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Safeguarding the Nuclear Fuel Cycle

Mining, Milling, and Conversion

Heather H. Erpenbeck, NEN-1
June 27, 2017
The Front End of the Fuel Cycle

- Current global demand for uranium is ~63,000 tonnes uranium per year (tU/yr)
- Majority of the annual uranium supply is consumed by the nuclear power sector
  - Mined uranium accounts for ~99% of the total
  - Secondary sources account for less than 1% of the total
Mining, Milling, and Conversion, of Uranium Sources

Uraninite (above), Eldorado Mine, Northwest Territories, Canada. Minor pyrite or chalcopyrite.
Photo credit (ID): Christopher O’Neill (163578)

Carnotite (below) in sandstone matrix, Harvey Black Mine, Arizona, United States.
Photo credit (ID): C. Stefano (264918)
http://www.mindat.org

Uranium ore concentrate, UOC, (above) from Cameco’s Rabbit Lake operation, Northern Saskatchewan, Canada.
Source: Cameco

Cylinders of high purity UF₆ (below) at the Metropolis Works Plant.
Questions to Consider

- At what point in the fuel cycle do full scope safeguards apply?
- What approaches does the International Atomic Energy Agency (IAEA) use to safeguard the front end of the fuel cycle?
- What challenges does the IAEA face in safeguarding the front end of the fuel cycle?
Industry Economics

- Supply and demand economics drive the uranium mining industry
  - Mining decisions are based largely on economic factors
  - No formal exchange exists for uranium
  - Number of operational uranium mines worldwide is in flux due to market forces

- Uranium is widespread in many different rocks, and even in seawater
  - Recovery and concentration processes are volume-intensive
  - Ore deposits of sufficiently high concentration (grade) are rare

[Graph showing Ux U3O8 Price Indicator, Full Historical Data]

Current price, lb: $25.50 (3/20/2017)
Source: The Ux Consulting Company, LLC
http://www.uxc.com
Uranium Sources

- Uraninite is the principal ore of uranium
- Over 230 named uranium minerals, seawater, phosphoric acid—other potential uranium sources
- Uranium may also be recovered as a by-product

Sources: World Nuclear Association and GlobalSecurity.org
http://www.world-nuclear.org/education/mining.htm
http://www.globalsecurity.org/wmd/world/iraq/al_qaim.htm

Uraninite, Eldorado Mine, Northwest Territories, Canada. Minor pyrite or chalcopyrite.
Photo credit (ID): Christopher O’Neill (163578)
http://www.mindat.org

Curienite, Pb[(UO₂)(VO₄)]₂·5H₂O, (yellow) in brachiopod fossil casts, Akashat Mine, Akashat, Iraq.
Photo credit (ID): J. Ralph (212702)
http://www.mindat.org
Uranium Mining

- Uranium mines operate in more than 20 countries around the world
- Approximately 53% of world production comes from just ten mines in five countries
  - Kazakhstan, Canada, Australia, Niger, and Namibia were the world’s largest producers in 2016 (in order)
  - These five provided ~83% of the world’s mined uranium
- Uranium occurs in potentially recoverable concentrations in many types of geological settings
- Vast recoverable uranium resources are known (5,718,400 tU)
  - Australia, Kazakhstan, Canada, Russia, South Africa, Niger, and Brazil (in order) own ~76% of these resources
  - Some uranium resources are not currently being mined

Source: World Nuclear Association
Uranium Resources and Reserves

A Significant Resource
The Four Corners Mine in Hardee County, Florida, United States, produces phosphate rock for fertilizer. The phosphorite deposits of central Florida are considered to contain the largest known uranium resource in North America. The average uranium concentration is 0.009%.

Photo credit: Mike Esterl/The Wall Street Journal
http://en.wikipedia.org/wiki/Uranium_mining_in_the_United_States

Significant Reserves
McArthur River in northern Saskatchewan, Canada, is the world’s largest, high-grade (~16.6% U; 19.5% U₃O₈) uranium deposit with proven and probable reserves of 152,044 Mt U₃O₈. Cameco is the majority owner (69.8%), with Areva as partner.

Source: Cameco
http://www.cameco.com/media/images/operations_photos/
## Largest-Producing Uranium Mines, 2016

