

**SAFEGUARDS FOR THE URANIUM EXTRACTION (UREX) +1A
PROCESS**

A Thesis

by

JESSICA SHAWN FEENER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2010

Major Subject: Nuclear Engineering

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Approved by:

Chair of Committee,	William S. Charlton
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ABSTRACT

Safeguards for the Uranium Extraction (UREX) +1a Process.

(May 2010)

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As nuclear energy grows in the United States and around the world, the expansion of the nuclear fuel cycle is inevitable. All currently deployed commercial reprocessing plants are based on the Plutonium – Uranium Extraction (PUREX) process. However, this process is not implemented in the U.S. for a variety of reasons, one being that it is considered by some as a proliferation risk. The 2001 Nuclear Energy Policy report recommended that the U.S. “develop reprocessing and treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation-resistant”. The Uranium Extraction (UREX+) reprocessing technique has been developed to reach these goals. However, in order for UREX+ to be considered for commercial implementation, a safeguards approach is needed to show that a commercially sized UREX+ facility can be safeguarded to current international standards.

A detailed safeguards approach for a UREX+1a reprocessing facility has been developed. The approach includes the use of nuclear material accountancy (MA), containment and surveillance (C/S) and solution monitoring (SM). Facility information was developed for a hypothesized UREX+1a plant with a throughput of 1000 Metric Tons Heavy Metal (MTHM) per year. Safeguard goals and safeguard measures to be implemented were established. Diversion and acquisition pathways were considered; however, the analysis focuses mainly on diversion paths. The detection systems used in the design have the ability to provide near real-time measurement of special fissionable material in feed, process and product streams. Advanced front-end techniques for the quantification of fissile material in spent nuclear fuel were also considered. The economic and operator costs of these systems were not considered. The analysis shows that the implementation of these techniques result in significant improvements in the ability of the safeguards system to achieve the objective of timely detection of the

diversion of a significant quantity of nuclear material from the UREX+1a reprocessing facility and to provide deterrence against such diversion by early detection.

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NOMENCLATURE

AFCI	Advanced Fuel Cycle Initiative
β	Nondetection Probability
BT	Buffer Tank
CCD-PED	Chlorined Cobalt Dicarbollide and Poly-ethylene Glycol
COEX	Co-Extraction
C/S	Containment and Surveillance
Cs	Cesium
FT	Fill Tank
GNEP	Global Nuclear Energy Partnership
IAEA	International Atomic Energy Agency
KMP	Key Measurement Point
Ln	Lanthanides
MA	Nuclear Material Accountancy
MBA	Material Balance Area
MBP	Material Balance Period
MTHM	Metric Tons Heavy Metal
MUF	Material Unaccounted For
NDA	Nondestructive Assay
Np	Neptunium
P	Probability of Detection
Pu	Plutonium
PUREX	Plutonium – Uranium Reduction Extraction
RT	Receiving Tank
S	Threshold
SFNDA	Spent Fuel Nondestructive Assay
SM	Solution Monitoring
SNM	Special Nuclear Material
SQ	Significant Quantity

Sr	Strontium
TALSPEAK	Trivalent Actinide Lanthanide Separation by Phosphorus Extractants and Aqueous Komplexes
Tc	Technetium
TRU	Transuranic
TRUEX	Transuranic Extraction
U	Uranium
UREX	Uranium Extraction

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CHAPTER I

INTRODUCTION

I.A. Motivation

As nuclear energy grows in the United States and around the world, the expansion of the nuclear fuel cycle is inevitable. The current commercial reprocessing technique, PUREX, is not implemented in the U.S. for a variety of reasons, one of which being that it is considered a proliferation risk. The 2001 Nuclear Energy Policy report recommended that the U.S. “develop reprocessing and treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation-resistant”. As such, the UREX+ reprocessing technique has been developed to reach these goals. UREX+ is very efficient (greater than 99.99% uranium [U] and plutonium [Pu] separation efficiency), significantly reduces the volume of high level waste, and has the potential to have proliferation resistant characteristics as there is never separated Pu. In order for UREX+ to be considered for commercial implementation, a safeguards approach is needed to show that UREX+ can be safeguarded to current standards.

I.B. Introduction to UREX+

UREX+ was born from the Global Nuclear Energy Partnership (GNEP), a partnership of countries aiming to improve the proliferation resistance of the nuclear fuel cycle while guaranteeing access to fuel supplies that was initiated in 2006 by the Bush administration. Domestically, GNEP was based on the Advanced Fuel Cycle Initiative (AFCI), and while GNEP has essentially terminated with the new Obama administration, the AFCI program continues with research and development “on proliferation-resistant fuel cycles and waste reduction strategies.”¹

An early priority in GNEP was to develop new reprocessing technologies. Reprocessing of used nuclear fuel takes fuel from nuclear reactors and reprocesses it to

¹This thesis follows the style of *Nuclear Technology*.

recover unused U, Pu, and other transuranics (TRUs) to use as additional fuel in reactors. Recovering these elements gains approximately 25% more energy from the original U (gains increase as the fuel is reprocessed again), reduces the volume of high-level waste, and the level of radioactivity is much smaller than used fuel. PUREX, which has been employed for over half a century, is well understood and proven to be commercially viable; but it is a proliferation concern because it separates Pu. PUREX also sends minor actinides to waste, increasing the radiotoxicity and volume. In addition, major heat generating radionuclides go into high-level waste streams which do not benefit heat management in geological repositories. Additional information on PUREX can be found in Ref. 2. New reprocessing technologies are designed to combine Pu with U and/or TRUs, rendering it more difficult to use the Pu in the manufacturing of weapons and reduces the high level waste volume, radiotoxicity, and heat generation.^{3,4}

There are several reprocessing techniques that fit the GNEP concept including Co-Extraction (COEX), NUEX, and UREX+. COEX separates U and Pu together (and possibly neptunium [Np]) as well as a pure U stream, leaving the other minor actinides and fission product together. NUEX separates U and then all TRUs, including Pu, together, with fission products separately. UREX+ separates U, technetium (Tc), cesium (Cs), and strontium (Sr), then has a suite of combinations of Pu and other TRUs. TABLE 1 compares different UREX+ processes. The further down the table the more pure the Pu products get.^{1,4}

UREX+ has U and Pu recovery efficiencies greater than 99.99% and has the ability to greatly reduce the volume, radiotoxicity, and heat generation of waste to be placed in long term geological storage by separating the Cs, Sr, and fission products from the TRUs. Since UREX+ never has separated Pu it has the characteristic of being intrinsically proliferation resistant. The down side of UREX+ is that it requires advanced chemistry to perform the separations, the separated TRUs will require remote fuel fabrication, and since the Pu is never separated it is harder to measure.

The UREX+1a process was chosen to safeguard for three reasons. First, GNEP was focused on UREX+1a. Secondly, since the Pu is kept with the curium (Cm) it makes for a more difficult measurement. Since Cm emits an order of magnitude more neutrons than Pu, one cannot simply measure the neutrons to determine the amount of Pu. Lastly,

TABLE 1.
Comparison of UREX+ processes⁵

Process	Prod. #1	Prod. #2	Prod. #3	Prod. #4	Prod. #5	Prod. #6	Prod. #7
UREX+1	U	Tc	Cs/Sr	TRU+Ln	FP		
UREX+1a	U	Tc	Cs/Sr	TRU	All FP		
UREX+1b	U	Tc	Cs/Sr	U+TRU	All FP		
UREX+2	U	Tc	Cs/Sr	Pu+Np	Am+Cm+Ln	FP	
UREX+2a	U	Tc	Cs/Sr	U+Pu+Np	Am+Cm+Ln	FP	
UREX+3	U	Tc	Cs/Sr	Pu+Np	Am+Cm	All FP	
UREX+3a	U	Tc	Cs/Sr	U+Pu+Np	Am+Cm	All FP	
UREX+4	U	Tc	Cs/Sr	Pu+Np	Am	Cm	All FP

U: uranium (removed in order to reduce the mass and volume of high-level waste)

Tc: technetium (long-lived fission product, prime contributor to long-term dose at Yucca Mtn.)

Cs/Sr: cesium and strontium (primary short-term heat generators; repository impact)

TRU: transuranic elements (Pu: Plutonium, Np: neptunium, Am: americium, Cm: curium)

Ln: lanthanide (rare earth) fission products

FP: fission products other than cesium, strontium, technetium, iodine, and the lanthanides

All FP: fission products plus lanthanides

it is felt that if UREX+1a can be safeguarded, the other UREX+ processes can be safeguarded as well. This is because the UREX+1a Pu product is more impure than most of the other UREX+ processes, therefore, if we can successfully measure and safeguard the Pu in a UREX+1a process, it can be done for the other processes as well. Since UREX+1a has a low material attractiveness, if the safeguard system can safeguard UREX+1a to current standards, it will be more proliferation resistant than PUREX.

A schematic of a UREX+1a process is shown in Fig. 1. Spent fuel is received by the facility and stored in the spent fuel pool. The fuel is then sheared where it is chopped up into small pieces. It then goes to the voloxidation and spent fuel dissolver step. Voloxidation involves heating the fuel pieces in air or oxygen (normally an oxygen rich environment) to separate the fuel from the cladding, decrease particle size of the fuel, which increases efficiency of the kinetics of downstream treatment operations, and can remove problematic constituents from the fuel prior to downstream treatment (i.e. tritium).⁶ In the dissolver step, the pieces of fuel are immersed in a nitric acid bath to fully separate the fuel from the cladding and hulls. The hulls and cladding go to the hulls and metal waste storage area.

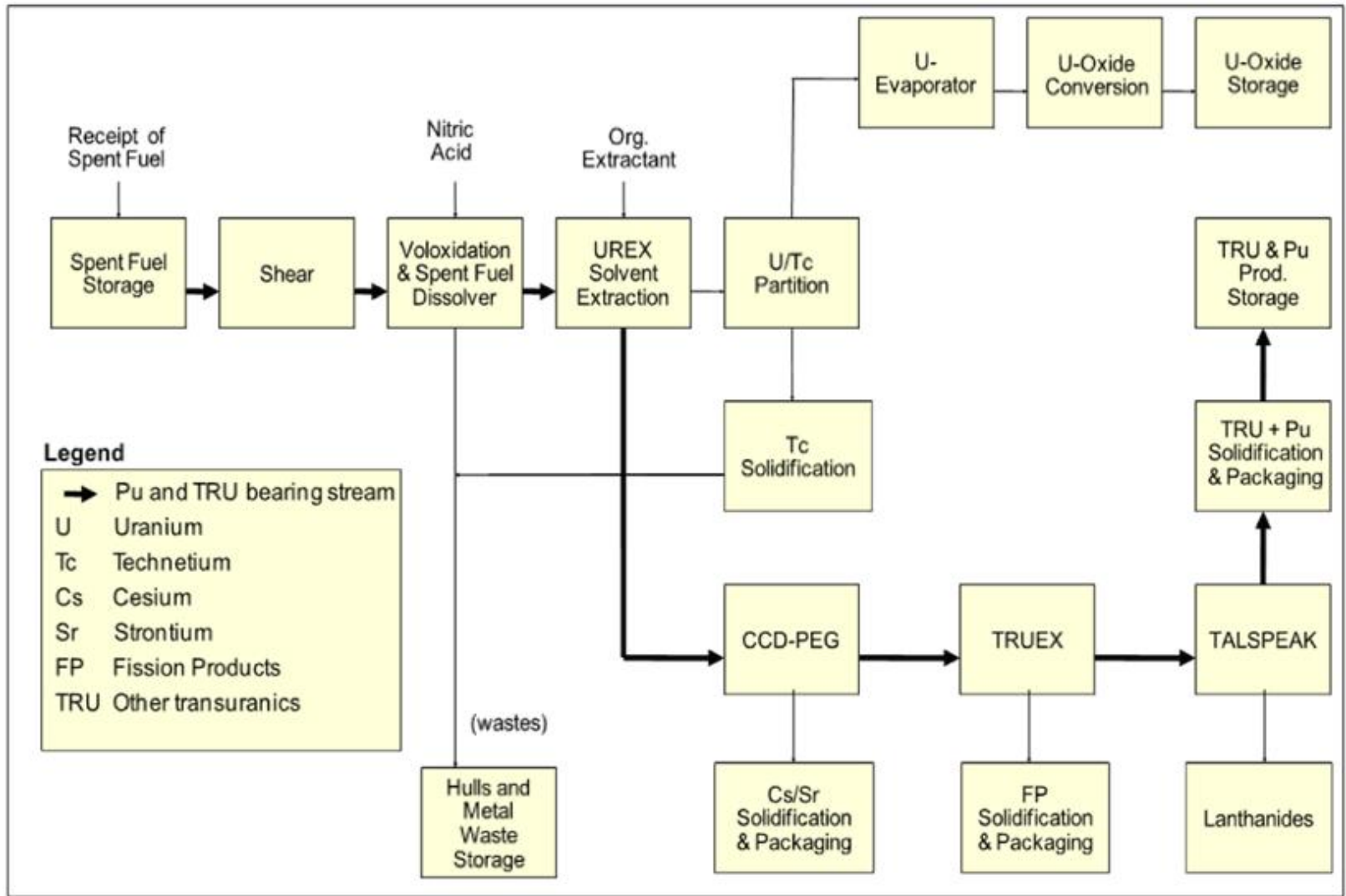


Fig. 1. UREX+1a process schematic.⁵

The fuel then enters the first Pu separation step, UREX, where the U and Tc are separated. In UREX, the U and Tc is the product and the raffinate is everything else. The next step is Chlorinated Cobalt Dicarbolide and Poly-ethylene Glycol (CCD-PEG) which removes the Cs and Sr. In CCD-PEG, the product is Cs and Sr and the raffinate is the TRUs plus fission products. The third step is Transuranic Extraction (TRUEX) where the fission products (minus lanthanides) are separated. In TRUEX, the product is the TRUs plus lanthanides and the raffinate is the fission products. Finally, the lanthanides are separated using Trivalent Actinide Lanthanide Separation by Phosphorus Extractants and Aqueous Komplexes (TALSPEAK). In TALSPEAK, the product is the lanthanides and the raffinate is the TRUs. The TRU product, including Pu, is solidified and packaged then moved to the storage area until it is shipped from the facility.^{7,8}

