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An Overview of Process Monitoring Related to the Production of Uranium Ore Concentrate

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Acronyms

ADU – ammonium diuranate
AP – Additional Protocol
CPPNM – Convention on the Physical Protection of Nuclear Material
CSA – comprehensive safeguards agreement
DOE – United States Department of Energy
IAEA – International Atomic Energy Agency
INFCIRC – Information Circular
ISL – in situ leach
ISO – International Organization for Standardization
ISR – in situ recovery
KAEC – Kazakhstan Atomic Energy Commission
kgs – kilograms
LEU – low enriched uranium
NMMSS – Nuclear Material Management and Safeguards System
NPT – Treaty on the Non-proliferation of Nuclear Weapons
NSG – Nuclear Suppliers Group
ONS – Office of Nuclear Security
U_3O_8 – triuranium octoxide
UF_4 – uranium tetrafluoride
UF_6 – uranium hexafluoride
UNSC – United Nations Security Council
UO_2 – uranium dioxide
UO_3 – uranium trioxide
UOC – uranium ore concentrate
US – United States

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1. INTRODUCTION

Uranium ore concentrate (UOC) in various chemical forms,[1] is a high-value commodity in the commercial nuclear market and a potential target for illicit acquisition, by both State and non-State actors. With the global expansion of uranium production capacity, control of UOC is emerging as a potentially weak link in the nuclear supply chain. Its protection, control and management thus pose a key challenge for the international community, including States, regulatory authorities and industry.

As of 2009, the market value for nameplate capacity of just UOC was worth approximately $8,000M assuming a market price of $55 per pound. This capacity was concentrated in 17 countries [1]. UOC is produced in various chemical forms. The chemical form of the final product is dependent upon several factors. These factors include the chemical form of the geological deposits (ore bodies) containing the uranium, uranium concentration within the ore body, capital equipment cost for mills, cost of raw materials to extract the uranium, regulatory requirements associated with environmental compliance and other cost factors that affect profit margin. The chemical form is also defined by contracts with conversion facilities. Most mines and mills produce UOC in the form of U_3O_8.

The construction cost, equipment design and extraction approach will affect the number of stages required to produce UOC. For example, an underground or open pit mine will require more stages and a higher capital investment than an in situ leach mine because in situ leach mines do not require milling equipment. UOC is typically loaded into 205-liter (55-gallon) drums (see figure 2). The drums are loaded into 20' International Organization for Standardization (ISO) intermodal containers and transported to the conversion plant by truck, rail or ocean vessel. Conversion of UOC to UF_4, UF_6, UO_2 or UO_3 takes place at a limited number of facilities in several countries. After conversion the majority of UOC is transported as bulk UF_6 in 14-ton steel cylinders as feed to an enrichment plant. The UF_6 is fed into an enrichment cascade to increase the isotopic concentration of ^{235}U in the UF_6 to a level referred to in the nuclear industry as low-enriched uranium (LEU). Some of the UOC is transferred to a fuel fabrication plant in the form of UO_3, where it is converted into UO_2 to produce fuel pellets that are loaded into bundles used for pressurized heavy water reactors. These reactors use natural uranium to produce electricity.

This document summarizes typical methods used by commercial producers to monitor production of UOC to ensure it meets specifications established by industry. Many of the same methods used by industry can provide information to State regulators and international inspectorates to support nuclear non-proliferation objectives for mines, mills, concentration, and purification processes.[2] The discussion focuses on current and proposed methods for determining the uranium concentration, quantity and throughput for various facilities. It evaluates current practice for monitoring the process of UOC production to determine if

[1] The most common chemical form of uranium ore concentrate (UOC) or yellowcake is triuranium octoxide [U_3O_8]. UOC can also be produced as ammonium diuranate [ADU], an intermediate form, uranium tetrafluoride [UF_4], uranium hexafluoride [UF_6], uranium dioxide [UO_2], and uranium trioxide [UO_3]. UOC is defined in this document as pure U_3O_8 (85% U). All other forms and concentrations are normalized to this chemical form.

[2] The sequential stages of mining, milling, extraction, concentration and purification will vary from facility to facility. Some facilities produce slurry at the mine that is shipped to a concentration plant. Other facilities have every stage of the process through purification at a single plant. In situ leach facilities do not have the milling stage.

practical improvements can be recommended to protect, manage and track the UOC inventory. Every facility should have the capability to detect loss, theft or diversion of a single drum (approximately half a metric ton) of UOC located at the facility over a period of one month independent of throughput [2]. This detection threshold is approximately equal to reporting requirements for imports or exports for nuclear suppliers, which is 500 kilograms of uranium [3]. This detection threshold will ensure a facility can detect the loss, theft or diversion of reportable quantities of UOC covered by international safeguards agreements because it is twenty times less than a significant quantity as defined by the International Atomic Energy Agency (IAEA) [4].

The detection threshold mentioned above is a practical limit that industry is capable of achieving. It is well below reporting requirements established by the IAEA. It is also a practical limit given it would be very difficult for a single insider to accumulate enough UOC over time to be of any concern. The most likely scenario is that a group of individuals, most likely managers or process engineers at a facility, could produce more UOC than declared for a specific facility and sell it on the black market to a State that needs natural uranium to support a clandestine weapons program. This non-State-to-State scenario is plausible if inventory management and tracking procedures are poor and the facility is located in a State that has limited regulatory oversight.

Discussions held with six of the seven top uranium producers at the Windhoek Conference determined that industry is currently capable of detecting the loss or theft of a single drum of UOC [2]. However, the timeliness, reporting methods and reportable quantities for loss, theft or diversion vary significantly from State to State and producer to producer. Permits granted by Australian regulators require industry to report the loss of an item independent of the quantity. Uranium producers in Australia are required to report the loss of a single sample [5]. Uranium producers in the United States are required to report an abrupt loss of 15 pounds or protracted loss of 150 pounds of UOC over a defined period [6]. Therefore, the detection threshold of a single drum is intended only to improve the completeness and transparency for reporting all aspects of UOC production in a State. Strengthening the capability to monitor the production of UOC is a confidence building measure that industry can undertake voluntarily. It is not intended as a point of discussion for redefining the starting point of international safeguards[3] for UOC. This document considers process monitoring methods and materials management concepts prior to the starting point of safeguards. The focus is on the capability for facility operators to detect the loss, theft or diversion of a single drum. The document evaluates current process monitoring practice and makes recommendations that, if implemented, should improve the State and operator's capability to detect the loss, theft or diversion of a single drum located at the facility within one month.

2. INTERNATIONAL REQUIREMENTS AND GUIDANCE

Currently there are only very limited international requirements and guidance applicable to the protection of UOC from theft or diversion, primarily those stemming from the Convention on the Physical Protection of Nuclear Material (CPPNM) and its 2005 amendment. Although not directly applicable to the protection of UOC from theft or

[3] See paragraph 2.11 of the International Atomic Energy Agency Safeguards Glossary: 2001 Edition, International Nuclear Verification Series No. 3.

diversion, also important to bear in mind are safeguards reporting requirements under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and the Guidelines for Nuclear Transfers of the Nuclear Suppliers Group (NSG Guidelines). Certain United Nations Security Council (UNSC) Resolutions such as 1540 require that States develop and implement regulatory requirements to prevent the use of natural uranium in the form of UOC for non-peaceful purposes by non-State actors and terrorists. Additional UNSC Resolutions (1696 and 1737) call on States to prohibit the sale of UOC to the Islamic Republic of Iran.

States that have signed a comprehensive safeguards agreement are required to report all quantities of natural uranium, referred to as source material, within their territory or under their jurisdictional control that are of a "composition and purity" suitable for isotopic enrichment or fuel fabrication. They are also required to report the quantity, composition and destination of all exports of natural uranium to non-nuclear weapons States, unless those exports are for non-nuclear purposes. The State is also required to report the quantity and composition of all imports of natural uranium unless the import of natural uranium is for non-nuclear purposes [7]. States that have signed the Additional Protocol are also required to report the location, operational status and annual production for uranium mines in their territory [8]. The IAEA can take samples of UOC during inspections to determine if the State declaration associated with the composition and purity are accurate for declared material. They also have certain measures such as information gathering and satellite imagery that can be used to evaluate the location and operational status of uranium mines and mills. However, there are challenges associated with independently verifying a State's declaration for "all" quantities of UOC and annual production for uranium mines reported to be operable under the Additional Protocol. The IAEA lacks the technical and human resources currently needed to independently verify all uranium in a State that has not reached the starting point at which safeguards are applied.

State regulators and industry face similar technical challenges because it is difficult to accurately quantify uranium content for all input streams, waste streams and in process holdup for a uranium processing facility. The uranium concentration varies significantly within the ore making if difficult to accurately determine the input streams to the concentration plant. The size and accessibility of the process equipment and heterogeneity of process materials make it difficult to accurately determine the uranium inventory in the various stages of the process. The chemicals used to extract, recover and concentrate the uranium limit the accuracy of the measurement systems. All of these factors cause significant technical challenges for estimating the uranium inventory in a mine and concentration plant. As a result of the attractiveness level of the material and the technical challenges associated with closing an accurate material balance across all stages of the process, the State regulatory authorities and industry take a graded approach to reporting requirements associated with loss, theft or diversion for UOC.

Industry is not required by State regulators to close a material balance for uranium at the mines. The United States Nuclear Regulatory Commission does not require uranium producers to report UOC inventory kept at the site. UOC stored at the in situ leach mines in the United States are not registered in the Nuclear Material Management and Safeguards System (NMMSS) database unless they are storing foreign obligated material [6 & 9]. The UOC is only entered into the national system of accounting when it is shipped from the concentration plant to a conversion facility [9]. Other countries most likely take a similar approach regarding reporting requirements for UOC that is not under safeguards or being considered for export; or is exported to a nuclear weapons State. Brazil's exports of ADU, which is not considered to be suitable for isotopic enrichment or fuel fabrication, to France do not have to be reported to the IAEA under Brazils comprehensive safeguards agreement [10]. All reporting of this material by Brazil is either on a voluntary basis or as a contractual commitment between operators in Brazil and France [10]. The combination of technical challenges associated with closing a material balance coupled to a lack of State requirements to register all UOC in a national database would make it difficult for the IAEA to independently verify undeclared UOC within a State. A scenario where a group of individuals could produce large quantities of UOC that is not of the composition or purity suitable for applying safeguards and store it until an opportune time for selling it on the black market to a State that has the technical means and processing capacity to purify and convert the UOC within a short period of time is not unreasonable. It is also not unreasonable to think such a scenario could be concealed from the corporation and the State given the current reporting requirements.