<table>
<thead>
<tr>
<th>Mine</th>
<th>Country</th>
<th>Principal Owner</th>
<th>Type</th>
<th>Production (tU)</th>
<th>% of world</th>
</tr>
</thead>
<tbody>
<tr>
<td>McArthur River</td>
<td>Canada</td>
<td>Cameco (69.8%)</td>
<td>underground</td>
<td>6,945</td>
<td>11</td>
</tr>
<tr>
<td>Cigar Lake</td>
<td>Canada</td>
<td>Cameco (50%)</td>
<td>underground</td>
<td>6,666</td>
<td>11</td>
</tr>
<tr>
<td>Tortkuduk</td>
<td>Kazakhstan</td>
<td>Areva/ Katco JV</td>
<td>in-situ leach</td>
<td>4,002</td>
<td>6</td>
</tr>
<tr>
<td>Olympic Dam</td>
<td>Australia</td>
<td>BHP Billiton</td>
<td>by-product/ underground</td>
<td>3,233</td>
<td>5</td>
</tr>
<tr>
<td>Inkai</td>
<td>Kazakhstan</td>
<td>Cameco/ Inkai JV</td>
<td>in-situ leach</td>
<td>2,291</td>
<td>4</td>
</tr>
<tr>
<td>Somair</td>
<td>Niger</td>
<td>Areva (63.6%)</td>
<td>open pit</td>
<td>2,164</td>
<td>4</td>
</tr>
<tr>
<td>Budenovskoye 2</td>
<td>Kazakhstan</td>
<td>Karatau JV/ KazAtomProm– Uranium One</td>
<td>in-situ leach</td>
<td>2,081</td>
<td>3</td>
</tr>
<tr>
<td>South Inkai</td>
<td>Kazakhstan</td>
<td>Betpak Dala JV/ Uranium One</td>
<td>in-situ leach</td>
<td>2,056</td>
<td>3</td>
</tr>
<tr>
<td>Central Mynkuduk</td>
<td>Kazakhstan</td>
<td>Ken Dala JSC/ KazAtomProm</td>
<td>in-situ leach</td>
<td>2,010</td>
<td>3</td>
</tr>
<tr>
<td>Ranger</td>
<td>Australia</td>
<td>Rio Tinto (68%)</td>
<td>open pit</td>
<td>1,994</td>
<td>3</td>
</tr>
<tr>
<td><strong>Top 10 total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>29,638</strong></td>
<td><strong>53%</strong></td>
</tr>
</tbody>
</table>

Uranium Mining and Extraction Methods

- No different than those for other commodities unless the ore is very high grade
- Basic extraction methods are generally correlated to the geology of uranium ore bodies
  - Surface mining (open pit or open cast mining)
  - Underground mining
  - Solution mining (in-situ leaching) and extraction (heap leaching)
  - By-product or tailings recovery

A. Kayelekera Open Cast Uranium Mine, Malawi.
Source: mining-technology.com
Solution Mining: In Situ Leaching (ISL)

• Most suitable for orebodies and deposits that are
  – Hosted by permeable material (sand or sandstone)
  – Confined above and below by impermeable strata (shale or clay)
  – Below the water table

• Orebody is left in place, and the process solution is injected into one of several wells. Uranium minerals are dissolved, then recovered, from the process solution.
Solution Mining: ISL

- Mining method with least physical impact
  - Little surface disturbance
  - Tailings and waste rock are not generated
  - Alternating, 5-spot, or 7-spot wellfield patterns are characteristic
- Lower capital costs relative to conventional mining
  - Effective method for mining low-grade deposits
  - Most prevalent production method (36% in 2009, 48% in 2016)

Pictorial Representation of the ISL Process
Source: Peninsula Energy Ltd.
http://www.pel.net.au/investor_info/uranium_outlook/what_is_in_situ_leach_or_in_situ_recovery_.phtml
ISL Mines

Operations at the Tortkuduk Uranium Mine in Chu-Sarysu Province, Kazakhstan, the world’s most productive ISL uranium mine in 2016 (4002 tU). The project is an Areva–Katco JV joint venture.
B. Photo credit: Andrea Bruce–The Washington Post

Cameco’s ISL Uranium Mining Operations at (C) Smith–Highland Ranch, Wyoming, United States and (D) Inkai, Chu-Sarysu Province, Kazakhstan. The Inkai project is a Cameco–Inkai JV joint venture.
Source: Cameco
http://www.cameco.com/media/features/jv_inkai/
Uranium Milling Operations

- Goal is to extract uranium ore concentrate (UOC or yellowcake) from uranium bearing ores or ISL pregnant solution

- Ore processing methods include
  - Size reduction (crushing and grinding) and sieving
  - Acid or alkaline leaching
  - Thickening
  - Concentration of uranium-rich solution
  - Extraction (solvent extraction or ion exchange)
  - Precipitation and drying/calcining

- Modern yellowcake is principally a mixture of uranium oxides
- “Legacy” yellowcake may contain uranium salts, hydroxide, sulfate, and peroxide
Typical Uranium Mining/Milling Flowsheet

1. Overburden
   - Uranium orebody
     - Drilling and blasting
       - Excavation
         - Removal
           - Sorting
             - Ore stock
               - Overburden and waste rock

2. Fresh water
   - Ore stock
     - Water treatment
       - Crushing, grinding, and sieving
         - Acid leaching
           - Washing/Thickening
             - Clarifying and filtering
               - Ion exchange
                 - Elution
                   - Precipitation
                     - Drying and calcination
                       - Mill tailings

3. Sodium chlorate
   - Sulphuric acid
     - Nitric acid
       - Ammonia
         - UOC
Uranium Mills

Uranium Ore Slurry Arrives (A) at the Key Lake Mill (B), Northern Saskatchewan, Canada.  
Source: Cameco  
http://www.cameco.com/media/images/operations_photos/

Ion Exchange Columns (C) and Filter Press (D), Taukent Uranium Production Facility, Chu-Sarysu Province, Kazakhstan. The Taukent Facility is associated with several Kazakh mines, including the Akdala ISL mine.  
Source: Uranium One  
http://www.uranium1.com/indexu.php?section=image%20gallery&page=0#
Uranium Milling Products: Yellowcake

A. Samples from the Six Major Steps in Areva’s Uranium Milling Process. Note that the calcined yellowcake (YC) is black.

Photo Credit: David Boily/AFP/Getty Images

B. Yellowcake from Kazatomprom’s Operations at the ULBA Metallurgical Plant, Eastern Kazakhstan. This yellowcake is gray–brown.