After the UREX separation step the U and Tc undergo ion exchange to separate them. The U then goes through the evaporator and is converted into U-oxide before going to storage until it is shipped from the facility.

All of the waste products (including, Tc, Cs, Sr, fission products and lanthanides) are solidified and packaged before being shipped from the facility.

I.C. Nuclear Safeguards and General Safeguards for Reprocessing Plants

After the detonation of the first nuclear weapon and the observation of its obvious destructive force, nuclear nonproliferation began. Weapons with such power must be controlled and the ability to produce them must be carefully monitored. The International Atomic Energy Agency (IAEA) was formed by the United Nations in 1957 and was tasked to safeguard nuclear materials in facilities that were placed under its monitoring by member states.⁹ Under the IAEA's comprehensive safeguards agreement, safeguards are applied to verify a State's compliance with its undertaking to accept safeguards on all nuclear material in all its peaceful nuclear activities and to verify that such material is not diverted to nuclear weapons or other nuclear explosive devices. In this regard, the technical objective is specified: "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". The second technical objective, to fully

address the verification of a State's compliance, is the detection of undeclared nuclear materials and activities in a State.¹⁰

With regard to the first technical objective, the IAEA has defined a set of Significant Quantities (SQ) based on the type of material. These values are derived from the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. The 'timely detection' refers to a set of timeliness goals that are broken down into categories based on the time it would take a state to form a nuclear device from the particular material. TABLE 2 gives the IAEA's Special Nuclear Material (SNM) SQs and timeliness detection goals.¹⁰

TABLE 2.
IAEA's SNM SQs and Timeliness Goals^{10,11}

Material Category	Material Type	Significant Quantity	Timeliness Goal (months)
Direct Use Material	Pu (separated) ^a	8 kg Pu	1
	HEU (²³⁵ U enrichment \geq 20%)	25 kg ²³⁵ U	1 (unirradiated) 3 (irradiated)
	Pu in Spent Fuel	8 kg Pu	3
	²³³ U	8 kg ²³³ U	1
Indirect Use Material	LEU (²³⁵ U enrichment < 20%)	75 kg ²³⁵ U	12
	Th	20 tons	12

^a For Pu containing less than 80% Pu.

I.C.1. Nuclear Material Accountancy

The safeguards framework begins with nuclear material accountancy (MA). MA includes, but is not limited to, dividing operations involving nuclear material into material balance areas (MBAs) and maintaining records on all quantities of nuclear material entering, leaving, and contained in the MBA. The nuclear material is measured at key measurement points (KMPs), a location where nuclear material appears in such a form that it may be measured to determine material flow or inventory. Most MBAs have KMPs where nuclear material enters and exits and an inventory KMP. The physical inventory of nuclear material is accounted for over a material balance period (MBP), the time between two consecutive physical inventory takings. The MBP length is determined

by the material unaccounted for (MUF). The MUF is calculated for a MBA over a MBP using the material balance equation:

$$MUF = (PB + X - Y) - PE \quad (1)$$

where PB is the beginning physical inventory, X is the sum of increases to inventory, Y is the sum of decreases from inventory, and PE is the ending physical inventory. If no diversion of material has occurred, one would expect the MUF to be zero. For item MBAs [MBAs where the elements nuclear material can be counted (e.g., fuel assemblies or cans of U-oxide powder)], MUF should be zero and a non-zero MUF is an indication of a safeguards problem. For bulk handling MBAs [MBAs where the material mass must be measured (e.g., solutions, etc.)], a non-zero MUF is expected because of measurement uncertainty and the nature of processing. In bulk handling MBAs, each term in the MUF equation will have measurement uncertainties associated with it and are combined with the material quantities to determine the total MUF uncertainty, σ_{MUF} . During any one MBP¹⁰, we seek to perform accountancy such that

$$3 \times \sigma_{MUF} \leq 1 \text{ } SQ. \quad (2)$$

The expression in Eq. (2) is a rule-of-thumb derived from hypothesis testing for a system with an expected MUF equal to zero but with a σ_{MUF} not equal to zero.

The probability of detection (P) is the probability that if a diversion of a given amount of material has occurred, the safeguard activities will lead to detection. The detection probability is denoted as $1-\beta$, where β is the nondetection probability. The false alarm probability, α , is the probability that statistical analysis of accountancy verification data would indicate that an amount of nuclear material is missing when, in fact, no diversion has occurred.

When analyzing a safeguards system, the system is typically tested against two hypotheses. The first hypothesis is that no diversion of material has occurred, which is called the null hypothesis or H_0 . The second hypothesis is that a diversion does occur, which will be called the diversion hypothesis or H_1 . The mathematical probability that a count (x) will occur above a threshold (S) if the null hypothesis is true is given by:

$$\alpha = \text{prob} (x > S \mid H_0) \quad (3)$$

where $H_0 \in (\mu = 0, \sigma = \sigma_{MUF})$, μ is the mean, and σ is the standard deviation.

The mathematical probability that a count (x) will occur below S if the diversion hypothesis is true:

$$\beta = \text{prob}(x \leq S \mid H_1) \quad (4)$$

where $H_1 \in (\mu = 1 \text{ SQ}, \sigma = \sigma_{MUF})$. α and β are preselected input parameters for designing sampling plans and performing statistical tests. α is usually set to 0.05 to minimize the number of false alarms. The values of $1-\beta$ are considered high probability levels if greater than 90% and low probability levels if less than 20%.¹⁰

Fig. 2 shows graphically how σ_{MUF} and α are used to determine the alarm threshold, S , and β . The measurement uncertainties are assumed to have a normal distribution around the true value of the measurement. The threshold is selected where any value above that threshold (to the right) will alarm the system and any value below it (to the left) will not. α is the area above the threshold under the No Diversion curve. β is the area below the threshold and under the Diversion curve. In this work, α is set and a threshold is found. β is then calculated from the threshold.¹⁰

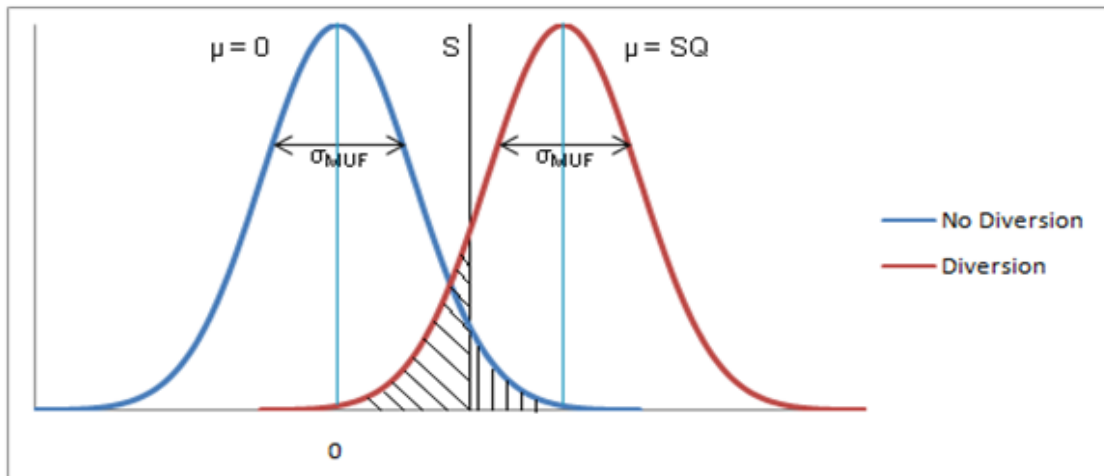


Fig. 2. Alarm threshold

Since the MA system cannot always reach the β goal, additional measures can be implemented to reach the goal and independently verify the correctness of the accountancy information. Additional measures include, but are not limited to Containment and Surveillance (C/S) and Solution Monitoring (SM).

I.C.2. Containment and Surveillance

The IAEA defines containment as, “structural features of a facility, containers or equipment which are used to establish the physical integrity of an area or items (including safeguards equipment or data) and to maintain the continuity of knowledge of the area or items by preventing undetected access to, or movement of, nuclear or other material, or interference with the items.” Examples of containment are storage containers, doors, and walls. The continuing integrity of the containment itself is usually assured by surveillance measures or seals.¹⁰

Surveillance is the collection of information through observation aimed at detecting movements of nuclear material or other items. Surveillance may also be used for observing various operations by obtaining relevant operational data. Examples of surveillance are cameras and detectors.¹⁰

The application of C/S is to complement nuclear material accountancy. The use of C/S measures is aimed at verifying information on movement of material, equipment and samples, or preservation of the integrity of safeguards relevant data.¹⁰

I.C.3. Solution Monitoring

SM is an element of a broader monitoring system known as process monitoring. Process monitoring “implies the collection and evaluation of a broad range of data from the process operations in a nuclear facility to make timely judgments regarding the location and movement of special nuclear material.”¹² SM helps guarantee continuity of information on process solutions as they move through the plant.

In SM, bulk volumes, masses, temperatures, pH, and concentrations are tracked through a facility. This includes the flow rates between tanks, the filling and emptying of the tanks, or both. SM can help ensure that the shifting of a diversion from one MBA inventory period to the next one does not occur. SM also has the ability to detect a diversion in real-time and not over a MBP.^{12,13,14,15}

I.C.4. Application of Safeguards to PUREX and Previous Work

The foundation for developing safeguard approaches for aqueous reprocessing begins with the well-established PUREX process. A simplified process flow schematic of the PUREX process is shown in Fig. 3. Since PUREX is the current, commercial

reprocessing technique, large scale aqueous reprocessing safeguards are based on and compared to the current PUREX safeguard systems and the results these safeguard systems achieve. The Rokkasho Reprocessing Plant in Japan is the newest commercial PUREX reprocessing plant in the world. It is designed to process 800 MTHM/year and its safeguard system is characterized by a MBP of 7-8 days, a false alarm rate of 5% and a nondetection probability of 5%. The PUREX process is a significant point of reference because there are modern large scale facilities under international safeguards. However, it should be noted that there are significant differences in the chemical processes between PUREX and UREX+.

There are ongoing, extensive efforts being pursued on front-end nondestructive assay (NDA) measurement techniques. In current reprocessing facilities, the front-end measurement uncertainties are too large to be beneficial to the MA system. Therefore, C/S is the main safeguards mechanism before a lower uncertainty destructive assay (DA) measurement can be taken after the spent fuel is dissolved. A NDA measurement with a low uncertainty at the front-end will greatly improve the MA before the spent fuel is dissolved. More information on some of these efforts can be found in Refs. 16, 17, and 18.