2.1 INFORMATION CIRCULAR 225 RECOMMENDATIONS

The CPPNM requires physical protection measures for nuclear material used for peaceful purposes while in international transport. Nuclear material is defined to include "uranium containing the mixture of isotopes as occurring in nature other than in the form of ore or ore-residue." Under Annex II, Categorization of Nuclear Material, Footnote (c) states that "natural uranium should be protected in accordance with prudent management practice." Annex I, Levels of Protection to be Applied in International Transport of Nuclear Material as Categorized in Annex II, further provides that for "natural uranium other than in the form of ore or ore-residue, transportation protection for quantities exceeding 500 kilograms of uranium shall include advance notification of shipment specifying mode of transport, expected time of arrival and confirmation of receipt of shipment [11]."

In 2005, the CPPNM was amended to also cover nuclear material used for peaceful purposes in domestic use, storage, and transport. The amendments did not change the provision regarding protection of natural uranium in accordance with prudent management practice or the specific requirements for international transport of natural uranium in greater than 500 kilogram quantities. The amendments are not currently in effect because they have not yet been ratified by the required two-thirds of the CPPNM parties.

The key IAEA guidance document for physical protection of nuclear material is IAEA Nuclear Series No. 13, Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Revisions 5). The purpose of this document is to provide guidance to States on how to develop or enhance, implement and maintain a physical protection regime for nuclear material, consistent with the CPPNM and its 2005 amendment. Table 1, Categorization of Nuclear Material, essentially reproduces Annex II of the CPPNM, including the statement in Footnote (c) that natural uranium should be protected in accordance with prudent management practice [11]. Paragraph 4.12 states that nuclear material required to be protected in accordance with prudent management practice should be secured against unauthorized removal and unauthorized access [11]. The document does not elaborate further on implementation of prudent management practice.

2.2 NUCLEAR SUPPLIER GUIDELINES FOR UOC TRANSFERS

The NSG consists of 45 member States. These States have agreed that fundamental principles for international safeguards and export controls should apply to nuclear transfers for peaceful purposes to any non-nuclear-weapon State and, in the case of controls on retransfer, to transfers to any State [3]. In this connection, suppliers have defined an export trigger list.[4] This list includes transfers of natural uranium product as well as technologies associated with converting this material to a form suitable for fuel fabrication or isotopic separation [3].

States that are members of the NSG agree that UOC should be placed under effective physical protection to prevent unauthorized use and handling. The levels of physical protection applied should be consistent with the CPPNM. The Group asserts that implementation measures for physical protection in the recipient country are the responsibility of the Government of that country [3]. However, in order to implement the terms agreed upon by the suppliers, the levels of physical protection on which these measures have to be based should be the subject of an agreement between the supplier and recipient [3].

From a international safeguards perspective, the NSG guidance states that suppliers should transfer UOC to a non-nuclear weapon State only when the receiving State has brought into force an agreement with the IAEA requiring the application of international safeguards on all UOC in its current and future peaceful activities. The NSG guidance provides that States are not required to report exports that are less than 500 kilograms [3]. The NSG guidance promotes cooperation between group members regarding compliance with the NPT, CPPNM and UNSCR 1540.

2.3 INFORMATION CIRCULAR 153 REQUIREMENTS FOR UOC

UOC is considered to be source material under the IAEA Statute and thus is a type of nuclear material as defined in a Non-proliferation Treaty (NPT) party's Comprehensive Safeguards Agreement (CSA) with the IAEA.[5] The CSA provides that safeguards will be applied "on all source or special fissionable material in all peaceful nuclear activities within the territory of the State, under its jurisdiction or carried out under its control anywhere" [CSA paragraph 2], but further provides that safeguards shall not apply to material in mining or ore processing activities [7].

Application of safeguards begins:

- when any nuclear material of a composition and purity suitable for fuel fabrication or for being isotopically enriched leaves the plant or the process stage in which it has been produced, or
- when such nuclear material, or any other nuclear material produced at a later stage in the nuclear fuel cycle, is imported into the State [CSA paragraph 34(c)].

However, there are reporting requirements in connection with exports and imports prior to this point. Specifically:

[4] Communication Received from the Permanent Mission of the Netherlands regarding Certain Member States' Guidelines for the Export of Nuclear Material, Equipment and Technology, INFCIRC/254/Rev.10/Part 1 (26 July 2011).

[5] The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons, INFCIRC/153 (Corrected).

- When any material containing uranium which has not reached the stage of the nuclear fuel cycle described above is directly or indirectly exported to a non-nuclear-weapon State, the State must inform the Agency of its quantity, composition and destination, unless the material is exported for specifically non-nuclear purposes; and
- When any material containing uranium which has not reached the stage of the nuclear fuel cycle described above is imported, the State shall inform the Agency of its quantity and composition, unless the material is imported for specifically non-nuclear purposes [7].

2.4 INFORMATION CIRCULAR 540 REQUIREMENTS FOR UOC

There are additional requirements for States who have brought the Additional Protocol[6] (AP) into force. Specifically, the State's Article 2 declaration must include:

- *Information specifying the location, operational status and the estimated annual production capacity of uranium mines and concentration plants and thorium concentration plants, and the current annual production of such mines and concentration plants for [the signatory State] as a whole. [The signatory State] shall provide, upon request by the Agency, the current annual production of an individual mine or concentration plant. The provision of this information does not require detailed nuclear material accountancy.* [8],
- *Information regarding source material which has not reached the composition and purity suitable for fuel fabrication or for being isotopically enriched, as follows:*

    (a) The quantities, the chemical composition, the use or intended use of such material, whether in nuclear or non-nuclear use, for each location in [the signatory State] at which the material is present in quantities exceeding ten metric tons of uranium . . . and for other locations with quantities of more than one metric ton, the aggregate for [the signatory State] as a whole if the aggregate exceeds ten metric tons of uranium . . . The provision of this information does not require detailed nuclear material accountancy;

    (b) The quantities, the chemical composition and the destination of each export out of [the signatory State] of such material for specifically non-nuclear purposes in quantities exceeding:

        (1) Ten metric tons of uranium, or for successive exports of uranium from [the signatory State] to the same State, each of less than ten metric tons, but exceeding a total of ten metric tons for the year;

    (c) The quantities, chemical composition, current location and use or intended use of each import into [the signatory State] of such material for specifically non-nuclear purposes in quantities exceeding:

        (1) Ten metric tons of uranium, or for successive imports of uranium into [the signatory State] each of less than ten metric tons, but

[6] Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards, INFCIRC/540.

exceeding a total of ten metric tons for the year;

it being understood that there is no requirement to provide information on such material intended for a non-nuclear use once it is in its non-nuclear end-use form. [8]

- *Information regarding the quantities, uses and locations of nuclear material exempted from safeguards pursuant to [paragraph 37 of INFCIRC/153];* [8]
- *Information regarding the quantities (which may be in the form of estimates) and uses at each location, of nuclear material exempted from safeguards pursuant to [paragraph 36(b) of INFCIRC/153]2/ but not yet in a non-nuclear end-use form, in quantities exceeding those set out in [paragraph 37 of INFCIRC/153]2/. The provision of this information does not require detailed nuclear material accountancy.* [8]

It is important to note that international safeguards obligations under INFCIRC 153 and INFCIRC 540 do not require States to provide detailed accountancy on UOC that has not reached the composition and purity for the application of safeguards [7]. Therefore, it is not common for States to require industry to implement detailed nuclear material inventory requirements at a facility. Uranium mines concentration plants are not required, from an international safeguards perspective, to develop the same material balance structure, identify key measurement points and systems or evaluate uncertainties in key measurement systems used to close a material balance for a defined inventory period [8]. The principal driver for detecting loss, theft or diversion is the commercial value of the UOC and to monitor the operational effectiveness of the process for extracting, concentrating and purifying the UOC. The terminology commonly applied to inventorying UOC that is beyond the starting point of safeguards (i.e., material control and accounting) will not be utilized throughout this document to provide some differentiation between UOC that is suitable for enrichment and/or fuel fabrication and UOC that is not suitable for enrichment and/or fuel fabrication. This document uses the term “materials management” instead of “accountancy” to denote the difference for UOC before and after the starting point of safeguards.

2.5 UNITED NATIONS SECURITY COUNCIL RESOLUTION 1540

On April 28, 2004, the United Nations Security Council adopted Resolution 1540. This resolution requires all States to combat all threats by terrorists or terrorist organizations threats to international peace and security. This includes threats associated with illicit trafficking of UOC for use in non-peaceful purposes. Resolution 1540 decides that all States shall implement the following:

- *refrain from providing any form of support to non-State actors that attempt to develop, acquire, manufacture, possess, transport, transfer or use nuclear, chemical or biological weapons and their means of delivery;*
- *effective laws which prohibit any non-State actor to manufacture, acquire, possess, develop, transport, transfer or use nuclear, chemical or biological weapons and their means of delivery, in particular for terrorist purposes, as well as attempts to engage in any of the foregoing activities, participate in them as accomplice, assist or finance them;*
- *effective measures to establish domestic controls to prevent the proliferation of*

nuclear, chemical, or biological weapons and their means of delivery, including by establishing appropriate controls over related materials and to this end shall:

- *develop and maintain appropriate effective measures to account for and secure such items in production, use, storage or transport;*
- *develop and maintain appropriate effective physical protection measures;*
- *develop and maintain appropriate effective border controls and law enforcement efforts to detect, deter, prevent and combat, including through international cooperation when necessary, the illicit trafficking and brokering in such items in accordance with their national legal authorities and legislation and consistent with international law;*
- *establish, develop, review and maintain appropriate effective national export and trans-shipment controls over such items, including appropriate laws and regulations to control export, transit, trans-shipment and re-export and controls on providing funds and services related to such export and trans-shipment such as financing, and transporting that would contribute to proliferation, as well as establishing end-user controls; and establishing and enforcing appropriate criminal or civil penalties for violations of such export control laws and regulations* [12].