Source: Kazatomprom
http://www.kazatomprom.kz/en/gallery/0/16

C. Yellowcake from Cameco’s Rabbit Lake Operation, Northern Saskatchewan, Canada.

Source: Cameco
http://www.cameco.com/media/images/operations_photos/
Requirements for Nuclear Reactor Fuel

- Natural and enriched uranium oxide are the most common feed materials for fuel fabrication.
- Chemical purity is known to affect fuel performance:
  - Neutron poisons (boron, cadmium, and certain lanthanides) are problematic.
  - Other impurities affect the physical or mechanical properties of a fuel.
  - Thorium impurities breed $^{233}$U—a proliferation concern.
- Standards exist to ensure that feed materials for fuel fabrication meet industry requirements, are nuclear-grade.
- Uranium ore concentrates (UOCs) and their thorium equivalents (ThOCs) are impure and must be refined:
  - Typical impurity levels far exceed industry requirements.
  - Significant UOC impurities include thorium, uranium daughters, and lanthanide elements.
Actinide Ore Concentrates are Impure

Average elemental concentrations in Australian UOCs as determined by multiple analytical methods.

ASTM standard C 753-04.
Chemical Conversion of Nuclear Material

- Encompasses those processes used to transform actinide ore concentrate or nuclear material into feed material for
  - Isotopic separation or enrichment
  - Fuel fabrication

- Processes affect purity and/or chemical form of a nuclear material—its isotopic composition remains unchanged
Conversion Processes

- Conversion processes (and facilities) may be classified according to the isotopic composition of the processed, or feed, material
  - Conversion 1 operations involve processing material at natural isotopic composition
    - Feed material is natural UOC or ThOC
    - Typical products are uranium tetrafluoride (UF₄), uranium hexafluoride (UF₆), and metallic and oxide forms of U and Th
    - Incorporation of criticality-safe design elements less important
  - Conversion 2 operations involve processing material at enriched isotopic compositions
    - Feed material is enriched U or UF₆, or reprocessed Pu
    - Typical products are carbide, metallic, nitride, and oxide forms of U and Pu
    - Incorporation of criticality-safe design elements is important

- Conversion processes are a combination of unit operations
## Operational Conversion 1 Facilities

<table>
<thead>
<tr>
<th>Country</th>
<th>Facility Name</th>
<th>Principal Owner</th>
<th>Process(es)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>Pilcaniyeu Conversion Facility</td>
<td>Comisión Nacional de Energía Atómica (CNEA)</td>
<td>Conversion to UF$_6$</td>
</tr>
<tr>
<td>Argentina</td>
<td>Cordoba Conversion Facility</td>
<td>Dioxitek SA/CNEA</td>
<td>Conversion to UO$_2$</td>
</tr>
<tr>
<td>Brazil</td>
<td>Fábrica de Combustivel Nuclear</td>
<td>Indústrias Nucleares do Brasil</td>
<td>Conversion to UO$_2$</td>
</tr>
<tr>
<td>Canada</td>
<td>Blind River Refinery</td>
<td>Cameco</td>
<td>Conversion to UO$_3$</td>
</tr>
<tr>
<td>Canada</td>
<td>Port Hope Conversion Facility</td>
<td>Cameco</td>
<td>Conversion to U metal, UF$_6$, and UO$_2$</td>
</tr>
<tr>
<td>China</td>
<td>Lanzhou Nuclear Fuel Complex</td>
<td>China National Nuclear Corporation</td>
<td>Conversion to UF$_6$</td>
</tr>
<tr>
<td>France</td>
<td>Comurhex Malvési</td>
<td>Comurhex</td>
<td>Conversion to UF$_4$</td>
</tr>
<tr>
<td>France</td>
<td>Areva NC W Plant</td>
<td>Cogema</td>
<td>Reconversion to U$_3$O$_8$ (depleted U)</td>
</tr>
<tr>
<td>France</td>
<td>Comurhex Pierrelatte</td>
<td>Comurhex</td>
<td>Conversion to UF$_6$</td>
</tr>
<tr>
<td>India</td>
<td>NFC–Hyderabad (UOP)- Block A</td>
<td>Department of Atomic Energy</td>
<td>Conversion to UO$_2$</td>
</tr>
<tr>
<td>Pakistan</td>
<td>Islamabad</td>
<td>Pakistan’s Ministry of Defense</td>
<td>Conversion to UO$_2$</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>Angarsk</td>
<td>MINATOM</td>
<td>Conversion to UF$_6$</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>Chepetski Machine Plant</td>
<td>JSC TVEL</td>
<td>Conversion to U metal, UF$_4$, and UO$_2$</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>Ekaterinburg (Sverdlovsk-44)</td>
<td>MINATOM</td>
<td>Conversion to UF$_6$</td>
</tr>
<tr>
<td>Turkey*</td>
<td>CNRC Nuclear FPP–Conversion</td>
<td>Turkish Atomic Energy Authority</td>
<td>Conversion to UO$_2$</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>Springfields</td>
<td>Nuclear Decommissioning Authority</td>
<td>Conversion to U metal, UF$_4$, UF$_6$, and UO$_2$</td>
</tr>
<tr>
<td>United States</td>
<td>Metropolis Works Plant</td>
<td>Allied-Signal and Sequoyah Fuel</td>
<td>Conversion to UF$_6$</td>
</tr>
</tbody>
</table>
Facilities with Conversion 2 Operations

