DIVERSION SCENARIOS IN AN AQUEOUS REPROCESSING FACILITY
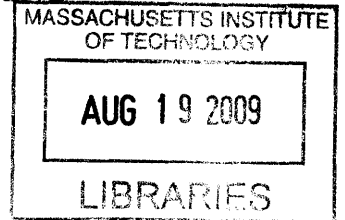
By

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Diversion Scenarios in an Aqueous Reprocessing Facility

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Abstract

The International Atomic Energy Agency requires nuclear facilities around the world to abide by heavily enforced safeguards to prevent proliferation. Nuclear fuel reprocessing facilities are designed to be proliferation-resistant and to use surveillance systems. While experience with small-scale reprocessing facilities has allowed for well understood safeguards, large-scale reprocessing facilities pose a new difficulty because of the larger error margins involved with the large volumes of spent fuel that is being processed. First, a hypothetical spent nuclear fuel reprocessing facility is described along with proliferation resistance methods typically used in actual facilities. This model establishes a foundation for studying diversion scenarios using a success tree method.

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Abbreviations

ARBI	Adjusted Running Book Inventory
ASAS	Automatic Sampling Authenticated System
Ba	Barium
CCTV	Closed Circuit Television
CRD	Camera/Radiation Detector
Cm	Curium
C/S	Containment and Surveillance
Fe^{+2}	Ferrous Ion
Fe^{+3}	Ferric Ion
FKMP	Flow Key Measurement Point
GPS	Global Positioning System
HAW	High Active Waste
HALW	High Active Liquid Waste
HKED	Hybrid K-Edge Densitometry
HMS	Hulls Monitoring System
IAEA	International Atomic Energy Agency
ICVD	Improved Cerenkov Viewing Device
IDMS	Isotope Dilution Mass Spectroscopy
IHVS	Integrated Head-End Verification System
IIV	Interim Inventory Verifications
IKMP	Inventory Key Measurement Point
ISVS	Integrated Spent Fuel Verification System

JNFL	Japan Nuclear Fuel Limited
KMP	Key Measurement Points
LASCAR	Large Scale Reprocessing Plant Safeguards
LASW	Low Active Solid Waste
MBA	Material Balance Area
MOX	Mixed Oxide
MUF	Material Unaccounted For
NDA	Non-Destructive Assay
$NH_2SO_3^-$	Sulfamate Ion
NO_2^-	Nitrite Ion
NO_3^-	Nitrate Ion
NRTA	Near-Real-Time Accountancy
OOC	Out of Commission
OSL	On-site Laboratory
OSP	Other Strategic Point
PCAS	Plutonium Canister Assay System
PIMS	Plutonium Inventory Measurement System
PIV	Physical Inventory Verification
Pu	Plutonium
PuN	Plutonium Nitride
$PuO_2(NO_3)_2$	Plutonyl Nitrate
PUREX	Plutonium Uranium Extraction
RBI	Running Book Inventory

RFID   Radio Frequency Identification

RRP   Rokkasho Reprocessing Plant

SMMS   Solution Measurement and Monitoring System

SQ   Significant Quantity

SRD   Shipper/Receiver Differences

TBP   Tri-*n*-butyl Phosphate

THORP   Thermal Oxide Reprocessing Plant

U   Uranium

UBVS   Uranium Bottle Verification System

UN   Uranium Nitride

$UO_2(NO_3)_2$-   Uranyl Nitrate

UREX   Uranium Extraction

VCAS   Vitrified Canister Assay System

WCAS   Waste Crate Assay System

WDAS   Waste Drum Assay System

WUM   Weapons Usable Material

Introduction

A nuclear reprocessing facility may be an excellent idea in terms of reducing waste entering the environment, but there is one major concern that keeps fuel reprocessing from becoming widely accepted. Public fear of proliferation has stunted the growth of interest in reprocessing. In developing and running a large-scale reprocessing facility, the complication is whether or not it can be built such that weapons-usable material (WUM) is properly accounted for at all stages from arrival to delivery. Despite all the current technology and safeguarding, determination of the limitations within reprocessing facilities in order to understand the risks involved is still a challenge.

This thesis explores such possible weaknesses by focusing on an aqueous reprocessing facility as the site for WUM diversion. The following sections describe the layout of a hypothetical aqueous reprocessing facility, safeguards requirements, surveillance systems, detection systems, chemical processes and their associated mechanical systems, and some potential methods for diversion. Given that the focus is on aqueous reprocessing, the main question is, "What is the facility's proliferation success tree structure?" This thesis analyzes attractive diversion scenarios for an aqueous fuel reprocessing facility using a success tree format.

This study focuses on the various approaches and the ease of proliferation from the facility operator's point of view. In other words, the facility operators themselves are the proliferators trying to defeat safeguards imposed by external organizations. The success of diversion is dependent on the probability of successfully defeating the various preventive measures considering that there may be multiple attempts or pathways taken without getting caught. For the purpose of this study, a success tree is used to compare different diversion

approaches. The overall study of attractive diversion scenarios for aqueous reprocessing facilities will determine the feasibility to divert material and hopefully prompts design reconsiderations that can target any current weaknesses.

1 Reprocessing Facility General Description

The focus of this study involves analyzing key information relevant to diverting material from a nuclear reprocessing facility. Because this information is sensitive material, reprocessing facilities do not make available complete and detailed descriptions of the facility. However, there is a general trend for how nuclear facilities are laid out and procedures for entering and exiting the facility. In the following sections, a fictitious reprocessing facility is crafted based on various sources describing real nuclear facilities. Referenced sources include published literature, pictures, videos, and personal tours of existing nuclear facilities. The crafting of such kind of fictional reprocessing facility is done in order to study potential diversion scenarios, which are discussed in later chapters.

1.1 General Description

The reprocessing facility consists of three major buildings (see Figure 1-1). The first is the main administrative building. The second is the reprocessing building where the actual fuel handling takes place. The last building is the shipment building. Entering the reprocessing building requires going either through the administrative building or the shipment building via underground tunnels. The reprocessing building is built as a containment building for the fuel. When the reprocessing building was first built, the construction was overseen by IAEA inspectors to verify that it was according to the schematics. Any changes made since the construction were also reviewed by IAEA inspectors.

The reprocessing facility has about 10,000 employees who ensure the continual reprocessing operation (Sellafield Ltd). This group of people handles not only the fuel reprocessing, but everything necessary to maintain a semi-independent reprocessing facility such as repairs, maintenance, and radiation protection. External to the facility's employees are police

who visit throughout the day and are on call for any emergencies. Resident IAEA inspectors are also on-site 24 hours a day and perform random inspections of the facility using their own equipment and their own laboratory (Iwamoto, Ebata, Fujimaki, & Ai, 2006).
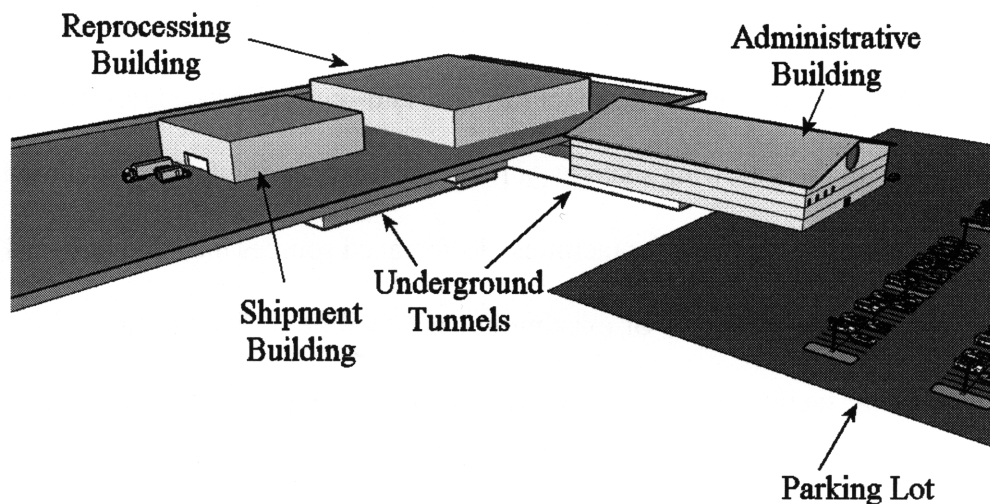
Figure 1-1. Reprocessing facility above shows the reprocessing building that is accessible via underground tunnels from either the shipment building or the administrative building. This facility is also enclosed with gates and monitored with cameras (not shown).

Personnel verification and logs are done via RFID name badges when entering secured areas. In addition, keys to enter certain restricted areas are distributed based on training and clearance levels. There is a key cabinet with keys to all areas accessible to the person in charge in the main operations room.

The reprocessing facility also continuously operates 24 hours a day, 7 days a week with few maintenance and major holiday shutdowns. During evening and night shifts, only minimum staff is on-site to verify processes are functioning normally. Other personnel remain on call for any emergencies.

1.2 Entering and Exiting Procedures

To enter the main building, an RFID name badge is required. This type of badge is distributed to everyone from administrators to maintenance staff. After entering the building,

there are several administrative offices. The fuel reprocessing occurs in a separate building that branches off from the main building.

The primary entrance to the reprocessing facility is from within the main building, although there are other exits such as those for the shipment building and emergencies that are not attached to the main building. Nonetheless, these exits are still confined within a fenced boundary under constant video surveillance. In order to enter the restricted area, an RFID name badge is required. This badge is obtained by undergoing radiation training and a thorough background check. The name badge is only used to enter the restricted area, and keys must be used to enter any further restricted areas within the reprocessing facility.

There is a video documenting a tour of the Thermal Oxide Reprocessing Plant (THORP) that goes through the entering process. The tour first enters a locker room where one removes shoes and socks and proceeds to put on special socks. Then, each individual passes through a turnstile and enters a shoe room. The setup of the facility entrance is similar to that shown in Figure 1-2. Everyone puts on a clean lab coat upon entering the shoe room and proceeds to a bench as directed. The shoe room is divided by a bench that cuts through the room to separate the clean area from the potentially contaminated area. Under the bench facing the unclean area are cubbyholes for storing shoes used in the potentially contaminated area. Shoes are put on by taking shoes out of the cubbyhole and swinging over the bench into them while avoiding stepping on the clean side of the bench. Everyone then signs in to enter the facility. To exit the facility, the entry procedure is reversed with a few additions such as frisking for contamination prior to exiting (sinema7, 2007). Detectors for this can include whole body detectors integrated into a turnstile like mechanism that allows only one person through at a time.
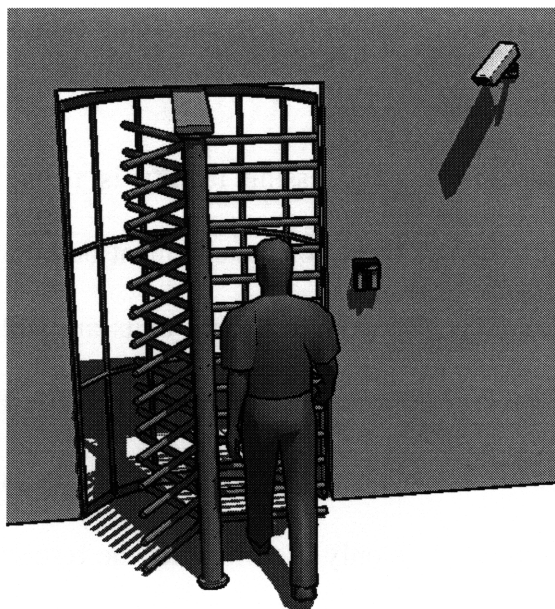
Figure 1-2. Man is entering the reprocessing building. Camera records the man entering while the turnstile has a weight that records his entering mass. RFID sensor grants access after successfully verifying identity via RFID.

In a personal tour of a power plant in Japan, a nearly full set of clothing was provided. This included a full body suit and a hardhat in addition to the socks and shoes, all of which were nearly identical to those worn by personnel except for the visitor tags and color coding. These were all returned to the facility at the end of the tour after frisking for contamination in a whole body detector and changing back into normal clothes. Personnel are required to wear working clothes inside the restricted area, and the employee uniform in the main building. When entering and exiting the restricted area, they undergo similar procedures as those described for visitors. The main difference would be the use of RFID badges to enter rather than signing in. With the level of security for entering and exiting, taking WUM out of the restricted area in one's person through the primary entrance is not a simple task.

In addition to the entering and exiting measures described above, other facilities are also known to use additional procedures and strategies for personnel entering or exiting accountability. For example, some facilities keep weight records prior to entering and compare

them to exiting weight (M. Golay, personal communication, February 18, 2009). Facilities that use this strategy prohibit eating and drinking in the facility because of the hazards related to fuel reprocessing. There are also no bathrooms within the facility, and personnel must use bathroom facilities in the main building. Because of this, weight should in principle not change, although bringing in tools and equipment for maintenance are likely handled differently in the entrance procedures.

