throughputs or capacities from currently operating nuclear fuel facilities was used in the analysis. For MOX facilities the range was 1-200 tons of heavy metal. For LEU fuel fabrication, the range was 48-2000 metric tons of U. For spent fuel processing the range was 25-1000 metric tons of heavy metal. All ranges were based on actual operating or planned facilities worldwide.

In the next few pages several underlying concepts are introduced as background for the analysis itself. The concept of significant quantities is introduced along with some background on the debate surrounding its definition. The material loss threats and loss mechanisms for which the MA are designed are discussed along with some basics on MA. From there the paper moves into the regulatory comparison discussing the similarities and differences between countries and organizations within countries. The remainder of the paper is devoted to application of the regulations to the three model facilities showing detection sensitivity.

Key Concepts and Issues

Significant Quantities

The IAEA safeguards objective is "the timely detection of diversion of 'significant quantities' of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection."[1] The IAEA defines a "Significant Quantity" (SQ) as the minimum amount of fissile material which could be used directly to create a nuclear explosive device. The IAEA considers 8 kilograms (kg) of plutonium (Pu), 25 kg of Uranium 235 (U235) in High Enriched Uranium (HEU), and 75 kg of U235 in LEU each to be one SQ.[1] The U.S., Russia, and China in their internal regulations set slightly more conservative thresholds as shown in the section of this report on material categories.

This report found that measurement errors create too much statistical "noise" to adequately detect diversions of significant quantities at larger throughput facilities regardless of whether one uses the IAEA's numbers or the country-specific internal numbers. Moreover, this report concluded that timely detection is not possible when facilities perform physical inventories on the scale of months, as is the current regulatory requirement across all three countries, U.S., Russia, and China.

In addition to the issue of timely detection of a SQ for large throughput facilities, some parties have voiced concern over the IAEA SQ amounts as currently defined and have discussed the need for a reduction in the amount that constitutes a SQ. A report published in 1995 by the Natural Resources Defense Council (NRDC) examined the minimum amount of Pu and HEU needed for pure fission nuclear weapons and proposed that the IAEA's significant quantities should have an eight fold reduction;[2] the implementation of that reduction place the new SQs at 1 kg of Pu, 1 kg of U233, and 3 kg of U235 contained in HEU. These NRDC proposed values are far lower than those of found within the regulations reviewed during this study. The NRDC report also acknowledged the fact that a well-designed safeguards program **should set accounting threshold limits at values less than the minimum amount needed for a weapon because materials can be diverted from more than one source.[2]** Acknowledgement and implementation of this recommendation by the international community would increase detection goals for the MA elements analyzed in this paper, which are currently not effective at higher throughputs as will be shown.

Material Loss Threats

There are two classes of potential material diverters – insider threat and outsider threat. An outsider threat is someone who does not have easy access to the facility where the material is stored. An insider threat, however, has access to and knowledge of the plant's operations. This eliminates some of the security safeguard features at the facility, thus making the insider's goal more easily attainable.[1] This paper is focused on the insider.

There are two main types of diversion scenarios considered which are abrupt theft and protracted theft. An abrupt theft is "the unauthorized removal of a large quantity of nuclear material in a single event."[3] A protracted theft is "the repeated unauthorized removal of small quantities of nuclear material during several events."[3] Protracted theft is carried out by an insider(s) since he/they would have opportunities to accumulate a significant quantity over a long period of time. Physical protection against protracted theft is less effective because the insider removes small amounts of material over an extended period of time at values below the detection thresholds. The material accounting elements modeled in this paper are currently viewed as some of the best measures to safeguard protracted theft. A combination of the two involves an insider reducing an outsider adversary's task by diverting and staging material outside key protection features such as storage vaults.

Material accounting regulations were originally written with the goal of quickly detecting the abrupt loss of a SQ of material;[1] however, what was considered timely was often the subject of debate and nebulously defined. Recently, protracted theft by an insider seems to have gained greater focus as a more likely threat. This can be attributed to the fact that it is the most difficult of the above scenarios to detect (i.e. most likely to be successful).

The IAEA keeps a record of confirmed illicit nuclear material trafficking incidents in the Incident and Trafficking Database (ITDB). According to this database, most of the incidents involving Pu and HEU theft between 1993 and 2007 were of quantities below 100 grams. The largest HEU confiscation was below 3 kg, while the largest amount of Pu confiscated was 363 grams. What is problematic is the material showed up on the secondary market. There is no evidence available that suggests the loss of materials were detected by the site's MA controls prior to their discovery on the secondary market. This raises the question as to how many thefts of this type **could occur** without detection.

Material Accounting Basics

Material Accounting (MA) is the system by which facility operators keep track of the nuclear material in the facility. One purpose of MA is to provide assurance that nuclear materials are accounted for properly and to detect the theft of nuclear materials. There are several key components, which all MA systems have in common. The first of these is the concept of establishing Material Balance Areas (MBAs). An MBA is defined as an area inside a facility such that the quantity of nuclear material (NM) in each transfer into or out of an MBA can be determined, and the physical inventory of NM in each MBA can be determined when necessary.[4] Each MBA receives a classification based on the quantity and type of its NM, and the rigor of MA regulations vary between different MBA classifications.

The next component is a regularly scheduled Physical Inventory Taking (PIT) of each MBA. This includes shutting down all the processes in the MBA, measuring all NM in the MBA, and recording all of the measurement data.[4] The last component is the material balance closing. This involves looking at the data from the previous physical inventory and combining it with data from the current physical inventory to determine the Inventory Difference (ID) for each MBA.[4] Error from measurements used during the physical inventories is propagated during the material balance closing to determine the Standard Error of Inventory Difference (SEID) for each MBA.[4] The ID and SEID are the two quantifiable metrics which indicate if a loss of material has occurred or not; the ID is the observed inventory difference between inventory periods, while the SEID is the uncertainty around the ID due to measurement errors. The observed ID is the quantity which provides an estimate of the true ID, and is algebraically equal to the true ID plus the combined errors due to measurement. The observed ID plus/minus multiples of the SEID creates an interval of values which most likely contains the true ID. So if the SEID is kept small, there is a smaller window where the true IDs will fall, and thus the observed ID gives a more precise estimate of the true ID. A large SEID, however, will create a wide interval around an observed ID, thus providing a relatively insensitive indicator as to whether or not material is actually missing. For this reason, any MA regulations require a maximum limit for an accounting system's SEID.

The probability of detecting the loss of a given quantity of material depends upon the MBA's SEID. The IAEA recommends that an accounting system strive for 95% detection and 5% false alarm probabilities.[4] In order to achieve this goal for loss detection of one SQ requires that the SEID satisfy the following[5]:

$$\sigma_{ID} \leq SQ/3.3$$

Although the regulations compared in this paper do not specify this detection goal, it is a common practice for most accounting systems, and thus is applied to this paper's model facilities. As noted before, the actual numerical value of "SQ" varies between the regulations examined.

Material Accounting Techniques

The classic approach to nuclear material accounting consists of taking physical inventories at regular time intervals and performing a material balance for the time period since the last physical inventory. This produces an ID and SEID which quantifies the amount and uncertainty of material lost during the balance period.

All of the accounting regulations compared in this report used this approach as their main accounting method; however, it has many shortcomings. Measurement uncertainty increases as facility throughput increases, and for the hypothetical facilities considered in this report, physical inventories are shown to provide little detection of material theft. Inventories are not taken frequently enough to provide adequate statistical detection sensitivity. Even when the physical inventory regulations are met, the acceptable SEID is too high to detect significant quantities lost over the balance period. In short, the inventory timelines are too long to be effective; they don't facilitate timely detection of abrupt material loss and smaller amounts of material can be taken over longer time periods without any accounting anomalies produced. With that said, this paper is not advocating increasing the frequency of physical inventory. The level of effort, effect on operations, and improvement in detection capability do not provide the improvement potentially needed.

Process monitoring (PM) is a safeguard technique which, when applied to material accounting, has the potential to address some of the uses related to the physical inventory requirements. While there is no single clear definition for process monitoring, it involves collecting data of the process while material moves through the facility. "Process monitoring often involves more frequent but lower quality measurements than Nuclear Material Accounting (NMA)."[6] Process monitoring data can be used in two main ways. One is simply to monitor the facility's behavior as a process control application. PM data can be combined with the accounting system to produce a near real time accounting (NRTA) system.[6] The later has the safeguard benefits of more timely detection and lower measurement error, as well as the operator benefit of less plant downtime and more accurate accounting of costly materials.

Of the countries' regulations considered in this paper, process monitoring only appears in the NRC[7], DOE[8], and Russian[9] regulations, while the Chinese[10] regulations available for this review do not mention the concept of process monitoring. In fact, only the NRC has a measurable process monitoring requirement, although its only for Category 1 MBA's; the DOE and Russia have suggestions for process monitoring but no regulations which require facilities to use this material control and accounting tool and/or define specific performance goals.

Regulation Comparison

For the MA regulations reviewed, all shared a similar structure. First, areas within a facility are categorized based on the amount and type of material which normally resides in that area. Different levels of accounting regulations are applied based on this categorization. Most MA is performed through regularly scheduled physical inventory takings and record keeping. These inventories are generally taken 1-2 times per year and require the plant to be shutdown. After the inventory, the material measurements are reconciled with the book inventory from the previously recorded inventory to produce an ID. Some states also have regulations on another way to account for material called process monitoring. This method involves measuring material very frequently as it flows through the processing areas of the facility.

This study is concerned with how MA regulations actually play out in commercial reprocessing and fuel fabrication facilities. The regulations compared come from the NRC,[7] DOE,[8] Russia,[9] and China.[10] Russian and DOE regulations specify four main categories of nuclear material, while Chinese and NRC regulations only have three categories. For the purpose of this study, only regulations from the first three categories of nuclear material are compared because these are the regulations which were applicable to the hypothetical facility models.

All of the tables presented in the Regulation Comparison section provide MA regulation criteria.[7, 8, 9, 10] In Appendix A there are material and inventory definitions which will further explain any unfamiliar terms found in these comparison tables.

Categories of Nuclear Material

MA regulations are different for different classes of NM, so it is important to first understand how material is categorized.

Categorization of NM is based both on favorability and quantity of the material. Favorability takes into account isotopic enrichment, physical/chemical form, ease of handling/transportation (encapsulated items that are heavy or have large dimensions are less likely to be stolen; materials with large dose rates are also less likely to be stolen). Each MBA receives a categorization based on the nuclear material present there; regulation criteria for the MBA are then based on this categorization.

The material amounts in the following tables represent the lower limit quantity required for an MBA to receive the category rating.

Category I

The most attractive and thus highly monitored NM is labeled Category I. Below is a table that specifies the material and quantity required in a certain MBA to obtain this category. The materials of interest in this category are mainly Pu, U233, and U235 HEU.

Table 1. Category I Materials

<table>
<tr><th colspan="3">US NRC</th><th colspan="3">Russia</th><th colspan="3">DOE</th><th>China</th></tr>
<tr><td>2kg Pu</td><td>2kg U233</td><td rowspan="2">5kg U235 in HEU</td><td colspan="3">Metal Product:</td><td colspan="3">Pure Products:</td><td>5kg HEU</td></tr>
<tr><td colspan="2"></td><td rowspan="2">2kg Pu/233</td><td rowspan="2">5kg U235 in HEU</td><td rowspan="2">2kg *mixture</td><td>2kg Pu/U233</td><td colspan="2" rowspan="2">5kg Separated Np237,Am241,Am243</td><td>2kg Pu</td></tr>
<tr><td colspan="3" rowspan="4">5kg in any combination computed by the equation mass = (mass contained U235) + 2.5*(mass U233 + mass Pu)</td><td>5kg U235</td><td></td></tr>
<tr><td colspan="3">PHNMC:</td><td>HGM:</td><td>6kg Pu/U233</td><td>20kg U235</td><td>10g Tritium</td></tr>
<tr><td rowspan="2">6kg Pu/U233</td><td rowspan="2">20kg U235 HEU</td><td rowspan="2">6kg *mixture</td><td colspan="3">20kg Seperated Np237,Am241,Am243</td><td rowspan="2"></td></tr>
<tr><td colspan="3">assembled weapons (any amount)</td></tr>
<tr><td colspan="10">*mixture; aggregate - for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf</td></tr>
</table>

Category II

The next most controlled NM is labeled Category II. Below is a table that specifies the material and quantity required in a certain MBA to obtain this category.

Table 2. Category II Materials

US NRC		
0.5kg Pu	0.5kg U233	1kg U235 in HEU
0.5kg in any combination computed by the equation mass = (mass contained U235) + 2*(mass U233 + mass Pu)		
10kg U235 in MEU		

Russia		
Metal Product:		
0.5kg Pu/233	1kg U235 in HEU	0.5kg *mixture
PHNMC:		
2kg Pu/U233	6kg U-235 in HEU	2kg *mixture
PLNMC:		
16kg Pu/U233	50kg U235 in HEU	16kg for *mixture

DOE		
Pure Products:		0.4kg Pu/U233
1kg U235	1kg Separated Np237,Am241,Am243	
HGM:	2kg Pu/233	6kg U235
6kg Seperated Np237,Am241,Am243		
LGM:	16kg Pu/233	50kg U235
50kg Separated Np237,Am241,Am243		

China
10g Pu
1kg HEU
20KG MEU
1g Tritium
300kg LEU
20kg Li

*mixture; aggregate - for the total mass of Pu, U-233, U-235, Np-237, Am, and Cf

Category III

The lowest level of NM this report details is labeled Category III. Below is a table that specifies the material and quantity required in a certain MBA to obtain this category. Category III is where NRC and Chinese categorization is the most different from Russian and DOE. The NRC and China both include LEU, enriched above natural but below 10% in U235 in this category, while Russia and the DOE do not address LEU until Category IV.

Table 3. Category III Materials

US NRC		
15g Pu	15g U233	15g U235 in HEU
or 15g combined quantity		
1kg U-235 in MEU		
10kg U-235 in LEU		

Russia		
Metal Product:		
0.2kg Pu/233	5kg U235 in HEU	0.2kg *mixture
PHNMC		
0.5kg Pu/U233	2kg U235 HEU	0.5kg for *mixture
PLNMC		
3kg Pu/U233	8kg U235 in HEU	3kg for *mixture

DOE		
Pure Products:		0.4kg U235
0.4kg Separated Np237,Am241,Am243		0.2kg Pu/233
HGM:	2kg U235	0.4kg Pu/233
2kg Separated Np237,Am241,Am243		
LGM:	3kg Pu/233	8kg U235
3kg Separated Np237,Am241,Am243		

China
0g-10g Pu
10g HEU
1kg MEU
0.1g T
10kg LEU
1kg Li

*mixture; aggregate - for the total mass of Pu, Pu-239, U-233, U-235, Np-237, Am, and Cf

Physical Inventory

Physical Inventory Taking (PIT) is the main method used to perform material accountancy on a full scale commercial fuel facility. PITs are complete inventories of all the nuclear material at a particular facility. These inventories require a full plant shutdown to ensure that material in process streams is measured and accounted. Measurement methods for PIT strive to be state of the art and thus have relatively low measurement uncertainties. However, a PIT is only required to take place as often as every 2-12 months. Inventory periods this infrequent result in large amounts of material measured in each accounting period. The accounting system's total measurement error increases as measured material increases, so a by-product of infrequent inventories is increased measurement uncertainties.

Inventory Frequency

Regulations specify the minimum required frequencies for physical inventory takings. Facilities typically perform these inventories at the minimum required frequency, or sometimes less often (some regulations allow a facility to negotiate an extended inventory frequency based on some other control measure put in place.)

China's regulations on inventory frequency are not easy to distinguish for different MBA categorization. The last part of this section details China's inventory regulations.

Category I

The table below details the required frequency for Category I MBA physical inventories and the maximum timespan allowed for inventory taking.

Table 4. Required Inventory Frequencies for Category I MBAs

	US NRC	Russia	US DOE
Interval	6 months	2 months	60 days *
			6 months**
Inventory Timespan	45 days	not specified	30 days
*process MBA where NM is converted between forms			
**storage MBA where NM is stored, typically with a TID			

Category II

The table below details the required frequency for Category II MBA physical inventories and the maximum timespan allowed for inventory taking.

Table 5. Required Inventory Frequencies for Category II MBAs

	US NRC	Russia	DOE
Interval	9 months	3 months	60 days *
			6 months**
Inventory Timespan	60 days	not specified	30 days
*process MBA where NM is converted between forms			
**storage MBA where NM is stored, typically with a TID			

Category III

The table below details the required frequency for Category III MBA physical inventories and the maximum timespan allowed for inventory taking.

Table 6. Required Inventory Frequencies for Category III MBAs

	US NRC	Russia	DOE
Interval	12 months	6 months	6 months *
			2 years**
Inventory Timespan	60 days	not specified	30 days
*process MBA where NM is converted between forms			
**storage MBA where NM is stored, typically with a TID			

China

The Chinese regulation details two different inventory frequency requirements:

For any nuclear facility, "A complete, strict physical inventory shall be made at least once a year."[10] A more frequent inventory schedule is employed for certain special nuclear materials; "For nuclear materials such as Pu 239, Uranium-233 (U233) and concentrated U with a content of Uranium-235 (U235) exceeding 20%, physical inventory shall be made at least biannually."[10]

Inventory Difference

After measurements of the physical inventory are taken, the ID for that material balance period can be calculated. The SEID can also be calculated at this time. Both of these quantities are metrics to help a facility determine if its measurement techniques are accurate and to evaluate the significance of differences in the inventory records. There are different criteria for each category of NM that determine whether there are issues with physical inventory control. The NRC, DOE, and China all have SEID limits which are given as a percentage of active inventory. Active inventory is an applicable measure of the amount of material subject to measurement error in an inventory period. It involves the sum of material additions and removals in the MBA during the balance period and it is approximately double throughput[11] for a throughput dominated facility. Throughput is the amount of input material to an MBA which is processed during the balance period.