- Conversion 2 operations may exist at multiple types of facilities classified by the IAEA as
  - Natural and Low-Enriched (LEU) Conversion and Fabrication Plants
  - Fabrication Plants Handling Direct-Use Material
  - Reprocessing Plants

- Examples include

<table>
<thead>
<tr>
<th>Country</th>
<th>Facility Name</th>
<th>Principal Owner</th>
<th>Process(es)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil</td>
<td>Fábrica de Combustivel Nuclear</td>
<td>Indústrias Nucleares do Brasil</td>
<td>Conversion of enriched UF₆ to UO₂</td>
</tr>
<tr>
<td>France</td>
<td>FBFC–Romans Facility</td>
<td>Cogema</td>
<td>Conversion of enriched UF₆ to UO₂</td>
</tr>
<tr>
<td>India</td>
<td>Coral (Kalpakkam Atomic Reprocessing Plant)</td>
<td>Department of Atomic Energy</td>
<td>Conversion of reprocessed Pu and U to PuO₂ and UO₂</td>
</tr>
<tr>
<td>Japan</td>
<td>Mitsubishi Nuclear Fuel Ltd.</td>
<td>Mitsubishi Heavy Industries Ltd., Mitsubishi Materials Corporation</td>
<td>Conversion of enriched UF₆ to UO₂</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>Machine Building Plant (Elektrosol)</td>
<td>JSC TVEL</td>
<td>Conversion of enriched UF₆ to UO₂</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>Mayak MOX Fuel Production Facilities</td>
<td>MINATOM</td>
<td>Conversion of weapons-grade Pu to PuO₂</td>
</tr>
</tbody>
</table>
Unit Operations

• Similar unit operations are used in Conversion 1 and 2 processes
  – Receipt of feed material
  – Dissolution
  – Filtration
  – Purification
  – Concentration by evaporation
  – Precipitation
  – Denitration
  – Reduction
  – Hydrolysis
  – Hydrofluorination
  – Fluorination
  – Distillation
  – Metal reduction
  – Direct oxide reduction
  – Electrolytic reduction
  – Calcination

• The conversion of UOC to UF$_6$ via the wet fluoride process is the most common process
Wet Fluoride Process: Unit Operations

- UOC receipt
- Dissolution
- Filtration
- Purification
- Concentration by evaporation or precipitation
- Denitration
- Reduction
- Hydrofluorination
- Fluorination

A wet process was used in conversion of UOC to UF₆ at Springfields Fuels Limited’s Springfields facility, United Kingdom.
Safeguards for Uranium Mines and Mills?


- The authors of the report
  - Regarded uranium mining and mineral processing (milling) as intrinsically dangerous
  - Proposed that an international Atomic Development Authority be solely responsible for uranium and thorium exploration, mining, milling, and distribution

- Controlling the fate of uranium and/or thorium *could* prevent a State from establishing a nuclear weapons program.
Starting Point of IAEA Safeguards

• The **starting point of IAEA safeguards** is defined in the model Comprehensive Safeguards Agreement (INFIRC/153 (Corrected))
  – Point in a nuclear fuel cycle at which full safeguards requirements specified in comprehensive safeguards agreements start to apply to nuclear material
  – Para. 33 excludes material in mining or ore processing activities from full scope safeguards
  – Under para. 34(c), the application of full safeguards requirements 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 a State*

• **Traditional interpretation:** *de facto* starting point of safeguards is at the product stage of a uranium conversion plant
Starting Point of Safeguards: Further Clarification

- Model Additional Protocol (INFCIRC 540)
  - Requires declarations regarding the “location, operational status, and the estimated annual production capacity of uranium mines and concentration plants.” (Art 2.a(v))
  - Requires party States to grant Complementary Access to the IAEA (Art 4.a(i))

- IAEA Policy Paper (PP) 18, 2003, revised 2009
  - Reaction to discovery of undeclared conversion activities in Iran
  - Effectively moved the starting point of IAEA safeguards from the product stage of a uranium conversion facility to the first point in the conversion process where highly pure uranium solutions are present
  - Required States to provide design information on entire plant for Design Information Verification (DIV) on an ongoing basis

Starting Point of Safeguards: Further Clarification, continued

• IAEA PP 21, 2013
  – Reaction to several events
  – Clarifies the definition of “nuclear material” to include any purified uranyl nitrate (UN) solution or UOC that meets the purity specification in ASTM C 753-04, the internationally recognized commercial standard for nuclear grade, sinterable uranium dioxide (UO₂); also included are any natural uranium metal, uranium alloy, UF₆, UF₄, UC₃, UCl₄, UO₂, U₃O₈, or UO₃ regardless of purity
  – Effectively moves the starting point of safeguards to the product stage at some uranium mills
  – Likely intended to cover States that do not have an Additional Protocol in force (Brazil and Argentina, for example)

## Starting Point of IAEA Safeguards, continued

### Table 1. Reference NUCP process/Possible starting point of safeguards

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Feed</th>
<th>Intermediate</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UOC, Scrap</td>
<td>Uranyl nitrate</td>
<td>Ammonium diuranate, UO₃, UO₂, UF₄, UF₆</td>
</tr>
<tr>
<td>Accountability unit</td>
<td>1 drum</td>
<td>In process</td>
<td>1 drum (UO₂)</td>
</tr>
<tr>
<td>Chemical/Physical form</td>
<td>Solid</td>
<td>Liquid/Slurry</td>
<td>1 cylinder (UF₆)</td>
</tr>
<tr>
<td>Batch size</td>
<td>1 drum=approx. 300 Kg</td>
<td>-</td>
<td>1 drum: approx. 325 Kg</td>
</tr>
</tbody>
</table>

![Diagram](image)

**Process description**
- UOC, Scrap
- Purification/Evaporation
- Reduction/Stabilization
- Conditioning/Blending
- Hydro-fluorination
- UO₂
- UF₆

**Note:** UOC feeding may be a possible starting point of safeguards under the revised policy assuming no practical accountability point between feeding and purification process, while storage areas for UO₂ drum and UF₆ cylinder were the starting points of safeguards under traditional practice.