1.3 External Surveillance

There are cameras outside the facility that feed to a recording system that stores information for about three months prior to being written over. There is a receptionist at the entrance during regular business hours. The front door is locked at all times and requires either an RFID badge or keys to enter. There are no metal detectors at the entrance to the main building although visitors may be required to walk under one prior to a tour. During non-business hours, only minimum staff is on site, and only cameras watch the entrance.

Every day, there are various routine security inspections done throughout the day to verify that the facility has not been breached. These are done by personnel on site and by police who visit every few hours. Personnel performing these security inspections verify that emergency exits and fences have not been tampered with. A more rigorous security inspection is done on a weekly basis to make sure that fuel-containing areas within the facility have not been compromised. Cameras and the associated monitors and recording system are also checked for signs of physical damage, while surveillance monitors are verified to be still capable of alarming should there be any signs of tampering in the area. Police inspections consist of verifying that any alarming condition related to a security breech does in fact send the proper signal to the police department.

1.4 Inside the Facility

According to information regarding the Rokkasho Reprocessing Plant (RRP) as described by Iwamoto et al. (2006), the inside of the facility is divided into five sections where all relevant processes occur. The first section is where material is received and stored. This area contains a large pool specifically designed to hold fuel in a particular configuration such that it prevents criticality. Fuel in the pool is very radioactive and requires a well-shielded and heavy transfer cask attached to a crane for movement. Also, there are various cameras and detectors around the pool to guard the spent fuel as shown in Figure 1-3.
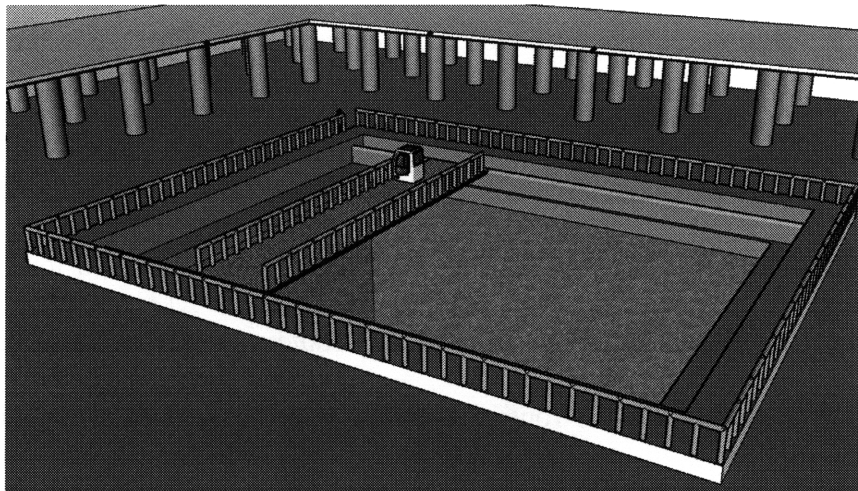
Figure 1-3. Spent fuel pool drawn to scale with crane moving across the pool. Camera surveillance located above columns.

Iwamoto et al. (2006) describes the next section as the area where all the main processes take place including the uranium conversion area. Processes in this area include fuel chopping, dissolving, and aqueous separation. There is also an On-Site Laboratory (OSL) for inspections that has the necessary equipment to perform tests on any stage of the reprocessing. Figure 1-4 shows the hot cells present in the OSL used by the IAEA inspectors. Wastes from the Main Process Area end up in the Waste Treatment and Storage Area, while uranium and plutonium go to the Mixed Oxide (MOX) Conversion Area. The final product ultimately goes to the Product

Storage Area. In terms of surveillance, there are over 50 monitoring systems and 70 cameras throughout the facility. These are primarily used by the IAEA and State inspectors, but can also occasionally be used by facility operators (Iwamoto, Ebata, Fujimaki, & Ai, 2006).
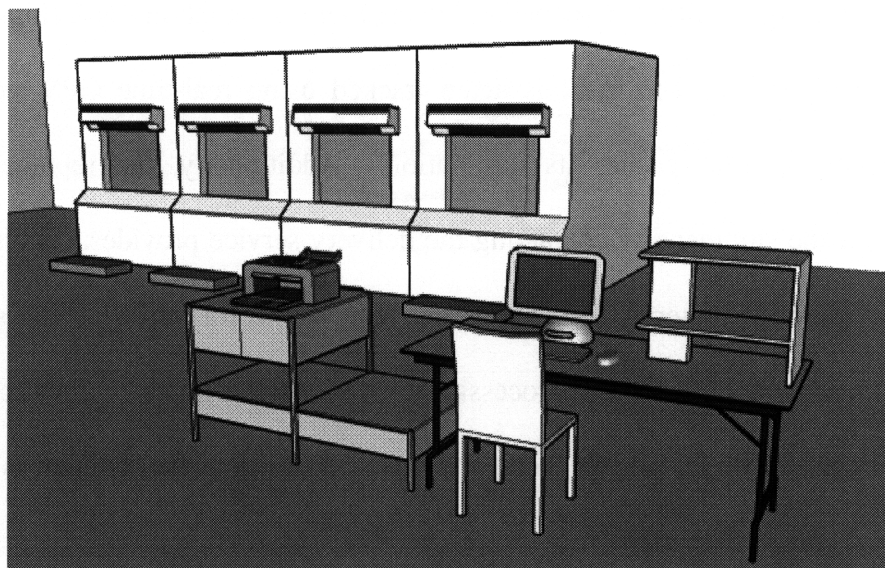
Figure 1-4. The hot cells shown here are representative of those found in the laboratory for sampling material. These hot cells have external arm manipulators to handle material inside. Image based on on-site laboratory photo of the Rokkasho facility (Matsuo, 2008, p. 15)

1.5 Fuel Shipments

The reprocessing facility is designed to handle fuel from power plants around the country. Nuclear fuel is received and dispatched in the form of fuel elements every two weeks. The fuel is transported in an ordinary looking shipping truck with a few markings indicating that special material is being handled. Additionally, the truck is accompanied by police vehicles while being continuously monitored via a global positioning system (GPS) using satellites to verify its location at all times. The truck driver is specially trained to deal with any problems that may arise during the fuel shipment.

The arrival site is a truck lock leading to the shipment building. Here, a team of trained employees verify the shipment by checking for the double seal on it as well as comparing its

contents to the shipment papers. The fuel is kept underwater in the transport cask until it is moved into the spent fuel pool. The fuel is identified during the movement. The entire process of receiving and moving the fuel is done by a qualified team following written procedures.

When new fuel is being dispatched, the fuel is placed in a shipping cask by the qualified team. The reprocessing facility is responsible for the fuel accountability and shipment until the shipment truck delivers it. The truck is again tracked using real-time GPS technology and escorted by police until it reaches its destination. Additionally, the reprocessing facility personnel monitor the shipment by contacting the delivery service provider. The shipper is not trained to handle nuclear material and thus is not responsible for verifying the shipping cask contents prior to departure from the reprocessing facility. The shipper is only accountable for transporting the cask while leaving the contents intact. The actual fuel content is then verified upon arriving at its new destination.

1.6 Conclusion

The reprocessing facility crafted above is intended as a representation of a real reprocessing facility. The use of the various assembled sources to create a fictional reprocessing facility is done as an example to determine weaknesses that a proliferator could potentially exploit. The resulting description of the facility and its use is carefully conceived and believed sufficiently accurate so that any exploitable weaknesses are minimized as would be the case in a real reprocessing facility.

2 Chemical Process and Mechanical Systems

Fuel separation is done to extract useful material from spent fuel. One method known as the aqueous process uses counter-current flow of two immiscible liquids, one aqueous and one organic, to extract "tagged" material from the solution. The following explains the mechanical process for decladding, the aqueous extraction process, and the components used in the extraction.

2.1 Fuel Chopping and Decladding

Spent fuel comes in complex forms of various element shapes and sizes held together by structural materials like zircaloy and aluminum. To take advantage of the aqueous process, spent fuel needs to be presented in liquid form. This is achieved by chopping the fuel elements and dissolving them in nitric acid. The nitric acid solution separates the fuel from the cladding material and prepares the fuel for the aqueous extraction process as will be discussed in the following section.

2.2 Aqueous Reprocessing

The extraction of materials is done through the careful manipulation of the wanted element's oxidation state such that it travels through various stages while sequentially being extracted from one liquid to the other through the use of contactors and immiscible liquids (Long, 1967, p. 163).

Figure 2-1 shows the main idea behind aqueous reprocessing. The decladding process previously explained also changes the valence states of plutonium and uranium to ones that will adequately interact with the aqueous process. This change of valence state acts as a tag for the material to be extracted.
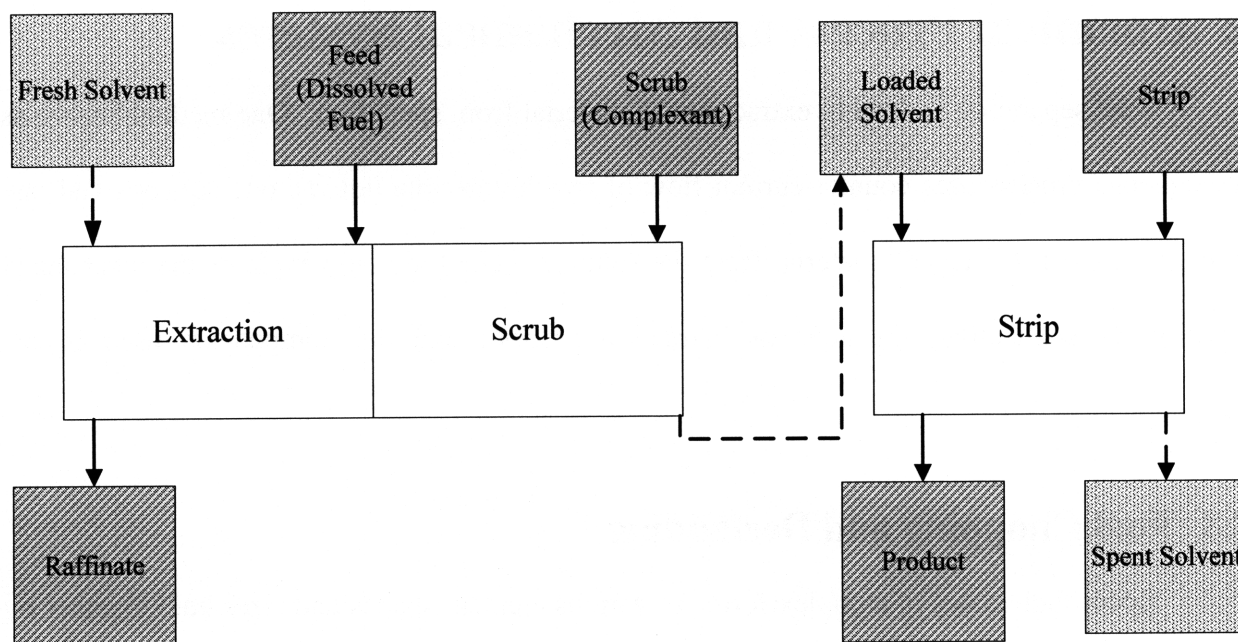
Figure 2-1. The aqueous process here describes the flow and separation of material through the various stages. This figure was based on another figure developed by Argonne National Laboratory (2006, p. 8).

For the Plutonium-Uranium Extraction (PUREX) process, the (IV) and (VI) states are preferable. The addition of the nitrite ion both reduces Pu(VI) and oxidizes Pu(III) to Pu(IV) as follows:

$$PuO_2^{+2} + NO_2^- + 2H^+ \rightarrow Pu^{+4} + NO_3^- + H_2O \qquad (2.1)$$

$$6Pu^{+3} + 2NO_2^- + 8H^+ \rightarrow 6Pu^{+4} + N_2 + 4H_2O \qquad (2.2)$$
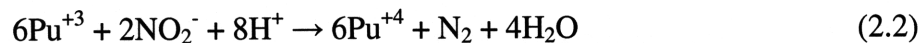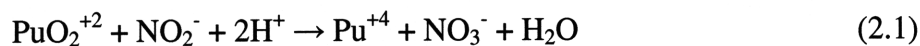
Uranium also undergoes a similar reaction to convert to its preferential valence state. In this state, the plutonium will be extracted using a solvent such as tri-*n*-butyl phosphate (TBP) (Long, 1967, p. 172). The TBP behaves such that it "extracts uranyl and plutonyl nitrates by forming disolvated complexes" as shown below (Long, 1967, p. 187):

$$UO_2^{+2} + 2NO_3^- + 2TBP_{org} \leftrightarrow UO_2(NO_3)_2 \cdot 2TBP_{org} \qquad (2.3)$$

$$PuO^{+2} + 2NO_3^- + 2TBP_{org} \leftrightarrow PuO_2(NO_3)_2 \cdot 2TBP_{org} \qquad (2.4)$$

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According to Benedict and Pigford (1957), in the PUREX process, fresh solvent along with the dissolved fuel first enters the extraction stage. The TBP preferentially selects the U and Pu because of the valence state while leaving behind a raffinate containing fission products. This U and Pu stream then proceeds to the scrubbing stage where lingering fission products are scrubbed off with a nitric acid solution and complexant and are then deposited into the raffinate. Next, the "raffinate is evaporated to recover nitric acid" and reduce the volume of the waste (p. 320).