Russia and China both have ID criterion that are not easily explained in a table, so the last two paragraphs of this section describe these regulations.

Category I

The table below details the SEID and ID criterion for identifying an MA anomaly for Category I NM.

Table 7. Inventory Anomaly Criteria for Category I MBAs

	US NRC	Russia	DOE
SEID Exceeding	0.1% active inventory		1% active inventory half a Cat. II quantity
ID Exceeding	3x SEID **AND** 0.2kg Pu; 0.2kg U233; or 0.3kg U235 in HEU	3x SEID 3kg Pu/U233 8kg U235 [1]2% Industrial [1]3% R&D	
	[1]total quantity of NM that was converted and underwent accounting measurements during the material balance period		

The DOE regulations present the SEID limits for Category I and II MBAs a little differently from what is shown in the tables above and below. These regulations say, "For Category I and II, MBAs, limits-of-error must not exceed a 2 percent of the active inventory during the inventory period and must not exceed a Category II quantity of material." Here, limits-of-error refers to the LEID which is two times the SEID.

Category II

The table below details the SEID and ID criterion for identifying an MA anomaly for Category II NM.

Table 8. Inventory Anomaly Criteria for Category II MBAs

	US NRC	Russia	DOE
SEID Exceeding	0.125% active inventory		1% active inventory half a Cat. II quantity
ID Exceeding	3x SEID **AND** 0.2kg Pu; 0.2kg U233; 0.3kg U235 in HEU; or 9kg U235 in LEU (>0.72% but <20%)	3x SEID 3kg Pu/U233 8kg U235 [1]2% Industrial [1]3% R&D	
	[1]total quantity of NM that was converted and underwent accounting measurements during the material balance period		

Category III

The table below details the SEID and ID criterion for identifying an MA anomaly for Category III NM.

Table 9. Inventory Anomaly Criteria for Category III MBAs

	US NRC	Russia	DOE
SEID Exceeding	less then the greater of 0.125% of active inventory or 4.5kg U235 contained in LEU		specified % of active inventory and specified amount of NM; each approved by DOE; site specific
ID Exceeding	site-specific basis	3x SEID	
		8kg U235	
		[1]2% Industrial	
		[1]3% R&D	
	[1]total quantity of NM that was converted and underwent accounting measurements during the material balance period		

Russia

Russia also has a slightly looser limit for MBA's in radiochemical plants that reprocess uranium-plutonium solutions. For MBAs of all categories this limit on the ID is 50 kg of U235 and 8 kg of Pu.[9]

Another interesting point about the Russian regulations available for this review is that they do not specify any strict SEID limits and detection thresholds. They have limits on the ID, but this is meaningless without a limit on the error associated with this ID. As mentioned earlier in the introduction, an inventory taking produces two quantifiable metrics, the observed ID and the accounting system's SEID. The observed ID plus/minus multiples of the SEID creates an interval of values which likely contain the true ID. A large SEID will result in a wide interval around an observed ID, thus providing a relatively insensitive indicator as to whether or not material is actually missing. By having no limit on the SEID, the Russian regulations allow an accounting system to have uncapped measurement error, and this can cloud the accuracy of the observed ID.

China

Although China's regulations made distinctions between the different MBA categories, those did not seem to apply to the accounting evaluation regulations. These said that for any material balance closing, if the ID exceeds two time the SEID, this constitutes an accounting anomaly and means material may have been lost.[10]

The regulations also specified limits on the SEID, although again, these do not relate to the MBA categories. If the SEID exceeds the limit for the certain facility type, then the measurement system is deemed inadequate and must be improved. The limits posted in the table on page 15 refer to the relative standard deviation of ID in the full course of balancing, indicated as a percentage of the total amount[10] (for throughput-dominated facilities this essentially equal to twice the throughput for the inventory period.)

Table 10. China's SEID Limit for Various Facility Types

Type of Facility	σ (ID) (%)
U enrichment	0.2
U processing	0.3
Pu processing	0.5
U post-processing	0.8
Pu post-processing	1

Process Monitoring Regulations

A prevailing goal of advanced safeguard techniques is to provide more timely detection of plant anomalies while minimizing the cost to the facility, both of which can be achieved through process monitoring.

The DOE describes process monitoring as "a methodology to ensure that special nuclear material (SNM) is in its authorized location and when effectively implemented, it is a useful tool to detect anomalous process conditions and indicate losses of SNM well before the scheduled physical inventory."[8]

Process Monitoring is only required by the NRC.[7] The DOE[8] and Russia[9] both mention that process monitoring is a useful tool, but they do not provide additional details or requirements for a process monitoring program. The Chinese regulations available for this review do not mention process monitoring at all.[10]

NRC

Only Category I MBAs are required to follow the NRC's process monitoring regulations. For process monitoring requirements, a distinction is made for two subclasses of Category I material which can be found in the process monitoring section of Appendix A. This appendix also contains other definitions related to the NRC's regulations on process monitoring.

The NRC's process monitoring regulations are detailed below:[7]

Unit Process Detection Capability

For each unit process, a licensee shall establish a production quality control program capable of monitoring the status of material in process. The program shall include:

Industrial Operations

(1) A statistical test that has at least a 95 percent power of detecting an abrupt loss of five *formula kilograms* within three working days of a loss of Category IA material from any accessible process location and within seven calendar days of a loss of Category IB material from any accessible process location;
(2) A quality control test whereby process differences greater than three times the estimated standard deviation of the process difference estimator **AND** 25 grams of Strategic Special Nuclear Material (SSNM) are investigated;
(3) A trend analysis for monitoring and evaluating sequences of material control test results from each unit process to determine if they indicate a pattern of losses or gains that are of safeguards significance.

R&D Operations

(1) Perform material balance tests on a lot or a batch basis, as appropriate, or monthly, whichever is sooner, and investigate any difference greater than 200 grams of Pu or U233 or 300 grams of U235 that exceeds three times the estimated standard error of the inventory difference estimator;
(2) Evaluate material balance results generated during an inventory period for indications of measurement biases or unidentified loss streams and investigate, determine the cause(s) of, and institute corrective action for cumulative inventory differences generated during an inventory period that exceed three formula kilograms of SSNM.

DOE

The DOE standard does not require process monitoring or specify a certain procedure for it. Instead the regulations say, "...if this methodology is used, the MC&A plan shall describe" the following:[8]

- "The methodology for division of processes into units for the detecting the loss of control of a significant quantity. The units shall be consistent with accessible measurements points that result from the process design. There is no limit or restriction on the number of units into which a process or facility can be divided."
- "The material control tests used for detecting abrupt losses of bulk material from a single process unit, the loss detection capability, and the timeliness of the detection."
- "The alarm threshold (critical value), which if exceeded initiates alarm resolution procedures."

Russia

The definition below comes from the Russian regulations and is similar to process monitoring:[9]

Operational control and accounting – Control and accounting of product during the production process that is based on measuring individual product parameters and monitoring their conversion and transfer between technicians during production process operations.

These regulations say book inventory should be monitored by performing operation accounting, but that the quantity of nuclear material actually present shall be determined when taking physical inventory. The regulations also say organizations which handle nuclear material shall develop an MC&A policy which, among other things, shall specify procedures for operational nuclear material accounting.[9]

Model Facilities

In order to understand the effectiveness of the physical inventory regulations that were compared above, these regulations were applied to several hypothetical nuclear fuel facilities. These facilities are based on three separate reports published by the IAEA in the 1980s. These reports provide a detailed description of a state system of accounting for and control of nuclear material (SSAC) for three different types of facilities. STR-150 describes a model LEU conversion and fuel fabrication facility[12], STR-185 describes a model MOX fuel fabrication facility,[13] and STR-193 describes a model spent fuel reprocessing facility.[14]

These IAEA reports contain descriptions of five of the principal elements of an SSAC.[12, 13, 14] These elements are nuclear material measurements, measurement quality, records and reports, physical inventory taking, and material balance closing. Measurement quality for each method was compared against current measurement target values[15] to ensure the model facilities would be an accurate description of facilities in operation today. Using this information, a material balance was performed for each model facility, and the SEID for the balance was calculated. The purpose of this exercise is to determine if the current material accounting regulations are effective at detecting loss of a significant quantity on nuclear material.

There are three MBA structures (feed, process, and storage) commonly used in nuclear fuel facilities. The model facilities here have been divided into these structures; MBA-1 is reserved for incoming feed material storage, MBA-2 is the process area, and MBA-3 is where the finished product is stored before shipping. MBA-1 and 3 typically contain items that are not hard to monitor, and require fewer measurements per inventory period. MBA-2 is where the conversion of material takes place, making material harder to track and requires more measurement methods.[12, 13, 14] For this reason, process MBAs typically have the largest ID and measurement uncertainty. For the purpose of examining the effectiveness of material accounting regulations, a material balance was performed only on MBA-2 since it will have the largest ID and SEID.

LEU Conversion and Fuel Fabrication Facility

General Characteristics

The original model facility had an annual throughput of 300 tons of UO2 with a nominal enrichment of 3.0 weight percent U235. Physical inventories which include process shutdown and cleanout equipment are taken twice a year. The feed materials are LEU hexafluoride (UF6) received from offsite, uranyl nitrate solution (UNH) received from offsite, and UO2 powder received from offsite and from scrap recovery. Products are LWR assemblies of both the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) type.[12]

This facility's only nuclear material of interest is U enriched in U235 less than 10% LEU. Because of this its MBA-2 receives a much lower categorization, and has looser inventory regulations. The NRC classifies this MBA as containing SNM of low strategic significance, their third most heavily safeguarded class of material. The DOE and Russia both classify this MBA as Category IV.

MOX Fuel Fabrication Facility

General Characteristics

The original model facility had an annual throughput of 500 kg of PuO2 and is capable of manufacturing MOX fuel assemblies for three different kinds of reactors: fast breeders (FBR, 30% Pu), light water reactors (LWR, 4% Pu), and heavy-water-moderated advanced thermal reactors (ATR, 1% Pu). Physical inventories which include process shutdown and cleanout equipment are taken 2-4 times per year. The feed materials are natural or depleted UO2 and PuO2 received from offsite. Products are MOX fuel assemblies for LWR (≈4% Pu).

This facility contains two nuclear materials of interest, both uranium and Pu. Because MBA-2 contains well over 0.2 kg of plutonium oxide, it receives Category I classification. The NRC and China both require this MBA to perform a complete physical inventory every 6 months, while the DOE and Russia require a minimum inventory frequency of 60 days. The SEID limit (given as a percentage of "active inventory") MBA-2 at this facility is 2% for the DOE, 0.1% for the NRC, and 0.5% for China, while Russia does not have a SEID limit. Under NRC regulation, this MBA must also have a Category 1A process monitoring accounting system in place.

Spent Fuel Reprocessing Facility

General Characteristics

The original model facility had an annual throughput of 200 tons of heavy metal and is capable producing LWR fuel with an initial enrichment of up to 5%, containing about 11 kg Pu per ton of U. Products are UO3 and concentrated plutonium nitrate solution. The conversion process from plutonium nitrate solution to PuO2 is not included in the reference facility.[14]

This facility contains two nuclear materials of interest, both U and Pu. Because MBA-2 contains well over 0.2 kgs of plutonium oxide, it receives Category I classification. The NRC and China both require this MBA to perform a complete physical inventory every 6 months, while the DOE and Russia require a minimum inventory frequency of 60 days. The SEID limit (given as a percentage of "active inventory") MBA-2 at this facility is 2% for the DOE, 0.1% for the NRC, and 0.5% for China, while Russia does not have a SEID limit. Under NRC regulation, this MBA must also have a Category 1A process monitoring accounting system in place.

Material Balance

The material balance based on the physical inventory is what permits the determination of whether significant losses or diversions have occurred undetected.[12, 13, 14] The model facilities were created and examined for the purpose of performing a hypothetical material balance which accurately reflects true values from current facilities. This was achieved by using reasonable throughput values and measurement uncertainties found at similar types of facilities operating today.

The material balance for MBA-2 of the model facilities was performed in order to test the effectiveness of various material accounting regulations. No diversion scenario or inventory difference was assumed for these material balances; instead their metric of detection ability was based on the calculated SEID for each model facilities' MBA. The SEID is defined as one standard deviation of an estimated inventory difference that takes into account all measurement error contributions to the components of the ID. In more simple terms, a SEID gives an interval of reasonable values around an observed ID, thus providing the measure of accuracy for the calculated ID. The SEID determines the accounting system's loss detection capability; too large of a SEID introduces lots of statistical noise which masks possible inventory differences. The SEID was found by propagating the error for all measurements in the material balance; an explanation of the method for this calculation can be found in the SEID Calculation section of Appendix B.

During a material balance, inventory is categorized in four different ways: beginning inventory (BI) is material stored in the MBA at the beginning of the balance period; ending inventory (EI) is material which remains in the MBA at the end of the balance period; input is material which was transferred to the MBA for processing during the balance period; output is material which was transferred out of the MBA as products during the balance period. Input and outputs make up the major portion of material mass in the MBA during the balance period.[12, 13, 14] When increasing throughputs for the model facilities SEID calculations, only the inputs and outputs changed. It was assumed that BI and EI would remain about the same for increased throughputs. For large throughputs, BI and EI don't contribute much to the SEID, but for low throughputs this contribution becomes more apparent.

The NRC, DOE, and China all have physical inventory regulations which specify a limit on the SEID. These limits are all percentages of the "active inventory" in the MBA. Active inventory is the quantity of material measured for accountability purposes since the last physical inventory, and for throughput-dominated facilities is essentially equal to twice the throughput for the inventory period.[11] For this comparison, active inventory will be taken to mean twice the amount of input nuclear material of interest for MBA-2.

Results

The results from the material balance are the calculated SEID for a range of reasonable throughput values. The SEID represents the absolute value of an interval (plus and minus) around the observed ID. All of the graphs in this results section have the range of throughput values on the x-axis. The y-axis values express the calculated SEID as well as the various regulations' SEID limits. The y-axis is centered on the observed ID, which was assumed to be 0. The x-axis values express the facilities annual throughput. As the throughput increases, so does the SEID, and this relationship can be seen in the graphs as y (SEID) is a function of x (throughput). SEID limits from the NRC, DOE, Russian, and Chinese regulations were also plotted on these graphs in order to assess their effectiveness.

The purpose of this section is not only to assess whether these model facilities' accounting systems are capable of meeting the various states' regulations; it's also to determine if the states' regulations are capable of detecting the loss of one SQ. The usual safeguard goal is to be able to detect the loss of a certain quantity with ≥95% detection and ≤5% false alarm probabilities. If the detection quantity is one SQ, this works out to the following limit;[4]

$$\text{SEID} \leq {}^{\text{SQ}}/_{3.3}$$

The standard IAEA significant quantities are used, the SEID detection threshold for one SQ (75kg U235) in the LEU facility is 757.6kg of U enriched to 3% U235. For the MOX and reprocessing facilities, the SEID detection threshold for one SQ (8kg Pu) is 2424.24 grams of Pu.

LEU

The World Nuclear Association provides information on currently operating LEU fuel fabrication facilities worldwide.[16] These data can be found below in Table 11. According to this information, the 20 pelletizing facilities in operation today have material throughputs ranging from 48 to 2000 metric tons of U per year. The SEID for the model LEU fuel fabrication facility was calculated using this range of throughputs in order to accurately reflect current facility throughputs.

Table 11. World LWR Fuel Fabrication Capacity (tonnes/year)

Country	Company	Location	Pelletizing
Belgium	AREVA NP-FBFC	Dessel	700
Brazil	INB	Resende	160
China	CNNC	Yibin	400
France	AREVA NP-FBFC	Romans	1400
Germany	AREVA NP-ANF	Lingen	650
India	DAE Nuclear Fuel Complex	Hyderabad	48
Japan	NFI (PWR)	Kumatori	360
	NFI (BWR)	Tokai-Mura	250
	Mitsubishi Nuclear Fuel	Tokai-Mura	440
	GNF-J	Kurihama	750
Kazakhstan	Ulba	Ust Kamenogorsk	2000
Korea	KNFC	Daejeon	600
Russia	TVEL-MSZ*	Elektrostal	1200
	TVEL-NCCP	Novosibirsk	200
Spain	ENUSA	Juzbado	300
Sweden	Westinghouse AB	Västeras	600
UK	Westinghouse**	Springfields	600
USA	AREVA Inc	Richland	1200
	Global NF	Wilmington	1200
	Westinghouse	Columbia	1500
** Includes approx. 220 tHM for RBMK reactors*			
*** Includes approx. 200 tHM for AGR reactors*			

The LEU model facility's MBA-2 would be classified as Category III by the NRC and China and as Category IV by the DOE and Russia. The NRC and China require an inventory frequency of 12 months for Category III. The NRC's SEID limit is 0.125% of active inventory, while China's SEID limit for uranium processing facilities is 0.3% of active inventory.

Figure 1 below shows the calculated SEID for the range of possible throughputs (48 to 2000 metric tons of U per year) given the NRC/Chinese requirements of a 12 month inventory frequency. This graph also provides the NRC's and China's SEID limits.

