Assessing uranium resources availability to 2060

Harikrishnan ‘Hari’ Tulsidas
Division of Nuclear Fuel Cycle & Waste Technology
Contributors

• Christine Atkinson, USA
• Jean Rene Blaise, France
• Thomas Pool, USA
• Douglas Underhill, USA
• Robert Vance, NEA
• Kimberly Warthan, USA
• Harikrishnan Tulsidas, IAEA
Outline

- Background
- Uranium Requirements
  - Reactor Requirements
  - Inventory Accumulation
- Uranium Supply
  - Secondary Supply
  - Primary mineral inventory
    - Resource classification
    - Uranium resources
    - Markets
    - Unconventional resources
  - Primary Production
- Supply – Demand Balance
- Conclusions
Uranium requirements

- Available Projections – Installed Capacity
  - World Nuclear Association – 2011
    - 2005 to 2030
  - International Energy Agency – 2011
    - 2010 to 2035
  - U. S. Energy Information Administration – 2011
    - 2008 to 2035
  - International Atomic Energy Agency – 2011
    - 2010 to 2050
Projected nuclear capacity

- **Installed Nuclear Generating Capacity – IAEA – 2011 (GWe)**

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
<th>2060</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>375</td>
<td>525</td>
<td>746</td>
<td>1228</td>
<td>1469</td>
</tr>
<tr>
<td>Mean</td>
<td>375</td>
<td>482</td>
<td>624</td>
<td>894</td>
<td>1029</td>
</tr>
<tr>
<td>Low</td>
<td>375</td>
<td>439</td>
<td>501</td>
<td>560</td>
<td>589</td>
</tr>
</tbody>
</table>
Determining “Fuel Intensity”

- Average of calculations from WNA “Global Nuclear Fuel Market” and NEA/EIA “Uranium 2009: Resources, Production and Demand”.
- High Case = 180 tU per year per GWe
- Mean Case = 177.3 tU per year per GWe
- Low Case = 171 tU per year per Gwe
- High & mean cases are higher due to more initial cores.
Projected Long-Term Uranium Requirements (tU)

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2060</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>67,500</td>
<td>94,500</td>
<td>134,280</td>
<td>177,660</td>
<td>221,040</td>
<td>264,420</td>
<td>8,100,360</td>
</tr>
<tr>
<td>Mean</td>
<td>66,488</td>
<td>85,459</td>
<td>110,635</td>
<td>134,571</td>
<td>158,506</td>
<td>182,442</td>
<td>6,260,084</td>
</tr>
<tr>
<td>Low</td>
<td>64,125</td>
<td>75,069</td>
<td>85,671</td>
<td>90,801</td>
<td>95,760</td>
<td>100,719</td>
<td>4,379,652</td>
</tr>
</tbody>
</table>
Commercial Inventory Accumulation

- **Utilities:** 2.0 years forward requirements
- **Producers:** 0.5 years forward supply
- **Brokers/Traders/Investors:** 10% of annual requirements
Commercial Inventories

- IAEA

- Low
- Mean
- High

- 2010
- 2020
- 2030
- 2040
- 2050
- 2060

- tU

- 0
- 100 000
- 200 000
- 300 000
- 400 000
- 500 000
- 600 000
- 700 000
## Secondary Supply

1. Highly enriched uranium (HEU)
2. Reprocessed uranium (RepU) from spent nuclear fuel
3. Plutonium for mixed oxide fuel (MOX)
4. Depleted uranium in the form of enrichment tails (DU) and underfeeding
5. Government holdings of natural (NU) and low enriched uranium (LEU)
Secondary supply

![Graph showing secondary supply](image_url)
Primary production requirements

- Reactor requirements
- Inventory accumulation
- Secondary supplies
- Primary production requirements
Primary production requirements

tU per year

2010 2020 2030 2040 2050 2060

Low Mean High
Cumulative production requirements

![Cumulative production requirements graph](image)
International resource classifications

Committee for Mineral Reserves International Report (CRIRSCO)

United Nations Framework Classification (UNFC-2009)

Exploration results
Mineral resources
- Inferred
- Indicated
- Measured
- Proved

Mineral reserves
- Probable

Consideration of mining, processing, infrastructure, metallurgical, economic, marketing, legal, environmental, social and governmental factors (the "modifying factors")