Previous works on UREX+ safeguards include developing approaches and identifying technical challenges that need to be addressed.⁵ There has also been an “advanced instrument scenario” developed, using a Safeguards Performance Model, for materials accountability for a UREX+1a reprocessing plant, that can be found in Ref. 19. Extensive work on SM and applying SM to safeguards has also been done. Information on this work can be found in Refs. 12, 13, 14, and 15. Additional information on advanced safeguard methods and safeguard system analysis can be found in Refs. 20 and 21.

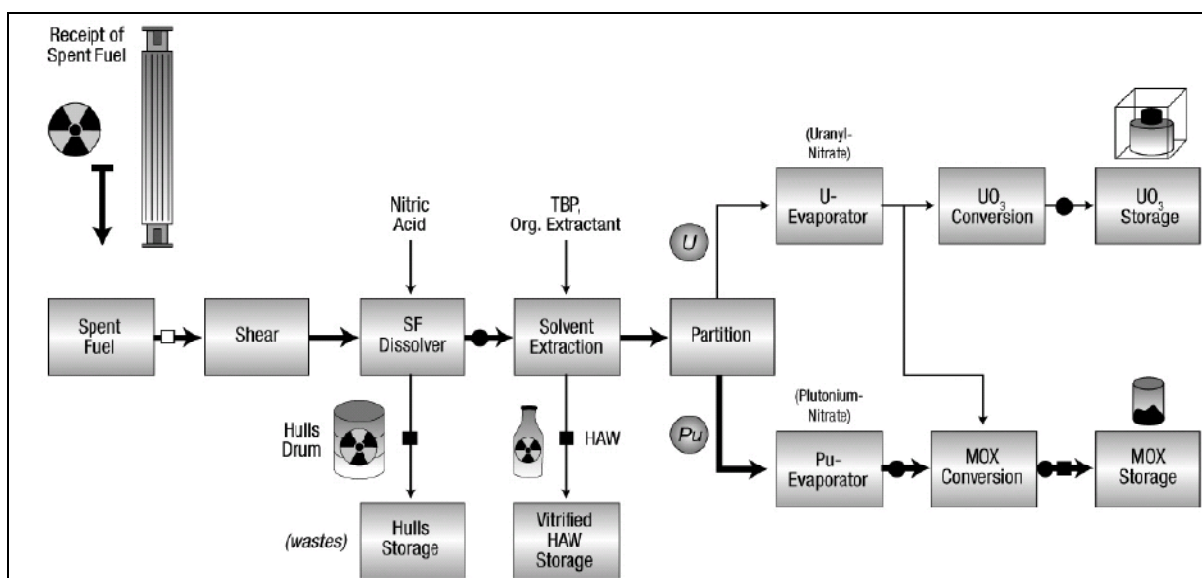


Fig. 3. Simplified process flow schematic of the PUREX process.⁵

I.D.Overview of the Safeguards Approach Development

The development of the safeguards approach designed in this work followed the basic procedure shown in Fig. 4. Facility information was established for a hypothetical 1000 MTHM/yr UREX+1a plant. The safeguard goals and safeguard measures to be implemented were then established. Safeguard goals include a detection probability of 95%, a false alarm probability of 5%, and establishing timeliness detection goals. Safeguard measures implemented consist of the definition of MBAs, MBPs, KMPs and the measurement systems to be implemented at the KMPs. The error model used for estimating uncertainties and the analysis and implementation of the C/S and SM systems to lower uncertainties was also included.

Diversion and acquisition pathways were identified and the approach was analyzed against these pathways. Diversion paths are hypothetical schemes in which a state could consider to divert nuclear material. Diversion strategies are postulated for purposes of developing facility level safeguard approaches. Acquisition paths are hypothetical schemes in which a state could consider to acquire nuclear material usable for manufacturing a nuclear explosive. This includes diversion schemes, undeclared facilities, and undeclared material. Acquisition strategies are postulated for the purposes of developing state level safeguard approaches. The safeguards design considered mainly

focuses on diversion paths and only a preliminary consideration of acquisition paths because the acquisition strategies are beyond the scope of this work.

If the safeguards goals are met the safeguards approach is completed. If the goals are not met the facility information, safeguard goals, and/or safeguard measure to be implemented can be changed to meet the goals. In this work, only the safeguards goals to be implemented were changed to meet the safeguard goals. Economic analysis of the safeguards approach was not considered.

There were several assumptions made in the safeguards approach. All uncertainties are assumed to be Gaussian functions and the random and systematic uncertainties in the measurement systems were assumed to be independent. Only abrupt diversions were considered, although, a MUF of less than 1 SQ was analyzed to assess the risk of protracted diversions. The same MBAs were used for MA and C/S.

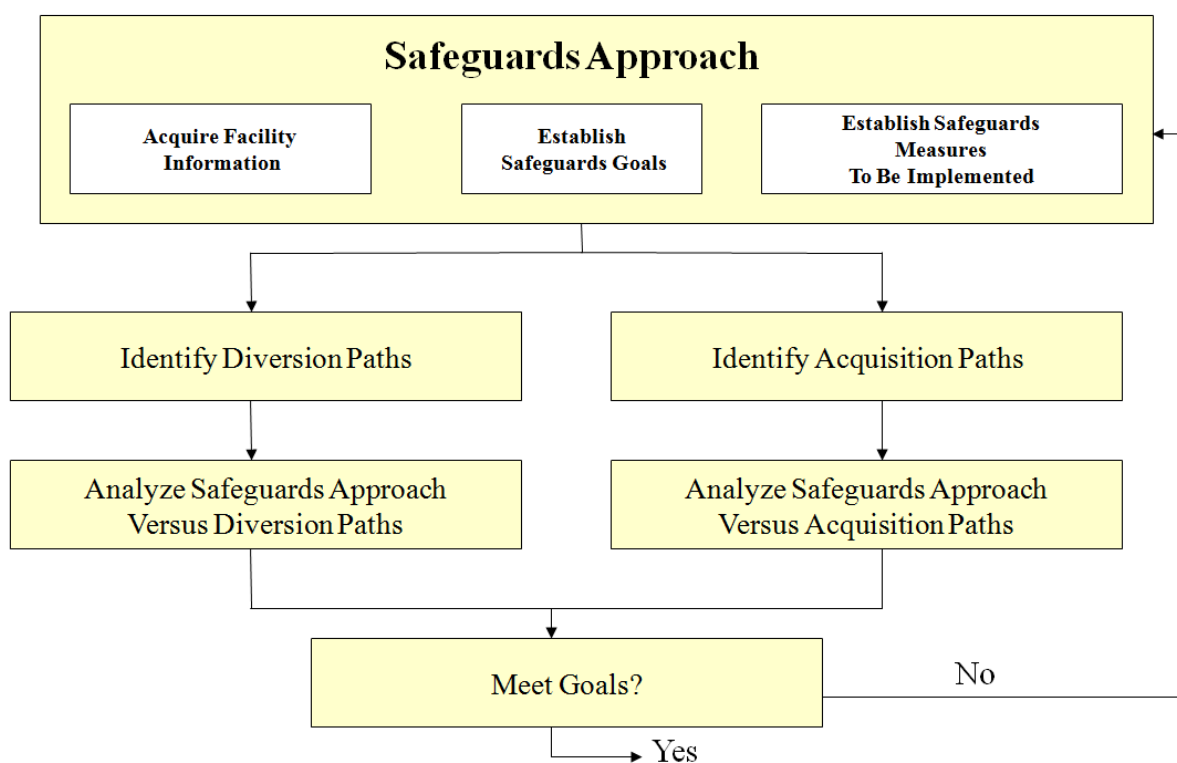


Fig. 4. Process used in designing the safeguard approach.

CHAPTER II

MATERIAL ACCOUNTANCY

II.A. Overview of the Nuclear Material Measurement Systems

The safeguards approach presents several nuclear material measurement systems. The measurement systems and how they are used in the safeguards approach are explained here.

One measurement system is a Spent Fuel Non Destructive Assay (SFNDA) measurement. The SFNDA was used as an unspecified NDA measurement to quantify the Pu content in spent fuel assemblies. There is extensive work being done on these NDA techniques and information on them can be found in Refs. 16, 17, and 18.

Another measurement technique is the Tension Metastable Fluid Detector (TMFD) for online alpha spectroscopy to quantify Pu and U concentration in solution. For alpha spectroscopy, the TMFD works by spinning the working fluid; therefore putting it under tension. This takes advantage of the weakened intermolecular bonds of liquids in sub-vacuum states. The alpha particles incident on the sufficiently tensioned working fluid can nucleate critical size vapor bubbles which grow from nanoscales and are then possible to see, hear and record. If the working fluid is spun slower or faster, more or less incident particle energy, respectively, is needed to nucleate a bubble. Therefore, the tension of the working fluid is proportional to the alpha particle energy threshold in the detector.²²

The K-edge densitometer (KED) was used to quantify the concentration of U. In KED a continuous-energy beam of photons from a tungsten-anode x-ray tube is transmitted through a liquid sample. Photon transmission through the sample is measured at two photon energies which closely bracket the k-absorption edge energy of the element of interest (U). The concentration of the measured element is a simple function of the photon transmission below and above the absorption edge, and the path length of x-rays through the sample.^{23,24}

The Hybrid K-edge/x-ray Fluorescence Densitometer (HKED) was used to quantify the U and Pu concentration. In HKED, KED is augmented by a simultaneous x-ray fluoresce (XRF) measurement of the specimen. The concentration of the most-

abundant actinide is determined by KED, and the XRF detector measures fluoresced x-rays emitted from sample face. Concentrations of other actinides are derived from attenuation-corrected ratios of XRF peak areas.^{23, 24}

Isotope Dilution Mass Spectroscopy (IDMS) is another measurement technique that was used to quantify the concentration of Pu and U. IDMS involves the addition of a measured quantity of a highly enriched isotope, known as the ‘spike’, to an aliquot of the sample. After chemical and isotopic equilibrium, the quantities of the isotopes in the sample are measured relative to the added isotope by mass spectroscopy. From the change in the isotopic ratios of the sample caused by the spike, the elemental content of the sample may be calculated.²⁵

The Active Neutron Coincidence Counter (ANCC) was used to quantify Pu concentration in oxide form. The ANCC uses a neutron source to bombard the sample with neutrons and records coincidence neutrons from fission in the sample. The fission rate is proportional to the amount of fissile material in the sample.

High Purity Germanium (HPGe) detectors were used to calculate the U concentration. HPGe’s are semiconductors that use the formation of ions in the detector material by the interaction of gamma rays with atomic electrons and the atomic nucleus. This creates a pulse that can be recorded that is linearly proportional to the energy of the incident gamma ray.²⁵

All concentration measurements must be paired with a volume or mass measurement to calculate the total amount of the given element or isotope. To measure volume in tanks a Dip Tube (DIPT) is used. To measure the mass of a given object a Gravimetry (GRAV) measurement is used, which simply means weighing the item.

To measure the leftover Pu and U on the clad and hulls the Plutonium Scrap Multiplicity Counter (PSMC) is used. The PSMC is a high efficiency neutron coincidence counter designed for measuring the multiplicity of the neutron emission from both spontaneous fission and induced-fission reaction in Pu and U.²⁶

A table of the detector uncertainties is given in TABLE 3. All uncertainties are from the “International Target Values 2000 for Measuring Uncertainties in Safeguarding Nuclear Material”²⁷ except the TMFD, which is still under development so a best guess uncertainty was used. The concentration measurement uncertainties are given with and without the volume/mass uncertainty. In the safeguards approach, the total uncertainty of

the concentration plus volume/mass is used but only referred to as the concentration measurement.

TABLE 3.
Uncertainties for the Detectors Used in Safeguards Approach

Detector	Total Uncertainty (%) ^(a)	Concentration + Volume/Mass	Total Uncertainty(%) ^(a)
SFNDA	10 ^(b)		
TMFD	0.8485	TMFD + DIPT	0.9220
HKED	0.6708	HKED + DIPT	0.7616
IDMS	0.2828	IDMS + DIPT	0.4583
KED	0.0625	KED + DIPT	0.3659
ANCC	0.2828	ANCC + GRAV	0.2915
HPGe	0.7071	HPGe + GRAV	0.7106
DIPT	0.3606		
GRAV	0.0707		

^(a) The total uncertainty is the random and systematic uncertainties summed in quadrature.

^(b) This is an estimated uncertainty that is not unreasonable for current SFNDA detectors to achieve.