Long (1967) then explains that the next step involves stripping the plutonium from the organic solvent. However, prior to stripping, it is necessary to destroy the nitrite ion so that it will not interact with the process. The addition of sulfamate ion does this as shown below:

$$NH_2SO_3^- + NO_2^- \rightarrow N_2 + H_2O + SO_4^{-2} \tag{2.5}$$
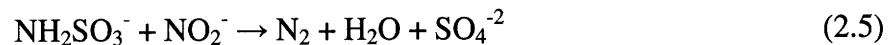
Ferrous sulfamate is used because the ferrous ion reduces plutonium to the (III) valence state so that it can properly interact. As the plutonium gets reduced, the ferrous ion gets oxidizes as follows (p. 172):

$$Pu^{+4} + Fe^{+2} \rightarrow Pu^{+3} + Fe^{+3} \tag{2.6}$$
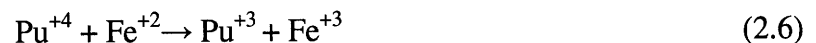
Continuing the flow of the U and Pu stream, the organic loaded solvent is contacted with an aqueous nitric acid aqueous strip where U remains in the organic phase while the Pu enters the product (Benedict & Pigford, 1957, p. 320).

The UREX process is similar to the PUREX process except for a few minor modifications. The important difference is that the ultimate goal of the UREX process is to retrieve U while containing the Pu within the raffinate, thus making it more proliferation-resistant. Meanwhile, the PUREX process is primarily used to obtain Pu (M. Regalbuto,

personal communication, November 2008).   The main modification to the PUREX process for U

extraction is the addition of a complexing agent to the scrub phase. This complexant prevents Pu

as well as Np from being extracted into the product (Thompson, Norato, Kessinger, Pierce,

Rudisill, & Johnson, 2002, p. 2)

2.3 Contactors

Contactors are used to separate the organic solvent from the aqueous solution by first

mixing the two phases and then allowing them to separate. This is done so that the two phases

interact thereby allowing the organic solvent to extract the appropriate species from the aqueous

solution. Three major types of contactors are typically used: pulse columns, mixer settlers, and

centrifugal contactors. These contactors fundamentally produce the same result, although the

method by which it is achieved is different.

A pulse column (See Figure 2-2) behaves very much like the liquid timer toys in which,

when turned upside down, colorful water flows downward as oil floats upward because of

density differences. In this application, however, the difference would be that oil and water are

not being used and the contactor is not turned over. Rather an organic solvent and aqueous

solution interact such that only certain materials are exchanged. According to Flagg, the column

contains materials such as sieves to provide a torturous path for the fluids that are flowing

through the column. The aqueous solution flows from the top down interacting with the feed

which enters from the center and the solvent which enters from the bottom. The liquids are

mixed and then separated as they flow through the pulsed column. Resulting is an organic

stream that flows out of the top of the column and an aqueous stream that is removed from the

bottom (Flagg, 1961).
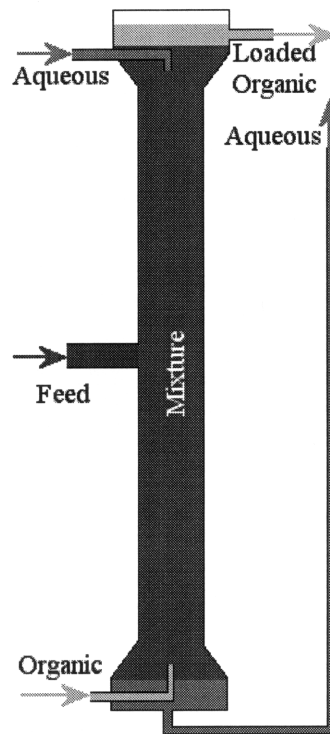
Figure 2-2. Pulse column above shows organic entering at the bottom, feed at the center, and aqueous at the top. Streams produce a mixture flowing through a torturous path. Fluid then separates into aqueous at the bottom and loaded organic at the top. Image based on image produced by Law (2008).

A mixer settler consists of two sections (See Figure 2-3). In the first section, the aqueous and feed solution and the organic solvent are thoroughly mixed with an impeller. The mixture then flows into another compartment where the solutions are allowed to separate by gravity. The aqueous and the loaded organic phases are separated and streamed out from their separate compartments (Law, 2008).

Centrifugal contactors work by insertion of aqueous solution, feed, and organic solvent from outside the contactor. The streams are mixed with mixing paddles that force the flow into a centrifugal bowl. The mixture then separates into a light phase of loaded organics drawn from the center and the heavy phase of aqueous solution drawn from the outside. See Figure 2-4.
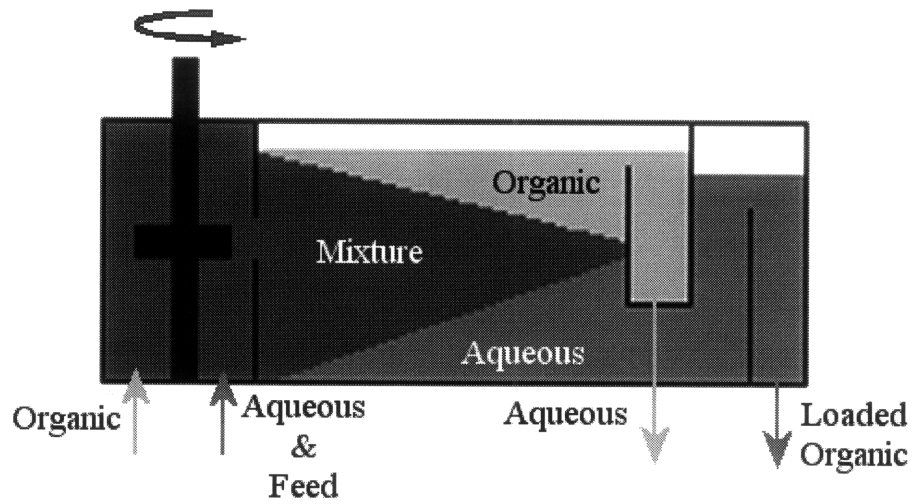
Figure 2-3. Mixer-Settler above has two main compartments. In the first section, aqueous and organic are mixed. The second section allows for material to separate by gravity. Image based on image produced by Law (2008).
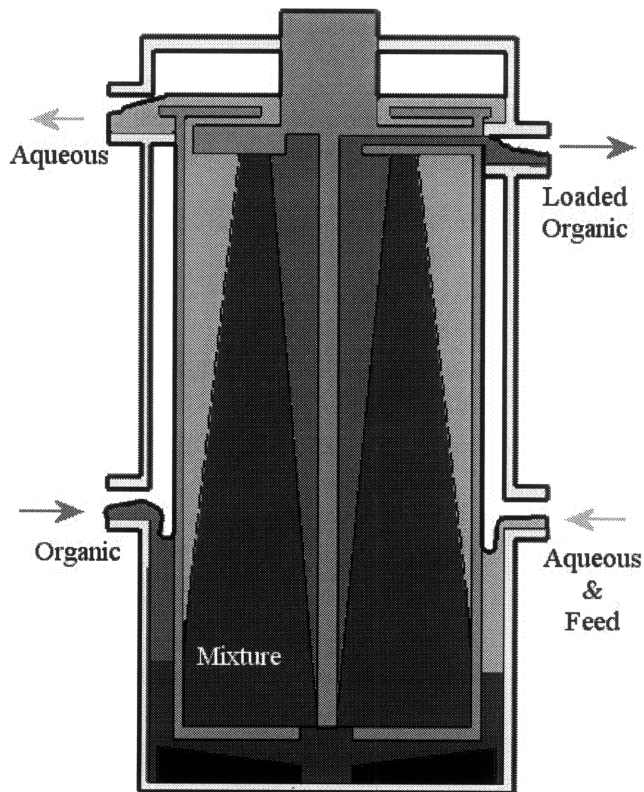
Figure 2-4. Centrifugal contactor showing the inlet of the organic phase on the lower left and the aqueous phase and feed in the lower right. Materials are mixed and then separated using centrifugal force. Loaded organic phase exits through the center toward upper right and aqueous phase exits from the outside toward the upper left. Image based on image produced by Law (2008).

3 Safeguards, Surveillance, and Detection

In many nuclear facilities, safeguards for protecting nuclear materials are imposed by the IAEA. These safeguards provide strict material handling requirements as well as material accounting regulations. Furthermore, the IAEA enforces these safeguards by conducting random inspections of the facilities. These may include visiting the sites in addition to collecting records of the facility's fuel shipments and operating history for later study offsite. Additionally, the IAEA uses their own equipment such as cameras, recorders, and detectors for inspecting these sites so as to prevent any unauthorized use of equipment.

For a reprocessing facility, the IAEA also attempts to impose safeguards that would quickly detect the diversion of a significant quantity (SQ). By doing so, the ability for a reprocessing facility to smuggle WUM is greatly reduced.

This concept works fine for small-scale reprocessing facilities because the IAEA does not have much trouble ensuring the safe and in-spec operation. Because of the small volumes of fuel being reprocessed, the IAEA does not face much difficulty in confirming that a SQ of WUM does not go unaccounted for simply because an SQ is far greater than the allowed accountability error margin.

On the other hand, for a large-scale reprocessing facility, the accountability error margin would be greater than several SQs because of the large volumes of spent fuel being processed. Thus, the proper accountability of WUM becomes resource-intensive requiring high precision, high accuracy, and constant surveillance in order to be proliferation resistant. Until now, the IAEA still has not been able to develop credible safeguards because of lack of experience and understanding (Iwamoto, Ebata, Fujimaki, & Ai, 2006, p. 1). With this in mind, this chapter

discusses proposed safeguards guidelines and potential requirements as well as surveillance and detection systems.

3.1 Determining Safeguards Requirements

Iwamoto et al. discusses methods developed with the help of IAEA and JNFL and used to create their own safeguards requirements for the RRP. Between the years of 1988 and 1992, LASCAR (Large Scale Reprocessing Plant Safeguards) was developed as a multinational forum that showed that "an effective safeguards approach could be implemented to a large scale reprocessing plant while maintaining an efficient use of resources." The following is a list of the LASCAR recommendations as described by Iwamoto et al.:

- High accurate measurement systems for the nuclear material accountancy

- Timeliness of verification by advanced nuclear material accountancy techniques

- Redundant and independent containment and surveillance systems

- Early consultations on facility characteristics especially early and continuing design information verification

- Authentication of equipment and systems made available by operator

- On-site verification capabilities

- Data acquisition and transmission

- The on-going or needed research and development tasks (Iwamoto, Ebata, Fujimaki, & Ai, 2006, p. 1).

Additionally, Appendix A in *Nuclear Safeguards and the International Atomic Energy Agency* (1995) describes the use of material balance areas (MBAs) to section of the facility into areas where inventories of items and amounts can be reliably taken. Key Measurement Points (KMPs) are also useful for measuring flow at strategic locations throughout the facility. Both

Near-Real-Time Accountancy (NRTA) of material along with Containment and Surveillance (C/S) of the material as it travels through the facility are necessary for maintaining safeguards (U.S. Congress, Office of Technology Assesment, 1995, pp. 114-115).

3.2 IAEA Surveillance and Detection Systems

Iwamoto et al. (2006) states that inspectors mostly use independent equipment, although occasionally they must share facility equipment that is used by operators because of limitations such as space and resources. Even though some sharing is unavoidable, great measures are taken to prevent tampering with the data or systems. For example, operators require approval prior to using shared equipment, signals are measured against reference standards, and C/S methods are used. Inspectors obtain samples for safeguards purposes through the Automatic Sampling Authenticated System (ASAS) using the Pneumatic Transfer Network (PTN) that connects sampling stations throughout the facility to the OSL. The OSL is particularly useful to both the IAEA and the State because it allows for timely and on-demand analysis by providing an area where questionable results can be identified and more carefully studied (pp. 2-3).