**Reference process stages and a possible starting point for full safeguards at a Conversion 1 facility.**

Safeguards Challenges: Logistical

• Uranium mining and milling practices are not standardized, and the scale of operations and ore grade vary significantly
  – Compare ore at McArthur River (~16.6% U) to that of a typical mine (0.05–0.5% U)
  – Complicates safeguards efforts
  – Verification activities might need to be customized

• The uranium mining industry is highly consolidated, with multi-national corporations operating in locations worldwide
  – Consequence of mergers, takeovers, and closures in the 1990s
  – Five companies produced ~73% of the mined uranium in 2009
  – Safeguarding mines and mills might require a State-level approach

<table>
<thead>
<tr>
<th>Company (?-?)</th>
<th>Principal Ownership</th>
<th>Tonnes U</th>
<th>%</th>
<th>Major Mining and Milling Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kazatampro (?-?)</td>
<td>Kazakh (wholly owned)</td>
<td>12,986</td>
<td>21</td>
<td>Budenovskoye 2, ULBA Metallurgical Plant (Kazakhstan)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7,467</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Cameco (?-?)</td>
<td>Canadian</td>
<td>10,438</td>
<td>17</td>
<td>McArthur River, Key Lake (Canada)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8,000</td>
<td>16</td>
<td>Crow Butte, Smith Ranch–Highland (US)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Inkai (as JV, Kazakhstan)</td>
</tr>
<tr>
<td>Areva (?-?)</td>
<td>French</td>
<td>8,176</td>
<td>13</td>
<td>Totkuduk (as Katco JV, Kazakhstan)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8,623</td>
<td>17</td>
<td>SOMAIR (as Areva NC Niger, Niger)</td>
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<tr>
<td>ARMZ- Uranium One (?-?)</td>
<td>Russian (wholly owned)</td>
<td>7,913</td>
<td>13</td>
<td>Priargunsky, Khiagda (Russia)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4,624</td>
<td>9</td>
<td>Zarechnoe (as JV Zarechnoe, Kazakhstan)</td>
</tr>
</tbody>
</table>

**Source:** World Nuclear Association

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**Joint ventures in blue**

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Implementing Safeguards at Uranium Mines

- Safeguards on uranium mines could serve three objectives
  - Establish a certified physical inventory of uranium
  - Verify the non-diversion of uranium source materials from declared uranium mines
  - Verify the absence of undeclared uranium mining

- Establishing a certified physical inventory of uranium
  - Uranium minerals may be heterogeneously distributed, and grade may vary throughout an orebody
  - Some low-grade uranium source materials may challenge the accuracy of current non-destructive analysis methods
  - Milling processes may be inefficient—a mine producing 1,000 MT of yellowcake typically extracts more than 1,000,000 t of ore

Implementing Safeguards at Uranium Mines

- Verifying the non-diversion of uranium source materials from declared uranium mines
  - Mining sites are vast and non-ideal for containment/surveillance measures
  - Definition of material balance areas (MBAs) would be critical, yet challenging
  - Might require an on-site, full-time inspection team

- Verifying the absence of undeclared uranium mining
  - Finding clandestine surface and underground mines might be possible using satellite imagery, ISL mining might be more difficult to detect
  - Detecting clandestine by-product mines would be most challenging

IAEA Inspectors in the Field

Complementary Access Activities at Olympic Dam, Australia. 

An IAEA Inspector Prepares to Take a UOC Sample. The activity was part of a training exercise conducted at the mineral processing facility associated with the Dolni Rozinka uranium mine in the Czech Republic. 
IAEA Safeguards at Conversion Facilities

- In 2015, 1286 facilities and MBA locations outside of facilities were under IAEA safeguards
  - 18 classified as Conversion Plants
  - 44 classified as Fuel Fabrication Plants, 10 as Reprocessing Plants
- Some Conversion facilities and operations are not safeguarded by the IAEA, and those which are include pilot or experimental facilities and operations
- Conversion facilities are regulated by each State, with material protection, control, and accounting (MPC&A) monitored by a State System of Accounting and Control (SSAC)
IAEA Safeguards at Conversion Facilities, Continued

- Safeguards approaches for conversion facilities include
  - Methods and equipment for independent verification of the flows of declared materials into and out of the facilities
    - Process monitoring equipment
    - Review of SSAC and facility MPC&A records
  - Methods and equipment for independent verification of the inventories of materials within the facilities
    - Containment and surveillance measures
    - Annual physical and interim inventory verifications
    - Short notice or unannounced inspections

- The definition of Key Measurement Points (KMPs) is critical
### Proposed flow and inventory key measurement points (KMPs) at a Conversion 1 facility.