II.B. Description of the Facility

Facility information was developed for a hypothesized UREX+1a plant with a throughput of 1000 MTHM per year. The plant is assumed to run continuously 365 days per year. The incoming spent fuel was assumed to have a Pu content of 1% and a U content of 96%. This makes the flow through the plant approximately 27.4 kg Pu/day and 2630.1 kg U/day. Because of the high separation efficiencies, the Pu and U waste is ignored (the same amount of Pu and U that enter the facility exit the facility as product). Pu and U concentrations at each separation step, provided by Argonne National Laboratory,⁸ are given in TABLE 4 and TABLE 5 respectively. The U content after UREX is negligible.

TABLE 4.

Pu Concentration at Each Separation Step

	Feed (g/L)	Raffinate (g/L)	Product (g/L)	Spent Solvent (g/L)
UREX	3.978	2.652	-	-
CCD-PEG	2.652	2.116	-	-
TRUEX	2.116	$2.81 \cdot 10^{-15}$	2.106	$3.49 \cdot 10^{-10}$
TALSPEAK	2.106	1.269	$5.24 \cdot 10^{-16}$	$3.97 \cdot 10^{-25}$

TABLE 5.

U Concentration at Each Separation Step

	Feed (g/L)	Raffinate (g/L)	Product (g/L)	Spent Solvent (g/L)
UREX	219.890	$2.54 \cdot 10^{-22}$	70.932	$3.22 \cdot 10^{-17}$

The plant's MBAs were established in two different ways. Fig. 5 shows one proposed MBA break down where all the Pu separation steps are in one MBA. Fig. 6 shows the other proposed MBAs with each Pu separation step in its own MBA. The further break down of the MBAs in Fig. 6 was done for several reasons. Because the MA and C/S MBAs are the same, the smaller MBAs are more applicable to the C/S system. Since it is likely that each separation step will be done in different halls within the plant, it is expected that each hall would have different C/S systems. A typical C/S system would not be continuous in several rooms or halls within a plant. The smaller MBAs also use the TMFD, a real-time measurement, between each MBA. It is assumed that the TMFD uncertainty will decrease after each separation step since there is less radioactive material after each separation step, resulting in longer MBPs. The smaller MBAs also have the potential to determine if a diversion has occurred faster than a larger MBA could. The disadvantage of having smaller MBAs is more KMPs and having to analyze more measurements. The MBAs and KMPs used in the safeguards approach are labeled in each schematic.

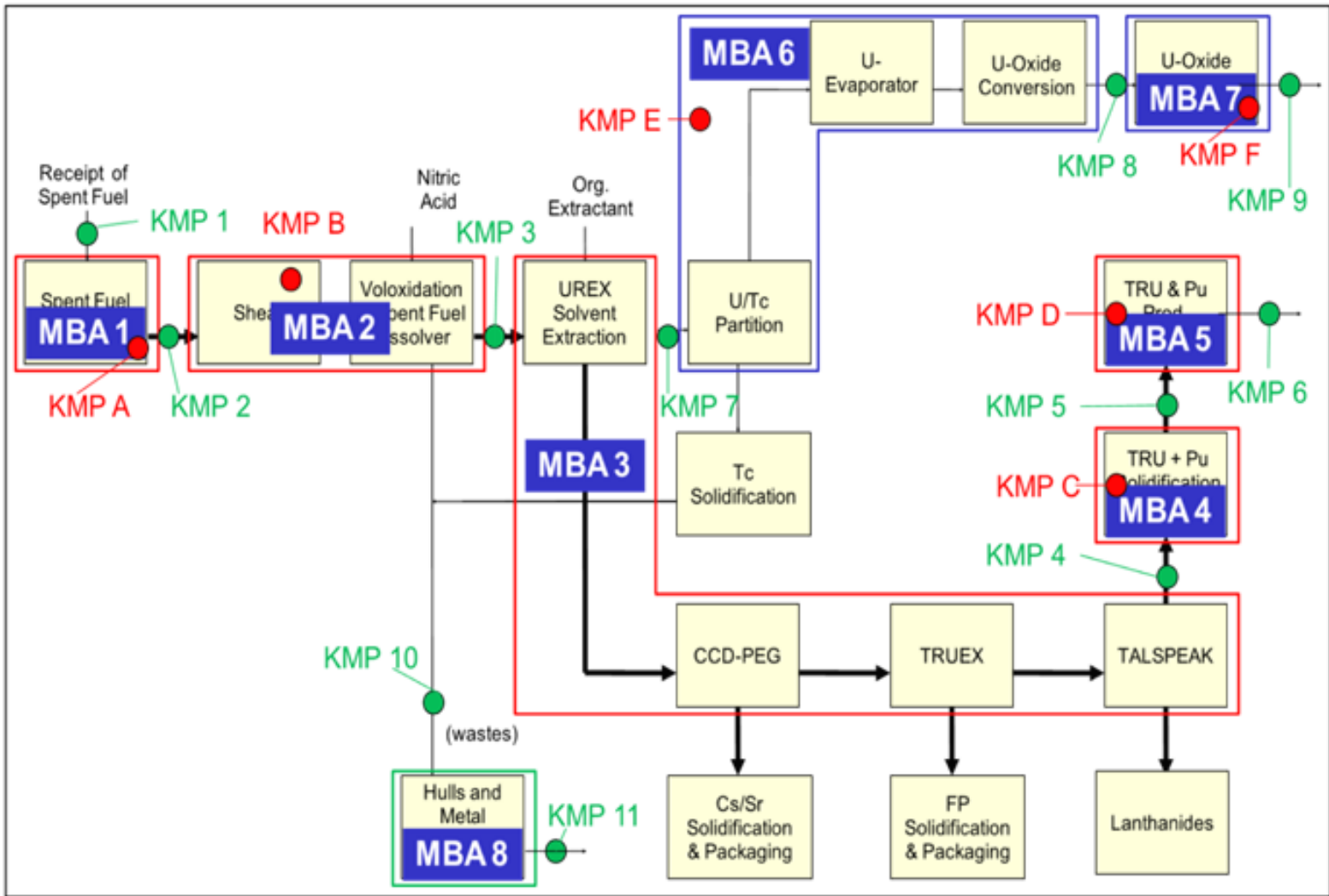


Fig. 5. MBA schematic where all the Pu separation steps are in one MBA.

Between each Pu separation step, there is a Receiving Tank (RT), Buffer Tank (BT) and Fill Tank (FT) as shown in Fig. 7. The RT continuously receives solution then ships it to the BT in one batch. The BT receives and ships solution on one batch. The FT receives solution in one batch and ships continuously. A graphical representation of the tank level versus time for all three tanks is shown in Fig. 8.

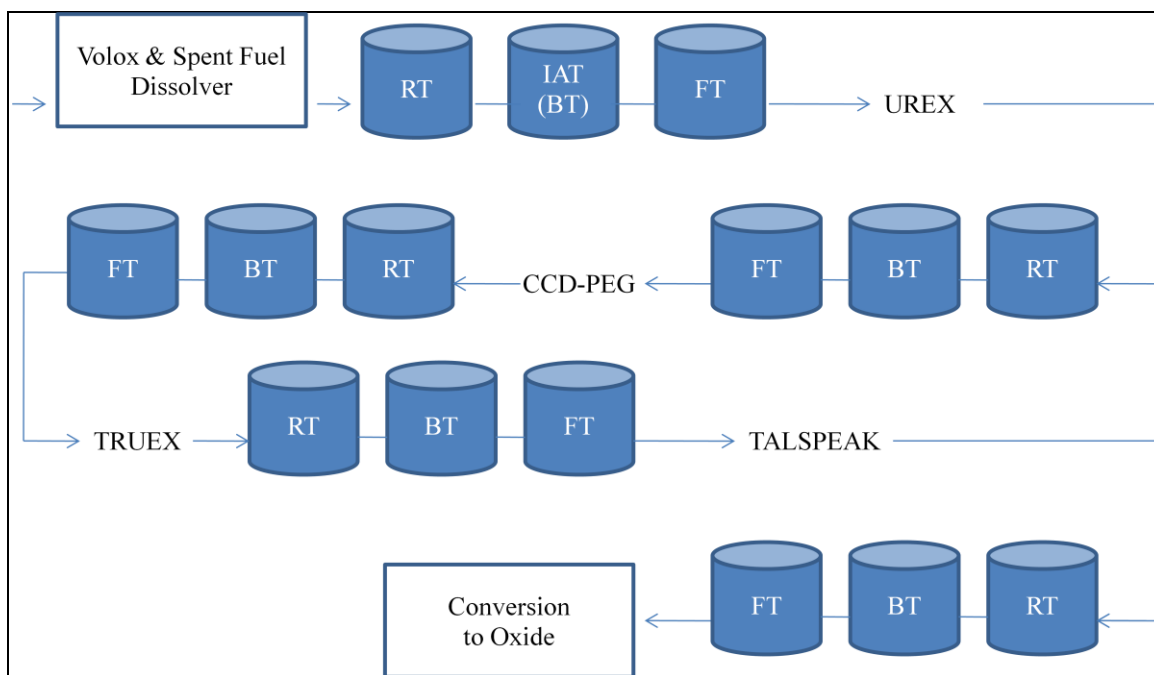


Fig. 7. RT, BT, and FT schematic.

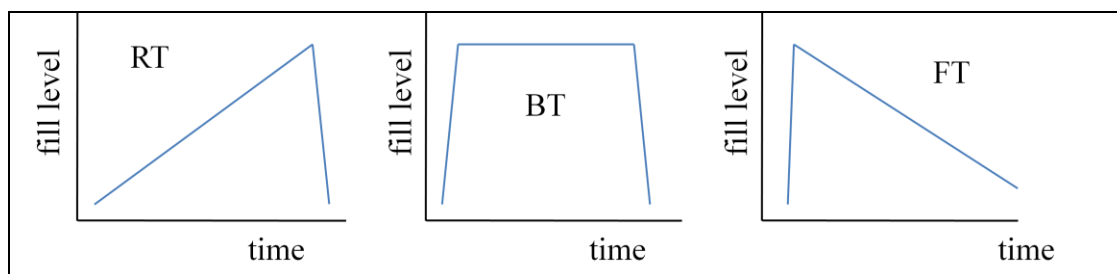


Fig. 8. RT, BT, and FT time versus tank fill level.

II.C. Material Accountancy System

Each of the MBAs in Fig. 5 and Fig. 6 were analyzed with the appropriate measurement techniques discussed in Sec. II.A. The MBPs and material accountancy nondetection probabilities (β_{MA}) were calculated as described in Sec. I.C.1. First, an uncertainty is calculated for zero MUF ($\mu = 0$ / null hypothesis [H_0]) by multiplying the amount of material (U or Pu) passing through the MBA per day by the detector uncertainty. This gives the uncertainty in grams per day (σ_t). The MPB is then calculated in days by iterating on

$$3 \times \sigma_t \times MPB \leq 1SQ. \quad (5)$$

The total uncertainty in all the measurements over one MBP with no diversion is

$$\sigma_{MUF} = MBP \times \sigma_t \quad (6)$$

which is also the standard deviation in Fig. 2. The threshold (S) was then calculated using the NORMINV function in excel which returns the inverse of the normal cumulative distribution for a specified probability ($1-\alpha = 95\%$), mean ($\mu = 0$), and standard deviation (σ_{MUF}).

The uncertainty in the measurement was then calculated over the MBP for a MUF of 1 SQ, σ_{MUF} , by multiplying the grams of material that pass through the MBA per MBP by the detector uncertainty (diversion hypothesis [H_1]). This is also the standard deviation in Fig. 2. β_{MA} was then calculated by using the NORMDIST function in excel that returns the normal distribution for the specified threshold (S), mean ($\mu = 1 SQ$), and standard deviation (σ_{MUF}).

Item accounting is used for MBA 1 therefore, the MUF should be zero and a non-zero MUF would indicate a diversion. As an additional measure, the bulk measurement of the Pu in the spent fuel assemblies was also analyzed. This is advantageous to detect partial diversions (fuel pins within the fuel assembly) of material. Using the SFNDA at KMPs 1 and 2 with the assumed SFNDA uncertainty of 10% the MBP is 0 days for a MUF of 1 SQ. This means that $3 \cdot \sigma_{MUF} > 1SQ$ for a MBP of zero days for the proposed detector and detector scheme. With the SFNDA uncertainty of 10%, the bulk measurement is not beneficial to the MA system. If the SFNDA uncertainty can be lowered to 1%, a MBP of 6 days can be achieved with a β_{MA} of 0.0328. If the MBP is

forced to be 30 days with the SFNDA uncertainty at 1%, the β_{MA} is 0.8318. KMP A would also use a SFNDA. This analysis is applicable to any reprocessing plant (i.e. PUREX, COEX, etc.) that has a spent fuel pool MBA and processes the same amount of Pu per year.