To meet the proposed safeguards requirements from the previous section, the RRP is divided into five major areas as described in section 1.3. These areas are where material accountability is performed and they correspond to the MBAs as shown in Figure 3-1. Johnson et al. (2001) further describes the Inventory Key Measurement Points (IKMPs) within the MBAs as being defined according to the materials measured as well as the method with which they are measured. Within MBA-1, there are two IKMPs, which are the spent fuel receipt and storage area and the head-end area. MBA-2 consists of three IKMPs: nuclear material in the main process area, nuclear material in the analytical area, and nuclear material in the uranium conversion area. MBA-3 only has one IKMP being the nuclear material in the waste treatment

and storage area. MBA-4 also has only one being the nuclear material in the MOX conversion area. MBA-5 has two IKMPs separately accounting for UO_3 and MOX product material in the storage area. Additionally, Flow Key Measurement Points (FKMPs) and Other Strategic Points (OSPs) are determined to verify flow between and within boundaries respectively (p. 3). The following sections show the application of safeguards for the various MBAs shown as described by Johnson et al. (2001).
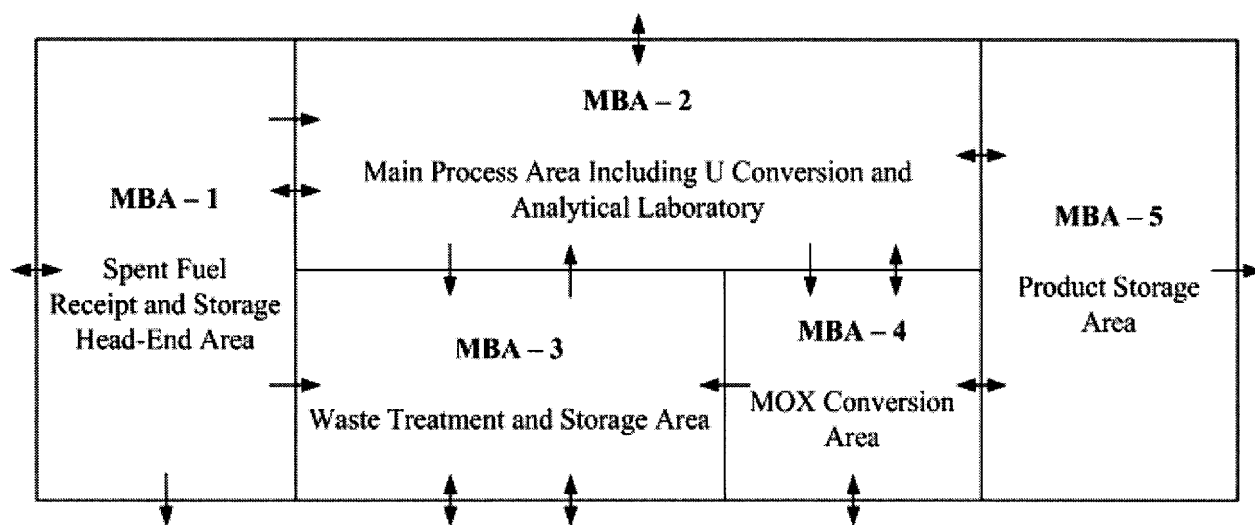
Figure 3-1. MBA structure for material accountancy at RRP as shown by Iwamoto et al. (2006)

3.2.1 MBA-1: Spent Fuel Receipt and Storage Head-End Area

The spent fuel surveillance in MBA-1 begins after its arrival at the facility. The fuel is transported in a cask to the spent fuel pool. In this process, the actual receipt of the fuel is verified using the Integrated Spent Fuel Verification System (ISVS), which consists of "time synchronized CCTV cameras and radiation detectors". The volume of dissolved fuel batches, or Input Batches, that are to be transferred to the MBA-2 is determined with the Solution Measurement and Monitoring System (SMMS). The uranium and plutonium are sampled using the ASAS or Hybrid K-Edge Densitometry (HKED). Left over solid waste such as the hulls and cladding material are checked for traces of uranium and plutonium using the Hulls Monitoring

System (HMS), which then correlates the ratios of uranium and plutonium to those of ^{244}Cm in both the hulls and dissolver solutions. A Shipper/Receiver Differences (SRD) evaluation is then performed on the nuclear material by balancing the Input Batches and the Head-End waste produced against the shipping reactor's declarations.

While the ISVS continuously monitors the spent fuel pool, the Head-End Process is checked on a monthly basis through Interim Inventory Verifications (IIV). SMMS, density correlations, and ASAS samples are used during the IIV.

Flow within MBA-1, which encompasses the transferring of fuel elements to the fuel chopper and subsequently the hulls to the storage, is monitored via the Integrated Head-End Verification System (IHVS), which "consists of a number of Camera/Radiation Detectors (CRDs) mounted in the cell walls, with additional CCTV units installed in the shear cell." The IHVS both confirms and records the spent fuel assembly and hull drum IDs. As for the dissolved fuel, it is monitored in the Head-End Process using SMMS.

Additionally, a Physical Inventory Verification (PIV) is performed yearly to verify spent fuel "using an Improved Cerenkov Viewing Device (ICVD)." Both samples and SMMS are used to confirm when the Head-End Process is cleaned-out (Johnson, et al., 2001, pp. 4-5).

3.2.2 MBA-2: Main Process Area

In the processes in MBA-2, Input Batches transferred over from MBA-1 are once again verified using SMMS for changes in inventory. The plutonium nitride batches that are to be sent to MBA-4 undergo volume verification via SMMS as well as HKED analysis using an ASAS sample. The uranyl nitrate that gets transferred to the conversion area within MBA-2 does not become verified, although UO3 does undergo Non-Destructive Assay (NDA) for verification using the Uranium Bottle Verification System (UBVS) and C/S measures. High Active Liquid

Waste (HALW) batches being sent to MBA-3 also undergo SMMS and ASAS sample verification. For this verification, plutonium is analyzed via a Pu-VI spectrophotometric method and uranium via Isotope Dilution Mass Spectroscopy (IDMS). On the other end of the spectrum, Low Active Solid Waste (LASW) also being sent to MBA-3 gets verified by the Waste Crate Assay System (WCAS), a passive neutron counting system that measures Pu content.

IIV is also done on a monthly basis for MBA-2 in which all vessel volumes undergo SMMS verification as well as random sampling. Estimates are determined for inventories that cannot be measured using "established process design algorithms." NRTA methods are used to perform interim evaluations of Material Unaccounted For (MUF).

As for flow within MBA-2, the facility's proper operation is ensured through solution monitoring. The SMMS in this area consists of sensors to detect temperature and pressures, with which solution levels and density can be determined, as well as "neutron sensors on the extraction systems." Random samples are also taken and analyzed in the OSL throughout the month. Additionally, NRTA methods are used to perform MUF evaluations every one or two weeks.

The MBA-2 PIV is also done on a yearly basis consisting of SMMS analysis on remaining solutions after clean-out. Additional random samples are also taken and studied at the OSL (Johnson, et al., 2001, p. 5)

3.2.3 MBA-3: Waste Treatment and Storage Area

In terms of waste treatment within MBA-3, vitrified High Active Waste (HAW) must be analyzed using the Vitrified Canister Assay System (VCAS) prior to its being released from safeguards. VCAS functions much in the same way as the HMS in MBA-1 by using ^{244}Cm neutron emission detection to determine its content and then using the Pu:U:^{244}Cm ratio found

through samples from the feed material and meltor to determine indirectly the nuclear material content. The neutron radiation data are then paired with cameras monitoring the measurement station and verifying canister IDs.

The monthly IIV involves SMMS and ASAS sample verification of the liquid waste inventories. Pu-VI spectrophotometric analyses are also done in the OSL. Solution monitoring also confirms the flow within MBA-using SMMS verification of the HALW feed rate to the meltor. Random HAWL samples are also taken to be studied using the VCAS. The yearly PIV done during clean-out involves verifying the inventory in MBA-3 using SMMS and random sample analyses (Johnson, et al., 2001, p. 6).

3.2.4 MBA-4: MOX Conversion Area

After PuN batches are transferred over from MBA-2, the material balance is again verified using SMMS. Before Mixed Oxide (MOX) powder canisters can be sent to the MBA-5 storage areas, content verification must be done using a Plutonium Canister Assay System (PCAS), which is "based on high level neutron coincidence counting and high resolution gamma spectroscopy." Additionally, a PCAS camera records canister IDs while MOX powder samples are taken for IDMS based destructive analysis. Waste being sent to MBA-3 undergoes Waste Drum Assay System (WDAS) verification, "which is based on passive neutron multiplicity counting and high resolution gamma spectroscopy."

The monthly IIV calls for SMMS verification and random sample HKED analysis of all solutions with Pu. The Plutonium Inventory Measurement System (PIMS) verifies the plutonium going into the MOX conversion lines by using a total neutron counting technique. NRTA methods also check for MUF regularly. SMMS is again used to verify flow within MBA-4, while PIMS monitors MOX powder flow in the conversion lines. During the yearly PIV

clean-out, PIMS is used to ensure the clean-out was properly done as well as to measure residual material. SMMS and samples are used to study any leftover solution (Johnson, et al., 2001, pp. 6-7)

3.2.5 MBA-5: Product Storage Area

Neutron detectors and surveillance cameras ensure the arrival of MOX canisters in MBA-5. The combination of cameras and detectors allow for the tracking of both filled and unfilled MOX canisters moving from the PCAS station in MBA-4 to MBA-5. IIV strategies have not been finalized although C/S, random sampling and measurements have been considered. PIV is done yearly by comparing stored values to expected values based on previous counts and C/S accounting methods (Johnson, et al., 2001, p. 7).

3.3 Material-Accountancy Challenges

Appendix A in *Nuclear Safeguards and the International Atomic Energy Agency* (1995) describes some of the difficulties in material-accountancy faced even after all the safeguards are in place. This issue makes both detecting the existence or absence of a diversion a non-trivial matter. The accurate accountancy of vast dissolved plutonium quantities is a particular concern.

One of the major difficulties involves error margins. The requirement is that MUF should not exceed 8 kg (1 SQ) or 3.3 percent of the annual throughput, whichever is larger. This requirement, thus, allows for several SQs of MUF in the error margins each year. To address this limitation, the Running Book Inventory (RBI) method can be used. However, this method works by subtracting the output Pu from the input Pu without considering the material in the system. If the value is far less than a SQ, diversion is not considered. However, this could lead to problems over a term longer than that for which the RBI method accounts. This then leads to

the use of NRTA paired with Adjusted Running Book Inventory (ARBI) using direct inventories of material in the system. The use of NRTA and ARBI on a frequent basis leads to a reduced uncertainty, allowing for the quicker detection of a diversion. However, to set up the NRTA system appropriately, it needs to be calibrated using long term real data that has not been affected by a diversion. Additionally, the NRTA system faces detection threshold limitations that are in excess of a SQ. In other words, a sudden diversion of a SQ may not be detected by NRTA (U.S. Congress, Office of Technology Assesment, 1995, pp. 117-120).

3.4 Conclusion

Although the use of safeguards helps reduce the risk of diversion, resource and technological limitations inhibit the existence of fully diversion-proof large reprocessing facilities. Nevertheless, safeguards do complicate any possible diversion of material.

4 Obtaining WUM within the Facility

One may wonder how sufficient material can be collected illicitly given safeguards, detection systems, and other preventive obstacles. This chapter analyzes methods for collecting WUM within the facility.

4.1 Diversion Methods

Data were obtained from a reprocessing facility performance simulation by examining the elemental concentrations that would be present in flow streams of material reprocessed at a typical aqueous reprocessing facility(Argonne National Laboratory, 2008). These data included a nominal scenario with the normally expected concentrations in addition to three facility misuse scenarios (see Appendix A – Sample Diversion Scenario Data). These simulated data consisted of the different materials present at the end of the reprocessing streams and their concentration without disclosure of how the facility's processes were altered. The study of these three diversion scenarios describes the results that might be potentially achieved given conceivable methods to divert WUM from a reprocessing facility.

Specific information such as the type of process used and the volumetric flow rates of the streams were not given. Thus, several assumptions were made in this respect. The product and raffinate stream concentrations indicate that a UREX process was used. In order to determine the total mass processed for the various materials, the ratios of the flow rates for the different streams were assumed to be those described by Thompson et al. (2002, p. 18) as shown in

The mass rate outputs were found for the nominal case using the concentrations, flow rate ratios, and the molar masses. The feed and the scrub flow rates together account for the material in the raffinate stream. The solvent flow rate determines the spent solvent stream mass rate,

while the strip flow rate correlates to the product stream mass rate. Table 5 in Appendix A –

Sample Diversion Scenario Data provides the results from these calculations.