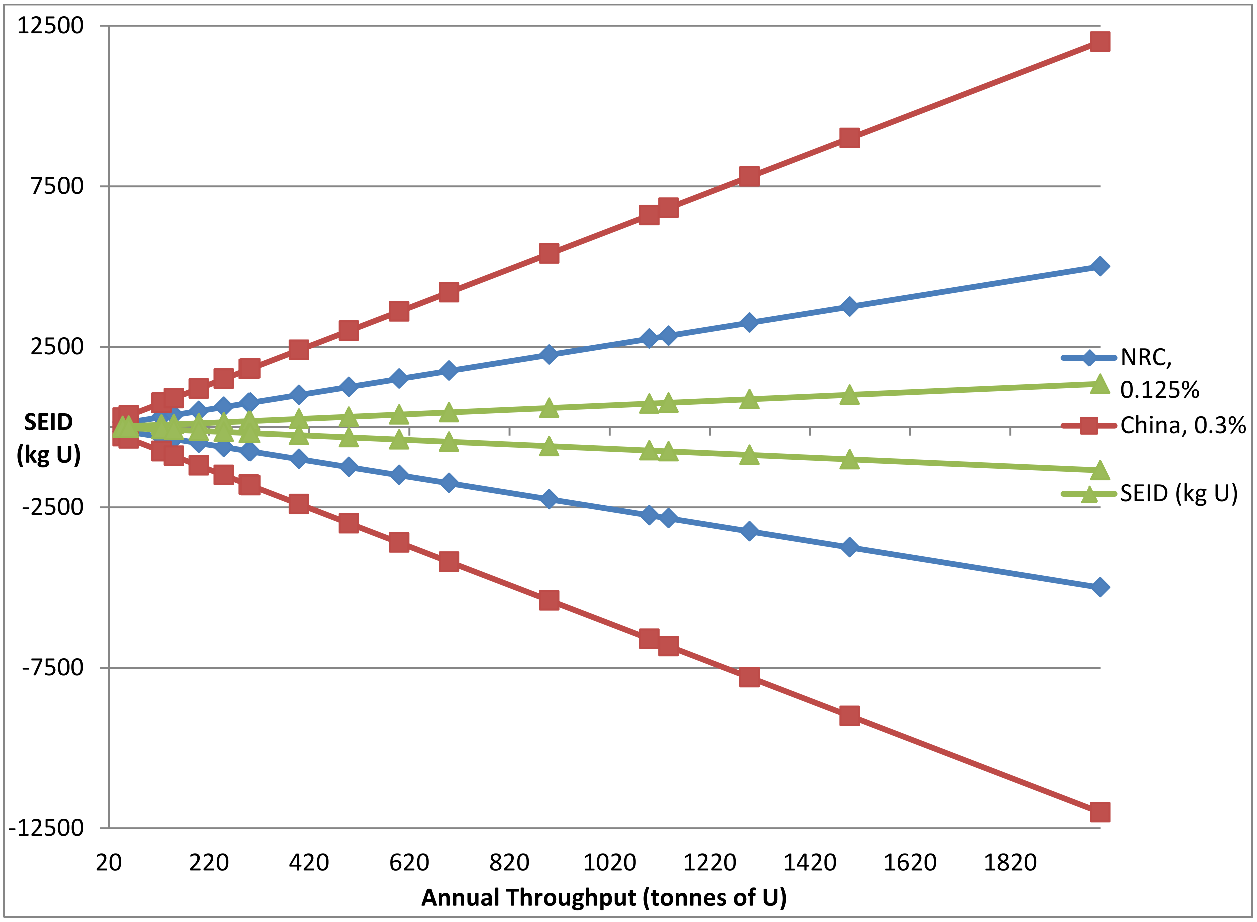


Figure 1. LEU Model Facility with 6 Month Inventory Period

As can be seen from Figure 1 above, this MBA's calculated SEID meets both the NRC and China's limits for all throughputs examined.

Figure 2 on page 21 shows the same data as the graph above, but the x-axis is on a logarithmic scale and is zoomed in to show details for annual throughputs from 48 to 1200 tonnes of U. The two horizontal lines represent the SEID threshold for detecting the loss of one SQ given 95% detection and 5% false alarm probabilities. The three vertical lines mark the annual throughput level at which the hypothetical SEIDs (either from regulations or calculated) exceed the detection threshold. NRC's regulations for this MBA specify the SEID should not exceed the greater of 4.5kg of U235 or 0.125%. For the first two data points the 4.5kg of U235 is greater which is why the NRC limit is flat for these two points.

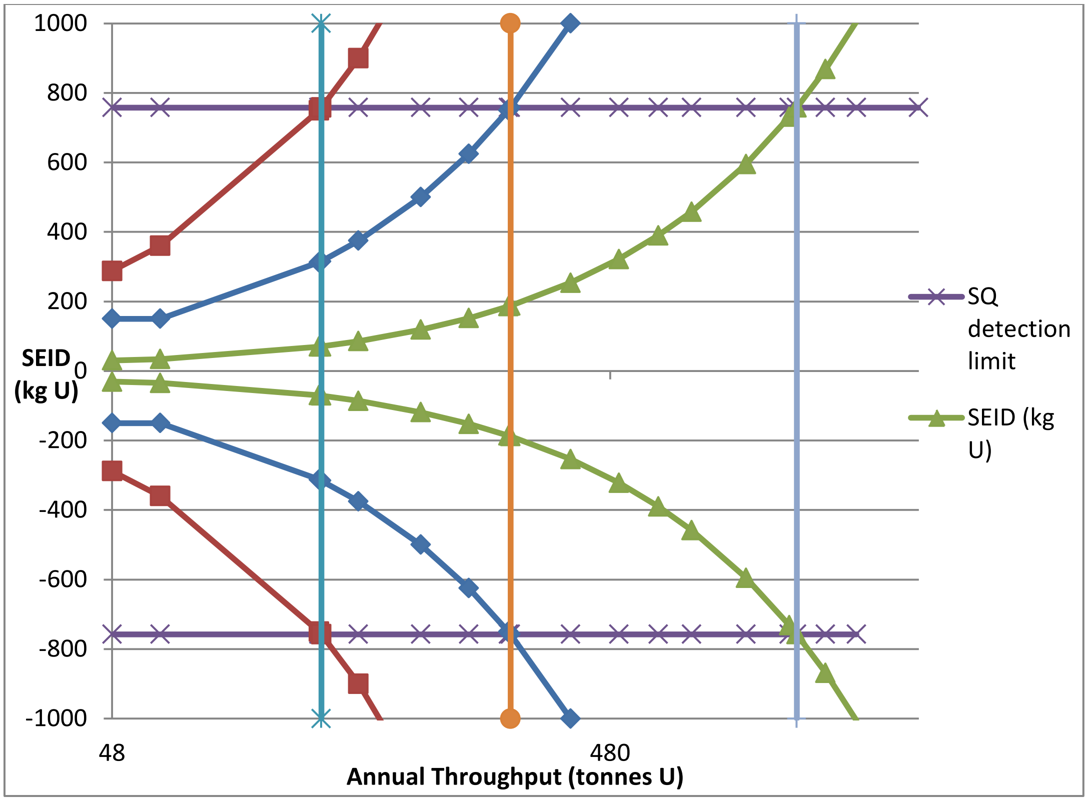


Figure 2. LEU Model Facility with 6 Month Inventory Period

Figure 2 above shows that China's limit crosses the SQ detection threshold for annual throughputs greater than 126 tonnes of U. The NRC's limit is the next to cross the SQ detection threshold for annual throughputs greater than 303 tonnes of U. Finally, the MBA's calculated SEID crosses the detection threshold for annual throughputs greater than 1138 tonnes of U. This shows that the NRC's and China's SEID limits are only effective at detecting the loss of one SQ for very small throughput facilities, well below the international average LWR pelletizing facility throughput of 727.9 tonnes of U per year.

The DOE and Russia require an inventory frequency of every 6 months for this MBA. Neither have a strict SEID limit for this category MBA, so SEIDs for material balances with this inventory frequency were not examined.

MOX

Actual throughputs from currently operating MOX fuel fabrication facilities were examined to determine a representative throughput values for this hypothetical facility. The data in Table 12 from a paper titled "Status and Advances of MOX Fuel Technology".[17] According to this information, the annual throughputs for current MOX fuel fabrication facilities range from 1-200 tons of heavy metal, so the SEID was calculated for this throughput range. Fuel assemblies produced in this facility are designed for use in LWRs and typically contain 4% plutonium although some fuel types contain more. To convert the throughput from mass of heavy metal to mass of Pu, the throughput value was multiplied by 4%.

Table 12. World MOX Fuel Fabrication Capacity (tonnes/year)

Country	Facility	Product	Capacity
Belgium	BN/Dessel	LWR FRs	40
	FBFC Int'l	LWR FAs	120-200*
France	CFCa	FBR FAs	10
	CFCa	PWR FRs	40
	MELOX	PWR FAs	100
India	Tarapur	BWR FAs	18
Japan	PFFF	ATR FAs	10
	PFPF	FBR FAs	5
Russian Federation	Paket	FBR FAs	0.3
	ERC	FBR FAs	1
UK	MDF	PWR FAs	8
** 120 tonnes/yr(BWR only); 200 tonnes/yr (PWR only)*			

Because MBA-2 in this facility has a large amount of Pu, it would be classified as Category I by the NRC, DOE, Russia, and China. For this MBA, the NRC and China require inventories every 6 months while the DOE and Russia require the every 2 months. SEID's were evaluated both for inventories occurring every 6 months and those occurring every 2 months.

Figure 3 below shows the calculated SEID for the range of possible throughputs given the NRC and Chinese requirements of a 6 month inventory frequency. This graph also provides the NRC's and China's SEID limits.

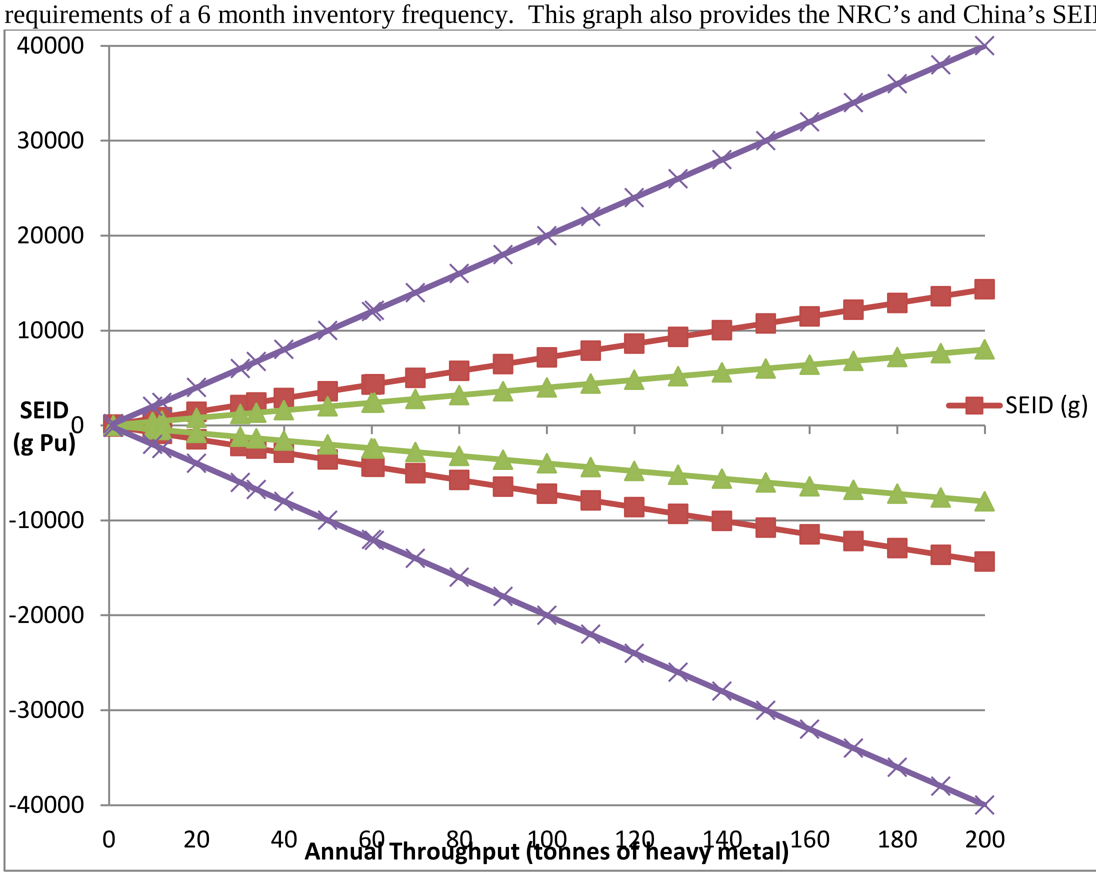


Figure 3. MOX Model Facility with 6 Month Inventory Period

This graph shows that for all annual throughputs from 1 to 200 tons of heavy metal, the material balance for MBA-2 has a SEID below China's SEID limit of 0.5% of active inventory, while it exceeds the NRC's SEID limit of 0.1% of active inventory. This facility would need to improve its accounting system for this MBA to meet the NRC requirements, but even this is not enough of an improvement. In order for this MBA's accounting system to detect the loss of one SQ (8kg Pu) with 95% detection and 5% false alarm probabilities, it's SEID needs to be ≤ 2424.24 grams of Pu This detection threshold was plotted alongside the calculated SEID, NRC 0.1% limit, and China's 0.5% limit in Figure 4 below.

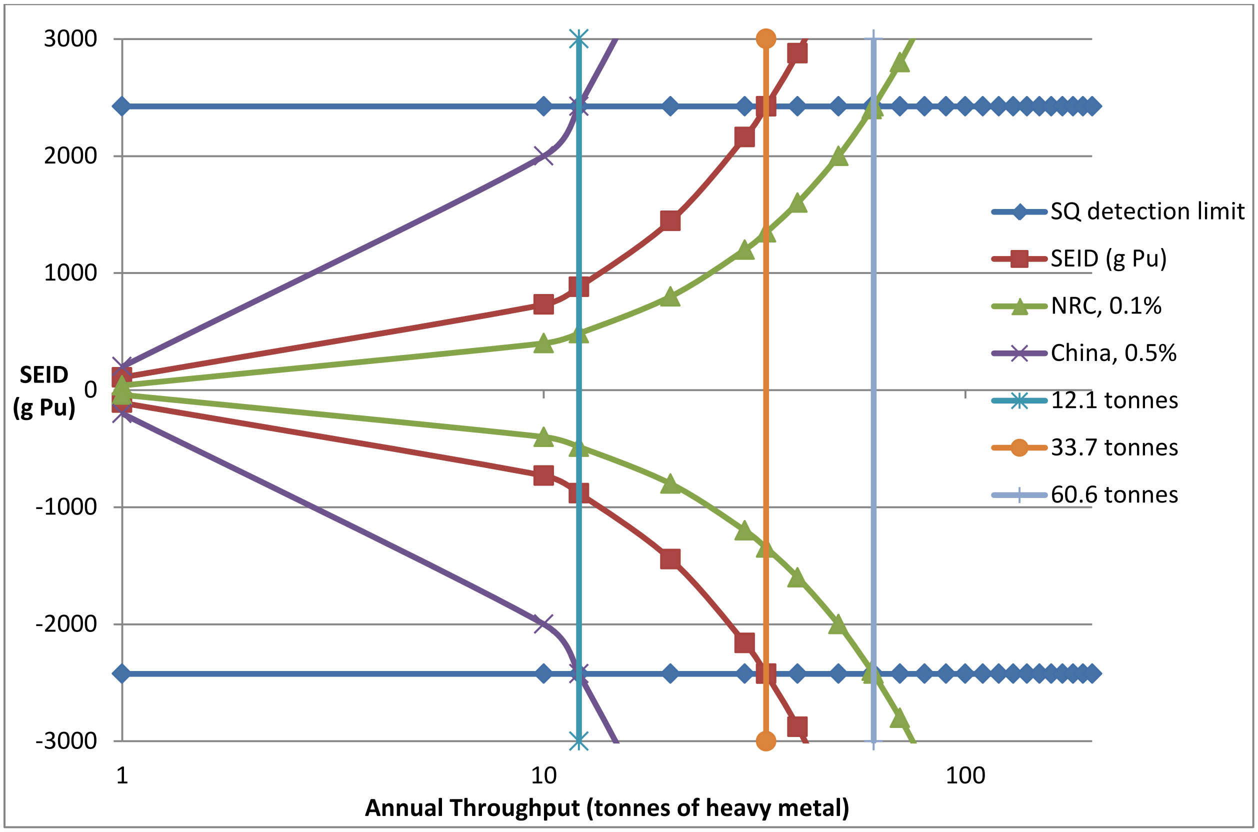


Figure 4. MOX Model Facility with 6 Month Inventory Period

Figure 4 above shows the same data as the previous graph, but the x-axis is on a logarithmic scale and is zoomed in to show details for annual throughputs from 10 to 100 tonnes of heavy metal. The two horizontal lines represent the SEID threshold for detecting the loss of one SQ given 95% detection and 5% false alarm probabilities. The three vertical lines mark the annual throughput level at which the hypothetical SEIDs (either from regulations or calculated) exceed the detection threshold. China's limit crosses the SQ detection threshold for annual throughputs greater than 12.1 tonnes of heavy metal. The calculated SEID is the next to cross the SQ detection threshold for annual throughputs greater than 33.7 tonnes of heavy metal. Finally, the NRC's limit crosses the detection threshold for annual throughputs greater than 60.6 tonnes of U.

The DOE and Russia have different regulations for this MBA and each require physical inventories every two months. The graph below shows the results from the SEID calculation for two month inventory periods. The DOE regulations say that the LEID must not exceed 2% of active inventory or a Category II quantity (for this MBA, 2kg of Pu). LEID is twice the SEID, so the DOE's SEID limits are 1% of active inventory or a half of a Category II quantity (1kg of Pu). For small throughputs, 1% of active inventory is the limit to be followed. Once the active inventory exceeds 100 kg of Pu, the SEID limit is fixed at 1 kg of Pu. The graph below shows annual throughputs from 1 to 200 tonnes, plotted logarithmically on the x-axis.