The analysis of U diversion is not considered in MBAs 1 or 2 because the diversion of any fuel material from these MBAs would be detected by the Pu diversion requirements. For example, an adversary would need to take 9.8 times more fuel pins (from MBA 1) or solution (from MBA 2) to reach 1 SQ of U than 1 SQ of Pu.

MBA 2, a bulk MBA, was analyzed with three different detector schemes. KMP 2 used the SFNDA and KMP 3 was analyzed with the IDMS, HKED, and TMFD. With a SFNDA uncertainty of 10% the MBP is zero days no matter what the measurement at KMP 3 is. Again, this indicates that a SFNDA uncertainty of 10% is not beneficial to the MA system. This is a bigger deal for MBA 2 than it is for MBA 1 because the bulk measurement is the only MA system; it is not secondary to item accounting as it is in MBA 1. Additional analysis was done to determine the uncertainty needed by the SFNDA measurement to achieve MBPs of 5, 6, 7, and 8 days for a MUF of 1 SQ. The SFNDA uncertainty needed and β_{MA} for each detector scheme and MBP is shown in TABLE 6. This analysis is applicable to any reprocessing plant that has a MBA from after the spent fuel pool to an input accountability tank or buffer tank (i.e. PUREX) and processes the same amount of Pu per year. It should be noted that since the TMFD is essentially an online measurement the shorter MBP is of less concern compared with the IDMS and HKED. The inventory KMP, KMP B, can be any of the measurement techniques used at KMP 3.

TABLE 6.

SFNDA Uncertainties and β_{MA} for Various MBPs for MBA 2 for a MUF of 1 SQ Pu

MBP (days)	SFNDA uncertainty (%)	Detector at KMP 3	β_{MA}
5	1.89	IDMS	0.1975
5	1.79	HKED	0.1968
5	1.71	TMFD	0.0839
6	1.55	IDMS	0.1521
6	1.43	HKED	0.1521
6	1.33	TMFD	0.0832
7	1.31	IDMS	0.1160
7	1.16	HKED	0.1143
7	1.04	TMFD	0.0835
8	1.12	IDMS	0.0840
8	0.94	HKED	0.0819
8	0.79	TMFD	0.0822

MBA 3 was analyzed with five different detector schemes. The detectors used at both KMPs, MBPs, and β_{MA} for a MUF of 1 SQ Pu for each detector scheme is shown in TABLE 7. The measurements that take place at both KMPs are taken at the BTs before UREX and after TALSPEAK (see Fig. 7). A DIPT is used to measure the volume and the detectors listed in TABLE 7 are used to measure the concentration of Pu. This measures the total Pu in each BT to ensure that no diversion has occurred. There are no inventory KMPs in MBA 3 because it assumed that in the event of a plant shutdown all the material in MBA 3 would be processed so there would be no inventory in the MBA.

TABLE 7.

MBPs and β_{MA} for MBA 3 for a MUF of 1 SQ Pu

Detector at KMP 3	Detector at KMP 4	MBP (days)	β_{MA}
IDMS	IDMS	15	0.0015
IDMS	HKED	10	0.0078
IDMS	TMFD	9	0.0225
HKED	HKED	9	0.0363
TMFD	TMFD	7	0.0562

MBA 3A, 3B, 3C, and 3D were each analyzed using the TMFD at KMPs 3, 3A, 3B, 3C, and 4. As explained above, it is assumed that the TMFD uncertainty will decrease at each step, but the decrease in uncertainty has not yet been tested. Therefore, the original total uncertainty of 0.9220% (uncertainty for the TMFD plus DIPT) was used, making this a conservative analysis. The measurements that take place at all KMPs are taken at the BTs between each separation step (see Fig. 7). The DIPT is used to measure the volume and the TMFD was used to measure the concentration of Pu. This measures the total Pu in each BT to ensure that no diversion has occurred. The MBP is 7 days and β_{MA} is 0.0562 for MBAs 3A, 3B, 3C, and 3D. There is no inventory measurement in MBAs 3A, 3B, 3C, and 3D because the amount of material in the actual separation process is small and it assumed that in the event of a plant shutdown all the material in these MBAs would be processed so there would be no inventory.

MBA 4 was analyzed with three different detector schemes. The detectors used at the KMPs, MBPs and β_{MA} for a MUF of 1 SQ Pu for each detector scheme is shown in TABLE 8. KMP C uses an ANCC.

TABLE 8.

MBPs and β_{MA} for MBA 4 for a MUF of 1 SQ Pu

Detector at KMP 4	Detector at KMP 5	MBP (days)	β_{MA}
IDMS	ANCC	17	0.0046
HKED	ANCC	11	0.0377
TMFD	ANCC	10	0.0840

MBA 5 used the ANCC at KMPs 5 and 6. This gives a MBP of 23 days and a β_{MA} of 0.0745 for a MUF of 1 SQ Pu. KMP D uses an ANCC.

MBA 6 is the first MBA where the diversion of U is analyzed. It was evaluated using 4 different detector schemes. The detectors considered at KMP 3 were used at KMP 7 by perturbing the uncertainty across the UREX separation step due to the loss of U. The UREX separation was assumed to have a 99.99% separation efficiency making the additional uncertainty 0.01%. KED was also considered at KMP 7. A HPGe

measurement is used at KMP 8. The results for a MUF of 1 SQ U (75 kg ^{235}U = 7500 kg U assuming 1% ^{235}U) are shown in TABLE 9. KMP E could use any of the detectors considered at KMP 7.

TABLE 9.
MBPs and β_{MA} for MBA 6 for a MUF of 1 SQ U

Detector at KMP 7	Detector at KMP 8	MBP (days)	β_{MA}
IDMS ^a	HPGe	112	0.0936
HKED ^a	HPGe	91	0.1438
TMFD ^a	HPGe	81	0.1697
KED	HPGe	118	0.0800

^aDetectors considered at KMP 3 with uncertainties perturbed across UREX separation step.

MBA 7 used a HPGe measurement at KMPs 8 and 9. This gives a MBP of 94 days and a β_{MA} of 0.1340 for a MUF of 1 SQ U. KMP F uses a HPGe.

MBA 8 uses a PSMC at KMPs 10 and 11. KMP 10 is to confirm that no Pu was diverted out of MBA 2 and no U was diverted out of MBA 6. No inventory KMP is needed at MBA 8 and no MBP or β_{MA} is given because the amount of material is small and it is essentially a waste MBA.

CHAPTER III

OTHER SAFEGUARD MEASURES

III.A. Incorporation of Other Safeguard Measures into Nondetection Probability

The nondetection probability (β) goal for the safeguards approach is 5% for any MBA. Since the MA system alone cannot always reach this goal, additional safeguard measures are used. If the additional safeguard measures are independent of the MA system, the total nondetection probability (β_{total}) can be calculated as

$$\beta_{total} = \beta_{MA} * \beta_i * \dots * \beta_{i+n} . \quad (7)$$

To reach the goal of $\beta_{total} = 5\%$, C/S and SM safeguard measures were considered, in addition to the MA system, in the safeguards approach.

Additional safeguard measures are also needed for defense in depth. This includes multiple independent and redundant layers of defense so that no single layer, no matter how robust, is exclusively relied upon. That way, if an adversary can defeat one of the safeguard systems, there are other systems in place that will detect a diversion of material. The more safeguard systems in place, the higher probability the adversary will fail.

III.B. Containment and Surveillance

Only the requirements of the C/S were evaluated because specific facility information is needed for designing C/S systems. The C/S was analyzed so the total nondetection probability for each MBA was 5%. Since the nondetection probability achieved by the MA system, β_{MA} , is a function of detector uncertainty, which is known, the nondetection probability for the C/S system, $\beta_{C/S}$, was calculated using:

$$\beta_{MA} * \beta_{C/S} = \beta_{total} = 5\%$$

Therefore

$$\beta_{C/S} = \frac{0.05}{\beta_{MA}} \quad (8)$$

Thus, any diversion the MA system may be detected by the C/S system. The results given in this section are for the same detector schemes considered in Sec. II.C.

As described in Sec. II.C., the bulk measurement systems for MBAs 1 and 2 are not beneficial to the MA system if the SFNDA uncertainty is 10%. This means that the C/S system would need to be able to detect any diversion of material and requires $\beta_{C/S}$ to equal 0.05 to meet the safeguard goals.

For MBA 1, if the SFNDA uncertainty can be lowered to 1%, then the MA system is advantageous to the safeguards system and relaxes the requirements of the C/S system. A graph of β_{MA} and $\beta_{C/S}$ versus MUF from 1 to 8 kg Pu to keep the β_{total} at 5% is shown in Fig. 9. Note that in the figure, $\beta_{C/S}$ is not given for a MUF of 8 kg; this is because the MA system alone reaches the nondetection probability goal ($\beta_{MA} < 0.05$).

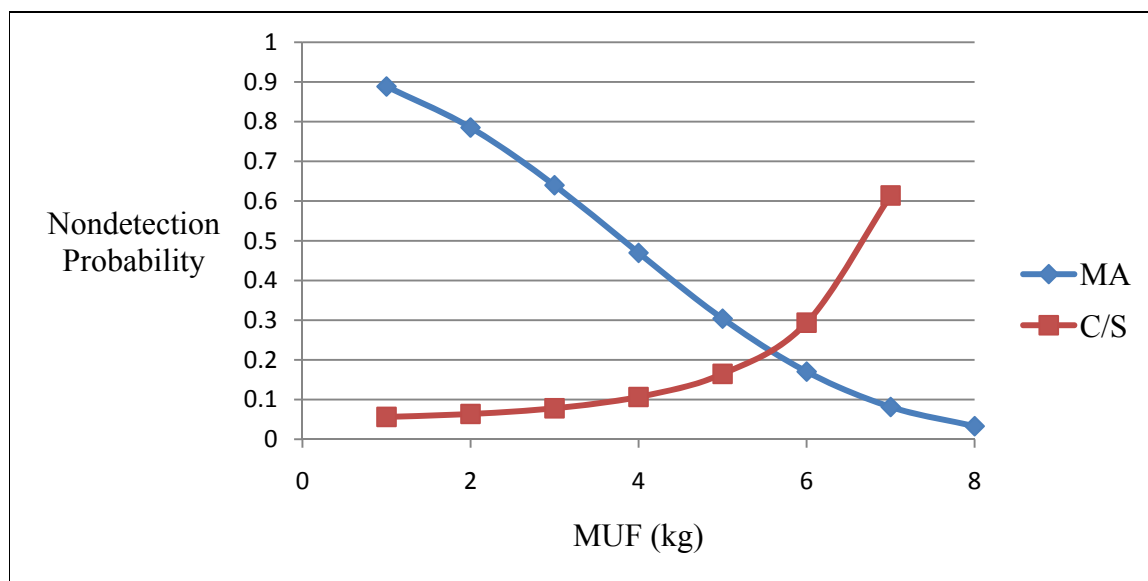


Fig. 9. β_{MA} and $\beta_{C/S}$ versus MUF for MBA 1 using a SFNDA uncertainty of 1%.

In Sec. II.C. MBA 2 was analyzed for the uncertainty needed by the SFNDA measurement needed to achieve MBPs 5, 6, 7 and 8 days for various detector schemes. $\beta_{C/S}$ is given in TABLE 10 for the same requirements and detector schemes. An example of β_{MA} and $\beta_{C/S}$ versus MUF from 1 to 8 kg Pu for MBA 2 is shown in Fig. 10. This example shows the result from having an IDMS at KMP 3 with a MBP of 7 days, making the SFNDA uncertainty at KMP 2 be 1.31%.

TABLE 10.