Table 1.
Volumetric Flow Rates of Streams in Nominal Scenario

Stream	Flow Rate [L/min]
Solvent	0.0171
Scrub	0.00315
Feed	0.00459
Strip	0.00859

Note. Values describe flow rates through the various streams in the nominal scenario. Obtained from Thompson et al. (2002, p. 18)

In order to calculate the mass output for the diversion cases, mass conservation equations

relating the fission products were used. Because the diversion scenarios are each unique, they

were independently analyzed in order to determine what adjustments had been made.

For the first diversion scenario, mass balance was achieved by comparing the UO_2 and

the Pu_4 mass rates. These were chosen because the total mass rate should be conserved if neither

UO_2 nor Pu_4 is being accumulated elsewhere. Only the raffinate and product stream

concentrations were considered because the spent solvent stream concentrations were over

twenty orders of magnitude smaller and thus not useful in solving a system of equations for three

unknowns. Thus, the spent solvent flow rate was considered to remain the same as in the

nominal case. In order to determine the new flow rates, the product and raffinate streams were

balanced independently using UO_2 and Pu_4 respectively because they have negligible impact on

each other. Table 2 shows the flow rate results from this calculation.

Use of these flow rates to determine the fission product mass rates indicated that they

were being conserved. Nonetheless, this scenario showed that there was more complexing agent

being added. It was also noted that the amount of Pu_4 in the product and spent solvent are

marginally increased. It is important to recognize that an increase this small may be difficult to

detect. Table 6 in Appendix A – Sample Diversion Scenario Data provides the results from these calculations.

Table 2.
Volumetric Flow Rates of Streams in the First Diversion Scenario

Stream	Flow Rate [L/min]
Solvent	0.0171
Feed and Scrub	0.00837
Strip	0.0107

Note. Values describe flow rates through the various streams in the first diversion scenario. Values were calculated using mass balance.

For the second diversion scenario, the same combination of UO_2 and Pu_4 could not be used for the mass balance because the Pu_4 appeared to be removed from the streams. After attempting to balance the Pu_4 to determine the flow rates, the resulting mass rate outputs of the other fission products were very different from the nominal case. Thus, Ba and UO_2 were chosen to be independently balanced because they were mainly concentrated in different streams. Again, the spent solvent flow rate was considered to remain the same as in the nominal case because of the negligible concentrations present. Table 3 shows the flow rate results from this calculation.

Table 3.
Volumetric Flow Rates of Streams in the Second Diversion Scenario

Stream	Flow Rate [L/min]
Solvent	0.0171
Feed and Scrub	0.00774
Strip	0.00859

Note. Values describe flow rates through the various streams in the second diversion scenario. Values were calculated using mass balance.

The flow rates determined from this calculation showed that most fission products did indeed balance. However, the major change is that most of the Pu_4 is removed from the raffinate stream, and there is a noticeable increase of Pu_4 in the product stream together with the UO_2.

This appears to be the result of greatly reducing the amount of the complexing agent. Neither the Pu_4 nor the other fission products balanced. It is possible that in this scenario, Pu_4 is being accumulated in the system itself waiting for the proliferator to collect it during the next maintenance shutdown. Table 7 in Appendix A – Sample Diversion Scenario Data provides the results from these calculations.

For the third scenario, the solvent concentrations are large enough to be incorporated in the mass balance, and thus UO_2, Pu_4, and TcO_4 concentrations are used to determine the flow rates. The UO_2 and Pu_4, concentrations were chosen for the same reasons as the mass balance in the first diversion scenario, and the TcO_4 concentration was chosen because it was largely present in spent solvent stream. The raffinate flow rate was determined by independently balancing the Pu_4 against the nominal case. As for the product and spent solvent streams, there is sufficient UO_2 and TcO_4 in both that a system of equations for two unknown needed to be solved to determine their respective flow rates. Table 4 shows the flow rate results from this calculation.

Table 4.
Volumetric Flow Rates of Streams in the Third Diversion Scenario

Stream	Flow Rate [L/min]
Solvent	0.00266
Feed and Scrub	0.00774
Strip	0.00216

Note. Values describe flow rates through the various streams in the third diversion scenario. Values were calculated using mass balance.

In this scenario, part of the UO_2 is being removed in the spent solvent stream and less is going into the product stream. There is also a significant TcO_4 and Pu_4 increase in the spent solvent. Perhaps the plot here is to remove the Pu_4 in trace quantities from the spent solvent

stream during the solvent cleaning step. Table 8 in Appendix A – Sample Diversion Scenario Data provides the results from these calculations.

4.2 Conclusion

The diversion methods described above are the main methods in which WUM can be diverted. In the UREX process, WUM can be diverted to the product stream and taken with the product, diverted to the spent solvent stream and collected during the solvent wash, accumulated within the system until it is collected during the cleanout, or it can even be taken directly from the raffinate stream. These methods of diversion, however, only address the issue of gathering the material within the facility. Another part of the problem is to determine how to retrieve and remove it from the facility successfully.

5 Diversion Scenario Success Tree Analysis

In order for a reprocessing facility to divert WUM while evading IAEA inspectors, a careful plan must be devised that includes various methods that lead to success. This chapter focuses on the development of diversion strategies for a UREX reprocessing facility and organizes them into a success tree structure. The study is not intended to be an all encompassing analysis, but rather to provide strategy examples and to lay grounds for further development.

5.1 Success Tree Methodology

In order to succeed at diverting material, there are two challenges that the facility needs to overcome. The first is that material must be obtained within the facility. The second is that it must be taken out of the facility. These two events can be further analyzed by studying the various possible diversion paths. This systematic approach of studying the necessary events leads to the success tree structure shown in Figure 5-1. Within the two main required events in the success tree, the various paths available are cut off to be shown in following figures. The following sections discuss the conceivable strategies to obtain material within the facility and the various measures that need to be overcome in order to take the material out of the facility.

5.1.1 Obtaining Material within the Facility

There are three main routes for obtaining WUM within the facility: material may be obtained as a trace contaminant of a different stream, sequestered in a control volume, or taken directly from the raffinate stream.
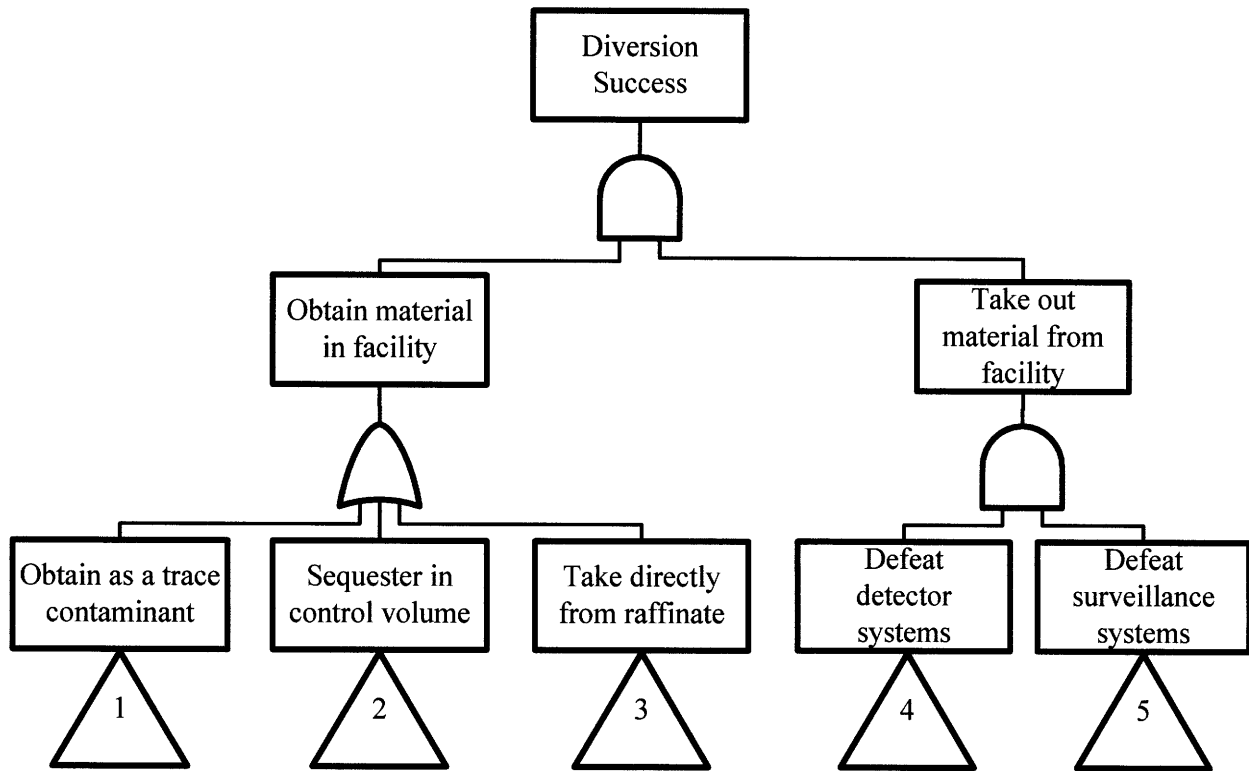
Figure 5-1. Success tree structure shows strategies to divert WUM.

5.1.1.1 Obtaining Material as a Trace Contaminant

In order to obtain WUM as a trace contaminant as was discussed in the first and third diversion scenarios in section 4.1, material needs to be rerouted to a different stream and then collected (see Figure 5-2). The rerouting of plutonium can be achieved by varying the process chemistry. The addition of extra complexant to the scrub leads to marginal increases of Pu_4 content in the spent solvent and product streams. The agent can also be substituted by one that behaves similarly to that used, except for pulling more Pu_4 into the other streams. The organic can also be changed or varied to produce a similar effect. The chemical process is described in section 2.2 and by Figure 2-1.

The material then needs to be collected after being redirected to a different stream. If the material is collected from the spent solvent stream, the spent solvent can be taken directly or the Pu_4 can be taken during the solvent washing step. If the material is taken from the product, it can

be collected as fuel bundles at the end of the process or it can be taken from the liquid product

directly.
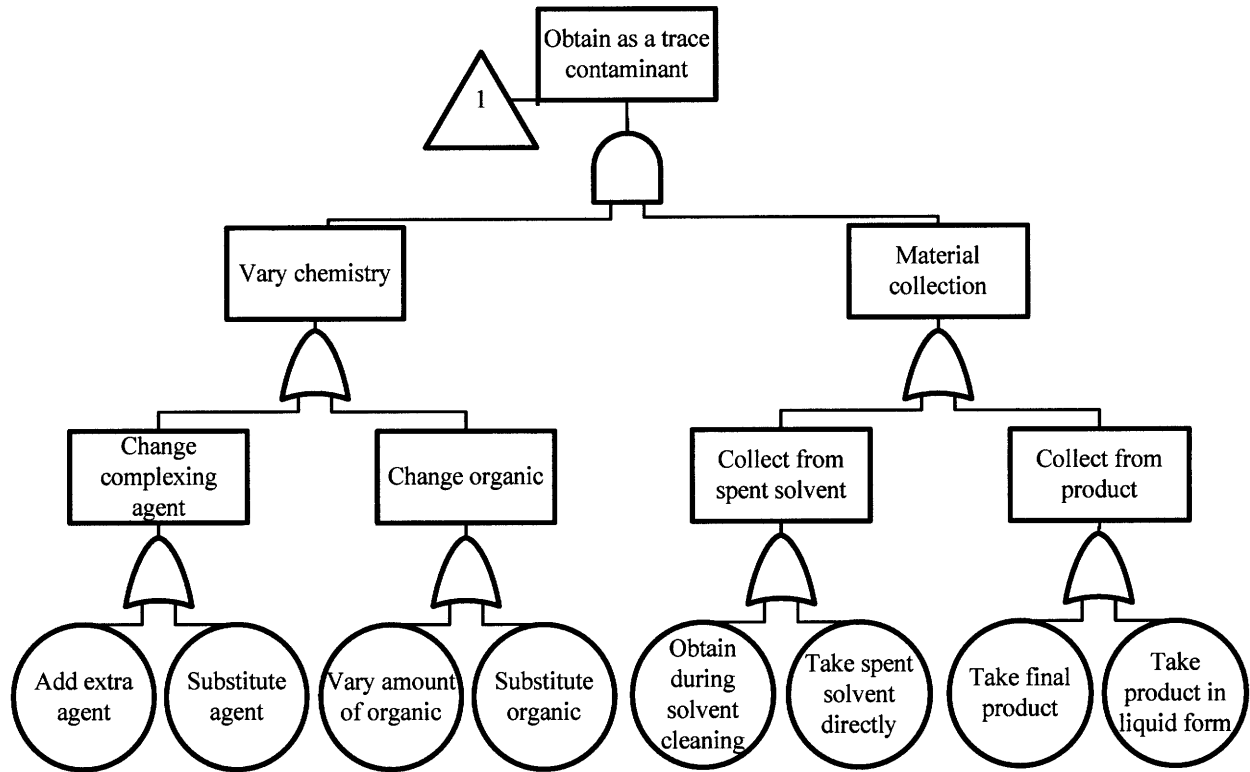
Figure 5-2. Tree branch shows available paths to obtain WUM as a trace contaminant from either the spent solvent or product streams by varying the chemistry in the process.