2.6 UNITED NATIONS SECURITY COUNCIL RESOLUTIONS 1696 AND 1737

On July 31, 2006, the United Nations Security Council adopted resolution 1696 demanding that the Islamic Republic of Iran suspend all enrichment and reprocessing related activities until all outstanding questions associated with previous IAEA inspections be fully addressed. This resolution requires that States act vigilantly to "prevent the transfer of any items, materials, goods and technology that could contribute to Iran's enrichment-related and reprocessing activities [13]." Additionally, on December 23, 2006, the Security Council adopted Resolution 1737 that reiterated the need for Iran to suspend all enrichment and reprocessing activities. This Resolution required that States take all necessary measures to prevent direct or indirect sale, supply or transfer of all items, materials, goods, equipment or technologies that would benefit Iran's enrichment or reprocessing activities. This Resolution specifically refers to items identified by the Nuclear Supplier Group [14].

3. OVERVIEW OF THE URANIUM ORE CONCENTRATE PRODUCTION PROCESS

Profitability for many of the commercial uranium producers can be significantly impacted by variations in uranium concentration of the ore, raw materials and capital equipment used to recover the uranium and efficiency of the recovery process. Monitoring, in general terms, is applied at the early stages of the uranium recovery process. The ore is sampled and analyzed to determine the uranium concentration of an ore body. This information is used to evaluate the commercial feasibility for constructing a mine, mill and concentration plant [15]. Various process monitoring methods and techniques are utilized throughout the stages of the process through conversion and purification to a form that is suitable for enrichment or fuel fabrication. Uranium producers incorporate equipment into the facility design to closely monitor the efficiency and effectiveness of the extraction, concentration and purification processes. Uranium producers also closely monitor the process to ensure they are compliant with State regulatory requirements to protect the public, workers and environment from unnecessary exposure from chemical and radiological hazards. The number and type of process points monitored varies from facility to facility. Some mines and mills produce intermediary product at satellite facilities that is used as feedstock for concentration plants. Other facilities include all stages of the process from ore removal through purification of the final product. Producers also monitor the process to estimate a uranium balance at certain stages. However, this monitoring effort is not designed to close a material balance in terms of detailed material accountancy.

3.1 COMMON UOC MATERIAL BALANCE METHODS

Corporations generally set loss detection thresholds that can be practically implemented. These detection thresholds are determined by the value of the product. The uranium producers get paid when the product is delivered to the conversion or fuel fabrication plant and determined by the receiver to be consistent with contract specifications. Uranium producers are generally not required to define material balance areas, identify key measurement points and systems or track inventories within the process. This is primarily due to large uncertainties associated with inputs and inventory retained within the process. Many of the facilities that include all stages will contain one to three significant quantities[7] of natural uranium within the process. The uncertainty in the amount of in-process inventory can easily vary by more than one significant quantity. The uranium concentration varies dramatically for the ore. Radiometric scanning devices are used to determine if the ore exceeds a threshold activity to enter the process (see figure 1). Ore that does not meet the gross activity levels defined by the facility is taken to a waste pile. This ore can be processed at a later date if market conditions are favorable. Ore that exceeds the count threshold is sent to the mill for further processing. The radiometric scanners only provide qualitative information on the uranium content. Therefore, it is impractical to accurately determine inputs to the process until the uranium is fully dissolved into solution. The uranium inventory is only estimated for a portion of the process.

Loss detection thresholds are often driven by corporate standards to minimize production losses or maximize production efficiencies. They are also tied directly to regulatory requirements. However, the primary focus of existing regulations is to protect the health and safety of the worker and public citizens and environmental protection; not safeguards. For example, UOC producers in the United States are required to report " . . . any incident in which an attempt has been made or is believed to have been made to commit a theft or unlawful diversion of more than 6.8 kilograms (kgs) [15 pounds] of such material at any one time or more than 68 kg [150 pounds] of such material in any one calendar year." [6] By contrast, the Australian Safeguards and Non-proliferation Office requires permit holders in Australia to implement accountancy measures that have uncertainties of 0.1% for the mass of yellowcake in a drum or 0.2% uncertainty for determining the total uranium concentration in the product [5]. The permit holders must also have controls in place that are capable of detecting the loss, theft or diversion of a single item (drum or sample container) within a two-hour period [5]. The timeframe for reporting the loss, theft or diversion of a single item from the Australian perspective is primarily driven by the political environment that the Australian uranium producers operate within. The Australian regulators have placed strict controls on the chain of custody for all items as a corrective action from the loss of samples experienced by one of the operators [16].

[7] A significant quantity is defined by the IAEA as ten metric tonnes of uranium independent of chemical or physical form.

The instrumentation commonly used to monitor the process provides state-of-health on process equipment. Sampling ports are installed at key locations to monitor the uranium concentration. Wet chemistry methods are used to monitor the uranium concentration in leachate, the aqueous and organic phases of the extraction process, the ion exchange resin and impurities in the final product. Flow meters are used to estimate throughput. Most of the monitoring is performed to balance consumption of raw materials relative to uranium concentration at various stages in the process. The waste streams are monitored to ensure uranium is discharged at acceptable levels. The resins and solvents contained in the ion exchange or solvent extraction columns are to determine if they can be reused or are no longer efficient. Solid waste that contains irrecoverable quantities of uranium is monitored to insure uranium is not released into sanitary waste streams. Irrecoverable waste is not continuously monitored like it is for a fuel fabrication or enrichment plant. No attempt is made to close a material balance around all input and output streams similar what is performed for enrichment of fuel fabrication facilities. The attractiveness of the natural uranium in process and in the waste streams, from a safeguards perspective, does not merit implementing a comprehensive system for UOC control and accountancy.

3.2 EXPLORATION

Uranium production begins with exploration to identify resources[8]. Uranium is contained in various geological formations that are analyzed to determine if uranium extraction from an identified deposit can be done in a cost effective manner. Exploration is performed in four stages. The first stage includes area selection. Maps of large areas are reviewed and the geology of the rock formations is researched to determine if the area has the potential for containing uranium deposits. Limited sampling is performed to identify areas that show potential for containing uranium at concentrations that permit economic recovery. The second stage includes surveys using radiation detection equipment and additional sampling of the rock formations. This is known as the reconnaissance phase of exploration. It is used to eliminate areas that are not economical for recovering the uranium. The third phase is referred to as the follow-up phase. It includes more detailed sampling and geochemical analysis. This phase of exploration includes more intensive sampling and on-the-ground analysis to locate specific areas that are economically feasible for mining. The final phase, referred to as the detailed phase, includes radiometric core sampling and analysis to locate specific areas for recovery. Uranium mining companies perform detailed analyses and comprehensive process planning before they mobilize to physically extract ore from the deposits [15]. This analysis and planning process includes working with the State and local regulators to develop the documentation necessary to receive a mining permit. The regulatory approval process will vary from State to State. The regulatory focus at this point is on radiological safety of the workers and the public and protection of the surrounding environment.

After permits are granted, the company will mobilize and begin removing the uranium from the deposits. This process is conducted using various techniques. The four primary techniques include open pit mining, underground mining, in situ recovery and heap leaching. Uranium has also been recovered from other sources such as coal, lignite and phosphates [15]. The cost of production will vary based on a number of factors including the

[8] This refers to instances where uranium is the primary product. Exploration to identify uranium resources is not performed when uranium is a by-product of another recovery process.

concentration of uranium in the ore or by-product material, depth, rock stability, remoteness and water conditions [15]. The cost can range from ten dollars per pound to several hundred dollars per pound for very low concentration sources such as seawater. The price on the black market could exceed the highest production cost because black market uranium is not driven by nuclear fuel cycle demand but rather by the intent and need of the end user.

During the production process the uranium ore is either physically removed or the geological formation may be leached in place by boring into the deposit and pumping a solution into the deposit that dissolves the uranium (see Appendix C). This specific process is referred to as in situ leaching (ISL) or in situ recovery (ISR). Processes associated with physical removal of the ore include open pit mining, underground mining and heap leaching. The physical removal techniques involve mechanical process equipment that may be quite large. The ore is blasted or cut from the earth and loaded into bucket trucks or specially designed ore handling cars.

3.3 ORE REMOVAL METHODS

3.3.1 OPEN PIT MINING

Uranium that is located near the earth's surface is usually mined using the open pit method. Surface level soil and rock is removed to expose the uranium ore. The area is mined to form benches to prevent collapse of the walls. Explosives are used to break up the rock, which is loaded into large dump trucks that can hold tons of rock (see figure 6). The material is typically transported to crushers and separators to prepare the ore for leaching. Appendix B provides a common flow sheet for an open pit mine.

3.3.2 UNDERGROUND MINING

Underground mining is performed when the uranium is located at depths that make the use of open pit method uneconomical. The ore is removed by digging a shaft into the uranium deposit. Horizontal tunnels are then excavated to access the ore. Underground mining also requires means to vent gases and to provide make up air for the miners [17].

Explosives or boring machines are used to break up the rock in underground mines. The broken rock is then hoisted to the surface using mechanical conveyors. Some mines crush the rock to a finer consistency and mix it with water because the uranium concentration is higher than normal [18]. This process results in a mud or slurry that is pumped to the surface and transferred to a mill for further processing.

Figure 1: Heap leach facility in Brazil

3.3.3 HEAP LEACHING

Uranium is also recovered from ore using a heap leaching method (see figure 1). The ore is removed, crushed and placed into heaps on a protective liner. The heaped ore is sprayed with a leaching solution. This solution leaches a portion of the uranium from the ore. The solution is collected in a reservoir and pumped into the processing stations. The tailings from the leaching process are monitored for uranium content. The waste rock is removed from the processing area and stored on a waste rock pile.