SFNDA Uncertainties and $\beta_{C/S}$ for Various MBPs for MBA 2 for a MUF of 1 SQ Pu toKeep β_{total} at 5%

MBP (days)	SFNDA uncertainty (%)	Detector at KMP 3	$\beta_{C/S}$
5	1.89	IDMS	0.2531
5	1.79	HKED	0.2540
5	1.71	TMFD	0.5956
6	1.55	IDMS	0.3288
6	1.43	HKED	0.3287
6	1.33	TMFD	0.6010
7	1.31	IDMS	0.4312
7	1.16	HKED	0.4376
7	1.04	TMFD	0.5985
8	1.12	IDMS	0.5950
8	0.94	HKED	0.6102
8	0.79	TMFD	0.6083

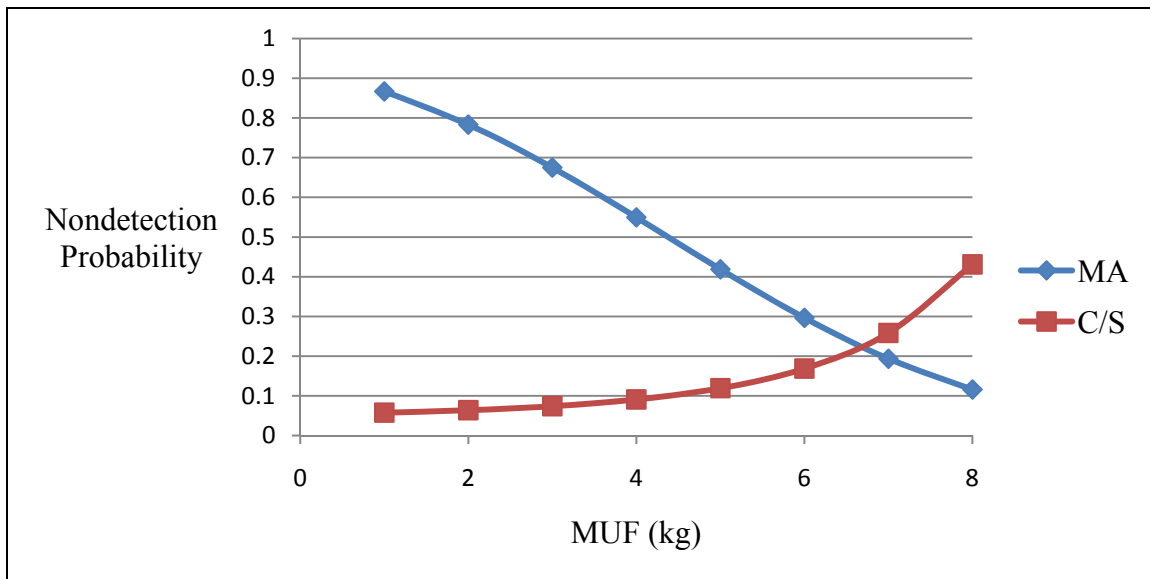


Fig. 10. β_{MA} and $\beta_{C/S}$ versus MUF for MBA 2 using a 7 day MPB, SFNDA uncertainty of 1.31% at KMP 2 and the IDMS at KMP3.

MBA 3 was analyzed with five different detector schemes. The detectors used at both KMPs, MBPs, and $\beta_{C/S}$ for a MUF of 1 SQ Pu for each detector scheme is shown in

TABLE 11. $\beta_{C/S}$ is not given in the first 4 schemes; this is because the MA system alone, reaches the nondetection probability goal for a MUF of 1 SQ Pu ($\beta_{MA} < 0.05$). A graph of β_{MA} and $\beta_{C/S}$ versus MUF from 1 to 8 kg Pu using the HKED at KMPs 3 and 4 is shown in Fig. 11. $\beta_{C/S}$ is not shown for a MUF of 8 kg; this is because β_{MA} , alone, has reached the β_{total} goal of 0.05.

TABLE 11.

$\beta_{C/S}$ for MBA 3 for a MUF of 1 SQ Pu to Keep β_{total} at 5%

Detector at KMP 3	Detector at KMP 4	MBP (days)	$\beta_{C/S}$
IDMS	IDMS	15	-
IDMS	HKED	10	-
IDMS	TMFD	9	-
HKED	HKED	9	-
TMFD	TMFD	7	0.8892

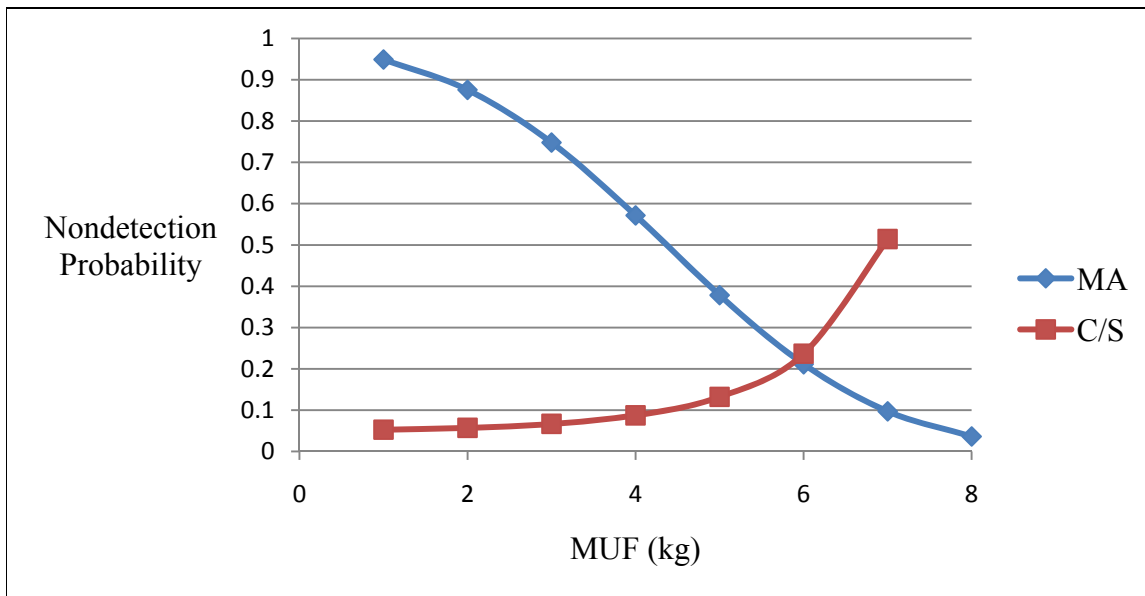


Fig. 11. β_{MA} and $\beta_{C/S}$ versus MUF for MBA 3 using the HKED at KMPs 3 and 4.

MBA 3A, 3B, 3C, and 3D were each analyzed using the TMFD at KMPs 3, 3A, 3B, 3C, and 4. For the MBP of 7 days the $\beta_{C/S}$ is 0.8892 for a MUF of 1 SQ Pu. The graph of β_{MA} and $\beta_{C/S}$ versus MUF from 1 to 8 kg Pu for MBAs 3A, 3B, 3C, and 3D using a TMFD at KMPs 3, 3A, 3B, 3C, and 3D is shown in Fig. 12.

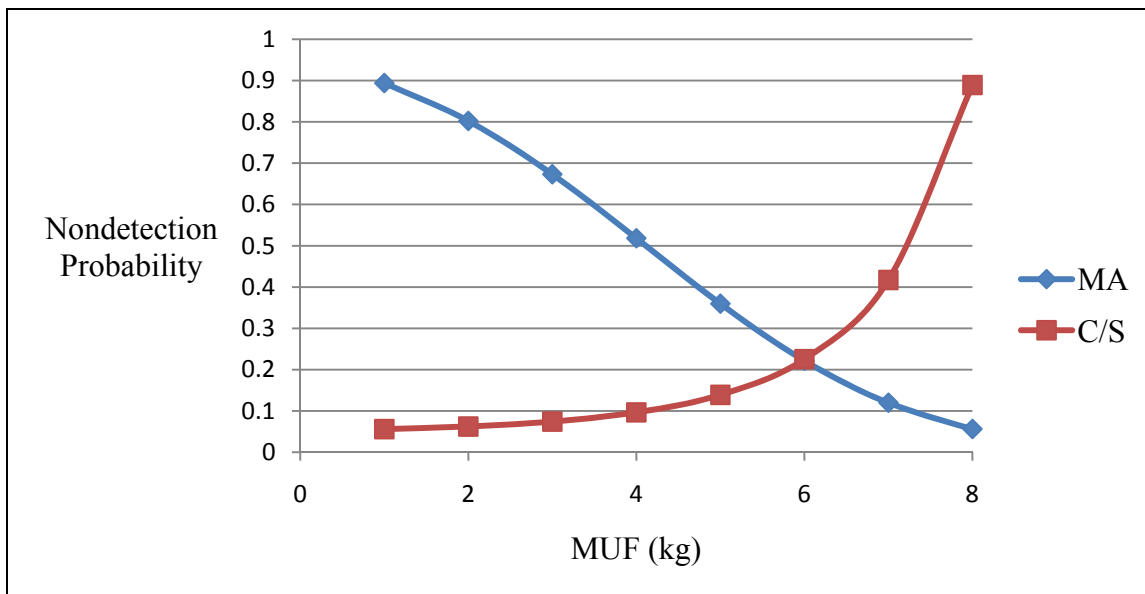


Fig. 12. β_{MA} and $\beta_{C/S}$ versus MUF for MBA 3 using the TMFD at KMPs 3, 3A, 3B, 3C, and 3D.

MBA 4 was analyzed with three different detector schemes. The detectors used at the KMPs, MBPs and $\beta_{C/S}$ for a MUF of 1 SQ Pu for each detector scheme is shown in TABLE 12. $\beta_{C/S}$ is not given in the first 2 schemes; this is because the MA system alone, reaches the nondetection probability goal for a MUF of 1 SQ Pu ($\beta_{MA} < 0.05$). A graph of β_{MA} and $\beta_{C/S}$ versus MUF from 1 to 8 kg Pu for MBA 4 using a TMDF at KMP 4 and the ANCC at KMP 5 is shown in Fig 13.

TABLE 12.

$\beta_{C/S}$ for MBA 4 for a MUF of 1 SQ Pu to Keep β_{total} at 5%

Detector at KMP 4	Detector at KMP 5	MBP (days)	$\beta_{C/S}$
IDMS	ANCC	17	-
HKED	ANCC	11	-
TMFD	ANCC	10	0.5951

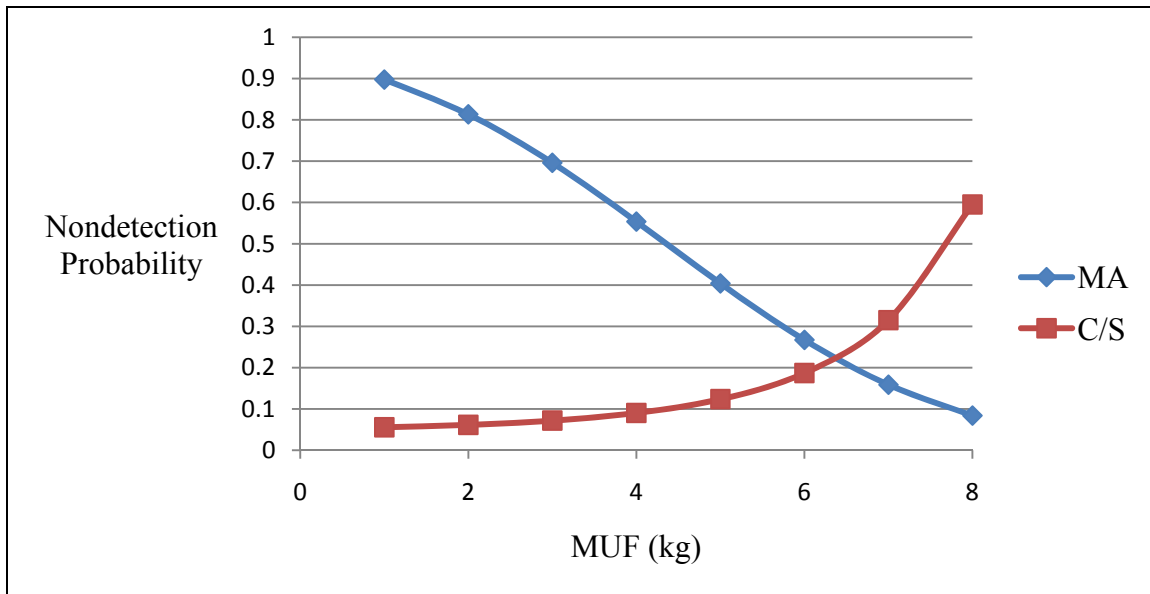


Fig 13. β_{MA} and $\beta_{C/S}$ versus MUF for MBA 4 using a TMFD at KMP 4 and a ANCC at KMP 5.

MBA 5 used the ANCC at KMPs 5 and 6. For the MBP of 23 days, the $\beta_{C/S}$ is 0.6716 for a MUF of 1 SQ Pu. A graph of β_{MA} and $\beta_{C/S}$ versus MUF from 1 to 8 kg of Pu for MBA 5 is shown in Fig. 14.