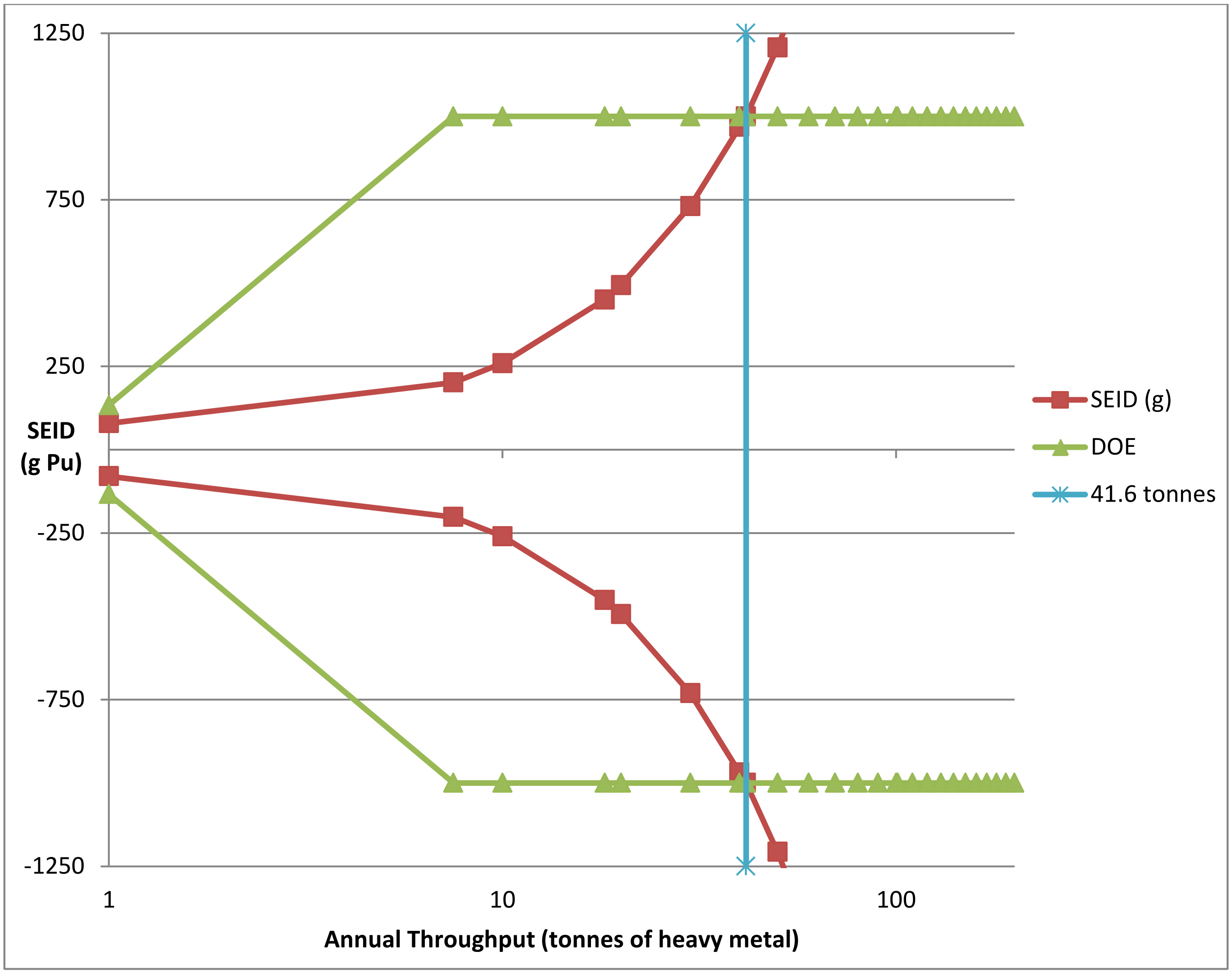


Figure 5. MOX Model Facility with 2 Month Inventory Period

As the annual throughput increases at and above 7.5 tonnes of heavy metal, the 1 kg Pu limit dominates over the 1% of active inventory limit. This can be seen above where the green line's slope ends and becomes horizontal. For this type of MBA (MOX fuel with 4% Pu) the DOE's 1% limit is only valid for very small annual throughputs (below 7.5 tonnes). The calculated SEID increases above the 1 kg Pu limit for annual throughputs over 41.6 MTHM. This MBA's SEID meets DOE requirements only for limited range of small annual throughputs (below 41.6 tonnes).

The SEID threshold for detecting the loss of one SQ given 95% detection and 5% false alarm probabilities is 2424.24 kg of Pu. The DOE's fixed SEID limit at 1 kg prevents this detection threshold from being crossed. While the DOE's SEID limit is effective at detecting the loss of one SQ, whether it can be practically implemented in medium and large throughput facilities is another issue.

Spent Fuel Reprocessing

Actual throughputs from currently operating spent fuel reprocessing facilities were examined to determine a representative throughput values for this hypothetical facility. The World Nuclear Association identified major current commercial LWR fuel reprocessing facility capacities which can be seen below in Table 13.[18] LaHague actually has two sites with max capacities of 1000 tonnes each. A report published by Pacific Northwest National Laboratory (PNNL) identified the conceptual Advanced Fuel Cycle Facility (AFCF) as a small reprocessing plant with 25 metric tons of heavy metal (MTHM) annual throughput.[19] Based on this information, the model reprocessing facility was assessed with annual throughputs ranging from 25 to 1000 metric tons of heavy metal. The model facility was assumed to reprocessing only LWR fuel which has a typical Pu concentration of 1%.[19] Fuel assemblies produced in this facility are designed for use in LWRs and contain 4% Pu. To convert the throughput from mass of heavy metal to mass of Pu, the throughput value was multiplied by 1%.

Table 13. Major Current Commercial LWR Spent Fuel Reprocessing Capacity

Country	Facility	Capacity (tonnes HM/yr)
France	LaHague	1700
UK	Sellafield (THORP)	900
Russia	Mayak	400
Japan	Tokai	90
	Rokkasho	800

Because MBA-2 in this facility has a large amount of Pu, it would be classified as Category I by the NRC, DOE, Russia, and China. For this MBA, the NRC and China require inventories every six months while the DOE and Russia require the every two months. SEIDs were evaluated both for inventories occurring every 6 months and those occurring every 2 months.

The graph below shows the calculated SEID for the range of possible throughputs given the NRC and Chinese requirements of a six month inventory frequency. This graph also provides the NRC's and China's SEID limits.

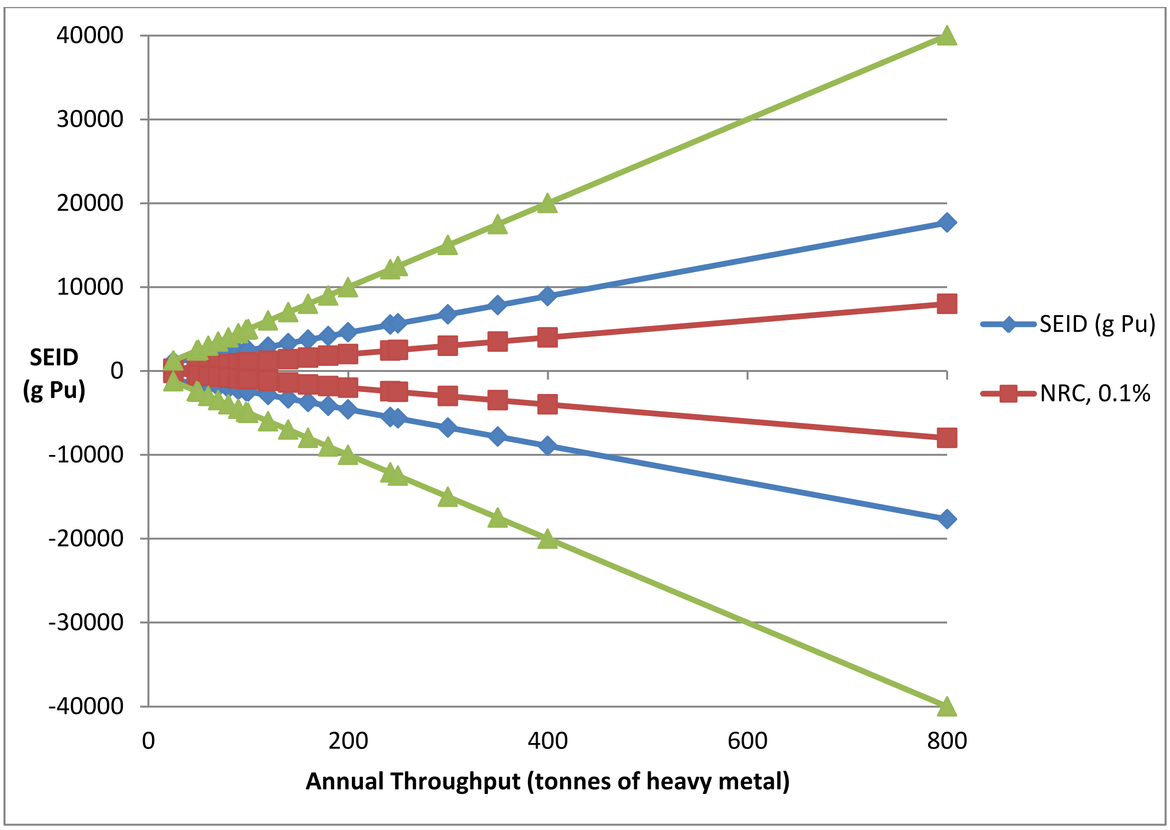


Figure 6. Spent Fuel Reprocessing Model Facility with 6 Month Inventory Period

The graph above shows that for all throughputs evaluated, the calculated SEID is below the Chinese regulation's limits but above the NRC's limits. The accounting system for this MBA would be sufficient by China's standards, but it would not be acceptable according to the NRC's regulations.

Even if this MBA's accounting system had a SEID below the NRC's limit, it would not necessarily be effective at loss detection. In order for this MBA's accounting system to detect the loss of one SQ (8kg Pu) with 95% detection and 5% false alarm probabilities, it's SEID needs to be ≤ 2424.24 grams of Pu. This detection threshold was plotted alongside the calculated SEID, NRC 0.1% limit, and China's 0.5% limit in Figure 7 below.

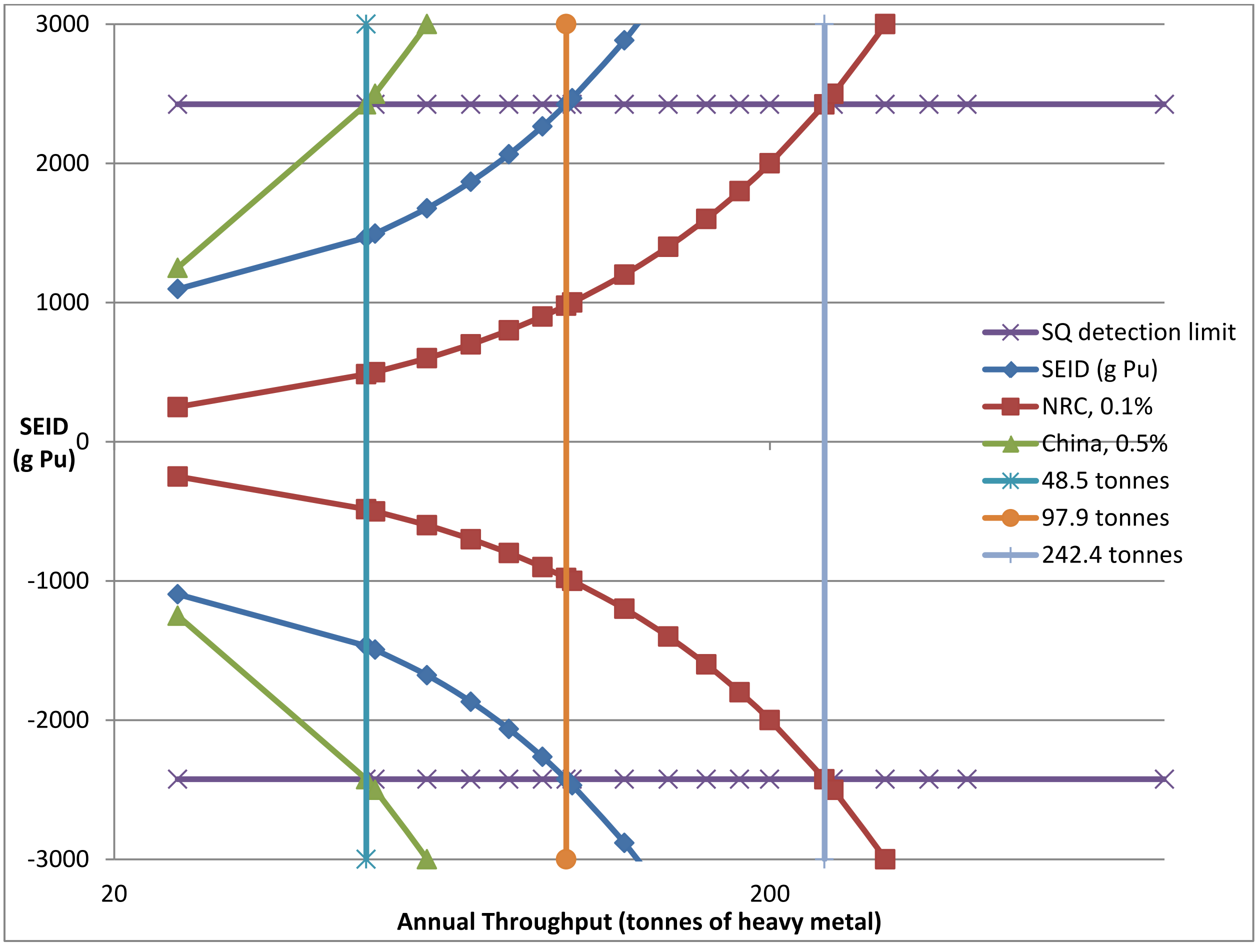


Figure 7. Spent Fuel Reprocessing Model Facility with 6 Month Inventory Period

Figure 7 above shows the same data as the previous graph, but the x-axis is on a logarithmic scale and is zoomed in to show details for annual throughputs from 40 to 400 tonnes of heavy metal. The two horizontal lines represent the SEID threshold for detecting the loss of one SQ given 95% detection and 5% false alarm probabilities. The three vertical lines mark the annual throughput level at which the hypothetical SEIDs (either from regulations or calculated) exceed the detection threshold. China's limit crosses the SQ detection threshold for annual throughputs greater than 48.5 tonnes of heavy metal. The calculated SEID is the next to cross the SQ detection threshold for annual throughputs greater than 98.3 tonnes of heavy metal. Finally, the NRC's limit crosses the detection threshold for annual throughputs greater than 242.4 tonnes of U. This means that China's limits are sufficient for small reprocessing facilities and the NRC's limits are sufficient for medium sized reprocessing facilities. Large facilities however are not capable of meeting these limits or detecting the loss of one SQ.

The DOE and Russia have different regulations for this MBA and they each require physical inventories every two months. The graph below shows the results from the SEID calculation for two month inventory periods. The DOE regulations say that the LEID must not exceed 2% of active inventory or a Category II quantity (for this MBA, 2kg of Pu). LEID is twice the SEID, so the DOE's SEID limits are 1% of active inventory or a half of a Category II quantity (1kg of Pu). For small throughputs, 1% of active inventory is the limit to be followed. Once the active inventory exceeds 100 kg of Pu, the SEID limit is fixed at 1 kg of Pu. The graph below shows annual throughputs from 25 to 800 tonnes, plotted logarithmically on the x-axis.

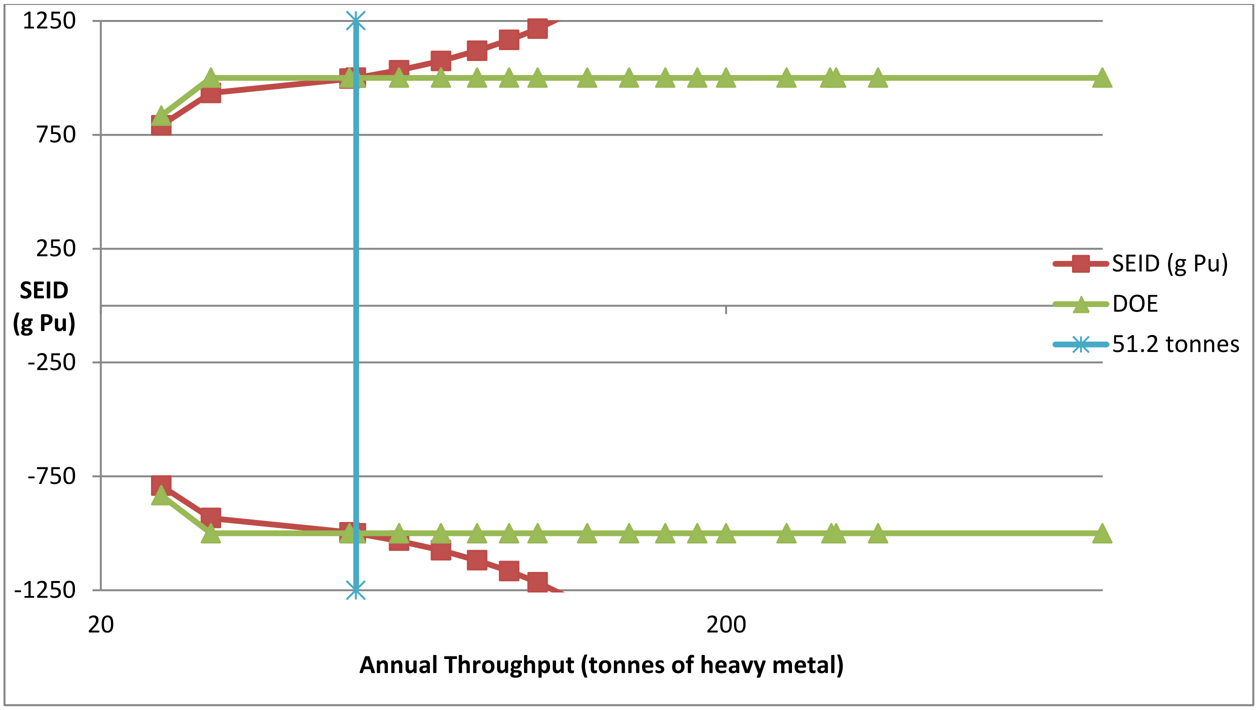


Figure 8. Spent Fuel Reprocessing Model Facility with 2 Month Inventory Period

As the annual throughput increases at and above 30 tonnes of heavy metal, the 1 kg Pu limit dominates over the 1% of active inventory limit. This can be seen above where the green line's slope ends and becomes horizontal. For this type of MBA (spent LWR fuel with 1% Pu) the DOE's 1% limit is only valid for very small annual throughputs (below 30 tonnes). The calculated SEID increases above the 1 kg Pu limit for annual throughputs over 53 MTHM. This MBA's SEID meets DOE requirements only for limited range of small annual throughputs (below 53 tonnes).