3.3.4 IN SITU LEACHING/RECOVERY

Some uranium is located between rock formations that permit pumping the leaching solution, which is referred to in the mining industry as lixiviant, into the deposit and extracting the uranium without excavation. This process is the predominant recovery technique used in Kazakhstan and the United States. The uranium is removed by controlled drilling in a specified pattern where multiple holes are drilled to pump the leaching solution into an area around a single hole where the uranium solution, commonly referred to as pregnant solution, is removed. These facilities are comprised of a network of piping that is used to pump the lixiviant into the deposit and to remove the pregnant solution. The pipes are located underground in areas where the temperatures are below freezing. The solution is pumped to storage ponds for short-term storage or directly into extraction and purification columns to concentrate the uranium. Appendix C shows the flow of material from an ISL/ISR operation.

3.3.5 UNCONVENTIONAL SOURCES

Uranium is present in lower concentrations in various forms. Uranium is a common by-product of gold and copper production. It is also present in phosphates and coal. The uranium ore concentrate produced in South Africa is a by-product of gold [19]. BHP Billiton produces uranium ore concentrate as a by-product from copper mining in Australia [20]. The Japanese have developed a resin fiber that extracts uranium from seawater [21]. The cost for recovering uranium from such sources is not profitable under current market conditions. However, the cost for recovering uranium from such resources may not prohibit certain States from attempting recovery at a higher cost if the uranium is needed as a source for a clandestine weapons program.

3.4 UOC PRODUCTION

3.4.1 MILLING

Milling is performed to reduce the size of the rock removed during open pit, underground and heap leaching process. Milling is done in multiple stages. Explosives are used to break the ore into a size that can be handled by large end loaders or scoops. The ore is loaded into large dump trucks and hauled to a primary crushing station. The primary crushers reduce the ore to a size that can be moved on conveyer systems to a secondary crusher. The secondary crushers reduce the ore to the size of a stone that can fit into one’s hand. This material is transferred via a conveyor system to a secondary pile. This pile feeds the tertiary and quaternary crushers. These crushers reduce the ore to a small pebble. This material is loaded into the final crushing stage where a rod mill is used to reduce the material to the size of coarse sand. The sand is sent to leaching tanks where the uranium removal process begins [22].

3.4.2 CONCENTRATION

The concentration stage begins with the addition of chemicals, acids or alkalis dependent upon the recovery process, to large tanks. The sand from the final crushing process is leached for several hours. The leaching is performed in two stages. The first stage includes oxidation from the U^{+4} to the U^{+6} valence state.

$$\text{(1) alkaline } UO_2 + 1/2O_2 \leftrightharpoons UO_3$$

$$\text{(2) acid } UO_2 + 2Fe^{+3} \leftrightharpoons UO_2^{+2} + 2Fe^{+2}$$

The second stage of the leaching process stabilizes the chemical form of the uranium. Sulfuric acid is used for the acid recovery method. Sodium carbonate, sodium bicarbonate or carbon dioxide is used for the alkaline method [15 & 23]. A flow diagram for each process is provided in Appendix A [23].

$$\text{(1) alkaline } UO_3 + CO_3^{-2} + 2HCO_3^{-} \leftrightharpoons UO_2(CO_3)_3^{-4} + H2O$$

$$\text{(2) acid } UO_2^{+2} + 6SO_4^{-2} \leftrightharpoons UO^2(SO_4)_6^{-4}$$

Figure 2: Drums of UOC with production details

The leached solution is transferred to classifiers, hydro-cyclones and thickeners. The sand is removed from the pregnant solution. Additional treatment with washing agents removes the slime from the pregnant solution. The solution is allowed to set for a period of time to allow any solids to settle. The solids and slime are pumped to a tailing pond to permit additional settling [22]. The uranium at this stage of the process is in the form of uranyl sulphate for systems that use sulfuric acid or uranyl carbonate for the alkaline treatment method. The uranium concentration at this stage of the process can range from 50 to 200 milligrams per liter [22].

The methods for extracting the uranium from the pregnant solution vary by process. The uranium can be extracted from the aqueous solution using solvents, ion exchange resin or both [15 & 23]. The methods selected will depend on the ore type, cost of raw materials, availability of raw materials and potential impact on the local environment of the waste streams for the various extraction techniques. The regulatory requirements defined by national authorities may determine the recovery method selected by the uranium producer. The alkaline recovery method is the only approved recovery method used in the United States.

3.4.3 PRECIPITATION AND PURIFICATION

The next stage in the production process includes precipitation and purification. The uranium contained in the extracted solution is neutralized to a pH dependent upon the recovery process [15 & 23]. Ammonium hydroxide, sodium hydroxide or lime is used to precipitate the uranium. The precipitate is pumped to filter presses that remove the excess water. The pressed material is sent to a calciner or oven and baked at elevated temperatures to form pure. Intermediate forms of UOC that do not go through the drying process may be packaged and shipped to a conversion facility where it is dried and processed dependent upon the chemical form.

3.5 PACKAGING AND STORAGE

Figure 3: 20' ISO shipping container of drums

The UOC from the ovens is packaged into standard Industrial Package (IP-1) metal drums (see figure 2). These drums are designed to transportation standards for low specific activity radioactive material [24]. The volume of the drum is nominally 210 liters (45 imperial gallon/55 US gallon). Alternate drum sizes such as 140L (30 imperial gallon/37 US gallon) may be used if permitted in the purchase contract. Lids are secured to the drums using approved procedures. The locking ring is tightly bolted to secure the material in the container. Some lids have a center hole for automated filling. These containers are specially designed with gaskets to prevent leakage during transport.

The drums hold approximately 350 kilograms (kgs) of uranium oxide. Approximately 35 drums of UOC are required to achieve one significant quantity of natural uranium as defined by the IAEA. The UOC and the drums are marked with unique identification numbers that are tied to the production lot number. This information is either painted onto the container using stencils or by applying pre-printed labels. This permits the producer to track the contents of the drum to a batch or lot number of product. The empty drums are weighed using approved scales to determine a tare weight. Some facilities simply used a declared tare weight from the manufacturer of the containers since they are manufactured to uniform standards. Full drums are weighed using the same scales to determine the gross weight of the UOC. The difference between the gross and tare weights is the inventory of UOC attributed to the individual drums. The filled drums are placed into special shipping containers and shipped to the conversion or fuel fabrication plant. These shipping containers can hold approximately 50 drums of product. One shipping container will have approximately two significant quantities of natural uranium. Therefore, it is important to apply effective controls to ensure this material is not diverted to a non-peaceful use.

Some satellite producers load product into larger containers. These intermediary containers are used to transport lower quality material to another facility where it is purified to meet customer specifications. For example, Kazatomprom used ТГК 118 containers to transfer approximately four tonnes of yellowcake to the purification plant.

3.6 INVENTORY MANAGEMENT

Figure 4: Kazatomprom transport containers

Many facilities have automated the drum filling and inventory management process. The drums are filled from a large hopper using an automated mechanical process. The drums are labeled and weighed using paper ledgers and computer based tracking and management systems. Calibrated scales are used to determine the net weight of the product in each drum.
Facilities that produce intermediary product may not have an automated filling capability. These facilities use manual methods for identifying the batch and net weight of the product.

4. TRANSPORTATION

UOC is shipped using various modes of transport. Shipments between satellite facilities are generally performed using trucks or rail. Some overland international shipments occur in Africa between the mines located in Malawi and the Port of Walvis Bay in Namibia and the mines located in Niger and the Port of Contonou in Benin. Various forms of UOC are shipped internationally. Most of the shipments are in the form of U_3O_8. The product for the Paladin facility in Malawi is UO_3. The product from the heap leaching facility in Brazil is ADU. This material is shipped to France for further processing and is exchanged for $LEUF_6$ that is converted into nuclear fuel at the Brazilian fuel fabrication facility [10]. The chemical form of the material is important because it affects the total uranium content in a single drum. Therefore, an intermodal container of ADU will have less significant quantities of uranium than will the same container with the same number of drums of U_3O_8.

Most international shipments occur by ship. The product from Canada, Australia, Benin and Namibia is shipped from ports in the various countries. The ports have specialized storage areas and shipping procedures that are approved by the State. The UOC is temporarily stored in warehouses that have restricted access. The shipments are closely coordinated to minimize the amount of time that the intermodal containers remain in storage at the port. The producers will hold the material in a secure area at the concentration plant until they are notified that the ship will arrive in port [2]. This reduces the potential for diversion of large quantities of material at the ports.

4.1 SHIPPING DOCUMENTATION

The documentation used to ship UOC in intermodal containers[9] is common throughout industry. This documentation includes the total mass of uranium contained in the shipment. It also includes safety related information regarding radiological hazards. The shipping documentation does not normally break the shipment down into a listing of individual drums. It generally contains information on a single intermodal container. The batch or lot number, date of production, tare weight and net weight is handwritten on the stenciled label of the

[9] The term “container” within the context of this document refers to the 20-foot intermodal units (see figure 3 above). This provides some differentiation between a single drum of UOC and a 20-foot ISO shipping unit of UOC drums.

drum. The gross weight for all drums is included on the bill of lading for the individual ISO containers. The bill of lading also includes the total weight for all ISO containers in the shipment. Industry asserts it tracks the contents of an ISO container to a single drum of UOC in the event there is a discrepancy in uranium mass when the conversion facility performs destructive analysis of the batch of uranium fed into their process [2]. A more detailed listing of the contents for the intermodal containers is retained at the production facility. However, it is not clear that a standard approach to documenting the location of a single drum is consistent across all producers. This is an area that needs to be evaluated to improve the capability for industry to detect the loss, theft or diversion of a single drum in a timely manner.

5. PROCESS MONITORING – CURRENT PRACTICE

The methods for monitoring the process for producing UOC are well established by industry. Most of the monitoring is performed to ensure the recovery process is efficient, the product meets the customer specification and to ensure all aspects of the production process are compliant with State and international safety and environmental protection requirements. Facilities also monitor the material balance in portions of the process but they are not required to close a material balance across input and output streams. Analyses are performed on ores, process water, reagents, and process solutions in the aqueous and organic phases [15]. This includes leach solution, leach liquors, pregnant liquors, barren liquors, barren organics, organics containing uranium and organics in raffinates [15]. Process solids also need to be analyzed. This includes leach residues, precipitates, filter cakes, uranium concentrates, other by-products or co-products and tailings [15].