5.1.1.2 Sequestering Material within the Control Volume

In order to sequester Pu_4 within the system as was described by the second diversion

scenario in section 4.1, the chemistry again needs to be altered (see Figure 5-3). In this case,

however, the complexant needs to reduced, withheld, or replaced by a different complexant to

force the Pu_4 to remain in the contactors (see chemistry flow in Figure 2-1). It is also possible to

change the organic solvent to one that will not interact with Pu_4 and thus leave it behind in the

system.

For material collection, the diverter must ensure that maintenance cleanouts are

performed before the material achieves a critical mass and collect it during the cleanouts.

Because cleanouts are normally scheduled to occur before much material would accumulate under nominal conditions, the change in chemistry must be properly done such that the material still does not accumulate at a rate faster than can be compensated for by the maintenance cleanouts. Furthermore, IIV and other inventories are typically performed on a monthly basis (see section 3.2). Methods to evade detection of these systems are discussed in future sections.
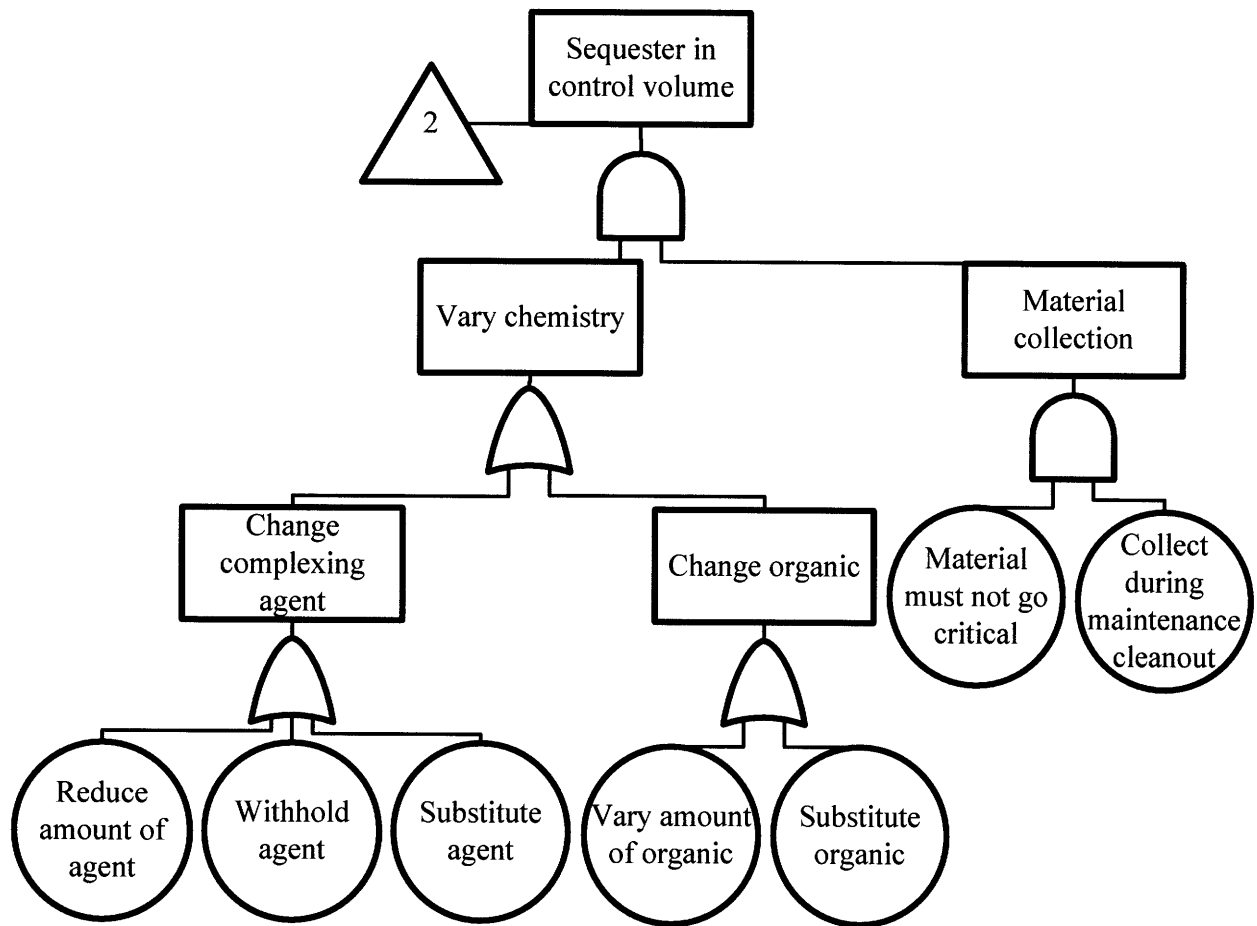
Figure 5-3. Tree branch shows available paths to obtain WUM by collecting the material within the system by varying the chemistry in the process.

5.1.1.3 Obtaining Material Directly from the Raffinate Stream

Plutonium can be taken from the raffinate stream right after the extraction step (see Figure 5-4). Nonetheless, this strategy is difficult because of the UREX process. The UREX process is devised to be proliferation-resistant by mixing plutonium with other highly radioactive

fission products. Special arrangements are necessary to transport this highly radioactive material. One possible tactic is to install extra piping during the facility's construction or during maintenance. This external piping can lead to a hidden room built during construction for the storage of diverted material. Either installed illicit piping or process piping can also be used to fill drums with WUM directly. The material can also be taken from the batches as they travel from MBA-2 to MBA-3, although this requires substituting with dummy batches in order to not be discovered immediately. Any dummy batches used in this strategy must necessarily behave as
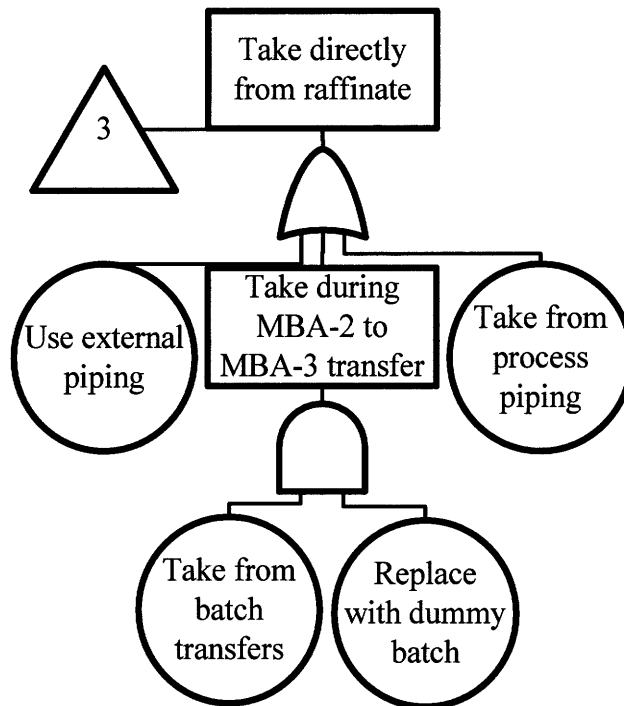
Figure 5-4. Tree branch shows available paths to obtain WUM by taking it directly from the raffinate stream.

5.1.2 Taking Material out of the Facility

After WUM is collected within the facility, there is still another problem to solve. Both the detector and surveillance systems need to be defeated in order to take WUM successfully out of the facility. This can be achieved by creating a distracting incident such as a fire or a

criticality accident. Such strategies may provide enough distraction to lower security such that the removal goes unnoticed. This method, however, would not allow for multiple incidents to occur, and the proliferator would need to take out all the material they have acquired at once or in a few steps. Independent detector and surveillance systems can also be targeted to prolong the time in which material can be removed.

5.1.2.1 Defeating the Detector Systems

There are four additional methods that can defeat the detector systems (see Figure 5-5). The first is a power failure of both external power and the backup power generator. A power failure would disrupt any detector systems that are not battery-equipped. Detectors with backup batteries can be targeted by methods such as improperly testing battery life or shorting the batteries. The second is to disrupt the detector system and cause a recorder failure. This can be done by breaking the mechanism that prints or the one that feeds the paper. Such failure can easily be an 'accidental' failure if the cause is improper paper or ink replacement. Other recorder systems such as those using magnetic technology can be targeted with strong magnets to erase data. The third method is that the detector itself can fail. This can happen if the signal is below the sensitivity tolerance and could work for the minor complexant changes that result in minute concentration differences. Overwhelming the detector with an external signal that prevents the detector from producing useful data is a potential technique that can also be used to cause a detector failure. The detector may also simply fail because of overtime wear and become Out Of Commission (OOC). The last method is that the detector system can be defeated if WUM is replaced with a dummy or material that produces similar radiation and chemical signatures and compensates for the lost mass as well.

Each of the three methods of diverting material described in section 5.1.1 would require defeating various detector systems in the different areas as described in section 3.2. Additionally, redundant systems of different detector types are typically used to monitor each station. The proliferator needs to strategically target each individual detector with methods that cause a common failure in order to avoid raising suspicion.
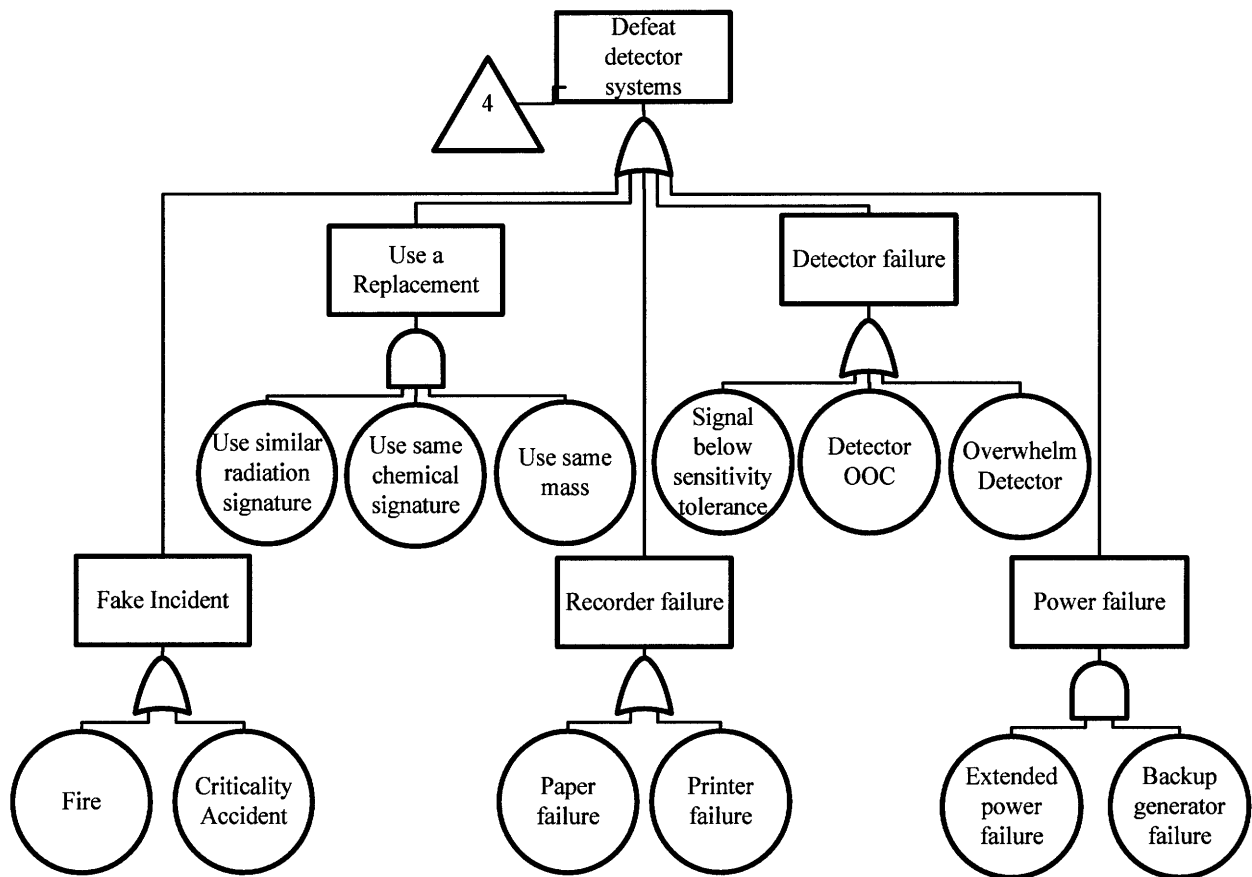
Figure 5-5. Tree branch shows potential strategies to defeat detector systems.