The SEID threshold for detecting the loss of one SQ given 95% detection and 5% false alarm probabilities is 2424.24 kg of Pu. The DOE's fixed SEID limit at 1 kg prevents this detection threshold from being crossed. While the DOE's SEID limit is effective at detecting the loss of one SQ, whether it can be practically implemented in medium and large throughput facilities is another issue.

Material Balance Conclusion

The results from these model facility material balances and SEID calculations reveal certain logical inconsistencies in the current physical inventory regulations. Many of the regulations which put a limit on the SEID are a function of the facility's annual throughput. When these limits were applied to realistic accounting systems, they were generally found to be effective at small throughputs and ineffective at large throughputs.

The regulatory SEID limits and calculated SEIDs were compared against the loss detection threshold for one SQ with 95% and 5% alarm and false alarm probabilities. The IAEA's definition for a significant quantity (SQ) was used in this evaluation. For the LEU facility, one SQ is 2500kg of U enriched to 3% in U235. For the MOX and reprocessing facilities, one SQ is 8kg of Pu. Many nuclear physicists agree that the actual quantity of material needed to make a fission weapon is less than the IAEA's SQ.[2] **Even without the most advanced technology, the NRDC argued that a fission weapon could be produced with a fraction of the material that makes up the**

IAEA's SQ. If the NRDC's arguments were to prevail, the SEID loss detection thresholds would be even lower than the ones that are examined in the paragraphs below.

LEU

For the LEU fabrication facility, only the NRC and China's SEID regulations for this MBA could be evaluated. The DOE and Russia have no strict SEID limit for this category MBA; both of their regulations mention that this limit is site specific but do not provide any further detail. Both the NRC and China's SEID limits were met in the process MBA for all annual throughputs examined (48-200 tonnes of U) given the required 12 month inventory period. However, the ability of the SEID limits to detect the loss of one SQ with a high probability was not possible for all throughputs examined. China's limit failed to meet this detection threshold for annual throughputs greater than about 126 tonnes of U. This throughput is very low for a LWR pelletizing facility; in fact, India's DAE Nuclear Fuel Complex is the only one currently in operation with an annual capacity this low. The NRC's SEID limit failed to meet the one SQ detection threshold for annual throughputs greater than 303 tonnes of U. While this level of throughput may be considered a medium sized LWR pelletizing facility, the three facilities of this type currently operating in the US have annual throughput capacities of 1200, 1200, and 1500 tonnes of uranium. The calculated SEID for this MBA performed much better than the two regulatory limits, with the detection threshold met for annual throughputs as high as 1138 tonnes of uranium. While this is acceptable for most currently operating facilities of this type, this detection capability is still not adequate for the three large facilities operating in the US if they were operating at full capacity.

MOX

The NRC and China require a six month inventory period for the process MBA in the MOX model facility, so their SEID limits were assessed using this inventory frequency. For the entire range of annual throughputs examined (1 to 200 tonnes of heavy metal), the calculated SEID was below China's limit but above the NRC's limit. China's SEID limit is only effective at detecting the loss of one SQ for annual throughputs at or below 12.1 tonnes of heavy metal. Five out of the eleven examined currently operating MOX fabrication facilities have throughput capacities greater than 12.1 tonnes. The NRC's SEID limit is much more effective since the detection threshold was crossed for throughputs greater than 60.6 tonnes of heavy metal. Only two out of the eleven currently operating MOX fabrication facilities examined have throughput capacities greater than 60.6 tonnes. The calculated SEID failed to meet the detection threshold for throughputs greater than 33.7 tonnes of heavy metal, and 4 of the current MOX facilities have throughput capacities greater than this. This MBA needs to reduce the error of its accounting system in order to meet the NRC's requirements. This improvement would make the accounting system capable of detecting the loss of one SQ with high probability for most of the currently operating MOX fuel fabrication facilities.

The DOE and Russia require a two month inventory period for the process MBA in the MOX model facility. The DOE has an SEID limit for this category MBA, but Russia does not have a limit for the SEID, only for the ID. The DOE's SEID limit for this MBA is the lesser between 1% of active inventory, or 1 kg of Pu. 1% of active inventory is the limiting regulation for annual throughputs up to 7.5 tonnes of heavy metal, and for throughputs greater than this the limit becomes fixed at 1 kg of Pu. This accounting system is capable of detecting the loss of one SQ for SEID values below 2424.24 kg of Pu; therefore the DOE's SEID limits are very capable of this loss detection. Whether the MBA's accounting system can attain an SEID at or below the DOE's limits is another issue. For the accounting system in the MOX model facility's process MBA, the DOE's SEID limit was met only for annual throughputs at or below 41.6 tonnes of heavy metal. This level of throughput is associated with small sized facilities. In order for larger facilities to meet the DOE's SEID requirements, measurement uncertainty could be reduced or more frequent inventory periods could be implemented.

Spent Fuel Reprocessing

The NRC and China require a six month inventory period for the process MBA in the reprocessing model facility, so their SEID limits were assessed using this inventory frequency. For the entire range of annual throughputs examined (25 to 1000 tonnes of heavy metal), the calculated SEID was below China's limit but above the NRC's limit. China's SEID limit is only effective at detecting the loss of one SQ for annual throughputs at or below 48.5 tonnes of heavy metal. The current smallest commercial LWR reprocessing facility has an annual capacity of 90 tonnes, and China's SEID limit is not capable of meeting the detection threshold for this sized facility. The NRC's SEID limit is much more effective and the detection threshold was crossed for throughputs greater than 242.4 tonnes of heavy metal. This level of throughput is representative of a small to medium sized facility. The calculated SEID failed to meet the detection threshold for throughputs greater than 98.3 tonnes of heavy metal. The commercial LWR reprocessing facility in Tokai, Japan is the only one currently operating with a capacity this small. This MBA needs to reduce the error of its accounting system in order to meet the NRC's requirements. This improvement would make the accounting system capable of detecting the loss of one SQ with high probability for small to medium sized reprocessing facilities, but most that are currently in operation have capacities much larger than this.

The DOE and Russia require a two month inventory period for the process MBA in the Reprocessing model facility. The DOE has an SEID limit for this category MBA, but Russia does not have a limit for the SEID, only for the ID. The DOE's SEID limit for this MBA is the lesser between 1% of active inventory or 1 kg of Pu. 1% of active inventory is the limiting regulation for annual throughputs up to 30 tonnes of heavy metal, and for throughputs greater than this the limit becomes fixed at 1 kg of Pu. This accounting system is capable of detecting the loss of one SQ for SEID values below 2424.24 kg of Pu; therefore the DOE's SEID limits are very capable of this loss detection. Whether the MBA's accounting system can attain an SEID at or below the DOE's limits is another issue. For the accounting system in the spent fuel reprocessing model facility's process MBA, the DOE's SEID limit was met only for annual throughputs at or below 53 tonnes of heavy metal. This level of throughput is associated with small and medium sized facilities. In order for larger facilities to meet the DOE's SEID requirements, measurement uncertainty could be reduced or more frequent inventory periods could be implemented.

Process Monitoring History

Process Monitoring (PM) has long been used in both nuclear and non-nuclear facilities to evaluate industrial processes and operating conditions.[20] It has been used as an international safeguards tool since the late 1970's.[20] During this time, the IAEA was facing the startup of the Tokai Reprocessing Plant in Japan and the possibility of the large-scale commercial reprocessing plant at Barnwell in the United States. "The technology holders, including France, Germany, Great Britain, the United States, and Japan joined the IAEA in what became the Tokai Advanced Safeguards Exercise (TASTEX) to investigate advanced techniques to improve international safeguards capabilities for the larger commercial plants coming on line."[20] One of their recommendations was for implementation of process monitoring, and thus it became one of the requirements in IAEA applied safeguards at the Tokai Reprocessing Plant.[20] "The standard for process monitoring, particularly for international safeguards, remained the application at Tokai through the 1990's."[20] Another early application of process monitoring occurred in the 1980s at the Barnwell reprocessing plant. Although the facility never went into production, as part of the startup PM data was collected at each unit process accounting area and NMA was performed daily or on a data-driven basis.[6]

What is Process Monitoring?

The term "Process Monitoring" (PM) has been used in different ways since its introduction to the safeguards communities in the late 1970's, but no general definition of it has been accepted to date.[21] A report published by the IAEA in 1987 surveyed the top literature on process monitoring and produced the following definition: [21]

"Process Monitoring is an extended form of containment and surveillance especially supporting near-real-time materials accountancy that makes the best use of information mainly acquired by facility operators in order to detect unusual (anomalous, abnormal) conditions (activities, movements, situations) that might be indicative of diversions".

This report also identified the basic elements of process monitoring as follows: [21]

a) Monitoring Points
    - Select monitoring points from the process.

b) Data and Sensors
    - Install various kinds of sensors or other instruments to acquire data from the monitoring points mentioned in a) above.
    - Make full use of instruments installed by plant operators, and install additional instruments necessary for safeguards purposes.

c) Computers and other Equipment
    - Install equipment in order to gather, convert, and process data, as mentioned in b) above, and if necessary make high level decisions and issue alarms according to the objective and criteria mention in d) below.

d) Objectives and Criteria
    - Establish objectives and criteria in order to attain safeguards goals.

Process monitoring is basically a real-time data collection system which focuses on the in-process portion of the facility. There are many different types of data that can be collected by a process monitoring system, as well as many different ways this data can be used. Each nuclear material facility is unique, and thus incorporation of process monitoring is unique to each facility.

To begin a process monitoring program, a decision is made about which process will be monitored. The identified process is then divided into logical process units. Regardless of the process, the goal is to identify the smallest process unit possible to "draw a box around." In other words, the process unit is bounded by the available input and output measurements or estimates. It may be necessary to add measurement points to provide sufficient data for process monitoring. The goal is to isolate any resulting process differences, so the smaller the process unit, the greater the chance of identifying, correcting and/or explaining process differences.

After process units are identified, all inputs and outputs are identified and analyzed for quality of control and measurements. Waste is evaluated to determine if it is significant enough to include as an output. Outputs that include relevant or significant salvage or waste streams (byproducts) that are generated as a result of the process. Measurement points are identified and documented. Normal statistical techniques, using data gained from studies conducted on the process are used to perform the evaluation of the cumulative differences.

Types of Process Monitoring Today

Current nuclear fuel plants already use some form of process monitoring to gather data about material as it is moved and converted throughout the facility. Without formal process monitoring programs in place, these plants already have some degree of integration between the process monitoring data and accountancy system.[22] "Existing reprocessing plants (also MOX and LEU plants) process a wealth of information including measurements for traditional materials accountancy, measurements for process monitoring and control, administrative checks, and sensors for physical security. While some of this data is integrated, these systems are traditionally separate."[23]

Process monitoring has many different applications and PM data can come in a variety of forms, but several key components are found in any PM system.[22] Commonalities of process monitoring are the subdivision of the process and placement of sensors so that data is continuously acquired while the facility is in operation. This allows much more frequent material measurements than is possible with a typical NMA system.[22] These common components are seen in each of two main process monitoring applications. Each of these applications provides unique benefits, and a plant can perform either or both forms of process monitoring.

PM for Process Control

A common approach for diverting SNM can occur from minor modifications to processing conditions. Process monitoring can be used to detect diversion by analyzing process control measurements (such as tank level, flow meters, density, or temperature) to detect abnormal plant operation.[24] This form of PM is like an extension of the material control portion of the old MC&A activities.[24] "Process monitoring strives for a real-time understanding of activities associated with the control of material as it moves through the process. It makes use of any and all indicators of process activity without concentrating on the strict accounting of nuclear material in process solutions."[25]

This application of process monitoring can satisfy the IAEA safeguards accountancy goal for timely detection of abrupt diversion. A traditional accounting system would not detect an abrupt loss until after the physical inventory which may only be performed 1-6 times a year. Process monitoring for process control would detect the abnormal plant operation immediately and would pinpoint the location of the anomaly which would then be investigated further. Many process control measurements are already taken by facility operators, and making use of this data for safeguards purposes could be cost effective.[22] When PM is properly implemented protracted diversions may still be the hardest scenario to detect for processes with very large quantities available since removing smaller quantities of material is easier to conceal in the slight variations of the plants processes. But PM will have added a great deal of complexity to the illicit act by make the margin of error much smaller per attempt and forcing a much larger number of attempts to collect a desired amount.

PM for Accounting

A more advanced application is to use process monitoring data in conjunction with material accounting to create a Near Real Time Accounting (NRTA) system. The concept of NRTA is simply to make the material balance closures and analyses more often than the previously accepted physical inventories which take place every two to twelve months. In most facilities that utilize PM data to enable NRTA, frequent balance closure is made possible by using process monitoring to aid in estimating in-process inventory. Frequent closures facilitate more timely detection of accounting anomalies as well as improve the system's sensitivity of detection by reducing the throughput dominated measurement errors.[25] Using PM to support NRTA can be seen as an extension of the accounting functions of MC&A.[25] If effective NRTA is achieved, it eliminates the need for a plant flush out which is required for traditional physical inventories. Therefore it provides safeguards advantages in improved detection sensitivity/timeliness and an operator advantage of less plant down time.

A report published by the NRC titled "The Use of Process Monitoring Data for Nuclear Material Accounting" was one of the first efforts to quantify the effectiveness of using PM data to enhance accounting efforts.[22] This report applied a NRTA system to two licensed fuel fabrication facilities and compared the effectiveness of the NRTA system to the traditional accounting system. This report found that the NRTA system's loss detection effectiveness was better than the capabilities of the current accounting systems.[22] The loss detection time periods were only a few days in contrast to many weeks, and measurement errors were only a small fraction of the typical facility's accounting system, largely as a consequence of the short time spans involved between measurements. Additionally, loss alarms generally localized the trouble point to a small part of the process area. This study also found that the new accounting system was better at detecting protracted diversions of material than the previous system.[22]

Another report published by Sandia National Laboratory in 2010 titled "The Integration of Process Monitoring for Safeguards" provides information on a recent process monitoring study.[26] This report describes how process monitoring was integrated with the existing Separations and Safeguards Performance Model (SSPM). The SSPM is a high-level materials tracking model of an aqueous reprocessing plant developed at Sandia for materials accountancy and process monitoring analysis with the original purpose being to simulate materials accountancy measurements. A process monitoring system was applied to this model and its effectiveness was compared against a traditional accounting system for four different diversion scenarios. Both abrupt and protracted diversions were modeled to occur during early and late times in the run. In all cases a total of 8 kg of plutonium were removed. Both the abrupt cases and the protracted case early in the run were detected in a timely manner, and the process monitoring system responded as intended. The late run protracted diversion, however, did not alarm and showed a scenario that must be addressed in future work. These results indicate the addition of process monitoring data to the accounting system appears to provide a significant advantage to the timeliness goal for detecting diversion, and the real-time process monitoring data makes it possible to respond well before one significant quantity of material as defined by the IAEA is removed.[26]

PM Conclusion

Integrating process monitoring data into a safeguards system has consistently shown improved detection capabilities and timeliness. However, one challenge in modern safeguards is how to quantify the benefit of using process monitoring data. Because process monitoring data can have several roles, it is necessary to consider the quantitative benefits of each possible role. Of the regulating bodies discussed here, none other than the NRC has set performance goals ("unit process detection capability" in the NRC MC&A regulations) for process monitoring. As mentioned previously, although the Department of Energy and Russian regulations mention the concept of process monitoring, they do not establish performance criteria. Also, even though the NRC mentions and establishes performance criteria, that criterion is dated in that it was established before the NRDC[2] analysis of significant quantities.

While it is clear that process monitoring could be used more frequently to enhance safeguards, due to lack of performance criteria it is currently not possible to quantify its benefits. This will remain the case until other regulating bodies set performance goals and requirements for process monitoring implementation.