Figure 5: Drill rigs for core sampling

Common methods for monitoring the process include various analytical techniques to determine the uranium concentration at each stage of the process, monitoring the flow of material through the system and monitoring fill levels of the tanks. The analytical results are combined with flow and tank volumes to estimate the total uranium inventory in process. However, sampling uncertainties in portions of the process result in large uncertainties for the uranium content is process equipment.

5.1 EXPLORATION

Industry uses a phased approach to determine the commercial feasibility for recovering the uranium. Commercial miners perform radiation surveys to identify potential deposits and conduct core sampling to estimate the concentration of uranium contained in the ore bodies. Geologists have a good understanding of how uranium deposits within rock formations. They use radiation mapping to determine where core samples should be taken. Specialized equipment is used to drill and remove core samples (see figure 5). These samples are destructively analyzed to determine the uranium concentration and optimize the ore removal process [15].

Uranium in nature decays to other radioactive isotopes. It is heterogeneously distributed throughout the rock and sand formations. This decay process generates gamma rays at various energies. Gamma spectrometers are used in the field to identify deposits within the ore formation that contain higher concentrations of uranium. These measurements cannot be used to quantitatively determine the uranium in ore. They are only used to make process decisions on where to mine the material.

The samples received from exploration are managed to ensure the results of the samples can be tracked to the core sample. Each facility laboratory has procedures to record sample details, issue sample numbers, document analytical progress and report results. The individual laboratories maintain record copies of analytical procedures, logs and ledgers of analytical activities and certificates for the standards used to calibrate and test the analytical systems. The samples are generally processed through a chain of custody procedure. This permits the facility to track analysis results back to a specific sample. Access to the information from the analysis is generally limited to individuals with a need to know.

Figure 6: Gamma-ray detectors for sorting ore

5.2 MILLING

The process monitoring activities performed on ore is dependent upon the type of mine. Open pit mines remove the rock using explosives. The rock is loaded into large dump trucks designed to the mine specifications. Some facilities utilize gamma scanners to determine if the ore grade meets the threshold set by process operations (see figure 6). Ore that has a uranium concentration that exceeds a threshold value is sent to the primary crushing station. Ore that is rejected is taken to the waste pile and dumped. Ore that is placed onto the waste pile may be processed if market conditions permit recovery of lower concentration ore. This process is used for mines that have a large throughput of low-grade ore. Mines that have high-grade ore, such as the underground mines in Canada, do not utilize a radiometric sorting process because all ore removed from the ore body is processed [18].

Samples of the ore are also collected and sent to the analytical laboratory. The samples are crushed and leached to remove the uranium. The ore is analyzed to determine the chemical nature of the ore to optimize the chemical recovery methods and control the cost for producing the concentrate. Several techniques that have the capability to determine multiple elemental constituents are used. This includes emission spectroscopy, X-ray fluorescence and inductively coupled plasma emission spectroscopy [15]. Results from these techniques can be generated in a relatively short period of time. They provide information on elements present in the ore.

5.3 CONCENTRATION AND PRECIPITATION STAGE

Samples are collected from the leachate and eluent streams and analyzed in the facility laboratory. The destructive analysis technique selected will depend on the chemical form of uranium in solution and other compounds that are of interest to efficient operation of the plant. In addition to uranium, process solutions are analyzed for manganese, ferrous and ferric iron, sulphate, chloride, fluoride, ammonia, carbonate, barium and other dissolved solids (such as zirconium, molybdenum and vanadium) [15]. Process solutions are also monitored for pH, free acids, oxidation and reduction potential and quantity of suspended solids. The organic solutions used to extract uranium prior to precipitation are also analyzed to ensure the solvents meet process specifications required for efficient recovery [15].

Samples of the pregnant solution will have enough uranium to use common titration methods (see figure 7). Aliquots are used when the concentration of uranium in the sample exceeds the concentration for the analyte of interest for specific methods. Samples from the waste streams may use different methods if the concentration of uranium is very low. A laser fluorometer is commonly used to determine uranium content [15].

Gamma spectroscopy using low or high-resolution detectors can be used to determine the uranium concentration in a solid matrix. This method is susceptible to variations in matrix density and homogeneity of the sample. The analysis requires interpretation of a complex gamma spectrum that includes primary and secondary daughter products unless these isotopes are separated using other laboratory techniques [15].

X-ray fluorescence is another common method used to determine uranium concentration. This method depends on the interaction of the electrons in atoms with the X rays. Lasers are often used to remove an electron from an inner shell around the nucleus. The gap left from the removed electron is immediately filled by another shell electron. This results in the release of energy that is specific to the element [15].

Figure 7: Laboratory equipment for determining uranium concentration

The total inventory of uranium contained within the liquid phases of the process is determined by combining the destructive analysis of the samples with flow instrumentation and tank volume indicators. Uranium contained in ion exchange resin will be estimated using destructive analysis of samples taken from the columns and resin loading. Some uranium will be contained in the rinsed resin that is recycled as well as spent resin that is discharged to the tailing pond. Samples are taken of each stream to estimate the total uranium contained in this stage of the process. The same approach is taken for other liquid phases of the process where the chemicals are recycled or discharged. The facility will closely monitor all discharges to the tailings pond to ensure they meet State standards for environmental compliance. The mass of uranium discharged to the tailings pond is estimated using flow rates and destructive analysis of the various waste streams. Established sampling procedures are used to obtain samples that are representative of the waste stream over a defined operational period. The focus of the analysis is to ensure the facility does not exceed approved discharge limits for processing constituents at any point in time. The facilities do not generally utilize this information for tracking the loss, theft or diversion of uranium.

One of the real challenges that operators face is accurately estimating the amount of uranium retained in the various process stages. Uranium concentration plants contain large quantities of piping with bends and elbows, valves, tanks, concentrators, hoppers, filter presses, calciners and ovens. All of this equipment has the potential for retaining uranium in various forms. On startup, a new facility will retain uranium within the process to a point where no additional uranium will accumulate unless a process upset occurs. These facilities do not have programs in place that provide for a means for accurately estimating uranium retained in the process. The capital investment and labor costs to develop a holdup measurement program for a concentration plant would be significant. This cost is balanced against the benefit that such a program would have given the large uncertainties that are typical of holdup measurement programs and the attractiveness level of the material. Operators monitor the process using other methods to detect the loss, theft or diversion of significant quantities of natural uranium.

It should be noted, however, that operators and the international nuclear safeguards and security community share a common interest in tracking uranium ore concentrate at the packaging and storage stage of the process. Operators often restrict access to the area of the facility where these activities occur. They often implement engineering and administrative controls to accurately measure the net weight of the product using calibrated scales, the total uranium content using automated or manual sampling techniques and labels to track an individual drum [2]. This is due to the commercial value of the product. However, the operator does not have a need to correlate or verify the production quantities relative to a declared throughput. Their focus is on making sure that every drum of UOC is delivered to the customer in accordance with the contract specifications. State and international inspectorates are more interested in correlating the number of drums produced to the declared throughput for a facility to independently verify that the operator is not producing undeclared material and selling it to a State that intends to use it for supporting a clandestine nuclear weapons program.

5.4 FINAL PRODUCT STAGE

Operators put much effort into monitoring the specifications of the final product. They have administrative procedures in place to sample each batch of product. Some facilities use automated sampling devices that collect multiple sub-samples over a production run. These samples are combined and thoroughly mixed to get a representative sample of the entire batch. The samples are sent to the laboratory for destructive analysis using the various methods mentioned above. The grams of uranium per gram of sample and all other potential impurities are determined using the destructive analysis techniques mentioned above. Customer samples are also collected from the blend of sub-samples and sent along with the drums to the customer to verify the operator’s analysis. The facility operator may also collect a third sample that may be sent to a referee laboratory in the event the customer’s analysis at the conversion plant disagrees with the concentration plant’s analysis of the batch. The UOC producer labels each drum with a unique identification. The samples collected for the batch are also labeled with unique identifiers to ensure the customer and the referee labs analysis can be tracked to the production batch. Operators are experienced in procedures that permit independent verification of the product whether it be the conversion plant or an independent national or international inspectorate.

The total quantity of uranium produced for a batch is calculated by multiplying the uranium concentration for production run to the total mass of UOC loaded into the drums. The net weight of UOC is determined by subtracting the tare weight of the drum from the total weight of the drum. The individual drums are weighed using a calibrated scale. These scales are capable of determining the weight to within ±0.2% [5]. Each facility has a scale calibration and maintenance program that ensures the scales are operating within the expected uncertainty. Measurement control programs are developed to assess the accuracy of the scales. The accuracy of the scales is important because the facility is paid on the amount of product delivered to the customer that meets the contract specifications. The mass of uranium produced for each batch is summed over the period of one year to determine the annual production quantity for the facility. This information is often recorded in the annual report of the producer to demonstrate to investors that the facility is meeting its production quotas and generating the revenue and profit that is important to corporate investors independent of whether they are privately held companies or State-owned.

The operator also applies a tamper-indicating device, commonly referred to as a seal, to each of the shipping containers after the drums are loaded into the container. The seal provides the operator with continuity of knowledge regarding the declared uranium content for the individual shipping containers. It also provides a means for detecting unauthorized access to the contents of the individual shipping containers. Each seal that is applied may have a unique identification number that can be tied back to the production batch. The operator has administrative procedures in place to order, inspect, store, distribute, apply and log each seal applied to a shipping container. All information associated with the shipment is kept in a database management system that tracks the batch number, net weight and analytical results for the individual containers. Access to the information is restricted to operations personnel that have a need to know the information.

Some operators also incorporate surveillance measures in the secure area where the product is sampled, packaged into drums, weighed and placed into shipping containers. These systems are not typically designed to the same standards as systems installed in facilities that have more attractive material. The storage and retrieval capacities of the computer hardware are not designed to the specifications of a typical containment and surveillance system utilized by the IAEA for international safeguards. However, they do provide a means for detecting unauthorized access, theft or diversion and so provide some level of deterrence from such acts for personnel that work at the facility.