Increasing level of geological knowledge and confidence
### NEA-IAEA Classification Scheme

<table>
<thead>
<tr>
<th>Recoverable at costs</th>
<th>IDENTIFIED RESOURCES</th>
<th>UNDISCOVERED RESOURCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>USD 40-80/KgU</td>
<td>Reasonably Assured Resources</td>
<td>Inferred Resources</td>
</tr>
<tr>
<td>USD 80-130/KgU</td>
<td>Reasonably Assured Resources</td>
<td>Inferred Resources</td>
</tr>
<tr>
<td>USD 130-260/KgU</td>
<td>Reasonably Assured Resources</td>
<td>Inferred Resources</td>
</tr>
</tbody>
</table>

**Decrementing economic attractiveness**: Decreasing confidence in estimates
Resources ‘mapped’

- United Nations Framework Classification (UNFC) used for alignment.
- “Uranium bridging document” under approval.
- Also in alignment with CRIRSCO reporting (Public reporting for companies).

<table>
<thead>
<tr>
<th>UNFC Classes and Sub-classes</th>
<th>UNFC Categories</th>
<th>NEA/IAEA Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Commercial Projects</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>On Production</td>
<td>1.1</td>
<td>Existing</td>
</tr>
<tr>
<td>Approved for Development</td>
<td>1.2</td>
<td>Committed</td>
</tr>
<tr>
<td>Justified for Development</td>
<td>1.3</td>
<td>Planned</td>
</tr>
<tr>
<td><strong>Potentially commercial projects</strong></td>
<td>2 2.1 1.2,3</td>
<td>Identified Resources</td>
</tr>
<tr>
<td>Development Pending</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Development On Hold</td>
<td>2.2</td>
<td>Prospective</td>
</tr>
<tr>
<td><strong>Non-commercial projects</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Development Unclarified</td>
<td>3.1</td>
<td>Unclarified</td>
</tr>
<tr>
<td>Development not Viable</td>
<td>3.2</td>
<td>Not viable</td>
</tr>
<tr>
<td><strong>Exploration projects</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exploration projects</td>
<td>3.2</td>
<td>Prognosticated Resources</td>
</tr>
</tbody>
</table>

*Inferred Resources*
U mining lifecycle and resources

Conceptual Studies

Scoping Studies

Pre-feasibility Studies

Feasibility Studies

Project Implementation

Remediation & Social re-integration

Exploration Project

Quantities in Place

Non-Commercial Project

Potential Commercial Project

Commercial Project

Resources

Reserves

Development Pending

Justified for Development

Approved For Development

On Production

Development Unclarified

Development Not Viable

Development On Hold

Potentially Commercial Project

Exploration Project

Target

Inventory

Exploration Project

3 3 4

3 3 4

3 2 1,2,3

2 2 1,2,3

1 1 1,2,3

Accurate and transparent management of essential materials throughout the lifecycle
## Uranium resources considered

<table>
<thead>
<tr>
<th>Type of Deposit</th>
<th>Resources (tU)</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphate</td>
<td>7,042,191</td>
<td>45.2%</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2,364,768</td>
<td>15.2%</td>
</tr>
<tr>
<td>Polymetallic</td>
<td>1,365,024</td>
<td>8.8%</td>
</tr>
<tr>
<td>Metasomatite</td>
<td>812,413</td>
<td>5.2%</td>
</tr>
<tr>
<td>Unconformity</td>
<td>728,007</td>
<td>4.7%</td>
</tr>
<tr>
<td>Intrusive</td>
<td>691,102</td>
<td>4.4%</td>
</tr>
<tr>
<td>Metamorphite</td>
<td>655,761</td>
<td>4.2%</td>
</tr>
<tr>
<td>Black Shale</td>
<td>530,627</td>
<td>3.4%</td>
</tr>
<tr>
<td>Q-P Conglomerate</td>
<td>389,908</td>
<td>2.5%</td>
</tr>
<tr>
<td>Volcanic related</td>
<td>339,451</td>
<td>2.2%</td>
</tr>
<tr>
<td>Surficial</td>
<td>280,028</td>
<td>1.8%</td>
</tr>
<tr>
<td>Gold Tailings</td>
<td>143,888</td>
<td>0.9%</td>
</tr>
<tr>
<td>Granite related</td>
<td>138,610</td>
<td>0.9%</td>
</tr>
<tr>
<td>Carbonate</td>
<td>50,000</td>
<td>0.3%</td>
</tr>
<tr>
<td>Lignite-Coal</td>
<td>40,000</td>
<td>0.3%</td>
</tr>
<tr>
<td>Collapse breccia pipe</td>
<td>9,154</td>
<td>0.1%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>15,580,932</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>
## Unconventional Uranium Resources