<table>
<thead>
<tr>
<th>KMPs</th>
<th>Measurement Points</th>
<th>Description</th>
<th>Chemical form</th>
<th>Container</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible flow KMPs</td>
<td>1</td>
<td>Feeding of UOC or scrap into the process</td>
<td>UOC/Various</td>
<td>Drum</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Receipt of scrap</td>
<td>Various</td>
<td>Drum</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Transfer of UO₂ or UF₆ batches</td>
<td>UO₂ or UF₆</td>
<td>Drum/Cylinder</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Transfer or discarding of waste</td>
<td>Various</td>
<td>Drum</td>
</tr>
<tr>
<td>Possible inventory KMPs</td>
<td>A</td>
<td>Storage of scrap and intermediate compounds</td>
<td>Various</td>
<td>Drum</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Conversion process area</td>
<td>Various</td>
<td>Various</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Storage of UO₂ or UF₆</td>
<td>UO₂ or UF₆</td>
<td>Drum/Cylinder</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>Storage of waste</td>
<td>Various</td>
<td>Drum</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>Sample in laboratory</td>
<td>Various</td>
<td>Various</td>
</tr>
</tbody>
</table>
Conclusions

• Vast recoverable uranium resources are known and spread throughout the world

• Chemical conversion processes are used to transform actinide ore concentrate or nuclear material into forms suitable for
  – Isotopic separation or enrichment
  – Fuel fabrication

• Processes affect purity and/or chemical form of a nuclear material—its isotopic composition remains unchanged

• A small number of unit operations are combined in a wide variety of chemical conversion processes
Conclusions, continued

- Conversion 1 processes have traditionally constituted the starting point of IAEA safeguards.
- Some conversion facilities and operations are not safeguarded by the IAEA, and those which are include pilot or experimental facilities and operations.
- The application of verifiable safeguards to uranium mines and mills is complicated by a number of factors.
Safeguarding the Nuclear Fuel Cycle

Supplementary Material

Heather Hawkins Erpenbeck, NEN-1
Mineral Resources and Reserves

- A mineral resource may contain a mineral reserve
- Mineral resource: concentration of a mineral in such form and amount that economic extraction of a commodity is currently or potentially feasible
- Mineral reserve: the portion of a mineral resource that can be economically mined at the time of determination
  - Proved to contain sufficient tonnage of amenable valuable material to justify the mining enterprise
  - Quantity and grade established with reasonable assurance by a responsible, qualified professional
- Mineral resources and reserves are reported separately

Source: Dictionary.InfoMine.com
Surface Mining

• Most suitable for shallow orebodies and deposits that are
  – Large volume or low-grade
  – Contiguous
  – Horizontally oriented

• Large wide pit dug to reach orebody

• Ore mined from pit bottom and hauled by road up sides
  – Bulldozers and shovel loaders load ore
  – Dump trucks remove ore from open pit

A. Ranger Open Pit Uranium Mine, Northern Territory, Australia. In 2009, Ranger was the top-producing open pit uranium mine (4,444 tU). In 2016, Ranger’s production declined (1,994 tU).

B. Rössing Open Pit Uranium Mine, Namibia. In 2009, Rössing was the second largest-producing open pit uranium mine (3,520 tU). Its production declined in 2016 (1,569 tU).

Sources: World Nuclear Association; mining-technology.com
**Underground Mining**

- Most suitable for orebodies far from the surface and deposits that are
  - High-grade
  - Fragmented
  - Vertically oriented or narrow

- Ore mined below ground and hauled through shafts or declines to surface
  - Horizontal passage from a slope to the depth of the mountain (adit)
  - Vertical passage to the working depth of the mine

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**A. Rabbit Lake Operation, Northern Saskatchewan, Canada.** Access to the Eagle Point underground mine is through an adit, a slope that winds down to the many levels of the mine.

**B. Remote Control Scoop Tram at the Eagle Point Underground Mine, Rabbit Lake Operation.** In 2009, Eagle Point was Canada’s second largest-producing mine (1,447 tU), but production was suspended in 2016. It was North America’s longest producing uranium mine.

*Sources:* World Nuclear Association; Cameco (http://www.cameco.com/media/images/operations_photos/)
Underground Mines

- Mine architecture not apparent from surface
- Characteristic features include
  - Facilities and equipment for hauling ore (hoist and/or headframe; conveyer belts)
  - Ventilating fans
  - Drainage ponds
  - Ore processing facilities (mills)
  - Piles of waste rock (tailings piles)

Head Frame, McArthur River, Northern Saskatchewan, Canada.
Source: Cameco
http://cameco.com/media/images/operations_photos/
Solution Extraction: Heap Leaching

- A less efficient alternative to milling
  - Approximately 70% of the total uranium is extracted from the ore

- Most suitable for orebodies and deposits that are
  - Low-grade
  - Uranium oxides

- Crushed ore is placed on top of an impermeable pad (thick plastic) supported by clay, silt, or sand, then sprayed with a process solution. The process solution filters through the heap and dissolves the uranium from the ore.
  - Process solution (usually sulfuric acid) is sprayed on the ore for 30–90 days
  - Pregnant solution is collected in pools and then pumped to a mineral processing facility or mill for further processing
Heap Leaching Operations

The Caetité Uranium Mine and Mill, Near Caetité, Bahia, Brazil (A), are operated by Indústrias Nucleares Do Brasil (INB). Uranium oxide ore (~ 0.25% U) from the open pit mine (B) is processed using the heap leaching method. The site produced 400 tons of uranium oxide concentrate in 2009.
Sources: INB and IAEA.org
By-Product Recovery

- Most suitable for
  - Multi-mineral orebodies that contain attractive material commodities (copper, gold, silver)
  - Markets in which demand for and price of uranium are high
  - Tailings of sufficient grade

- May be associated with surface or underground mining operations

A. Olympic Dam Underground Mine, Australia. Olympic Dam is a multi-mineral orebody said to be the world’s fourth largest remaining copper deposit; its fifth largest gold deposit; and its largest uranium deposit. The orebody has been mined using underground mining methods.