As mentioned previously, the net weight of the UOC, uranium concentration in grams uranium per gram of sample, the sequential drum identification number that is tied to a batch and seal number, where applicable, is often stored in a paper or electronic ledger at the facility [2]. This ledger also includes a listing of all impurities for each batch. It also contains a listing of all drums that are placed into a single shipping container. The results from the radiological surveys required to meet international transport are also recorded [2]. This information is used to develop the shipping documentation necessary for State authorities to approve the shipment. The operator keeps these records in a format that permits easy retrieval in the event the customer or the State authority has questions on the batch of material. This level of detail provides the operator with a quality record for each batch and drum of UOC. Access to this information is generally restricted to individuals that have a need to know. Electronic records are protected by user names and passwords to restrict access the information. Facilities have administrative and engineering controls in place to protect against loss of the data.

Although the operator is not required to keep detailed nuclear material accountancy records or implement procedures for determining and propagating measurement uncertainties for each key measurement system, they do apply quality controls to the process monitoring equipment that are consistent with industry standards. The quality assurance programs implemented by the producers generally provide adequate measures to detect anomalies in the process that would occur if someone at the facility attempted to divert significant quantities of UOC. During a recent tour of a mine in Namibia, the author was informed that the facility has over 4,000 signals reporting to the plant control facility. Approximately 20% of these monitoring points are used to track uranium inventory within the process. Response procedures are developed that prioritize the facility's response to an alarm that is dependent upon the impact the alarm has on the efficiency and effectiveness of the process. These monitoring locations, while not dedicated to safeguards and security, provide a means for monitoring the uranium inventory within the process [25]. Assistance could be provided to State regulators and industry that leverage the use of existing process monitoring systems for safeguards and security purposes. Certain process monitors could be identified as "key detection points and systems" similar to the concept of key measurement points and systems associated with detailed nuclear material accountancy system for a facility that is under IAEA safeguards.

Some of these monitoring points are located at the vent stacks to the scrubbers and drying ovens. The operator is required to monitor all discharges to the environment. The type of monitoring is dependent upon State regulatory requirements, which vary from State to State. This includes discharges of fluorine, uranium and other process related chemicals that are discharged as a result of the drying process. These discharges are often sent through chemical scrubbers to trap harmful gases and solids prior to release to the surrounding environment. Samples are taken of the vent gases at this stage of the process to estimate the amount of uranium being discharged to the environment. This information provides indicators of nuclear material losses over a defined operating period. The processes and procedures for monitoring discharges could be evaluated to determine if anomalies provide an indication of overproduction relative to the operator declaration.

6. INVENTORY TRACKING DURING TRANSPORT

The engineering and administrative controls for developing shipping documentation and for tracking UOC during transport will vary from facility to facility. Most facilities use paper ledgers or electronic databases to document and track the individual drums that are loaded into a shipping container. Each of the shipping containers has a nameplate welded to the container that provides a tare weight and lists the maximum gross weight permitted for the shipping container. The International Maritime Organization defines the minimum acceptance criteria for low specific activity hazardous materials for international transport [24]. Each State will also develop specific regulatory requirements that must be met to safely transport UOC within their territory. These transport companies work with the facility operator to develop shipping documentation that meets the international and national standards. The couriers or consignees do not take possession of UOC at any time during the shipment. They provide a logistical transport service under a contract with the UOC production company.

The UOC drums are loaded into the shipping containers in a controlled area at the production facility (see figure 8). They are secured inside of the container using straps and bands to prevent movement of the drums during shipment. The detailed contents for each shipping container are maintained by the facility in the event an issue with the shipment occurs. The intermodal shipping containers are locked once the drums are loaded. A seal is placed on the container to provide an indication of unauthorized access to the shipping container.

Figure 8: UOC drums loaded into a 20-foot ISO shipping container

The individual intermodal containers are loaded onto trucks or railcars and transported over land to a conversion facility or to a shipping port. The routes for transport are often pre-approved by the State regulatory authority [26]. The level of protection afforded to the shipment will vary from State to State. Some States require armed escorts for shipments [26]. Others apply protective measures that are consistent with hazardous materials shipments. These measures include close coordination between the shipper, shipping company, the receiver and State regulator. Some corporations have the ability to track material globally via satellite.

Product that is shipped by truck over long distances has designated locations where the material can remain stationary for short periods of time. The concentrate may be transferred to another concentration plant where it is secured until all concentrate is transported to the port [2]. Or, it is transferred to large, secure warehouses at the port. The warehouses may be owned or leased by the mining corporation or they may be owned and operated by a separate logistics company. Access to the warehouses is restricted. The warehouses also have surveillance cameras and physical protection systems in place to detect unauthorized access. The design of the security systems at the warehouses is typical for protecting a valuable commodity.

The inventory of UOC shipped from the concentration plant to the converter is verified by visual observation and by comparing information provided on the bill of lading. The producers work closely with their customers to track delivery of every container because it impacts the amount of payment they receive on the shipment.

Procedures for resolving shipper/receiver differences are defined in the delivery contract between the UOC producer and the converter. Concentration plants that produce nuclear fuel grade product have the capability to accurately determine the uranium concentration for each drum. The converter confirms these values when the material is fed into the conversion process. Homogeneous samples are collected at the conversion facility when the contents of a single drum or batch of drums are dissolved prior to being fed into the process. The results from the homogeneous sampling effort are used to make adjustments to the values produced at the concentration plant. The issue, however, is that a significant amount of time may elapse before these adjustments can be made. This is due to delays in processing at the conversion plant. Some drums may sit in the storage area at the converter for up to two years before they are processed. Regulations may need to be strengthened that require converters to identify shipper/receiver differences in a timelier manner.

7. APPLICABILITY OF CURRENT PRACTICE TO SAFEGUARDS AND SECURITY

Many of the current process monitoring practices currently employed by the operators can be leveraged to strengthen measures for detecting loss, theft or diversion of UOC in process, storage and transport. The international safeguards requirements for UOC that is not in a chemical form that is suitable for enrichment or fuel fabrication do not require detailed nuclear material accountancy. In addition, international recommendations for securing UOC in process, storage and transport only require the application of prudent management practice. No international or national guidance exists that provides more definition on what is or is not prudent.

7.1 DETECTION THRESHOLD

As referenced previously, discussions with industry experts during the Windhoek Conference indicated that operators are capable of detecting the loss, theft or diversion of a single drum located at the facility within one month [2]. This capability is driven by the commercial value of a single drum, which is approximately $US 50K. A single container of 50 drums is worth approximately $US 2.5M. An overseas shipment on a large ocean vessel of 50 shipping containers is valued at approximately $US 125M. The commercial producers of UOC have administrative and engineering controls in place to ensure they receive payment for all drums of product. The current capability to detect the loss, theft or diversion of a single container located at the facility within one month exceeds the international requirements currently outlined in the Nuclear Suppliers Group reporting requirements of 500 kgs of uranium within one year. Acceptable industry standards for detecting the loss, theft or diversion of a single drum located at the facility within the period of one month are not considered to be unreasonable if industry agrees to this criterion. Agreement to this detection threshold will ensure that all safeguards and security related concerns are addressed by an industry best practice.

The use of current process monitoring to detect the loss, theft or diversion of a drum equivalent quantity of uranium (approximately 350 kgs) from the process is a different challenge. Uranium producers utilize various process monitoring methods such as in-line equipment, volume indicators and sampling and analysis programs throughout the process to evaluate the efficiency and effectiveness of the recovery process, consumption of raw materials and discharges to the tailing ponds or other waste streams. These systems are capable of detecting fluctuations in uranium concentration within the various stages of the process. However, operators typically do not use these monitoring methods within the framework of a safeguards and security context. They are used to monitor the efficiency and effectiveness of the process to concentrate uranium.

Nuclear material inventory procedures also vary from site to site. Some regulators require the facility to conduct a comprehensive inventory once per year. The operator is required to interrupt the flow of feed into the concentration plant and estimate retained inventory. This requirement is defined by the State to meet certain regulatory requirements. This requirement goes beyond what is required by the IAEA for material that is before to the starting point of safeguards. It is not clear that this practice is common for all uranium concentration plants. Facilities in the United States are not required to interrupt the feed supply to estimate the retained inventory at the plant at a given point in time [27].

Illicit production or over-production of uranium inventory is a separate issue. Currently the State is required to report under the Additional Protocol the location, operational status and estimated annual production of individual uranium mines and concentration plants. The State is also required to provide the same information for the entire State. The IAEA may conduct complementary access visits to mines and concentration plants within the State to independently verify the State declaration. However, these visits are not routine given the low attractiveness of the UOC. Therefore, it is important for the State regulatory authority to have the capability to independently verify over-production at an individual plant. The process monitoring methods utilized by the operators do not provide the State with an independent assessment capability of the facility declaration for UOC throughput.

Security measures implemented at the concentration plants vary from facility to facility. Satellite facilities that produce intermediate product have limited industrial security. Other facilities that produce pure product have variations in the combination of fencing, surveillance cameras, personnel access controls and seals for individual drums or shipping containers. Discussions with personnel from Atomredmetzoloto and Kazatomprom indicate they attach seals to individual drums or hoppers. Facilities in the United States and Namibia are not required to attach seals to the individual drums [2 & 27]. The security systems procedures in place are defined by the perceived threats that will vary dependent upon the socio-economic and political stability of the area where the mine is located. This approach is consistent with the concept of applying prudent management practice to protecting UOC in process and storage at the concentration plant.

Security of the UOC while in transport also varies by facility and by State. Security measures for transporting UOC in the United States is much different from those required by other countries. Transport of UOC within the United States is conducted under strict regulatory requirements, within a stable political environment and with an excellent communication infrastructure. The material is transferred as hazardous, low specific activity cargo in accordance with United States Department of Transportation and Nuclear Regulatory Commission requirements. It is also subject to individual state requirements that are dependent upon the route the over land transport takes. Transport of UOC in some regions is conducted under a weak regulatory infrastructure, in a less stable political environment and with limited communication capabilities for reporting issues during transport. Some governments require full military escorts for UOC transported through their territory [28]. This difference is partially due to valid threat assessments in the region and opportunism to extract revenue for a commodity that is not currently produced in the country.