Conclusion

The purpose of this paper was to compare the different nuclear material accounting regulations held by the NRC, the DOE, Russia and China. These regulations were first compared side by side in various tables. However, the actual differences were not seen until these regulations were applied to hypothetical model LEU, MOX, and spent fuel reprocessing facilities. The two parameters of the regulations that were examined using the model facilities were the required inventory frequencies and limits placed on the material balance's SEID. One logical inconsistency observed was that Russia has no limit on a material balance's SEID (e.g., the magnitude of the error). While their regulations do set secondary limits based on a fixed quantity, their regulations allow an accounting system to have any amount of measurement error. At large throughputs with large errors the secondary fixed quantity limits become of questionable value. The NRC and China's SEID limits are both a percentage of the MBA's active inventory. For very small throughputs the allowed SEID is small and thus the accounting system is capable of detecting the loss of one SQ. For medium and large throughputs, however, the allowed SEID grows too large to effectively detect significant diversions of material. The DOE has a strict SEID limit for Category I and II MBA's, but Category III and IV MBA SEID limits are site specific so these categories were not examined for the DOE. For the two cases examined (Pu processing, Category I MBA), the DOE's SEID limit is the lesser of 1% of active inventory or 1kg of Pu. For very small throughputs, 1% of active inventory was the dominant limit and the calculated SEIDs for the two model facilities were well below this limit. For active inventories greater than 100kg of Pu (this would be considered a small facility), the variable SEID limit switches to a fixed amount of 1kg of Pu. While a SEID this small would be effective at detecting the loss of even half of one SQ, a traditional accounting system could not realistically produce a SEID this small for facilities with medium and large annual throughputs.

The calculated standard errors (SEIDs) for the measurements used in the model facilities material balances are not exact. However, the individual measurement uncertainties used in the calculations were very close to the IAEA's international target values,[15] and the throughput ranges examined were based on currently operating facilities of the same, so the calculated SEIDs were a good approximation of actual operating facilities' SEIDs. For each model facility examined, the accounting system was capable of detecting the loss of one SQ only for small annual throughputs. If the suggested eight fold reduction to a SQ was applied, the model facilities' accounting systems would not be capable of detecting diversion of this new SQ for even the smallest annual throughputs examined. The only way to improve the accounting systems in this case is to reduce the material balances' SEIDs. This can be done either by improving individual measurements uncertainties or by reducing the material throughput for each balance period. Accounting system's measurement techniques are already near state of the art, a slight reduction in error would be very costly and a major reduction in error is currently impossible. Thus the most effective to reduce the SEIDs is to make more frequent material balances. This reduces the material throughput per balance period, thus reducing the absolute uncertainty for each individual measurement which in turn reduces the SEID. The only issue with this solution is that typical physical inventories require a plant shutdown and take several days of downtime to complete. Process monitoring used in combination with a NRTA system can facilitate daily material balance closures while the plant continues to operate.

A commonality between all the MC&A regulations compared is that they do not establish an accounting system's minimum detection capability. Most of the regulations place limits on the SEID as a percentage of throughput. This means that as throughput increases, so does the allowable SEID of the accounting system, and thus the system's detection capability decreases. These regulations should instead define specific detection goals and establish fixed limits on the SEID which will allow the accounting system to meet the detection goals. As shown earlier, this is the case when DOE defines not just the SEID as a percent of active inventory but also sets a requirement where the limit itself cannot exceed a stated fixed value. The results from the three model facilities showed that with current accounting practices, as throughput increases, SEIDs quickly exceed the one significant quantity detection capability. If process monitoring data is incorporated into the accounting system, more frequent balance closures can take place which will facilitate better detection capabilities. Even though many facilities collect PM data for operator control, in most cases this data is not being applied to the facility's safeguards. This may be due to the lack PM requirements in state's MC&A regulations. Of the states/organizations MC&A regulations examined, only the NRC provided specific regulations for process monitoring and it is only currently applied to two Category 1 facilities in the U.S.

Appendix A: Regulations

Material Definitions

United States

NRC NRC: 10 CFR Part 74 - Material Control and Accounting of Special Nuclear Material (10 CFR Part 74.53 Process Monitoring) Washington DC: Nuclear Regulatory Commission

As far as taking physical inventories are concerned, the U.S. NRC categorizes NM solely based on the isotope, enrichment, and quantity. The materials of interest are Pu, U-235, and U-233. For Pu and U-233, enrichment is not addressed. However, this is not the case for U-235. Highly Enriched Uranium (HEU) is defined as U enriched to 20% or more in U-235. Medium Enriched Uranium (MEU) is defined as U enriched to 10% or more but less than 20% in U-235. Low Enriched Uranium (LEU) is defined as U enriched above natural U but less than 10% in U-235.

DOE U. S. Department of Energy Regulations

1. US DOE Order – DOE O 474.2 – Nuclear Material Control and Accountability – June 27, 2011
2. U.S. DOE Standard – DOE-STD-1194-2011 – Nuclear Materials Control and Accountability – June 2011

The DOE takes a different approach to material definitions than the NRC does. While quantities of specific isotopes are still important, there is less emphasis on enrichment, but instead categories are defined based upon the material form. The elements/isotopes of interest here are Pu, U-232, and contained U-235; separated Np-237, Am-241, and Am-243. Material forms of these are assigned an attractiveness level from A-E, and quantities of these material forms govern the Category number assigned. The highest attractiveness level (A) is given to Weapons which includes assembled weapons and test devices. Attractiveness level B is for **Pure Products** which include pits, major components, button ingots, recastable metal, and directly convertible materials. **High-Grade Materials (HGM)** are assigned attractiveness level C and these include carbides, oxides, nitrates, solutions (≥25 g/L), fuel elements/assemblies, alloys/mixtures, and UF4/UF6 (≥50% enriched). **Low-Grade Materials (LGM)** are attractiveness level D which includes solutions (1-25 g/L), process residues requiring extensive reprocessing, Pu-238 (except waste), and UF4/UF6 (≥20% < 50% enriched). The last attractiveness level (E) is not of interest to this report.

Russia

Federal Rules and Regulations Regarding the Use of Atomic Energy- NP-030-12 -, "Basic Nuclear Material Control and Accounting Rules" Adopted by the Federal Environmental, Industrial, and Nuclear Regulatory Authority Order No 255, Dated 17 April 2012.

Materials of interest are Pu (denotes Pu of any composition that contains no more than 60% Pu-238), U-233, U-235, Np-237, Am, and Cf. Russia defines materials in much the same way as the DOE. Russia does not address weapons like the DOE; however, the DOE's next three material definitions have very similar Russian counterparts. Russia defines a **Metal Product** as follows: Metal product and billets; ingots, small pellets/meal, and their alloys and mixtures; fuel elements and assemblies containing metallic and intermetallic fuel; defective product and waste reprocessed by smelting. This definition is very similar to the DOE's Pure Products. **Product with High Nuclear Material Content (PHNMC)** is defined as follows: carbides, oxides, chlorides, nitrides, fluorides and their alloys and mixtures; fuel elements and assemblies containing fuel from the compounds listed above; other product with a concentration (content) of nuclear material at least 25 g/l. This definition is nearly identical to the DOE's High-Grade Materials. Russia's **Product with Low Nuclear Material Content (PLNMC)** is defined as follows: product requiring complex processing; product with a concentration (content) of nuclear material from 1-25 g/l. This definition is nearly identical to the DOE's Low-Grade Materials.

China

1) Nuclear Safety Guide HAD 501/01 – Nuclear Material Accountancy of LEU Conversion and Fuel Fabrication Facilities – Approved and Released by the Chinese National Nuclear Safety Administration September 1, 2008.

2) Nuclear Safety Guide HAF 501/01 – Rules for Implementation of the Regulations on Nuclear Materials Control of the People's Republic of China - Released by National Nuclear Safety Administration, Ministry of Energy, and Commission of Science Technology and Industry for National Defense on September 25, 1990

Materials of interest are Pu, U-235, U-233, Tritium, and Lithium. All of the forms of interest are for unirradiated materials. Distinctions are made between HEU, MEU, and LEU (same as NRC's definitions for enrichment); however the regulations are not clear if the U is enriched in U-235 or U-233. Categorization of Pu, U, T, and Li are set by the quantity of the elements. This differs from the NRC, DOE, and Russia's categorization of U which is based on the isotopic quantity of U-233 and U-235.

Inventory Definitions

Below are several definitions which are important to understanding physical inventory control procedures. These definitions come from the NRC's MC&A regulations.[7] Similar definitions can also be found in the DOE[8] and Russian[9] regulations in most cases.

Abrupt loss: a loss occurring in the time interval between consecutive sequential performances of a material control test which is designed to detect anomalies potentially indicative of a loss of (SSNM) from a specific unit of SSNM (i.e., a quantity characterized by a unique measurement) introduced into a process.

Active Inventory (same definition for DOE and NRC): sum of additions to inventory, beginning inventory, ending inventory, and removals from inventory, after all common terms have been excluded. Common terms are any material values which appear in the active inventory calculation more than once and come from the same measurement.

- Russia does not define active inventory, however a quantity which they use in a similar way is defined as follows: total quantity of the given nuclear material that was converted and underwent accounting measurements during the material balance period or physical inventory.

Beginning inventory (BI) (same definition for DOE, NRC, and Russia): book inventory quantity at the beginning of an inventory period, and is the reconciled physical inventory entered into the books as an adjusted inventory at the completion of the prior inventory period.

Inventory difference (ID) (same definition for DOE and NRC): arithmetic difference obtained by subtracting the quantity of SNM tabulated from a physical inventory from the book inventory quantity. Book inventory quantity is equivalent to the beginning inventory (BI) plus additions to inventory (A) minus removals from inventory (R), while the physical inventory quantity is the ending inventory (EI) for the material balance period in question (as physically determined). Thus mathematically, $ID = BI + A - R - EI$.

- Russia's definition of ID is nearly the same, except the signs are flipped. Thus mathematically, $ID = EI + R - BI - A$. This does not matter since the absolute value of the ID is important, not the relative value.

Limit of Error of the Inventory Difference (LEID) (same definition DOE and NRC): Twice the standard error of the estimated measurement uncertainty associated with the ID.

Standard Error of the Inventory Difference (SEID) (same definition DOE, NRC, and Russia): standard deviation of an inventory difference that takes into account all measurement error contributions to the components of the ID.

Estimator: a function of a sample measurement used to estimate a population parameter.

Tamper-Indicating Device (TID) (DOE definition): device that may be used on items such as containers and doors, which because of its uniqueness in design or structure, reveals violations of containment integrity.

NRC Process Monitoring (PM)

Definitions

These definitions come from the NRC's MC&A regulations.[7]

Process difference (PD) : means the determination of an ID on a unit process level with the additional qualification that difficult to measure components may be modeled.

Process yield : means the quantity of SSNM actually removed from a unit process compared with the quantity predicted (based on a measured input) to be available for removal. Process yield differs from a process difference in that holdup and side streams are not measured or modeled.

Formula kilogram: SSNM (Cat. I) in any combination in a quantity of 1000 grams computed by the formula, grams = (grams contained U-235) + 2.5 (grams U-233 + grams Pu).

Estimator: a function of a sample measurement used to estimate a population parameter.

Category I Subclasses for PM

Category IA material: SSNM directly useable in the manufacture of a nuclear explosive device, except if:

(1) The dimensions are large enough (at least two meters in one dimension, greater than one meter in each of two dimensions, or greater than 25cm in each of three dimensions) to preclude hiding the item on an individual;

(2) The total weight of an encapsulated item of SSNM is such that it cannot be carried inconspicuously by one person (i.e., at least 50 kilograms gross weight); or

(3) The quantity of SSNM (less than 0.05 formula kilograms) in each container requires protracted diversions to accumulate five formula kilograms.

Category IB material: means all SSNM material other than Category IA.

Appendix B: Model Facilities

Variance Calculation

The equations used in the SEID calculation can be found below. This method has been adapted from the STR reports which form the basis of the model facilities.[12,13,14]

The random error variance of the total element weight of each stratum, $V_r(x_{kqpt})$, can be calculated using equation 1 below:

$$V_r\left(x_{kqpt}\right) = x_{kqpt}^2\left(\frac{\delta_{rq..}^2}{n_k m_k} + \frac{\delta_{r.p.}^2}{r_k m_k} + \frac{\delta_{r..t}^2}{c_k r_k m_k}\right) \tag{1}$$

Some of the errors for the bulk weight methods are given on an absolute basis rather than a relative basis. These can be converted to the relative values using the relationship found below in equation 2:

$$\delta_{rq..} = \frac{n_k m_k \sigma_{rq..}}{x_{kqpt}} \tag{2}$$

where δ is the relative standard deviation and σ is in absolute units.

To find the random variance of the ID, $V_r(ID)$, $V_r(x_{kqpt})$ is summed over all the strata as seen below in equation 3.

$$V_r(ID) = \sum_{k=1}^{K} V_r(x_{kqpt}) \tag{3}$$

The systematic error variance of the ID, $V_s(ID)$, can be calculated from equation 4 below:

$$V_s(ID) = \sum_q M_{q..}^2 * \delta_{sq..}^2 + \sum_p M_{.p.}^2 * \delta_{s.p.}^2 + \sum_t M_{..t}^2 * \delta_{s..t}^2 \tag{4}$$

The statistics $M_{q..}$, $M_{.p.}$, and $M_{..t}$ are calculated as follows:

For each value of q, calculate

$$M_{q..} = \sum_{k=1}^{K} A_k * x_{kqpt} \tag{5}$$

Where A_k = +1 for input and beginning inventory strata and A_k = -1 for output and ending inventory strata.

For each value of p, calculate

$$M_{.p.} = \sum_{k=1}^{K} A_k * x_{kqpt} \tag{6}$$

For each value of t, calculate

$$M_{..t} = \sum_{k=1}^{K} A_k * x_{kqpt} \tag{7}$$

The total variance of ID, V(ID) is the sum of the random and systematic variances:

$$V(ID) = V_r(ID) + V_s(ID) \tag{8}$$

The standard deviation of the ID, SEID is the square root of this total variance:

$$\sigma_{ID} = \sqrt{V(ID)}$$

(9)For the LEU conversion and MOX fabrication facilities; In the systematic error equation (3) f (NRC, NRC: 10 CFR Part 74 - Material Control and Accounting of Special Nucelar Material Various) (DOE, DOE Standard - Nuclear

Materials Control and Accountability 2011)or the statistic $M_{q..}$, x_{kqpt} is replaced with $n_k m_k$ and $\delta^2_{sq..}$ in the $V_s(ID)$ equation is replaced by $\sigma_{sq..}$.

Example Variance Calculation

Below are tables from the excel sheet used to perform the measurement variance calculation for the spent fuel reprocessing model facility's MBA-2 material balance. The LEU and MOX model facilities' variance calculation was performed using similar excel spreadsheets.

User Inputs

Table 14. User Inputs for Variance Calculation

	random error			systematic error		
	bulk	sample	analytical	bulk	sample	analytical
method #	δrq..	δr.p.	δr..t	δsq..	δs.p.	δs..t
-	0	0	0	0	0	0
1	0.002	0.003	0.006	0.001	0.002	0.002
2	0.02	0.06	0.2	0.03	0.06	0.1
3	0.002	0.002	0.0025	0.001	0.001	0.001
4	0.001	0	0.5	0	0	0.5
5	0	0	0.002	0	0	0.001
		Throughput =	250000	(g Pu)		

The light green cells seen above represent all the user inputs that can be changed within the variance calculation. The 6x6 block of light green cells are the relative random and systematic measurement errors. The lowest light green cell represents the amount (grams) of plutonium for the designated material balance period.

MBA-2 Data

Table 15. MBA-2 Data Tabulation for Variance Calculation

	stratum	items/batch	#batches	samples/batch	analysis/samp.	bulk	sample	analytical	new
	(k)	n_K	m_K	r_K	c_K	q	p	t	x_{kqpt} (g Pu)
	1	1	2	2	1	2	2	2	1987
	2	1	2	2	1	2	2	2	22
Input	4	1	63.039714	2	2	1	1	1	250000
Output	5	1	31.519857	2	2	3	3	3	243643.66
Output	6	1	32.790819	1	1	2	2	2	1124.293
Output	7	1	39.654014	1	1	2	2	2	580.32124
Output	8	17	3.0503087	17	1	-	-	4	1292.3141
	9	1	2	2	1	2	2	2	6331
	10	1	2	2	1	2	2	2	93
	11	1320	1	1320	1	4	-	5	515

The figure above shows the data for each stratum in MBA-2. This data includes how many items are in each batch, the total number of batches for a given balance period, the number of samples taken for each batch, and the number of analyses performed for each sample. This table also specifies measurement method number for bulk, sample, and analytical measurements for each stratum. The last column in this table shows the amount of material in each stratum. The cells filled with white are the beginning and ending inventories in MBA-2 for the balance period. The light blue cells are the material inputs and outputs of MBA-2 for the balance period. All of the data in the white filled cells came from STR-193. The data in the light blue cells has been scaled up from the original data in STR-193. This scaling was based on the modified throughput and will be explained further in the following section.

Throughput Scaling

The data for the input and output were scaled to match different throughput levels, but the beginning and ending inventories were not. This was done because the bulk of material in a process MBA is input and output material which scales linearly with throughput. Beginning and ending inventory however is more of a fixed quantity which doesn't change much for different throughput levels. For very small throughputs this could introduce some error into the model, but the results of interest occur for medium and large throughputs, so this error for very small throughputs is negligible to the purpose of this model.

Table 16. Throughput Scaling for Variance Calculation

	stratum	original throughput		batch ratio	mass ratio	
	(k)	m_K	x_{kqpt} (g Pu)	x/m [g Pu]	x/total	Material Type
Input	4	248	983507	3965.754	1	dissolver solution
Output	5	124	958501	7729.847	0.9745747	Pu product solution
	6	129	4423	34.28682	0.0044972	HAW disposal
	7	156	2283	14.63462	0.0023213	LAW disposal
	8	12	5084	423.6667	0.0051693	measured discards

The table above shows how the MBA-2 data was scaled with changing throughput for the input and output stratum. A batch ratio (x/m) was made by dividing the original material amount (x) by the original number of batches for the balance period. The amount of material in the stratum was then divided by the batch ratio to obtain the new number of batches for the balance period. A mass ratio was created by dividing the original material amount in the stratum by the original total amount of throughput. Stratum 4's input material is the entire MBA's throughput, so stratum 4's mass ratio equals 1. The mass ratio was then multiplied by the new total throughput to obtain the newly scaled material amount in stratums 4-8.