5.1.2.2 Defeating the Surveillance System

In order to defeat the surveillance system, cameras and entrance detectors both need to be defeated (see Figure 5-6). Described below are various strategies that can help to achieve this.

Defeating the camera system can include simply knowing where all the cameras are located and avoiding their paths. This perhaps may be impossible because the cameras are likely

directed at areas being guarded. There is, however, the possibility that the operator can change the camera viewing range such that another person taking material out would not be recorded on the system. This strategy requires synchronized acting of the camera operator and the person taking the material.

Another method can involve causing the cameras to fail. This can be done by aiming the light of a strong laser at the lens. However, if the functionality of the cameras is checked regularly, this approach may be too risky because it would be obvious that the cameras had been subject to tampering.

The camera system can also be targeted where the data are stored. If this is a computer, a virus could take care of it, but this might also raise suspicion. Perhaps an even better method would be to wipe out the hard drive by using a strong magnet or similar tactic. In such an event, IAEA inspectors cannot blame the facility for the camera surveillance failure because the facility can easily claim that the hard drive has simply gone bad and needs replacement.

The defeat of the entrance detectors is another tricky business. There are three exits that can be used for taking the material out of the reprocessing building. These include the main exit, the shipment exit, and the emergency exit.

Material can be taken out through the regular exit. The use of this exit requires defeating both the weight and the contamination detectors. The weight detector is the one described in section 1.2 in which weight of personnel entering the facility is compared to their exiting weight. Two possible ways to deal with this challenge are to simply turn it off or to carry something of equal mass in and leave it behind. The contamination detector could also be defeated by turning it off or changing the tolerance. However, if logs are kept for the readings of these detectors, other approaches need to be considered.

If the shipment exit is used, material can be taken out as part of a shipment. Such a shipment would need to be either a real or fake shipment. In a real shipment, the WUM would accompany the rest of the shipment. A fake shipment would be a shipment devised to ship out legitimate material in paperwork only and not in reality. The use of the shipment exit poses problems such as inspectors being extra cautious for shipments.
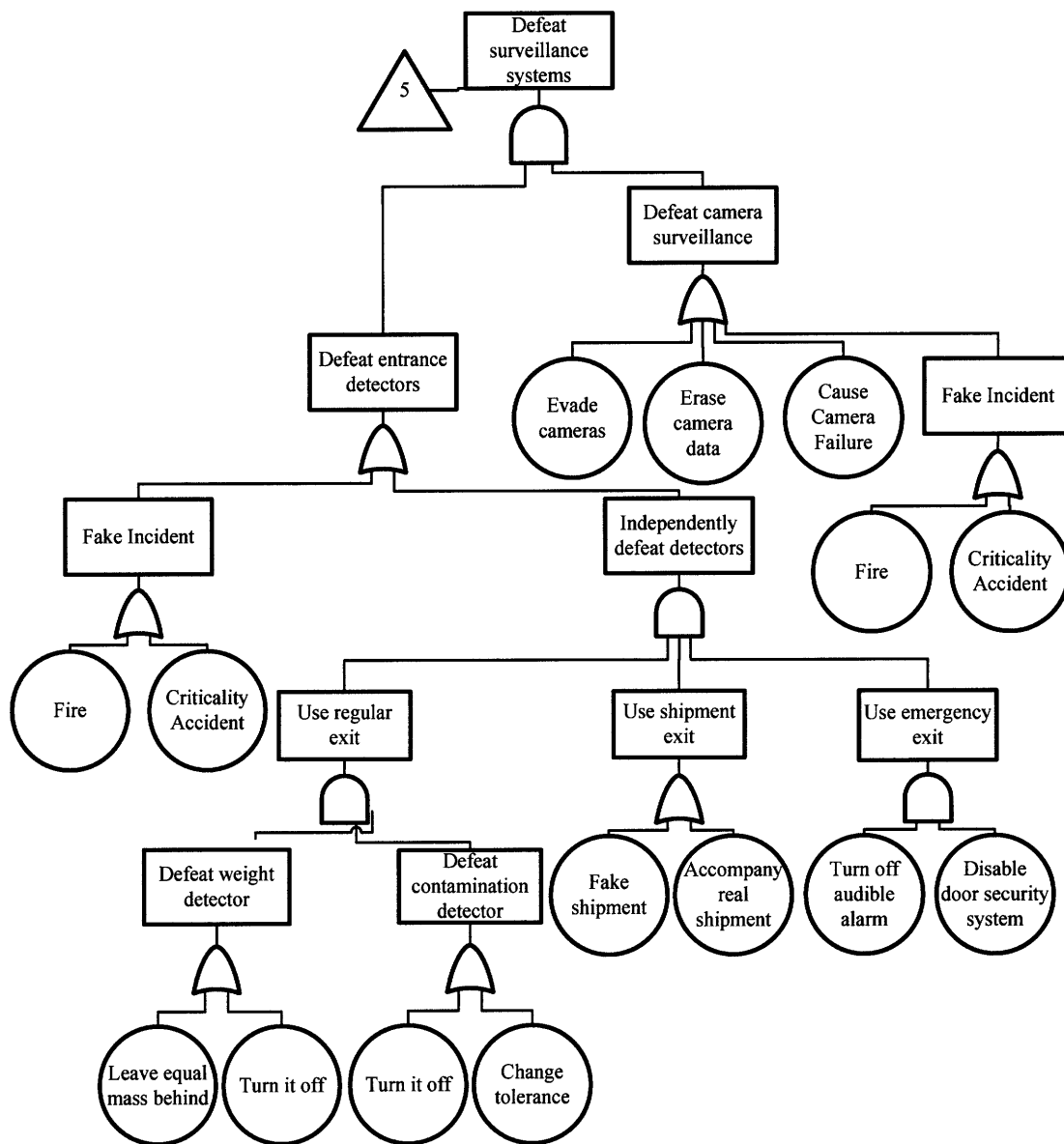
Figure 5-6. Tree branch shows potential strategies to defeat surveillance systems.

The emergency exit can be used during a real or created emergency, but inspectors will likely be waiting outside helping other employees out of the building. Alarms and security systems enabled on the doors could also be disabled. If the disarmament goes unnoticed, the door would remain unmonitored until it is tested on security checks.

5.2 Other Considerations

The strategies analyzed in the last section involve the evasion of onsite detection. Other considerations that were not included in this analysis, but which are also important for a successful diversion, include evading offsite detection. This can include detection of various conditions of the facility by analyzing particulate exhaust using externally located detectors or airplanes collecting samples as well as heat production using satellites imaging.

6 Conclusion

By fabricating a hypothetical UREX reprocessing facility, describing the chemical process, and studying how material is processed, safeguarded, and moved within the facility, a success tree for the diversion of WUM was created. The diversion success tree was developed by considering both the preventive measures that need to be overcome in order to succeed and the many pathways that can be used to achieve this. Analysis of the various diversion strategies using this structure allowed for the exposure of the various complexities and potential weaknesses involved in the diversion of WUM. The success tree, although not all-inclusive, allows for the comprehension of how such kinds of diversions can be carried out. Although not included in this study, the success tree can further be used to calculate the probability of success for minimal path sets if probabilities are obtained for the individual events. These probabilities need to be obtained from reliable and credible sources such as government institutes that conduct these types of studies.

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Appendix A – Sample Diversion Scenario Data

Table 5.
Nominal Scenario for UREX Fuel Reprocessing

	Molar Mass (g/mol)	Raffinate	Product	Spent Solvent	Raffinate	Product	Spent Solvent	Mass Rate (g/min)
			Moles			Mass Rate (g/min)		
H	1.01	7.37E-01	1.73E-02	5.25E-05	5.75E-03	1.50E-04	9.05E-07	0.0059
Ag	107.87	1.55E-04	2.08E-24	6.55E-52	1.29E-04	1.93E-24	1.21E-51	0.0001
Agent	75.07	1.55E-01	1.93E-03	4.89E-27	9.03E-02	1.25E-03	6.27E-27	0.0915
Am	243.00	5.72E-04	9.13E-24	1.63E-49	1.08E-03	1.91E-23	6.77E-49	0.0011
Ba	137.33	2.79E-03	3.75E-23	1.18E-50	2.97E-03	4.42E-23	2.77E-50	0.0030
Cd	112.41	1.68E-04	2.26E-24	7.11E-52	1.46E-04	2.18E-24	1.37E-51	0.0001
Ce	140.12	3.67E-03	5.87E-23	1.05E-48	3.98E-03	7.06E-23	2.50E-48	0.0040
Cm	247.00	2.79E-05	4.45E-25	7.94E-51	5.33E-05	9.45E-25	3.35E-50	5E-05
Cs	132.91	3.97E-03	5.32E-23	1.68E-50	4.08E-03	6.07E-23	3.81E-50	0.0041
Eu	151.96	1.89E-04	3.02E-24	5.38E-50	2.22E-04	3.94E-24	1.40E-49	0.0002
F	19.00	1.15E-02	1.54E-22	4.84E-50	1.68E-03	2.51E-23	1.57E-50	0.0017
Gd	157.25	1.74E-04	2.77E-24	4.94E-50	2.11E-04	3.74E-24	1.33E-49	0.0002
La	138.91	1.89E-03	3.01E-23	5.37E-49	2.03E-03	3.60E-23	1.28E-48	0.0020
Nd	144.24	6.04E-03	9.64E-23	1.72E-48	6.74E-03	1.19E-22	4.24E-48	0.0067
Np	237.00	2.02E-04	3.09E-24	8.95E-57	3.71E-04	6.28E-24	3.63E-56	0.0004
NpO2	269.00	2.22E-04	6.68E-24	2.73E-52	4.62E-04	1.54E-23	1.26E-51	0.0005
Pd	106.42	2.89E-03	3.87E-23	1.22E-50	2.38E-03	3.54E-23	2.22E-50	0.0024
Pm	145.00	1.81E-05	2.90E-25	5.16E-51	2.03E-05	3.61E-25	1.28E-50	2E-05
Pr	140.91	1.71E-03	2.73E-23	4.86E-49	1.86E-03	3.30E-23	1.17E-48	0.0019
Pu_4	976.00	7.43E-03	1.05E-19	4.59E-45	5.61E-02	8.76E-19	7.66E-44	0.0561
Rb	85.47	8.81E-04	1.18E-23	3.72E-51	5.83E-04	8.67E-24	5.44E-51	0.0006
Rh	102.91	9.88E-04	1.32E-23	4.18E-51	7.87E-04	1.17E-23	7.35E-51	0.0008
RuNO	131.08	4.51E-03	6.05E-23	1.91E-50	4.58E-03	6.81E-23	4.27E-50	0.0046
Sm	150.36	1.20E-03	1.92E-23	3.41E-49	1.40E-03	2.47E-23	8.78E-49	0.0014
Sr	87.62	1.84E-03	2.47E-23	7.78E-51	1.25E-03	1.86E-23	1.17E-50	0.0012
TcO4	162.00	8.34E-08	2.52E-04	3.18E-26	1.05E-07	3.50E-04	8.82E-26	0.0004
UO2	270.03	3.19E-26	1.05E-01	5.88E-26	6.67E-26	2.43E-01	2.71E-25	0.2432
Y	88.91	1.08E-03	1.73E-23	3.08E-49	7.44E-04	1.32E-23	4.68E-49	0.0007
ZrO	107.22	8.56E-03	1.29E-22	2.05E-56	7.10E-03	1.18E-22	3.75E-56	0.0071

Note. The calculated ratios were based on values provided in "Demonstration of the UREX Solvent Extraction Process with Dresden Reactor Fuel"(p. 18). The following stream volume flow rates in L/min were used: solvent 0 .0171, scrub 0.00315, feed 0.00459, strip 0.00859. The total mass was 0.442 grams in one minute.