7.2 TIMELINESS OF DETECTION

The IAEA timeliness goal for UOC that is suitable for enrichment and/or fuel fabrication is one year. This is consistent with some State requirements for conducting annual physical inventories for individual mines. In addition, some States have reporting requirements of if a single item (drum or sample) cannot be accounted for during a scheduled inventory period at the facility [5 & 16]. Operators have administrative procedures in place that provide direction on how and when to report to the State authorities. They also have procedures in place for recovering UOC items that cannot be accounted for.

Reporting times for potential shipper/receiver differences for UOC shipped overseas is not well understood. Some shipments may take more than one month to go from the facility shipping area to the port and then to the converter. Although operators are confident they can detect the loss, theft or diversion of a single drum, they could not assure that it would be detected within one month for international transports. The operators did, however, state that the shipments are closely monitored to ensure the material was adequately accounted for during transport because of the commercial value of the product.

8. AREAS FOR POTENTIAL IMPROVEMENT

Industry and State regulators support practical improvements to control measures for UOC that they consider to be cost effective and implementable. Industry agrees that tracking UOC to a single drum while it is located at the facility is feasible and responsible [2]. Industry also supports reasonable reporting requirements that provide them with the capability to conduct an internal investigation to resolve the issue before the loss, theft or diversion is reported to the State and the international community. Industry and State regulators agree that UOC inventory management procedures and security measures should be standardized across industry. However, the measures implemented should take into consideration the location and socio-economic and political environment within which the facility operates as part of the threat assessment and security system design. This permits the State and industry to apply a graded approach to securing UOC in process, storage and transport.

The IAEA Nuclear Security Department has established a working group of UOC safeguards and security consultants that is providing guidance on measures to strengthen controls on UOC at the facility and during transport. This consultancy is currently developing technical guidance that should be considered by the State and operators when designing materials management procedures and security systems for concentration plants. These recommendations considers the application of current practice for strengthening materials management and security measures for UOC that meets the IAEA definition for being beyond the starting point of safeguards. This technical guidance will provide practical recommendations to effectively secure UOC that is based on defined target materials. The technical guidance promotes the use of a graded approach for designing the security system [29].

From a nuclear non-proliferation perspective, one of the most significant challenges is to independently verify State declarations for estimating annual throughput. It is important that the international safeguards community and State regulators have the capability to independently verify that UOC is not being used for non-peaceful purposes. The importance of this need is emphasized when one looks at the relationship between the IAEA defined significant quantity of ten tonnes of uranium to the annual throughput of the world's leading producer of UOC. The leading producer of UOC is Kazatomprom, a State-owned company in Kazakhstan. Kazatomprom is approaching an annual throughput for UOC of 20,000 metric tonnes [30]. The IAEA defined significant quantity is approximately 0.05% of the annual throughput of the State.

Recent discussions with personnel from Kazatomprom revealed that mining companies operating in Kazakhstan are required to remove 90% of the uranium from the ore before they can move operations to other deposits [31]. This regulation results in a scenario where the mining company may have to produce drums of UOC at a cost that is well beyond the current market value. Regulations of this type may encourage mining companies to seek funding from sources that are willing to pay higher than market values for the UOC.

One potential scenario is that management at any single mine, or corporate management for multiple mines in any country, decides to illicitly traffic UOC on the black market. Managers at the mine could over-produce UOC and place it into storage until the opportunity arises to ship a single inter-modal container that has approximately two significant quantities of uranium to an end-user that is developing a clandestine weapons program.

The IAEA currently has limited resources that it can use to independently verify State declarations for UOC production. It is dependent upon the Member State to develop a regulatory infrastructure with an independent inspection and enforcement capacity capable of detecting and deterring non-State actors from producing UOC that can be sold illicitly on the black market. Therefore, it is very important that the State regulatory authorities responsible for enforcing effective safeguards and security measures in a producing country, has the capability to independently verify the estimated annual throughput at individual facilities.

Looking at production in Kazakhstan as an example, Kazatomprom currently operates approximately 18 in situ leach mines. The annual production and product quality for the individual mines varies. At the present time, KAEC faces a real challenge for independently verifying the annual throughput at each mine because they currently lack a legal basis for conducting safeguards and security inspections at the individual mines due to a lack of regulations in this area. They also lack the technical and financial resources to conduct independent assessments to verify the annual throughput at individual mines and concentration plants. KAEC has requested assistance from of the United States Department of Energy (DOE) and the IAEA in addressing this issue. Kazatomprom and KAEC are willing to provide DOE with access to their ISL mines to determine measures that could be useful for strengthening controls on UOC. Kazakhstan is not the only State that has requested assistance from the IAEA on these matters. Regulatory authorities from several African States have requested similar assistance. The Office of Nuclear Security (ONS) within the IAEA Nuclear Safety and Security Department is developing a program to assist Member States in this area. This program focuses on developing technical guidance and providing training on the technical guidance. It does not currently provide for developing technical measures that can be used to independently verify operator throughput [29].

The current practice of process monitoring at the mines and concentration plants is designed to evaluate the efficiency and effectiveness of the various stages of the process. Operators do not think in terms of how these systems could be used to support strengthened inventory management or security measures at the facility. They also do not think in terms of the need for the State regulatory authority or the IAEA to independently verify the annual throughput at the plant. This is an area where technical improvements could be made. For example, process monitors could be developed and installed at a key point(s) in the process that provides the State regulator and the IAEA with a means for correlating the throughput, at some point upstream from the drum packaging area, to the number of drums produced over a specified period of time. Such a system would have to be carefully designed to ensure the IAEA has the capability to independently verify the State declaration either at the site or remotely. The system should also be non-intrusive. The design should take into consideration that larger-than-normal uncertainties are acceptable when looking for a gross defect of a single drum over a period of time that is much shorter (one month) than is required from an international safeguards perspective (one year).

In addition, some improvements could be made to standardize and automate tracking of shipping containers. Currently, industry has the capability to track individual containers by batch number but placing seals on each drum is not a universal industry practice. The seal is currently only placed on the shipping container that has more than one significant quantity of UOC. The consultants providing guidance to the IAEA on this issue should review current practice to see if low cost improvements can be made to improve the capability to track individual shipping containers in a timely manner. This will provide the nuclear non-proliferation community with a means for detecting and recovering UOC that is diverted during transport.

In addition, security specialists should work with State regulators and industry to provide a technical basis to the application of prudent management practice as it relates to security at the mines and concentration plants. This technical basis document would evaluate all stages of the process and provide practical recommendations for how graded materials management and security measures can be defined for a specific facility and incorporated into the regulations of a specific State. This would provide for a standardized approach to the application of security measures at facilities that is based on threats that are well defined.

An evaluation of the current practice relative to timeliness of reporting for the potential loss, theft or diversion of UOC in transport should also be conducted. The international safeguards community, industry and logistics companies recognize the importance of tracking UOC globally but it is not clear that the communications infrastructure is in place or that standardized reporting requirements currently exist. Blind studies should be developed and conducted to test industry’s ability to detect and recover a single shipping container during transport. Industry standards for reporting shipper/receiver differences that are timelier than what currently exists should also be developed.

9. CONCLUSION

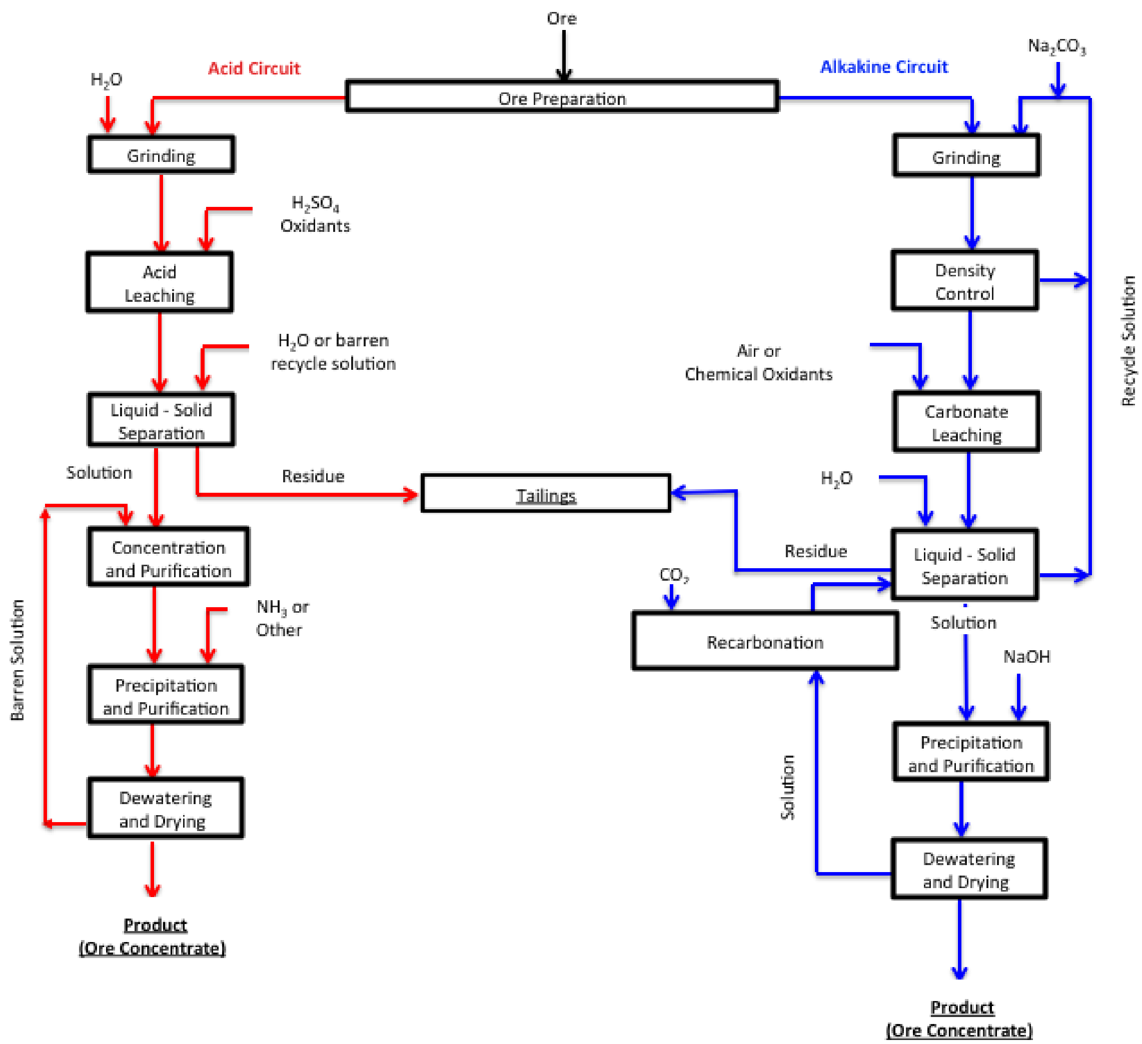
The uranium industry currently applies process monitoring methods and techniques across all stages of the process. The methods and techniques in place are used to monitor the efficiency and effectiveness of the uranium recovery process. They are designed to maximize production and minimize the cost for producing UOC. The State regulator can use many of the same methods and techniques to independently verify the annual throughput at the mines and concentration plants. This approach provides Member States that are compliant with their non-proliferation obligations with measures to detect and deter misuse of UOC product by non-State actors. However, it does not provide the IAEA with a mechanism to independently verify the State declaration. Technical measures that provide the IAEA with the capability to independently correlate throughput at a specific facility with the number of drums produced over a specified time period needs to be developed. This will provide the

IAEA and the State regulatory authority with a means for detecting illicit production of UOC.