B. Projection of the Proposed Expansion of Olympic Dam at 20 years. The expansion plan includes an open pit mine and ore processing facilities to increase ore production six-fold.

Sources: bhpbilliton.com; abc.net.au
Mine Waste Solutions Tailings Recovery Operation, Witwatersrand Basin, South Africa. Mine Waste Solutions (MWS) is a gold and uranium tailings recovery operation that consists of 14 tailings deposits from three gold and uranium mines that operated for 50 years. When the operation is fully commissioned, MWS will use high-pressure water canons and a pressure leaching process to extract gold and uranium from the tailings. The total measured and indicated uranium resources are reported at ~22,455 tU.

Source: First Uranium
Wet and Dry Processes

- Conversion processes are described as either *wet* or *dry*

  - **Wet** processes involve
    - Dissolution of feed material followed by purification of resultant solutions
    - Precipitation or denitrification of intermediate products from purified solutions
    - Exposure of intermediate products to controlled environments

  - **Dry** processes involve
    - Exposure of feed material to high temperatures and/or pressures and/or controlled environments
    - Purification of intermediate products
Conversion of UOC to UF₆

- Highest tonnage conversion process used today
- Process flow sheet is often complicated, with multiple stages and several intermediate compounds
- Final product is nuclear-grade UF₆—feed for isotopic enrichment processes or for production of high-purity UO₂

A wet process is used in the two-stage conversion of UOC to UF₆ at Comurhex’s Malvézi and Pierrelatte facilities. These two Conversion 1 facilities are operated by Areva.
Conversion of UOC to UF₆, Continued

- Two general chemical routes to UF₆: *wet fluoride* and *dry fluoride*
  - *Wet fluoride*: solvent extraction is used to purify a solution that is chemically converted to UF₆
  - *Dry fluoride*: a distillation process is used to purify UF₆ following chemical conversion

- All established routes require elemental fluorine for the conversion of UF₄, a process intermediate, to UF₆
  - Production of UF₆ consumes the majority of fluorine gas (F₂) produced each year
  - Specialized equipment is required to process and store fluorine-containing gases and compounds
  - Fluorine gas may be generated on-site by electrolysis of hydrofluoric acid (HF) in a fused salt of potassium bifluoride (HF₂K)
Fluorine Use at Conversion 1 Facilities

Fluorine use at the Port Hope Conversion Facility, Port Hope, Canada.
Source: Cameco
http://www.cameco.com/media/images/operations_photos/

Anhydrous hydrogen fluoride gas cylinder at the Metropolis Works Plant, Metropolis, Illinois.
UOC Receipt

- UOC received in 200-liter drums, typically 400–500 kg/drum
  - Drums are check-weighed, and UOC sampled
  - UOC samples are analyzed for uranium and impurities, both soluble and insoluble

- UOC removed from drums by tipping into feed hoppers, or via pneumatic/vacuum transfer

A. UOC from Cameco’s Rabbit Lake operation, Northern Saskatchewan, Canada.
   Source: Cameco
   http://www.cameco.com/media/images/operations_photos/
B. UOC samples taken at a Conversion 1 facility.
Dissolution

- UOC dissolved in concentrated nitric acid (HNO₃) at $T = 70$–$90^\circ C$ for $t = 2$–$12$ h, resulting in a uranyl nitrate or UN (UO₂(NO₃)₂) slurry
  - Typical dissolution reactions:
    \[
    \begin{align*}
    U_3O_8 + 8HNO_3 & \rightarrow 3UO_2(NO_3)_2 + 2NO_2 + 4H_2O \\
    (NH_4)_2U_2O_7 + 6HNO_3 & \rightarrow 2UO_2(NO_3)_2 + 2NH_4NO_3 + 3H_2O
    \end{align*}
    \]
- Dissolution process may be either batch or continuous, but requires agitation in either case
- Process equipment includes dissolution vessels and controllers for temperature, flow, conductivity, and pH
Filtration and Purification

- UN slurry is cooled, then filtered
  - Produces a filter cake that is washed with water
  - Filtered solution concentrated to ~300 g U/liter
  - Process equipment includes rotary vacuum, continuous flatbed, and/or batch vacuum filters

- Solvent extraction is commonly used to purify the UN solution
  - Tri-\textit{n}-butyl phosphate in kerosene are typical extractant and diluent, respectively
  - Purified solution diluted to ~100–150 g U/liter
  - Process equipment includes mixer–settler boxes
Concentration by Evaporation or Precipitation

- Purified UN solution may be
  - Evaporated
  - Reacted with ammonia to precipitate ammonium diuranate or ADU ((NH₄)₂(U₂O₇)