<table>
<thead>
<tr>
<th>Deposit type-subtype</th>
<th>Resources UDEPO (tU)</th>
<th>Grade (ppm)</th>
<th>IAEA UDEPO deposits</th>
<th>World deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porphyry copper</td>
<td>100 000</td>
<td>10-40</td>
<td>7</td>
<td>691</td>
</tr>
<tr>
<td>Peralcaline complexes</td>
<td>393 210</td>
<td>50-250</td>
<td>13</td>
<td>125</td>
</tr>
<tr>
<td>Carbonatites</td>
<td>122 342</td>
<td>30-300</td>
<td>11</td>
<td>848</td>
</tr>
<tr>
<td>IOCG</td>
<td>2 308 602</td>
<td>30-250</td>
<td>14</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Lignite and coal</td>
<td>7 358 112</td>
<td>1-500</td>
<td>33</td>
<td>1600</td>
</tr>
<tr>
<td>Black shale</td>
<td>1 489 147</td>
<td>10-200</td>
<td>44</td>
<td>Several hundred</td>
</tr>
<tr>
<td>Phosphates</td>
<td>13 553 900</td>
<td>50-150</td>
<td>50</td>
<td>1635</td>
</tr>
<tr>
<td>Total</td>
<td>25 325 313</td>
<td></td>
<td>172</td>
<td>5 - 6000</td>
</tr>
<tr>
<td>Sea water</td>
<td>4 500 000 000</td>
<td>3.3 ppb</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Conventional U resources - 7 096 600 tU (The ‘Red Book’ 2011)
Resource distribution by type

<table>
<thead>
<tr>
<th>Average grade (% U)</th>
<th>Resources (tU)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 0.05</td>
<td>10 700 749</td>
<td>68.7</td>
</tr>
<tr>
<td>0.05 – 0.1</td>
<td>1 408 819</td>
<td>9.0</td>
</tr>
<tr>
<td>0.1 – 0.3</td>
<td>2 799 487</td>
<td>18.0</td>
</tr>
<tr>
<td>0.3 – 1.0</td>
<td>249 566</td>
<td>1.6</td>
</tr>
<tr>
<td>&gt; 1.0</td>
<td>422 311</td>
<td>2.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Size of deposit (tU)</th>
<th>Number of deposits</th>
<th>Resources (tU)</th>
<th>% of total resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1 000</td>
<td>36</td>
<td>19 850</td>
<td>0.1</td>
</tr>
<tr>
<td>1 000 – 5 000</td>
<td>112</td>
<td>286 692</td>
<td>1.8</td>
</tr>
<tr>
<td>5 000 – 10 000</td>
<td>82</td>
<td>555 587</td>
<td>3.6</td>
</tr>
<tr>
<td>10 000 – 20 000</td>
<td>56</td>
<td>786 802</td>
<td>5.0</td>
</tr>
<tr>
<td>20 000 – 50 000</td>
<td>57</td>
<td>1 747 994</td>
<td>11.2</td>
</tr>
<tr>
<td>50 000 – 100 000</td>
<td>23</td>
<td>1 563 014</td>
<td>10.0</td>
</tr>
<tr>
<td>&gt;100 000</td>
<td>19</td>
<td>10 620 993</td>
<td>68.2</td>
</tr>
<tr>
<td>Total</td>
<td>385</td>
<td>15 580 932</td>
<td>100.0</td>
</tr>
</tbody>
</table>
## Production methods