Calculation

Once the tables above were created it was possible to perform the variance calculation. The cells in the tables above were linked using excel formulas to perform the same calculations that were presented in the variance calculation at the beginning of Appendix B.

Measurement Errors

The reports from which the model facilities were created provide the basis for the measurement errors used in the SEID calculations.[14,15,16] In order to confirm that these errors are likely values for current measurement techniques used in similar facilities, the STR provided errors were compared against values from the IAEA's report titled "International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials".[17] All but one measurement method were found to have reasonable measurement errors. The one error which was not reasonable was adjusted to agree with the International Target Value.

In the next three sections, measurement methods and associated errors are presented in various tables to provide a comparison of the STR values and the target values. In most cases the measurement errors from STR-150, STR-185, and STR-193 were at or below the target values[15] for the same measurement type. Some of measurement methods found in the STRs did not have corresponding methods in the target value document, so similar methods or materials were compared. The errors which did not agree but were close enough to be considered reasonable are highlighted with yellow. The one measurement error which disagreed strongly is highlighted in red. This error was adjusted in the model to reflect the value found in the target value document.

A few of the waste measurements uncertainties used in the SEID calculations were large, around 10%-50% error. The waste material streams were small compared to the rest of the in process materials, so these large uncertainties did not make a large impact on the SEID calculations.

Analytical Measurements

Table 17. Analytical Measurement Errors

MOX model facility				International Target Values 2010			
material	method	R (% rel)	S (% rel)	material	method	R (% rel)	S (% rel)
PuO2 pdr	amperometric	0.3	0.05	Pu oxide	titration	0.15	0.15
MOX	amperometric	0.2	0.1	U/Pu oxide	titration	0.2	0.2
dirty powder	amperometric	0.25	0.1	U/Pu oxide	titration	0.2	0.2
grinder sludge	amperometric	0.25	0.1	U/Pu oxide	titration	0.2	0.2
solid waste	NDA gamma	3.5	3.5	Pu waste	drum assay	10	5
liquid waste	alpha	1.8	0	waste solution	alpha	7	7
samples	various	0.2	0.1	NA	NA		
LEU model facility				**International Target Values 2010**			
material	method	R (% rel)	S (% rel)	material	method	R (% rel)	S (% rel)
UO2 pdr	gravimetric	0.06	0.02	U(pure com.)	gravimetric	0.05	0.05
sintered pellets	gravimetric	0.009	0.02	U(pure com.)	gravimetric	0.05	0.05
sintered scrap	gravimetric	0.061	0.02	U(pure com.)	gravimetric	0.05	0.05
UF6	gravimetric	0.02	0.003	U(pure com.)	gravimetric	0.05	0.05
dirty powder	titration	2.3	0.14	NA	NA		
ADU scrap	titration	2.3	0.14	NA	NA		
grinder sludge	titration	3	1	NA	NA		
liquid waste	fluorimetric	25.1	2	NA	NA		
solid waste	NDA gamma	10	25	NU, dirty scrap	NaI detector	15	5
Reprocessing model facility				**International Target Values 2010**			
material	method	R (% rel)	S (% rel)	material	method	R (% rel)	S (% rel)
dissolver solution	isotope dilution	0.6	0.2	spent fuel sol.	isotope dilution	0.2	0.2
waste solution	alpha count	20	10	Pu waste solution	alpha	7	7
Pu nitrate solution	amperometric	0.25	0.1	Pu oxide/nitrate	titration	0.15	0.15
measured discards	NDA	50	50	NA	NA		
samples	various	0.2	0.1	NA	NA		

Bulk Measurements

The errors for bulk measurements given in the MOX and LEU STRs are stated in absolute values while target values document only provides relative errors. The bulk measurement values for the MOX and LEU hypothetical facilities are reasonable values for typical mass scales used during physical inventories.

Table 18. Bulk Measurement Errors

MOX hypothetical facility				International Target Values 2010			
material	method	R (% rel)	S (% rel)	material	method	R (% rel)	S (% rel)
MOX powder	Powder scale	2 g	.3 g		electronic balance	0.05	0.05
MOX pellets	Pellet tray scale	2 g	.3 g		electronic balance	0.05	0.05
MOX scrap	scrap scale	2 g	.3 g		electronic balance	0.05	0.05
liquid waste	drum scale	2 g	.3 g		electronic balance	0.05	0.05
samples	Analyst balance	.001 g	0		electronic balance	0.05	0.05
LEU hypothetical facility				International Target Values 2010			
	method	R (% rel)	S (% rel)	material	method	R (% rel)	S (% rel)
UO2 powder	Powder scale	20 g	10 g		electronic balance	0.05	0.05
sintered pellets	Pellet tray scale	10 g	5 g		electronic balance	0.05	0.05
UO2 scrap	scrap scale	10 g	5 g		electronic balance	0.05	0.05
liquid waste	drum scale	50 g	25 g		electronic balance	0.05	0.05
UF6	UF6 scale	500 g	1000 g		electronic balance	0.05	0.05
UO2 rods	Pellet stack scale	.3 g	.2 g		electronic balance	0.05	0.05
Reprocessing hypothetical facility				International Target Values 2010			
material	method	R (% rel)	S (% rel)	material	method	R (% rel)	S (% rel)
product solution	electromanometer	0.2	0.1	high conc. waste	electromanometer	0.2	0.2
waste	electromanometer	2	3	low conc. waste	electromanometer	1	1
samples	Analyst balance	0.1	0		electronic balance	0.05	0.05

Sampling

Table 19. Sampling Measurement Errors

MOX hypothetical facility			International Target Values 2010		
material	R (% rel)	S (% rel)	material	R (% rel)	S (% rel)
PuO2 powder	0.1	0	Pu oxide	0.1	*
MOX powder	0.2	0	MOX	0.2	*
sintered pellets	0.2	0	MOX	0.2	*
dirty powder	0.5	0	MOX scrap (dirty)	10	*
grinder sludge	3.5	2	MOX scrap (dirty)	10	*
MOX scrap	0.2	0	MOX scrap (clean)	1	*
liquid waste	4	2	liquid waste	5	5
LEU hypothetical facility			International Target Values 2010		
material	R (% rel)	S (% rel)	material	R (% rel)	S (% rel)
UO2 powder	0.2	0	UO2 powder	0.2	*
sintered pellets	0.21	0	UO2 pellets	0.05	0.05
dirty powder	3.3	0	U scrap (dirty)	10	*
ADU scrap	5.4	2.8	U scrap (dirty)	10	*
grinder sludge	3.5	2	U scrap (dirty)	10	*
sintered scrap	3.3	1.9	U scrap (clean)	1	*
liquid waste	4	2	high active liquid waste	5	5
UF6	0.03	0.05	LEUF6	0.05	*
Reprocessing hypothetical facility			International Target Values 2010		
material	R (% rel)	S (% rel)	material	R (% rel)	S (% rel)
dissolver solution	0.3	0.2	reprocessing input solution	0.3	0.2
waste solutions	6	6	high active liquid waste	5	5
Pu nitrate solution	0.2	0.1	Pu nitrate solution	0.2	*

* Values have not yet been defined

Facility Descriptions

LEU

Process Description

Conversion

Solid UF6 is received as an input to the facility. Steam is used to sublime the UF6, and the now gaseous UF6 is bubbled through water to produce UO2F2 solution. Next, gaseous ammonia (NH3) is added to this solution to precipitate ammonium diuranate (ADU). This results in slurry which is centrifuged, dried, calcinated, and reduced to UO2 which is then milled and blended. UNH solution received from off site is fed directly to precipitation while UO2 powder from offsite is fed directly to the pelletizing process. Liquid wastes are transferred to holding tanks were they are mixed and sampled for analytical determination of U before discard. Clean scrap is sample for analytical chemistry and transferred to scrap recovery. Random containers of blended UO2 products are thief sampled for analytical U determination. UO2 is transferred to storage in the fabrication area. [12]

Fabrication and Assembly

Once UO2 powder is analyzed it is blended, milled, granulated, pressed, and sintered into UO2 pellets. Next, these pellets are ground to dimensional tolerances and dried. Pellets from boats are randomly sampled for analysis. Scrap is collected in containers and sampled for chemical determination before transfer to scrap recovery. Pellets are loaded into rods based on stack length; however, total pellet weight is recorded and used for accountability values for each individually identified rod. Finally the rods are assembled into bundles which are the ultimate product. [12]

Solid Waste Treatment

Solid wastes are sorted, packaged, and assayed. Burnable materials are incinerated. The ash is nondestructively assayed and, depending on the results, either packaged for burial or returned to scrap recovery. Non-burnable materials are nondestructively assayed, compacted, and packaged for burial. [12]

Scrap Recycle

There are three process used to handle scrap recycle. The first is for scrap pellets and involves milling, oxidation to U3O8, and reduction back to UO2 powder. The second process is for clean scrap other than pellets. This material is milled, dissolved in nitric acid, and precipitated with ammonia to produce ADU; this is filtered, dried, and calcined to UO2. The third process handles dirty scrap. Here material is oxidized, leached, and dissolved in nitric acid. The solution is purified by a solvent extraction and subsequently stripped back into an aqueous phase. ADU is precipitated with ammonia and this material is converted to UO2 as described above. The UO2 from these three processes is milled, blended, and thief sampled for chemical assay prior to sending it to storage. [12]

Analytical Laboratory

Samples are taken at different process steps and sent to the analytical laboratory for analysis for purposes of both process control and for nuclear material accountancy.[12]

Nuclear Material Flow

Process Flow Diagram

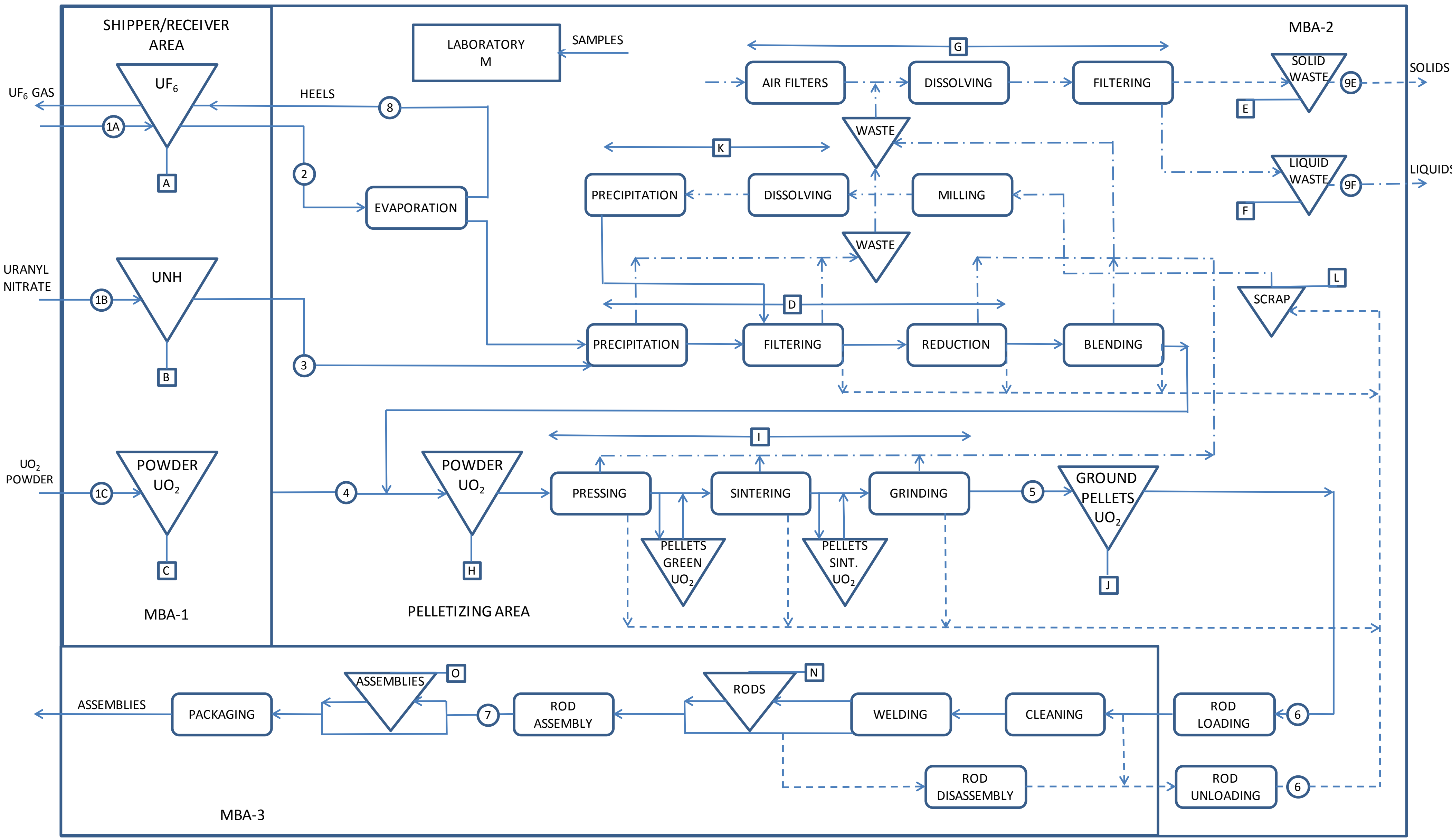


Figure 9. Process Flow Diagram; shows the three MBAs, the nine flow key measurement points, and the fifteen (A-O) inventory key measurement points.

Description of Flow KMPs

Table 20. Description of Flow Key Measurement Points for LEU Model Facility

KMP	Description	Form	Container	Sampling Methods	Measurement Method
1A	UF6 flow from vendor recorded in MBA-1	UF6	cylinder	from shipper	b - UF6 cylinder scale e - gravimetric i - mass spectrometry
1B	UNH flow from vendor recorded in MBA-1	UNH	tank	one thief sample from each tank	b - UNH tank platform scale e - gravimetric i - mass spectrometry
1C	UO2 flow from vendor measured in MBA-1	UO2 powder	buckets	one thief sample each from 3 buckets of 40 bucket batch	b - powder scale e - gravimetric i - mass spectrometry
2	UF6 flow to conversion measured in MBA-2	UF6	cylinder	none	b - mass difference from full cylinder and empty cylinder weight on UF6 cylinder scale i&e - factor
3	UNH flow to conversion measured in MBA-2	UNH	tank	none	b - flow meter during UNH piping i&e - factor from KMP-1B
4	UO2 flow to pelletizing measured in MBA-2	UO2 powder	buckets	one thief sample each from 3 buckets of 40 bucket batch	b - powder scale e - gravimetric i - mass spectrometry or values from KMP-1C
5	sintered pellets flow to storage in	UO2 pellets	tray	5 pellets/batch selected at random	b - pellet stack scale e - gravimetric
6	rod loading in MBA-2 transfer to MBA-3	clad and welded fuel rods	clad	N/A - use pellet factor	b - pellet stack scale e - gravimetric on pellets from KMP-5
6	reject sintered pellets flow from MBA-3 to MBA-2	UO2 pellets	rods	N/A	values from rod loading
7	assembly flow from MBA-3 for	assembli es	clad	N/A - use rod values from KMP-	sum rod values from KMP-5,6
8	heels measured in MBA-2	UF6	cylinder	none	b - mass difference e - factor from KMP-1A
9E	solid waste measured in MBA-2	miscel-laneous	barrels	N/A	NDA gamma-ray count
9F	liquid waste measured in MBA-2	liquid waste	drums	each drum mixed and sampled	b - drum scale e - flourometric

Description of Inventory KMPs

Table 21. Description of Inventory Key Measurement Points for LEU Model Facility

KMP	Description	Form	Container	Sampling Methods	Measurement Method
A	UF6 storage in MBA-1	solid in cylinder	cylinder	item seal verification	value from KMP-1A
B	UNH storage in MBA-1	UNH	tank	N/A	factor from KMP-1B b - UNH tank platform scale
C	UO2 powder storage in MBA-1	UO2 powder	buckets	item seal verification	values from KMP-1C
D	residual hold-up in UF6 to UO2 conversion in MBA-	ADU and uranium oxides	process equipme nt	N/A	gamma-ray survey meter
E	waste storage in MBA-2	miscellane-ous solids	barrels	N/A	NDA gamma-ray count
F		liquid	drums	each drum mixed and sampled	b - drum scale e - flourometric
G	residual hold-up in waste process MBA-	miscel-laneous	equipme nt	N/A	gamma-ray survey meter
H	UO2 powder storage in MBA-2	UO2 powder	buckets	item seal verification or thief sample for analysis	values from KMP-4 or b - powder scale e - gravimetric i - mass spectrometry
I	residual hold-up in pellet fabrication	UO2 powder,	equipme nt	N/A	gamma-ray survey meter
J	sintered pellet storage in MBA-2	pellets	trays	item verification	values from KMP-7
K	residual hold-up in scrap recovery in MBA-2	ADU and uranium oxides	process equipme nt	N/A	gamma-ray survey meter
L-1	scrap storage in MBA-2	ADU	drums	each drum stirred and sampled	b - scrap scale e - titration
L-2		dirty powder	drums	each drum tumble mixed and sampled	b - scrap scale e - titration
L-3		grinder sludge	buckets	each bucket stirred and sampled	b - scrap scale e - titration
L-4		green scrap	drums	N/A	b - scrap scale e - calculated from UO2 and lubricant weights
L-5		sintered scrap	drums	5 pellets per drum at random	b - scrap scale e - titration
M	lab inventory in MBA-2	various	vials/ envelope	N/A	various b, e, and i
N	rod inventory in MBA-3	rods	clad	item verification	values from KMP-6
O	assembly inventory in MBA-3	assemblies	clad	item verification	values from KMP-6