Table 6.
First Diversion Scenario for UREX Fuel Reprocessing

	Molar Mass (g/mol)	Raffinate	Product Moles	Spent Solvent	Raffinate	Product Mass Rate (g/min)	Spent Solvent	Mass Rate (g/min)
H	1.01	6.88E-01	1.80E-02	5.25E-05	5.80E-03	1.95E-04	9.05E-07	0.0060
Ag	107.87	1.43E-04	1.92E-24	6.06E-52	1.29E-04	2.23E-24	1.12E-51	0.0001
Agent	75.07	1.79E-01	1.95E-03	4.92E-27	1.13E-01	1.57E-03	6.32E-27	0.1143
Am	243.00	5.29E-04	8.95E-23	1.62E-48	1.08E-03	2.34E-22	6.74E-48	0.0011
Ba	137.33	2.58E-03	3.47E-23	1.09E-50	2.97E-03	5.11E-23	2.57E-50	0.0030
Cd	112.41	1.56E-04	2.09E-24	6.57E-52	1.46E-04	2.52E-24	1.26E-51	0.0001
Ce	140.12	3.40E-03	5.75E-22	1.04E-47	3.98E-03	8.65E-22	2.49E-47	0.0040
Cm	247.00	2.58E-05	4.37E-24	7.91E-50	5.33E-05	1.16E-23	3.34E-49	0.0001
Cs	132.91	3.67E-03	4.92E-23	1.55E-50	4.08E-03	7.02E-23	3.52E-50	0.0041
Eu	151.96	1.75E-04	2.96E-23	5.36E-49	2.22E-04	4.83E-23	1.39E-48	0.0002
F	19.00	1.06E-02	1.42E-22	4.48E-50	1.68E-03	2.90E-23	1.45E-50	0.0017
Gd	157.25	1.60E-04	2.72E-23	4.92E-49	2.11E-04	4.59E-23	1.32E-48	0.0002
La	138.91	1.74E-03	2.95E-22	5.35E-48	2.03E-03	4.41E-22	1.27E-47	0.0020
Nd	144.24	5.58E-03	9.45E-22	1.71E-47	6.74E-03	1.46E-21	4.22E-47	0.0067
Np	237.00	1.87E-04	3.39E-24	8.19E-57	3.71E-04	8.62E-24	3.32E-56	0.0004
NpO2	269.00	2.05E-04	5.94E-23	2.19E-51	4.62E-04	1.71E-22	1.01E-50	0.0005
Pd	106.42	2.67E-03	3.58E-23	1.13E-50	2.38E-03	4.09E-23	2.05E-50	0.0024
Pm	145.00	1.68E-05	2.84E-24	5.14E-50	2.03E-05	4.42E-24	1.27E-49	0.0000
Pr	140.91	1.58E-03	2.67E-22	4.84E-48	1.86E-03	4.04E-22	1.17E-47	0.0019
Pu_4	976.00	6.87E-03	3.87E-18	6.49E-44	5.61E-02	4.05E-17	1.08E-42	0.0561
Rb	85.47	8.14E-04	1.09E-23	3.44E-51	5.83E-04	1.00E-23	5.03E-51	0.0006
Rh	102.91	9.14E-04	1.23E-23	3.86E-51	7.87E-04	1.35E-23	6.80E-51	0.0008
RuNO	131.08	4.17E-03	5.60E-23	1.76E-50	4.58E-03	7.88E-23	3.95E-50	0.0046
Sm	150.36	1.11E-03	1.88E-22	3.40E-48	1.40E-03	3.03E-22	8.74E-48	0.0014
Sr	87.62	1.70E-03	2.28E-23	7.19E-51	1.25E-03	2.15E-23	1.08E-50	0.0012
TcO4	162.00	4.36E-08	2.01E-04	1.15E-26	5.91E-08	3.50E-04	3.17E-26	0.0004
UO2	270.03	2.15E-28	8.39E-02	2.05E-26	4.86E-28	2.43E-01	9.47E-26	0.2432
Y	88.91	1.00E-03	1.69E-22	3.07E-48	7.44E-04	1.62E-22	4.66E-48	0.0007
ZrO	107.22	7.91E-03	2.46E-22	3.26E-56	7.10E-03	2.83E-22	5.98E-56	0.0071

Note. The calculated ratios were derived based on nominal data and mass balance. The following stream volume flow rates in L/min were used: solvent 0.0171, feed and scrub 0.008371, strip 0.0107. The total mass was 0.465 grams in one minute.

Table 7.
Second Diversion Scenario for UREX Fuel Reprocessing

	Molar Mass (g/mol)	Raffinate	Product Moles	Spent Solvent	Raffinate	Product Mass (g/min)	Spent Solvent	Mass Rate (g/min)
H	1.01	7.40E-01	1.68E-02	5.25E-05	5.77E-03	1.46E-04	9.05E-07	0.0059
Ag	107.87	1.55E-04	2.08E-24	6.55E-52	1.29E-04	1.93E-24	1.21E-51	0.0001
Agent	75.07	3.11E-07	3.88E-09	9.80E-33	1.81E-07	2.50E-09	1.26E-32	0.0000
Am	243.00	5.72E-04	8.83E-24	1.57E-49	1.08E-03	1.84E-23	6.51E-49	0.0011
Ba	137.33	2.79E-03	3.75E-23	1.18E-50	2.97E-03	4.42E-23	2.77E-50	0.0030
Cd	112.41	1.68E-04	2.26E-24	7.11E-52	1.46E-04	2.18E-24	1.37E-51	0.0001
Ce	140.12	3.67E-03	5.67E-23	1.01E-48	3.98E-03	6.82E-23	2.41E-48	0.0040
Cm	247.00	2.79E-05	4.30E-25	7.64E-51	5.33E-05	9.13E-25	3.23E-50	0.0001
Cs	132.91	3.97E-03	5.32E-23	1.68E-50	4.08E-03	6.07E-23	3.81E-50	0.0041
Eu	151.96	1.89E-04	2.92E-24	5.18E-50	2.22E-04	3.81E-24	1.34E-49	0.0002
F	19.00	1.15E-02	1.54E-22	4.84E-50	1.68E-03	2.51E-23	1.57E-50	0.0017
Gd	157.25	1.74E-04	2.68E-24	4.75E-50	2.11E-04	3.62E-24	1.28E-49	0.0002
La	138.91	1.89E-03	2.91E-23	5.17E-49	2.03E-03	3.48E-23	1.23E-48	0.0020
Nd	144.24	6.04E-03	9.32E-23	1.65E-48	6.74E-03	1.15E-22	4.08E-48	0.0067
Np	237.00	2.02E-04	1.67E-09	6.52E-42	3.71E-04	3.39E-09	2.64E-41	0.0004
NpO2	269.00	2.22E-04	5.17E-24	2.12E-52	4.62E-04	1.20E-23	9.73E-52	0.0005
Pd	106.42	2.89E-03	3.87E-23	1.22E-50	2.38E-03	3.54E-23	2.22E-50	0.0024
Pm	145.00	1.81E-05	2.80E-25	4.96E-51	2.03E-05	3.48E-25	1.23E-50	0.0000
Pr	140.91	1.71E-03	2.63E-23	4.67E-49	1.86E-03	3.19E-23	1.13E-48	0.0019
Pu_4	976.00	1.55E-19	1.10E-03	7.98E-29	1.17E-18	9.23E-03	1.33E-27	0.0092
Rb	85.47	8.81E-04	1.18E-23	3.72E-51	5.83E-04	8.67E-24	5.44E-51	0.0006
Rh	102.91	9.88E-04	1.32E-23	4.18E-51	7.87E-04	1.17E-23	7.35E-51	0.0008
RuNO	131.08	4.51E-03	6.05E-23	1.91E-50	4.58E-03	6.81E-23	4.27E-50	0.0046
Sm	150.36	1.20E-03	1.85E-23	3.28E-49	1.40E-03	2.39E-23	8.44E-49	0.0014
Sr	87.62	1.84E-03	2.47E-23	7.78E-51	1.25E-03	1.86E-23	1.17E-50	0.0012
TcO4	162.00	8.70E-09	2.52E-04	6.48E-26	1.09E-08	3.50E-04	1.80E-25	0.0004
UO2	270.03	6.31E-28	1.05E-01	6.16E-26	1.32E-27	2.43E-01	2.84E-25	0.2432
Y	88.91	1.08E-03	1.67E-23	2.96E-49	7.44E-04	1.27E-23	4.50E-49	0.0007
ZrO	107.22	8.56E-03	2.06E-22	3.27E-56	7.10E-03	1.90E-22	6.00E-56	0.0071

Note. The calculated ratios were derived based on nominal data and mass balance. The following stream volume flow rates in L/min were used: solvent 0 .0171, feed and scrub 0.00774, strip 0.00859. The total mass was 0.304 grams in one minute.

Table 8.
Third Diversion Scenario for UREX Fuel Reprocessing

	Molar Mass (g/mol)	Raffinate	Product	Spent Solvent	Raffinate	Product	Spent Solvent	Mass Rate (g/min)
			Moles			Mass Rate (g/min)		
H	1.01	7.25E-01	3.83E-02	6.85E-04	5.66E-03	8.32E-05	1.84E-06	0.0057
Ag	107.87	1.55E-04	8.27E-24	5.88E-46	1.29E-04	1.92E-24	1.69E-46	0.0001
Agent	75.07	1.55E-01	7.70E-03	4.30E-21	9.03E-02	1.25E-03	8.58E-22	0.0915
Am	243.00	5.72E-04	3.62E-23	2.55E-44	1.08E-03	1.90E-23	1.65E-44	0.0011
Ba	137.33	2.79E-03	1.49E-22	1.06E-44	2.97E-03	4.42E-23	3.87E-45	0.0030
Cd	112.41	1.68E-04	8.98E-24	6.38E-46	1.46E-04	2.18E-24	1.91E-46	0.0001
Ce	140.12	3.67E-03	2.33E-22	1.64E-43	3.98E-03	7.03E-23	6.12E-44	0.0040
Cm	247.00	2.79E-05	1.77E-24	1.25E-45	5.33E-05	9.41E-25	8.19E-46	0.0001
Cs	132.91	3.97E-03	2.12E-22	1.50E-44	4.08E-03	6.07E-23	5.32E-45	0.0041
Eu	151.96	1.89E-04	1.20E-23	8.44E-45	2.22E-04	3.92E-24	3.42E-45	0.0002
F	19.00	1.15E-02	6.11E-22	4.34E-44	1.68E-03	2.51E-23	2.20E-45	0.0017
Gd	157.25	1.74E-04	1.10E-23	7.75E-45	2.11E-04	3.73E-24	3.24E-45	0.0002
La	138.91	1.89E-03	1.20E-22	8.43E-44	2.03E-03	3.58E-23	3.12E-44	0.0020
Nd	144.24	6.04E-03	3.82E-22	2.70E-43	6.74E-03	1.19E-22	1.04E-43	0.0067
Np	237.00	2.02E-04	1.21E-23	3.12E-40	3.71E-04	6.21E-24	1.97E-40	0.0004
NpO2	269.00	2.22E-04	2.65E-23	7.83E-44	4.62E-04	1.54E-23	5.61E-44	0.0005
Pd	106.42	2.89E-03	1.54E-22	1.09E-44	2.38E-03	3.54E-23	3.10E-45	0.0024
Pm	145.00	1.81E-05	1.15E-24	8.10E-46	2.03E-05	3.59E-25	3.13E-46	0.0000
Pr	140.91	1.71E-03	1.08E-22	7.62E-44	1.86E-03	3.29E-23	2.86E-44	0.0019
Pu_4	976.00	7.43E-03	3.53E-19	4.40E-20	5.61E-02	7.44E-19	1.14E-19	0.0561
Rb	85.47	8.81E-04	4.70E-23	3.34E-45	5.83E-04	8.67E-24	7.60E-46	0.0006
Rh	102.91	9.88E-04	5.27E-23	3.75E-45	7.87E-04	1.17E-23	1.03E-45	0.0008
RuNO	131.08	4.52E-03	2.41E-22	1.71E-44	4.58E-03	6.82E-23	5.98E-45	0.0046
Sm	150.36	1.20E-03	7.59E-23	5.36E-44	1.40E-03	2.46E-23	2.14E-44	0.0014
Sr	87.62	1.84E-03	9.83E-23	6.98E-45	1.25E-03	1.86E-23	1.63E-45	0.0012
TcO4	162.00	5.92E-08	6.71E-04	2.68E-04	7.42E-08	2.35E-04	1.16E-04	0.0004
UO2	270.03	4.65E-26	3.53E-01	5.27E-02	9.72E-26	2.05E-01	3.79E-02	0.2432
Y	88.91	1.08E-03	6.85E-23	4.83E-44	7.44E-04	1.31E-23	1.14E-44	0.0007
ZrO	107.22	8.56E-03	5.10E-22	3.62E-44	7.10E-03	1.18E-22	1.03E-44	0.0071

Note. The calculated ratios were derived based on nominal data and mass balance. The following stream volume flow rate ratios were used: solvent 0.00266, feed and scrub 0.00774, strip 0.00216. The total mass was 0.442 grams in one minute.