- Evaporation process may be either batch or continuous
  - Solution concentrated to ~1100 g U/liter (super saturated) in the form of uranyl nitrate hexahydrate (UO₂(NO₃)₂·6H₂O)
  - Solution must be heated and/or agitated to prevent solidification
  - Process equipment includes simple boilers and/or multi-effect evaporators

- Precipitation process
  - Ammonia added to precipitate ADU
  - Resulting slurry is filtered to produce ADU cake
  - ADU cake is dried, then calcined at ~400°C to produce uranium trioxide (UO₃)
  - Process equipment includes batch vacuum filters and driers
Denitration and Reduction

- Concentrated UN solution is denitrated to produce $\text{UO}_3$
  - Reaction liberates $\text{H}_2\text{O}$ and $\text{NO}_x$
  - Product may be hydrated under controlled conditions to increase its reactivity

- Uranium trioxide from either route is reduced to the dioxide ($\text{UO}_2$)
  - Reaction requires $\text{H}_2$ or cracked ammonia and high temperatures ($T = 550–600^\circ\text{C}$)

$$\text{UO}_3 + \text{H}_2 \rightarrow \text{UO}_2 + \text{H}_2\text{O}$$

- Process equipment includes rotary reduction kilns or fluidized bed reactors

Notional cartoon of a fluidized bed reactor.
http://www.flsmith.com/en-us/Products/Product+Index/All+Products/Pyroprocessing/FluidBedSystems/FluidBedSystems
Hydrofluorination

- UO₂ is converted to UF₄, also known as green salt, using anhydrous, concentrated, or dilute HF at \( T = 350-450^\circ C \)

\[
\text{UO}_2 + 4\text{HF} \rightarrow \text{UF}_4 + 2\text{H}_2\text{O}
\]

- Reaction rate and conversion efficiency increase with decreasing water content
- Process equipment includes rotary reduction kilns and fluidized bed reactors constructed of Inconel and Monel, corrosion-resistant nickel-based alloys; off-gas scrubbers; and condensers

Green salt produced at the Chepetsky Mechanical Plant in the Udmurt Republic, Russia.
Source: JSP CMP
http://www.chmz.net/site2/product/u/2.jpg
**Fluorination**

- **UF₄** is fluorinated by contact with F₂ gas at high temperature ($T \sim 450^\circ C$ for fluidized bed, $T \sim 130^\circ C$ for flame reactor)

  \[ \text{UF}_4 + \text{F}_2 \rightarrow \text{UF}_6 \]

  - Other fluorinating agents may be used, but are less common
  - Process equipment includes fluidized bed or flame reactors

- **UF₆** may be produced through more direct routes, but cost of F₂ gas prohibits large-scale production

  \[ 2\text{UO}_3 + 6\text{F}_2 \rightarrow 2\text{UF}_6 + 3\text{O}_2 \]
  \[ \text{UO}_2 + 3\text{F}_2 \rightarrow \text{UF}_6 + \text{O}_2 \]

- Purified UF₆ is stored in solid form in sealed pressure vessels
URANIUM HEXAFLUORIDE SPECIFICATIONS

The following specifications apply to uranium hexafluoride produced from natural (non-irradiated) uranium:

<table>
<thead>
<tr>
<th>Item</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum vapor pressure of filled container at 200°F in pounds per square inch, absolute</td>
<td>75</td>
</tr>
<tr>
<td>Minimum weight percent of UF₆ in material</td>
<td>99.5</td>
</tr>
<tr>
<td>Maximum mol percent of hydrocarbons, chlorocarbons, and partially substituted halohydrocarbons</td>
<td>0.01</td>
</tr>
<tr>
<td>Maximum number of parts of elements indicated per million parts of total uranium:</td>
<td></td>
</tr>
<tr>
<td>Antimony</td>
<td>1</td>
</tr>
<tr>
<td>Arsenic</td>
<td>3</td>
</tr>
<tr>
<td>Boron</td>
<td>1</td>
</tr>
<tr>
<td>Bromine</td>
<td>5</td>
</tr>
<tr>
<td>Chlorine</td>
<td>100</td>
</tr>
<tr>
<td>Chromium</td>
<td>10</td>
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<tr>
<td>Molybdenum</td>
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<tr>
<td>Niobium</td>
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<tr>
<td>Phosphorus</td>
<td>50</td>
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<td>Ruthenium</td>
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<tr>
<td>Silicon</td>
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<tr>
<td>Tungsten</td>
<td>1.4</td>
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<tr>
<td>Vanadium</td>
<td>1.4</td>
</tr>
<tr>
<td>Uranium-236</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Maximum total number of parts of the following listed elements forming nonvolatile fluorides having a vapor pressure of one atmosphere or less at 572°F per million parts of total uranium: 300

(aluminum, barium, beryllium, bismuth, cadmium, calcium, chromium, copper, iron, lead, lithium, magnesium, manganese, nickel, potassium, silver, sodium, strontium, thorium, tin, zinc, and zirconium.)

(Reviewed June 2001, complies with ASTM G787-03)
State-Initiated Safeguards Efforts

- Kazakhstan, the top uranium producer and exporter, complies with the requirements of its Comprehensive Safeguards Agreement (CSA) with the IAEA, and its Additional Protocol (AP)
- Australia, Canada, and the US have more restrictive safeguards policies for exports of mined uranium
- A high level of confusion persists among uranium producers and IAEA Member States concerning the language within PP 21 and its applicability