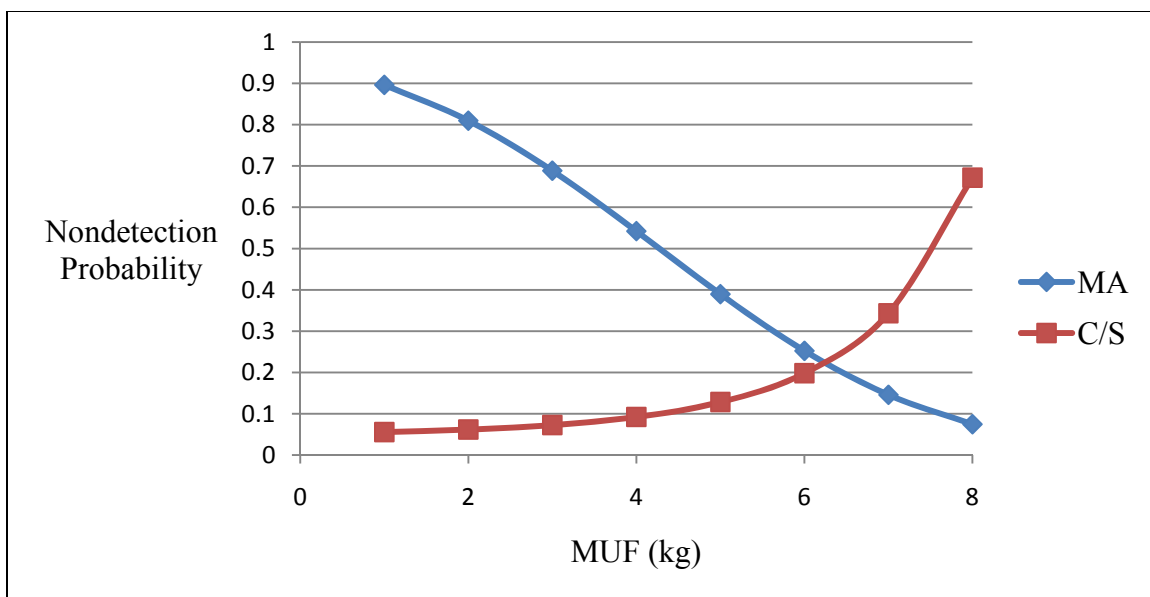


Fig. 14. β_{MA} and $\beta_{C/S}$ versus MUF for MBA 5 using a ANCC at KMPs 5 and 6.

MBA 6 was evaluated using 4 different detector schemes. The detectors considered at both KMPs, MBPs, and $\beta_{C/S}$'s are shown in TABLE 13 for a MUF of 1 SQ U.

TABLE 13.

$\beta_{C/S}$ for MBA 6 for a MUF of 1 SQ U to Keep β_{total} at 5%

Detector at KMP 7	Detector at KMP 8	MBP (days)	$\beta_{C/S}$
IDMS ^a	HPGe	112	0.5342
HKED ^a	HPGe	91	0.3476
TMFD ^a	HPGe	81	0.2947
KED	HPGe	118	0.6252

^aDetectors considered at KMP 3 with uncertainties perturbed across UREX separation step.

MBA 7 used the HPGe at KMPs 8 and 9. For the MBP of 94 days, the $\beta_{C/S}$ is 0.3731 for a MUF of 1 SQ U.

There is no graph showing β_{MA} and $\beta_{C/S}$ versus MUF for the U MBAs because there is no time constraint. The MBPs are long enough that they could easily be decreased to detect MUF less than 1 SQ.

These results show that the less total uncertainty in the detector system for each MBA, the MA nondetection probability decreases. In turn, the C/S nondetection probability can increase, (to keep the total nondetection probability at 5%) decreasing the requirement on the C/S system.

III.B.1. Summary of the Material Accountancy and Containment and Surveillance

Results

TABLE 14 shows the MA and C/S results for all the detector schemes and SFNDA uncertainties considered at MBAs 1 and 2. TABLE 15 shows the MA and C/S results for all the detector schemes considered at MBAs 3, 3A, 3B, 3C, 3D, 4, 5 ,6 ,7 and 8.

TABLE 14.
MBA 1 and 2 MA and C/S Results

MBA 1				
Detector at KMPs 1 & 2	SFNDA uncertainty (%)	MBP (days)	β_{MA}	$\beta_{C/S}$
SFNDA	10	0	0	0.05
SFNDA	1	6	0.0328	-
SFNDA	1	30	0.8318	0.0601
MBA 2				
KMP 2 SFNDA uncertainty (%)	Detector at KMP 3	MBP (days)	β_{MA}	$\beta_{C/S}$
1.89	IDMS	5	0.1975	0.2531
1.79	HKED	5	0.1968	0.2540
1.71	TMFD	5	0.0839	0.5956
1.55	IDMS	6	0.1521	0.3288
1.43	HKED	6	0.1521	0.3287
1.33	TMFD	6	0.0832	0.6010
1.31	IDMS	7	0.1160	0.4312
1.16	HKED	7	0.1143	0.4376
1.04	TMFD	7	0.0835	0.5985
1.12	IDMS	8	0.0840	0.5950
0.94	HKED	8	0.0819	0.6102
0.79	TMFD	8	0.0822	0.6083

TABLE 15.
MBA 3, 3A, 3B, 3C, 3D, 4, 5, 6, 7, and 8 MA and C/S Results

MBA 3				
Detector at KMP 3	Detector at KMP 4	MBP (days)	β_{MA}	$\beta_{C/S}$
IDMS	IDMS	15	0.0015	-
IDMS	HKED	10	0.0078	-
IDMS	TMFD	9	0.0225	-
HKED	HKED	9	0.0363	-
TMFD	TMFD	7	0.0562	0.8892
MBA 3A, 3B, 3C, 3D				
Detectors at KMPs 3, 3A, 3B, 3C, 4		MBP (days)	β_{MA}	$\beta_{C/S}$
TMFD		7	0.0562	0.8892
MBA 4				
Detector at KMP 4	Detector at KMP 5	MBP (days)	β_{MA}	$\beta_{C/S}$
IDMS	ANCC	17	0.0046	-
HKED	ANCC	11	0.0377	-
TMFD	ANCC	10	0.0840	0.5951
MBA 5				
Detector at KMP 5	Detector at KMP 6	MBP (days)	β_{MA}	$\beta_{C/S}$
ANCC	ANCC	23	0.0745	0.6716
MBA 6				
Detector at KMP 7	Detector at KMP 8	MBP (days)	β_{MA}	$\beta_{C/S}$
IDMS ^a	HPGe	112	0.0936	0.5342
HKED ^a	HPGe	91	0.1438	0.3476
TMFD ^a	HPGe	81	0.1697	0.2947
KED	HPGe	118	0.0800	0.6252
MBA 7				
Detector at KMP 8	Detector at KMP 9	MBP (days)	β_{MA}	$\beta_{C/S}$
HPGe	HPGe	94	0.1340	0.3713
MBA 8				
Detector at KMP 10	Detector at KMP 11	MBP (days)	β_{MA}	$\beta_{C/S}$
PSMC	PSMC	-	-	-

III.C. Solution Monitoring

The incorporation of a SM system can reduce the requirements or completely get rid of the need of the C/S system on MBAs containing solution. If the SM system is independent of the MA and C/S systems, the total nondetection probability is

$$\beta_{MA} * \beta_{C/S} * \beta_{SM} = \beta_{total} = 5\% \quad (9)$$

where β_{SM} is the SM nondetection probability. As shown in Fig. 7, there is a RT, BT, and FT before and after each Pu separation step. The SM system will monitor the concentration and volume of each RT and FT as it fills and empties. This is independent of the MA system, as the MA system confirms that no diversion has occurred by analyzing the total Pu in each BT. The concentration measurement will be done using the TMFD, as it is a real-time measurement and the DIPT for volume measurement. Under normal conditions, as the RTs and FTs fill and empty, the concentration measurement should be constant, oscillating around its nominal value, and the volume measurement should steadily increase and decrease. This is shown in Fig. 15 for the RT. If the adversary were to take solution from the line and not replace the solution, the volume measurement should detect this diversion, as shown in Fig. 16. If the adversary were to take solution from the line and replace the solution with another solution (with the same density), the concentration measurement should detect this diversion as shown in Fig. 17.

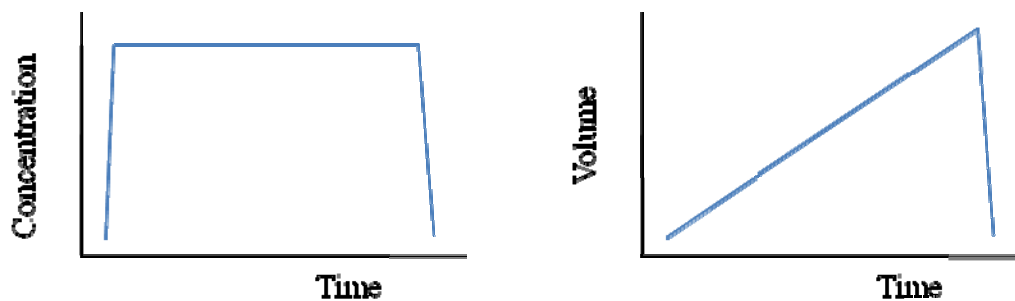


Fig. 15. Normal concentration and volume graphs for RT filling and emptying.

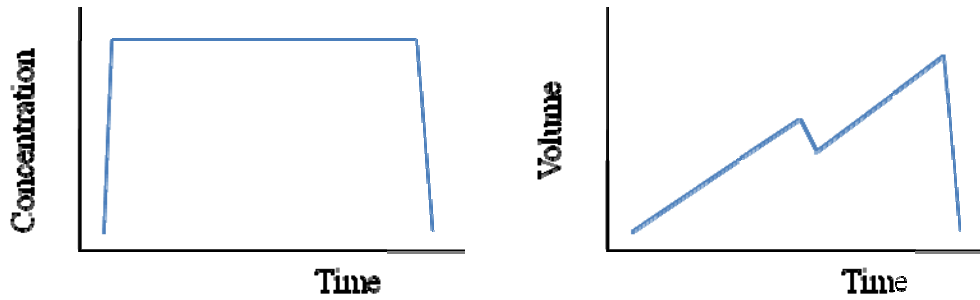


Fig.16. Diversion of solution without replacing the diverted solution, concentration and volume graph for RT filling and emptying.

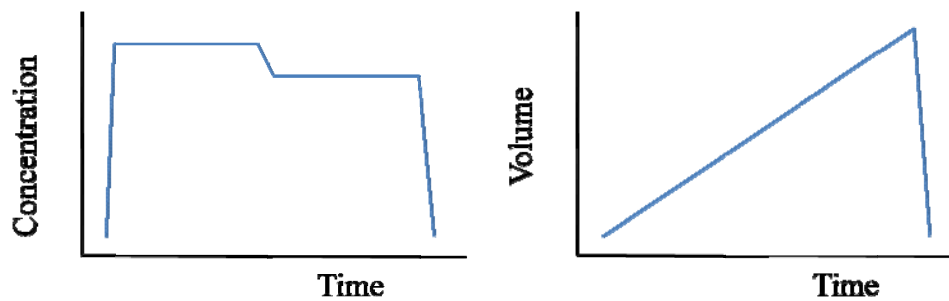


Fig. 17. Diversion of solution while replacing the diverted solution with another solution (with the same density) concentration and volume graph for RT filling and emptying.

β_{SM} was found by

$$\beta_{SM} = 1 - P_{SM} = 1 - (P_V^{SM} * P_C^{SM}) \quad (10)$$

where P_{SM} is the SM probability of detection, P_V^{SM} is the SM volume probability of detection, and P_C^{SM} is the SM concentration probability of detection. The SM was used on MBAs 3A, 3B, 3C, and 3D and was analyzed for a period of 7 days since that is the MA MBP for these MBAs. P_V^{SM} and P_C^{SM} were calculated using the same basic principles as computing β_{MA} explained in Sec. II.C. First, the mass of Pu per MBP was calculated by dividing the mass of Pu per year by the MBPs per year to get 191.8 kg Pu/MBP. This is the same for all the considered MBAs (since losses in the process were essentially negligible). The liters (L) of solution entering and exiting each MBA per MBP were then calculated by dividing the kgs of Pu per MBP by the Pu concentration. A table of the liters of solution entering and exiting each MBA per MBP is shown in TABLE 16.