MOX

Process Description

Pellet Production

The reference facility uses PuO2 and UO2 as feed material. This input material is weighed and transferred either to open pans if the powder requires calcining, to the powder mill if the particle size needs adjusting, or to the blender if the powders are ready for further processing. Once the powders are blended, the MOX powder is sent to the pellet press which produces green pellets. Rejected pellets are granulated and returned to the blending operation for recycle. Acceptable pellets are loaded into open pans for sintering. Green pellets are sintered to ceramic in a high temperature heating process. Next pellets are ground to a specified diameter, dried, and examined (visual examination, weight, and density). Grinder sludge, chips, and rejected pellets are fed to scrap recovery.[13]

Fuel Rod Manufacturing

Quality control certified pellets are taken to the pellet stack preparation box. Next, pellets are moved from transfer containers and positioned in V-trough trays designed for a single rod loading. The trays are weighed and the tray tare weight is subtracted from the gross weight. The trays are heated and swept with a dry cover gas in an attempt to remove any residual moister in the pellets. The dried pellets are then loaded into clad tubes with the necessary end caps, spacers, springs, and insulator pellets in place. Once the rods are loaded, the second end plug is welded into place. Each fuel rod is checked for surface contamination, and then a series of quality control tests are performed. Rejected fuel rods are brought back to the rod loading box for repair or scrapping. Completed fuel rods are transferred to the fuel rod storage area to await further quality control tests before being used to produce fuel assemblies. [13]

Fuel Element Assembly

Quality control certified rods are transferred to the fuel element assembly area. The rods are positioned in the proper array and welded (or bolted) into place. Defective rods are returned for repair or scrapping. Completed fuel assemblies are examined to ensure proper loading, distribution, and integrity. Each assembly receives a unique serial number. The assemblies are checked once more for quality, and those that are certified are wrapped in polyethylene bags and transferred to storage until shipped.[13]

Analytical Laboratory

Samples are taken at different process steps and sent to the analytical laboratory for analysis for purposes of both process control and for nuclear material accountancy.[13]

Nuclear Material Flow

Process Flow Diagram

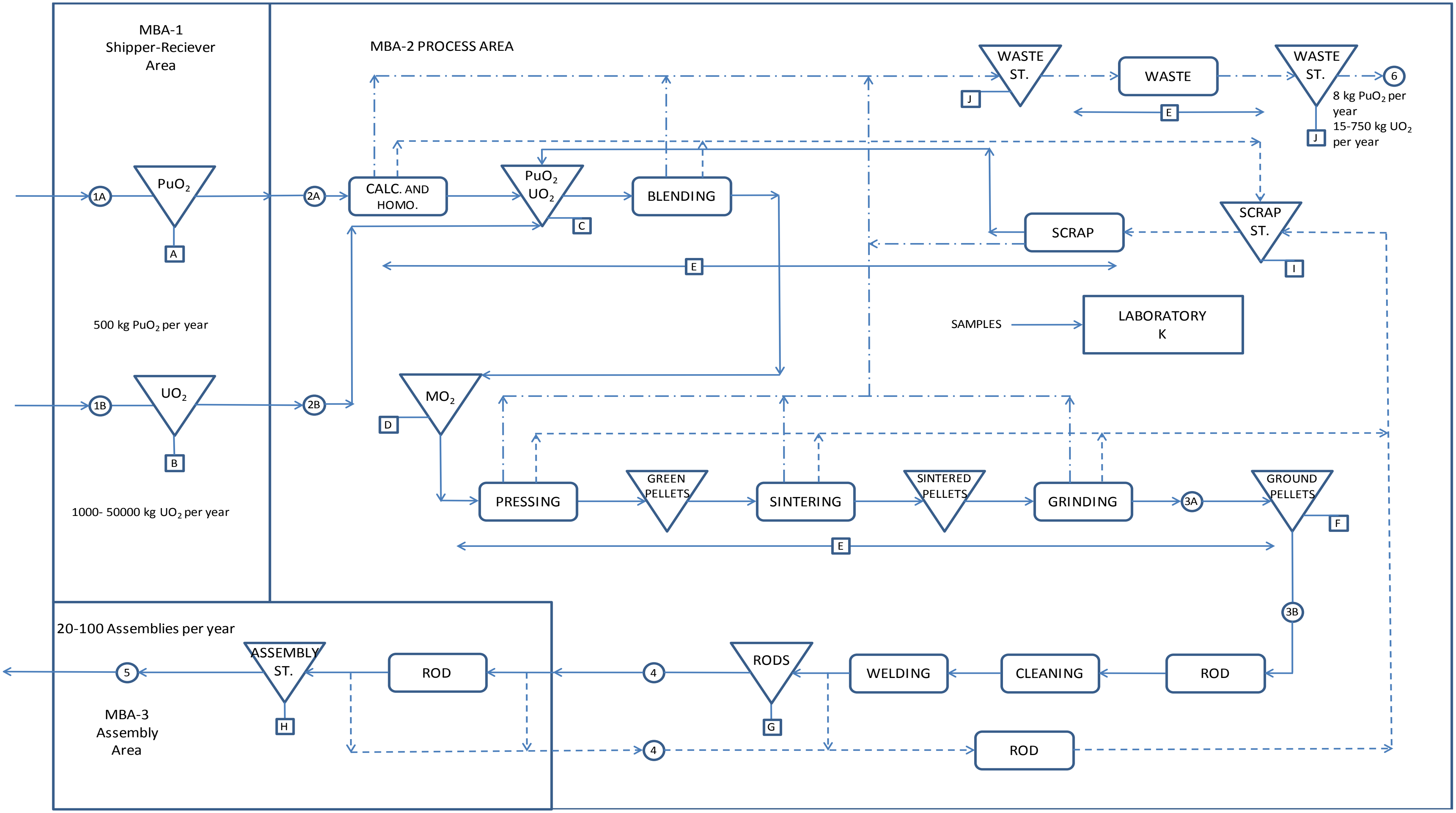


Figure 10. Process Flow Diagram; shows the three MBAs, the six flow key measurement points, and the eleven (A-K) inventory key measurement points.

Description of Flow KMPs

Table 22. Description of Flow Key Measurement Points for MOX Model Facility

KMP	Description	Form	Container	Sampling Methods	Measurement Method
1A	PuO2 flow from vendor measured in MBA-1	PuO2 Powder	can	one thief sample each from 3 cans of 8 can batch	b - powder scale e -amperometric titration (3 per sample)
1B	UO2 flow from vendor measured in MBA-1	UO2 Powder	buckets	one thief sample each from 3 buckets of 20 bucket batch	b - powder scale e - gravimetric
2A	PuO2 flow to process in MBA-2	PuO2 powder	can	none	values from KMP-1A
2B	UO2 flow to process in MBA-2	UO2 Powder	buckets	none	values from KMP-1B
3A	ground pellets flow to storage in MBA-2	MOX pellets	tray	5 pellets/batch selected at random	b - pellet tray scale e - amperometric and Davies-Gray Titration (3 per sample)
3B	pellet stacks to rod loading	MOX pellets	stack tray	N/A	b - pellet stack scale e - factors from KMP-3A
4	rods loaded in MBA-2 transfer to MBA-3	clad and welded fuel rods	clad	N/A	values from KMP-3A and B
4	reject rods flow from MBA-2 to MBA-3	MOX rods	rods	N/A	values from rod loading
5	assembly flow from MBA-3 for shipment	assembli es	clad	N/A	sum of rod values from KMP-4
6	solid and liquid wastes measured in	waste	drums	N/A	gamma spectrometry

Description of Inventory KMPs

Table 23. Description of Inventory Key Measurement Point for MOX Model Facility

KMP	Description	Form	Container	Sampling Methods	Measurement Method
A	PuO_2 powder storage in MBA-1	PuO_2 powder	can	item seal verification	value from KMP-1A
B	UO_2 powder storage in MBA-1	UO_2 powder	buckets	item seal verification	values from KMP-1B
C	PuO_2 and UO_2 powder storage in MBA-2	PuO_2 and UO_2 powder	cans or buckets	item seal verification or thief sample for analysis	values from KMP-2A and B or b - powder scale e - gravimetric and 3 amperometric per sample
D	MOX powder storage in MBA-2	MOX powder	cans	one thief sample each from 3 cans of 50 can batch	b - powder scale e - amperometric and Davies-Gray Titration (3 per sample)
E	residual hold-up in process equipment	plutonium and uranium oxides	process equipment	N/A	gamma-ray survey meter
F	ground pellet storage in MBA-2	pellets	trays	item verification	values from KMP-3A
G	rod inventory in MBA-2	rods	clad	item verification	values from KMP-3A and B
H	assembly inventory in MBA-2	assemblies	clad	item verification	values from KMP-4
I-1	scrap storage in MBA-2	dirty powder	can	each can tumble mixed and sampled	b - scrap scale e - amperometric and Davies-Gray Titration (3 per sample)
I-2		grinder sludge	drum	each drum stirred and sampled	
I-3		green scrap	can	5 pellets per can at random	
I-4		sintered scrap	can	5 pellets per can at random	
J	waste storage in MBA-2	miscellan-eous solid	drums	N/A	gamma spectrometry
		liquid	drums	each drum mixed and sampled	b - scrap scale e - titration
K	lab inventory in MBA-2	various	bottles vials and envelopes	N/A	various b and e

Spent Fuel Reprocessing

Process Description

Spent Fuel Storage and Head End Treatment

The spent fuel storage and head end area includes all operations from the receipt of spent fuel until the point at which the input accountancy measurement is performed. Once the dissolved fuel solution has been measured it is considered to be in the process area. The head-end area includes: [14]

- Spent fuel cask receiving and unloading
- Spent fuel storage
- Transfer of spent fuel to the chop-leach or mechanical cell
- Removal and disposal of fuel assembly end pieces not containing nuclear material
- Chopping of the spent fuel into short pieces suitable for leaching
- Dissolution of U, Pu, and fission products from the chopped pieces
- Clarification of the dissolver solution; transfer to the input accountancy tank; input accountancy measurement of U and Pu in the clarified solution
- Disposal of leached hulls and other solid wastes from clarification operations

Spent fuel is received at the facility through the spent fuel receiving bay and stored in closed containers (baskets). Baskets are loaded, stored, and taken as a unit to the transfer chute leading to the mechanical cell. Here, the fuel assembly end pieces are removed and the fuel rods are sheared into short pieces for dissolution. The dissolver solution is clarified and adjusted to a specified concentration. The leached hulls from the dissolver are removed to high activity waste storage.

Chemical Process

The Purex process with mixer-settler contactors is used to carry out the recovery and purification of the uranium and Pu. First the solution is decontaminated by removing fission products. Next the uranium and plutonium are separated and each processed through purification steps to further remove fission products. During these processing, a range of different liquid and solid wastes are generated. All of these wastes are monitored for nuclear material content before disposal. [14]

Product Storage

The purified uranyl nitrate solution is concentrated by evaporation, converted to UO3, and transferred to storage. The plutonium nitrate solution is evaporated to a concentration of about 250 g/l and then transferred to storage. These products are shipped to conversion and fabrication facilities as needed. [14]

Analytical Laboratory

Samples are taken at different process steps and sent to the analytical laboratory for analysis for purposes of both process control and for nuclear material accountancy. [14]

Nuclear Material Flow

Process Flow Diagram

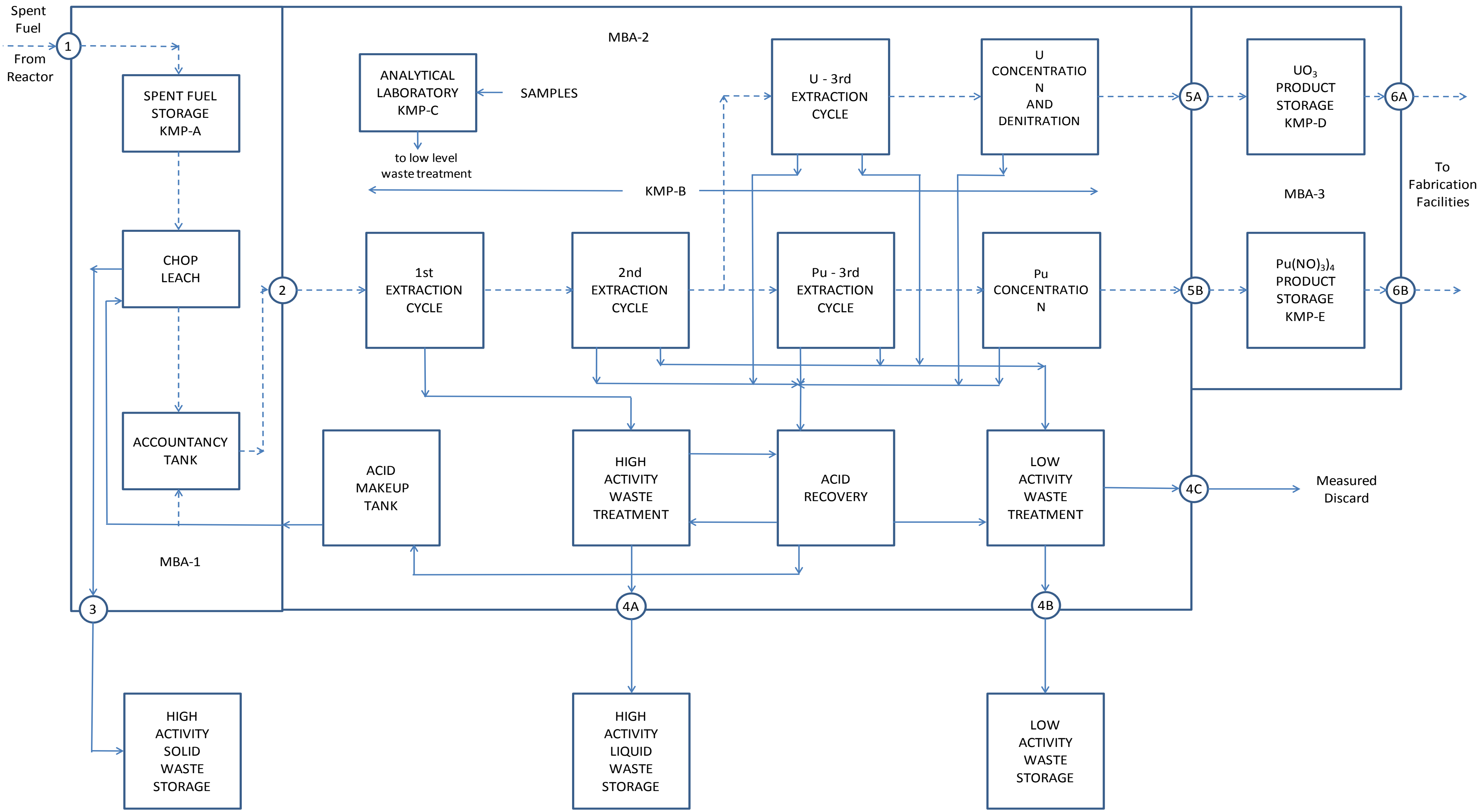


Figure 11. Process Flow Diagram; shows the three MBAs, the six flow key measurement points, and the five (A-E) inventory key measurement points.

Description of Flow KMPs

Table 24. Description of Flow Key Measurement Points for Reprocessing Model Facility

Description of Flow Key Measurement Points (KMPs)					
KMP	Description	Form	Container	Sampling Methods	Measurement Method
1	receipt of spent fuel	fuel assembli	shipping cask	N/A	shipper's values accepted
2	transfer of input solution to MBA-2	solution	tank	recirculating sampler 2 samples/batch	b - electromanometer e and i - isotope dilution
3	transfer of leached hulls to storage	leached hulls	drum	N/A	e - gamma spectrometry i - value from KMP-2
4A	high activity liquid waste to storage	solution	tank	recirculating sampler 1 samples/batch 1 analysis/sample	b - dip tube manometer e - colorimetric for U alpha count for Pu i - value from KMP-2
4B	low activity waste to storage	solution	tank	recirculating sampler 1 samples/batch 1 analysis/sample	b - dip tube manometer e - colorimetric for U alpha count for Pu i - value from KMP-2
4C	measured discard	miscellan-eous solids and	drum	N/A	e - passive gamma and neutron coincidence i - value from KMP-2
5A	uranium product to storage	UO3 powder	metal bottle	inline proportional sampler 2 samples/batch 2 analyses/sample	b - beam and pendulum e - gravimetric i - mass spectrometry
5B	plutonium product to storage	plutoniu m nitrate solution	tank	recirculating sampler 2 samples/batch	b - electromanometer e - amperometric
6A	uranium product shipped offsite	UO3 powder	metal bottle	N/A	values from KMP-5A
6B	plutonium product shipped offsite	plutoniu m nitrate solution	L-10 bottle	proportional sampler 1 samples/batch	b - constant volume overflow pot e - amperometric

Description of Inventory KMPs

Table 25. Description of Inventory Key Measurement Points for Reprocessing Model Facility

Description of Inventory Key Measurement Points (KMPs)					
KMP	Description	Form	Container	Sampling Methods	Measurement Method
A	spent fuel storage	fuel assemblies	baskets	N/A	shipper's values
B	in-process inventory	solution	tanks	recirculating sampler 1 samples/batch 1 analysis/sample	b - dip tube manometer e - colorimetric for U alpha count for Pu i - mass spectrometry
C	analytical laboratory	samples	sample bottles	N/A	various
D	uranium product storage	UO_3 powder	metal bottles	N/A	values from KMP-5A
E	plutonium product storage	plutonium nitrate solution	tank	recirculating sampler 1 samples/batch	b - dip tube manometer e - amperometric

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