<table>
<thead>
<tr>
<th>Mining Method</th>
<th>Resources (tU)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-pit (OP)</td>
<td>10 854 111</td>
<td>69.7</td>
</tr>
<tr>
<td>Underground (UG)</td>
<td>2 840 520</td>
<td>18.8</td>
</tr>
<tr>
<td>Open-pit / Underground (OP / UG)</td>
<td>479 650</td>
<td>3.1</td>
</tr>
<tr>
<td>In situ leaching (ISL)</td>
<td>1 261 686</td>
<td>8.1</td>
</tr>
<tr>
<td>Other (Mine waste, Tailings)</td>
<td>144 965</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>15 580 932</strong></td>
<td><strong>100.00</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resource Type</th>
<th>Resources (tU)</th>
<th>% of U 2060 resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphate</td>
<td>7 042 191</td>
<td>45.2</td>
</tr>
<tr>
<td>Cu, Au, Ag (Olympic Dam)</td>
<td>1 365 024</td>
<td>8.8</td>
</tr>
<tr>
<td>Gold (Quartz pebble cong.)</td>
<td>389 908</td>
<td>2.5</td>
</tr>
<tr>
<td>Other (Rare earths, Cu, Ni, …)</td>
<td>268 591</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>9 065 714</strong></td>
<td><strong>58.2</strong></td>
</tr>
</tbody>
</table>
Production costs

<table>
<thead>
<tr>
<th>Cost category</th>
<th>Resources (tU)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>&lt; US$ 80 / kgU</td>
<td>2 240 217</td>
</tr>
<tr>
<td>M</td>
<td>US$ 80 – 130 / kgU</td>
<td>2 426 156</td>
</tr>
<tr>
<td>MH</td>
<td>US$ 130 – 210 / kgU</td>
<td>8 115 118</td>
</tr>
<tr>
<td>H</td>
<td>US$ 210 – 260 / kgU</td>
<td>1 777 272</td>
</tr>
<tr>
<td>VH</td>
<td>&gt; US$ 260 kgU</td>
<td>1 022 169</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>15 580 932</td>
</tr>
</tbody>
</table>
### Mining capacity

<table>
<thead>
<tr>
<th>Mining capacity (tU/yr)</th>
<th>Number of deposits</th>
<th>Resources (tU)</th>
<th>% of total resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-200</td>
<td>58</td>
<td>267 432</td>
<td>1.7</td>
</tr>
<tr>
<td>200-400</td>
<td>126</td>
<td>963 876</td>
<td>6.2</td>
</tr>
<tr>
<td>400-1 000</td>
<td>101</td>
<td>5 257 905</td>
<td>33.7</td>
</tr>
<tr>
<td>1 000 – 2 000</td>
<td>61</td>
<td>5 068 517</td>
<td>32.5</td>
</tr>
<tr>
<td>2 000 – 4 000 &gt; 4 000</td>
<td>28</td>
<td>1 371 437</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>2 651 765</td>
<td>17.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Project status</th>
<th>Number of production centers</th>
<th>Total mining capacity (tU/yr)</th>
<th>Associated resources (tU)</th>
<th>Average grade (%U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing</td>
<td>78</td>
<td>106 862</td>
<td>2 199 433</td>
<td>0.055</td>
</tr>
<tr>
<td>Planned</td>
<td>60</td>
<td>42 434</td>
<td>1 194 350</td>
<td>0.032</td>
</tr>
<tr>
<td>Prospective</td>
<td>247</td>
<td>150 047</td>
<td>12 187 149</td>
<td>0.015</td>
</tr>
</tbody>
</table>
Remaining resources

![Graph showing remaining resources from 2010 to 2060 with lines for Low, Mean, and High scenarios. The graph shows a downward trend with the Low scenario closest to the y-axis at 0 and the High scenario furthest from the y-axis at 20,000,000 tU.]
Conclusion

- Existing uranium resources will not constrain the use of nuclear power in the next half century.
- However, constraints on nuclear fuel supply may, from time to time, develop in the form of production capability or cost.
- It seems possible that an unforeseen rapid push for more nuclear capacity might require a surge in uranium production that could not be met due regulatory and environmental constraints.
- It is considered very unlikely that any reactor would ever be shut down for a lack of fuel resulting from a shortage of natural uranium.
Thank you