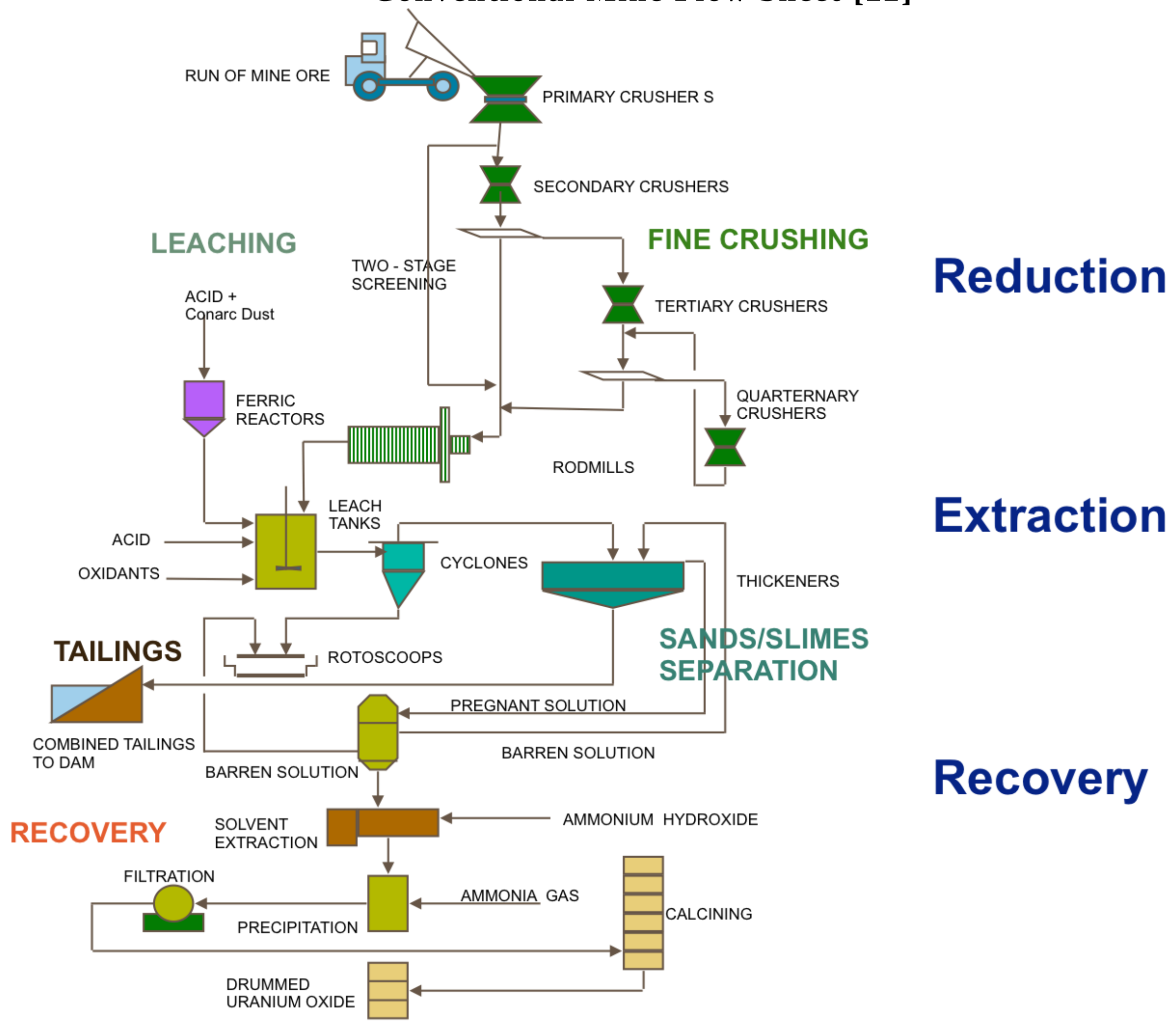
Recent meetings with State regulators, the IAEA and industry indicate a willingness by all parties to strengthen controls on UOC in the packaging and storage stage of the process and during transit. Industry has stated that they have the capability to detect the loss, theft or diversion of a single drum of product located at the facility. This is driven by the commercial value of the UOC. However, standards for timeliness of detection and reporting are needed. The current practice at each site for conducting drum inventories and for reporting the loss theft or diversion of UOC should be evaluated. Recommendations that provide for standardizing hardware and software should be drafted and provided to State regulators and industry. All recommendations must be cost effective and practical to implement at individual facilities.

Prudent management practice for UOC in process, storage and transport is not well defined. Nuclear security experts should develop a set of practical recommendations across all stages of the process that State regulators and industry can reference when they develop regulations and design security systems and procedures for specific facilities. These recommendations should provide for a graded approach for implementing security measures for UOC in process, storage and transport. They should consider the installation and sustainability costs and practicality for full implementation at all facilities.

Appendix A
Uranium Process Flow Sheets for Acid and Alkaline Methods [23]

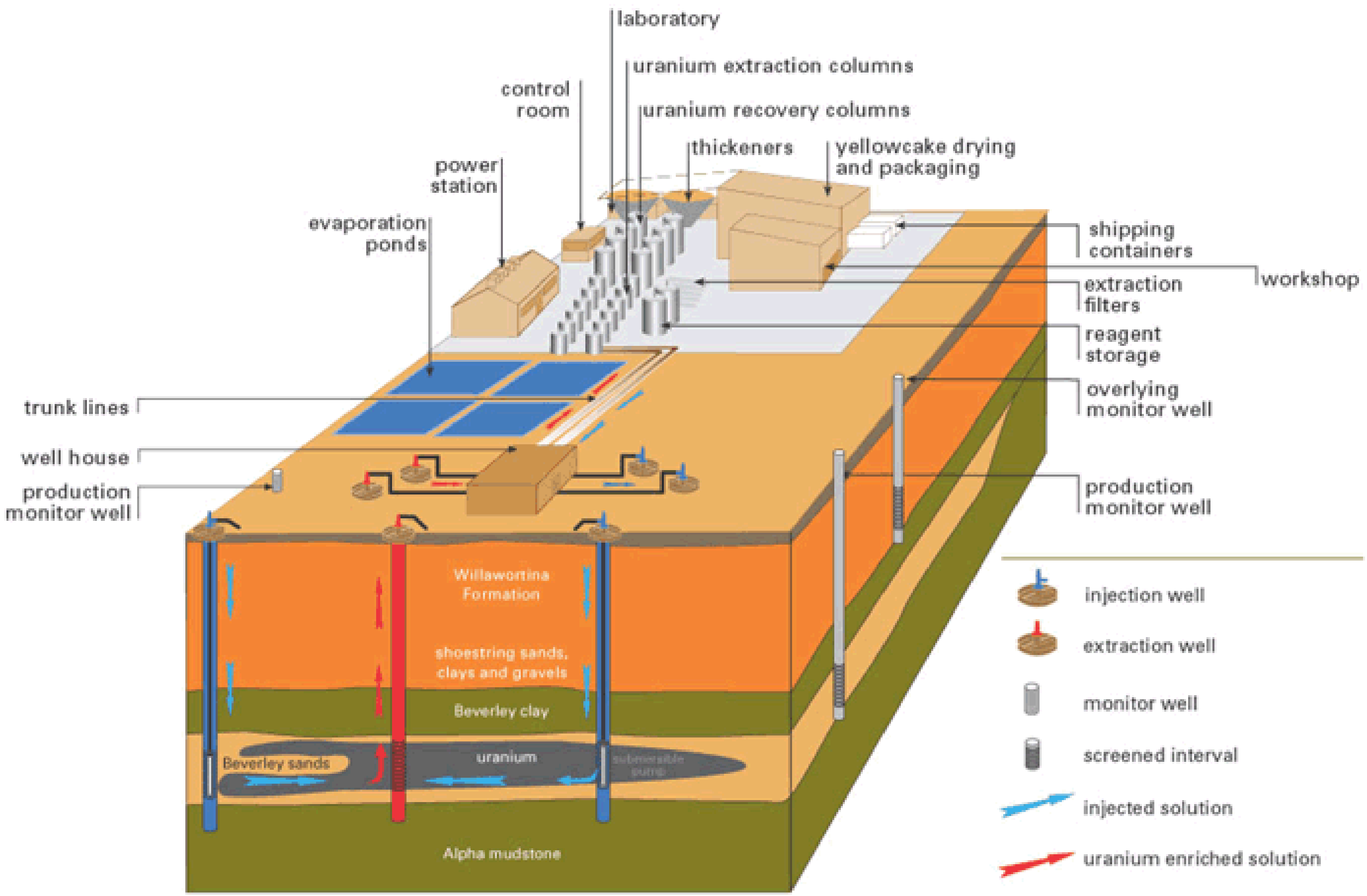


Appendix B
Conventional Mine Flow Sheet [22]



Appendix C

Flow Sheet for ISL [32]



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