TABLE 16.
Liters of Solution per MBP for MBAs 3A, 3B, 3C, and 3D

	MBA 3A (L/MBP)	MBA 3B (L/MBP)	MBA 3C (L/MBP)	MBA 3D (L/MBP)
Entering	$4.82 \cdot 10^4$	$7.23 \cdot 10^4$	$9.06 \cdot 10^4$	$9.11 \cdot 10^4$
Exiting	$7.23 \cdot 10^4$	$9.06 \cdot 10^4$	$9.11 \cdot 10^4$	$1.51 \cdot 10^5$

To calculate P_V^{SM} the L/MBP entering and exiting the MBA was multiplied by the volume uncertainty and combined to get the total MUF uncertainty, σ_{MUF} , in L over one MBP. The threshold (S) is then calculated using the NORMINV function in excel which returns the inverse of the normal cumulative distribution for a specified probability ($1-\alpha = 95\%$), mean ($\mu = 0$), and standard deviation (σ_{MUF}). The SM volume nondetection probability (β_V^{SM}) was then calculated by using the NORMDIST function in excel that returns the normal distribution for a specified threshold (S), mean ($\mu = \# \text{ of } L \text{ for } 1 \text{ } SQ$), and standard deviation (σ_{MUF}). P_V^{SM} is then found by $1 - \beta_V^{SM}$.

To calculate P_C^{SM} the kgs Pu/MBP entering and exiting the MBA was multiplied by the TMFD uncertainty and combined to get the total MUF uncertainty, σ_{MUF} , in kgs in one MBP. The threshold (S) is then calculated using the NORMINV function in excel which returns the inverse of the normal cumulative distribution for a specified probability ($1-\alpha = 95\%$), mean ($\mu = 0$), and standard deviation (σ_{MUF}). The SM concentration nondetection probability (β_C^{SM}) was then calculated by using the NORMDIST function in excel that returns the normal distribution for the specified threshold (S), mean ($\mu = 1 \text{ } SQ \text{ in kgs}$), and standard deviation (σ_{MUF}). P_C^{SM} is then found by $1 - \beta_C^{SM}$.

Since the nondetection probability achieved by the MA and SM systems is a function of detector uncertainty, which is known, the nondetection probability for the C/S system is found from

$$\beta_{C/S} = \frac{0.05}{\beta_{MA} * \beta_{SM}} \quad (11)$$

For a MUF of 1 SQ Pu, β_{SM} is 0.0082 over the 7 day MBP for all the MBAs considered. A graph of β_{MA} , β_{SM} , and $\beta_{C/S}$ versus MUF to keep β_{total} at 5% for MBAs 3A, 3B, 3C, and 3D is shown in Fig. 18. $\beta_{C/S}$ is not given for a MUF of 6 kg and greater because the MA and SM systems achieve a β_{total} of 5%.

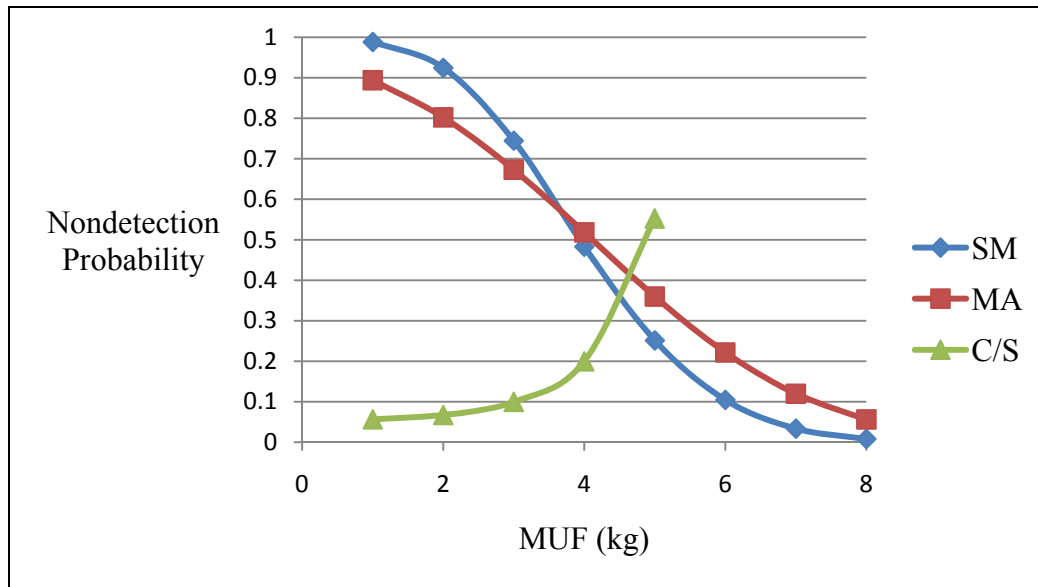


Fig. 18. β_{MA} , β_{SM} , and $\beta_{C/S}$ versus MUF to keep β_{total} at 5% for MBAs 3A, 3B, 3C, and 3D.

β_{SM} is slightly different for each of the MBAs because the concentration of Pu decreases after each separation step and the volume of solution approximately doubles from MBA 3A to 3D. This makes for a competing effect on β_{SM} . More solution is needed to obtain a given amount of Pu which decreases β_{SM} and σ_{MUF} increases after each separation step because the amount of solution increases as the solution is diluted which increases β_{SM} . The differences between each MBAs are small and are shown in Fig. 19. β_{SM} is dependent on facility information and if the solution volume increase were less, β_{SM} would change accordingly.

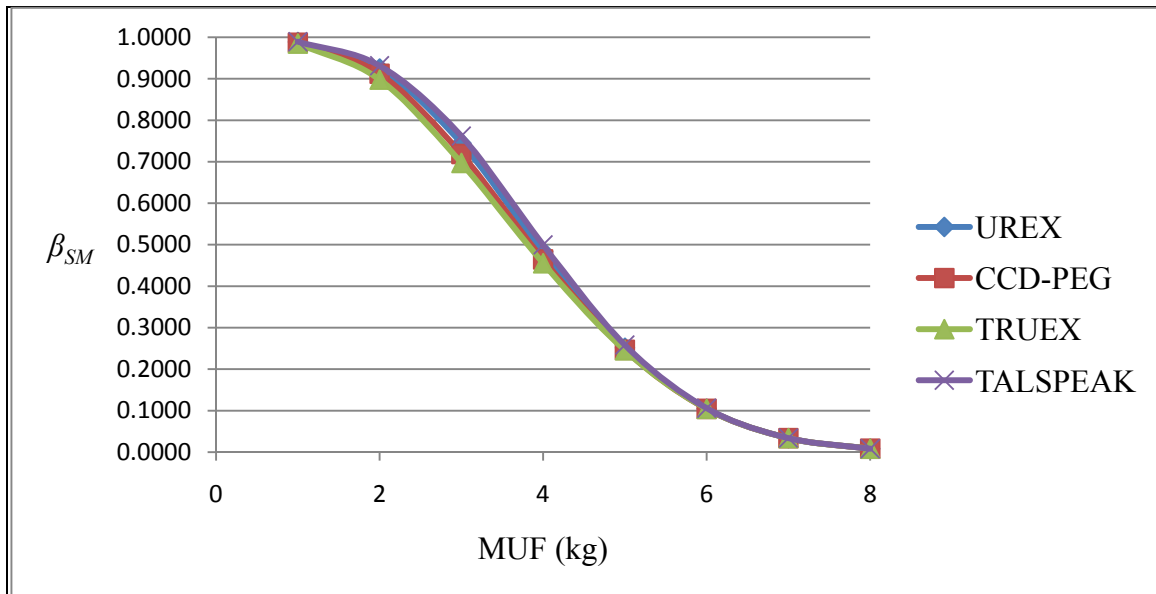


Fig. 19. β_{SM} for MBAs 3A, 3B, 3C, and 3D for a MUF from 1 to 8 kg Pu.

CHAPTER IV

PROPOSED UREX SAFEGUARDS APPROACH

The proposed safeguards approach for the UREX+1a facility uses the MBA scheme shown in Fig. 6, where each of the Pu separation steps are in separate MBAs. The detector systems used at each KMP is given in TABLE 17. The decision to use the TMFD between each separation step was chosen in the attempt to provide real-time measurement on all solution streams. HKED and IDMS both have lower uncertainties which yield longer MBPs which will decrease operation costs, but both systems are also costly and do not provide real-time measurements. Because the TMDF is a real-time measurement, the shorter MBPs are of less concern and will only marginally increase operation cost because the measurements are taken in real-time and no plant shut down is needed. The decision to use the MBA scheme where each Pu separation step is in its own MBA was done for several reasons. First, since the MA and C/S MBAs are the same, the smaller MBAs are more applicable to the C/S system. The smaller MBAs are also applicable to the SM system and have the potential to determine if a diversion has occurred faster than a larger MBA. Lastly, it is assumed that the TMFD uncertainty will decrease at each separation step resulting in longer MBPs. The detector uncertainties used are the same as given in Sec. II.A. The MBA's MBP and nondetection probabilities correlating to the KMPs given in TABLE 17 for a MUF of 1 SQ are shown in TABLE 18.

TABLE 17.
Detectors at each KMP for the Proposed Safeguard Approach

KMP	Detector
1	Item + SFNDA
2	Item + SFNDA
3A, 3B, 3C, 3D	TMFD
4	TMFD
5	ANCC
6	ANCC
7	TMFD
8	GRAV
9	GRAV
10	PSMC
11	PSMC

TABLE 18.
MBPs and β_s for a MUF of 1 SQ for each MBA for the Proposed Safeguards Approach.

MBA	MBP	β_{MA}	$\beta_{C/S}$	β_{SM}
1	-	-	0.05	
2	-	-	0.05	
3A, 3B, 3C, 3D	7	0.0562	-	0.0082
4	10	0.0840	0.5951	
5	24	0.0745	0.6716	
6	81	0.1697	0.2947	
7	94	0.1340	0.3731	

KMP 10 and MBA 8 are used to confirm that no Pu was diverted out of MBA 2 and no U was diverted out of MBA 6. No MBP is given for MBA 8 because the amount of material is small and it is essentially a waste MBA.

CHAPTER V

SUMMARY AND CONCLUSIONS

Facility information was acquired for a hypothetical 1000 MTHM/yr UREX+1a facility and the goals of the safeguards system were established based on the SQ and timeliness goals set by the IAEA. The MA system was designed and analyzed and then the requirements of the C/S system were determined to achieve the safeguard goals; a total nondetection probability at 5% and a false alarm probability of 5%. A SM system was then designed and analyzed to observe how it could relax the requirements of the C/S system. It was shown that the additional safeguard measures resulted in relaxed C/S system requirements to keep a certain β_{total} or a decrease in β_{total} .

The given safeguard approach shows that a UREX+1a facility can be safeguarded to the same standards as current reprocessing facilities. The goals of the system were reached and the MBPs are close to similar sized, current PUREX reprocessing facilities. Since UREX+1a has a lower material attractiveness and can be safeguarded as well as PUREX, UREX+1a is more proliferation resistant reprocessing technology.

Front end measurement techniques were considered and uncertainties must decrease in order to be advantageous to the MA system. A range of uncertainties were given that, if met, would result in reasonable MBPs. The results showed that SFNDA uncertainties close to 1% are needed to provide value to the MA system. These results are applicable to any reprocessing plant that has a spent fuel pool MBA and/or a MBA from after the spent fuel pool to an input accountability tank or buffer tank (i.e. PUREX, COEX) and processes the same amount of Pu per year. Currently the C/S system would need to detect any diversion.

The shortest MBP achieved by the MA system is 7 days. Since these MBAs use the TMFD, a real-time measurement, the shorter MBP is of less concern. If the TMFD, along with any of the detectors used in the safeguards approach, uncertainties could be decreased or new detectors developed with lower uncertainties, the MBPs on all MPAs could be lengthened, decreasing operation costs. It should be noted that the TMFD is still

being developed and may not achieve the uncertainty used in the safeguards approach. If the TMFD uncertainty is larger than used here or not used in the safeguards approach at all, the safeguard goals can still be met with the other detector schemes considered. The other detector schemes will not have real-time measurements but the UREX+1a facility can be safeguarded to the same standards as current reprocessing facilities.

Future work includes the analysis of acquisition pathways and protracted diversion scenarios. Testing of the TMFD is ongoing and better detector uncertainties could be used to refine the safeguards system. There are also extensive efforts on front end measurement techniques. If these detector uncertainties could be decreased bulk SNM measurement techniques could be used in addition to item accounting and C/S.

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