URANIUM IN PHOSPHATE ROCKS AND FUTURE NUCLEAR POWER FLEETS

S. GABRIEL, A. BASCHWITZ, G. MATHONNIERE
sophie.gabriel@cea.fr
CEA, DEN/DANS/I-tésé

Presented by A. MONNET CEA, DEN/DANS/I-tésé
Plan

- Supply of Uranium
  - Sources of information
    - Conventional resources
    - Unconventional resources
      - Seawater
      - Phosphate rocks
  - Very long term demand – Energy scenarios

- Supply and Demand adequacy
  - Exclusive deployment of PWR
  - Possible deployment of FR from 2040
Natural Uranium resources – Information

Global information :
- « The Red Book » (OECD/NEA and IAEA publication)
  - **Conventional**: established history of production (primary product, co-product or important by-product)
  - **Unconventional**: very low grade or minor by-product
    - Seawater
    - Phosphate rocks
  - **Secondary supply**: already extracted

- World Nuclear Association
- Annual report of companies
- Other sources…

Technical publications
<table>
<thead>
<tr>
<th>Recoverable at costs</th>
<th>Identified</th>
<th>Undiscovered</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reasonably Assured</td>
<td>Inferred</td>
</tr>
<tr>
<td>&lt; 40 $/kg U</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>40-80 $/kg U</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>80-130 $/kg U</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>130-260 $/kg U</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Sub total</strong></td>
<td><strong>4.4</strong></td>
<td><strong>2.7</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7.1 MtU</strong></td>
<td></td>
</tr>
</tbody>
</table>

Separate categories reflecting different levels of confidence in the quantities reported.

All resource categories are defined in terms of costs of uranium recovered at the ore processing plant.
Unconventional Uranium resources: Seawater

4,000 MtU at very low grade (3.3 µg/l)...

- Process huge volumes (1,200 tU/yr require at least to process 1 km³/d of water)
  - Active pumping: Energy return <1
  - Strong natural currents
  - Restricted maritime areas

- Extraction technology has been proven on a laboratory scale, but
  - Cost estimates are very high, lot of uncertainties
  - Energy rate of return?
  - Environmental balance?
  - U as a By-product?

...Major technical breakthrough needed
Phosphate rocks reserves + U content $\Rightarrow$ U reserves in phosphates rocks:

<table>
<thead>
<tr>
<th></th>
<th>Phosphate reserve</th>
<th>Uranium reserve</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Voto &amp; Steven (1979)</td>
<td>223 Gt (US)</td>
<td>22 MtU</td>
</tr>
<tr>
<td></td>
<td>293 Gt (Free World)</td>
<td>29 MtU</td>
</tr>
<tr>
<td>Red Book (2009)</td>
<td>-</td>
<td>7.3-7.6 MtU</td>
</tr>
<tr>
<td>USGS (2011)</td>
<td>65 Gt</td>
<td>22 MtU</td>
</tr>
</tbody>
</table>

- Phosphate reserve 65 Gt
- 100 ppm U
- 72% phosphoric acid
- 83.7% recovery
- 3.9 MtU reserve
Unconventional Uranium resources: Phosphate rocks (2/2)

- U from Phosphate: **By-product** or **Primary product**?

**Phosphate production**
- 176 Mt
- (U by-product)
- 100 ppm U
- 72% phosphoric acid
- 83.7% recovery
- **10.6 ktU/yr**
- 100-150 $/kgU

**Uranium production**
- (U primary product)
- Phosphoric acid cost: **257 $/t**
- Specific cost for U recovery: **130 $/kgU**
- 100 ppm U
- 72% phosphoric acid
- 83.7% recovery
- **« No limit capacity »**
- ≈ **3,000 $/kgU**
Limits of available Uranium reserves

- **7 Mt**: Identified conventional uranium resources

- **21 Mt**: 17 Mt of conventional resources
  - (7 Mt of identified + 10 Mt of undiscovered)
  + 4 Mt from phosphate rocks

- **39 Mt**: 17 Mt of conventional resources
  - (7 Mt of identified + 10 Mt of undiscovered)
  + 22 Mt from phosphate rocks (former optimistic estimate)

- **90 Mt**: very optimistic view rather than an evaluation
  (takes into account the hope that mining exploration will find substantial new resources, but is not a geologist point of view)
Forecasting studies on the development of nuclear power
Exclusive deployment of PWRs (1/3)

- Only PWRs can be built.
- When the consumed and engaged U exceed the limit, building a new reactor is impossible.

C2

A3

21 Mt limit

2065

2097

2124

Reactors End of Life

All U engaged
No more construction

All U consumed
No more production
7 Mt: Identified conventional uranium resources
21 Mt: 17 Mt of conventional resources (7 Mt of identified + 10 Mt of undiscovered) + 4 Mt from phosphate rocks
39 Mt: 17 Mt of conventional resources (7 Mt of identified + 10 Mt of undiscovered) + 22 Mt from phosphate rocks
90 Mt: very optimistic view rather than an evaluation
**Exclusive deployment of PWRs (3/3)**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>A3</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 Mt limit</td>
<td>2091</td>
<td>2100</td>
</tr>
<tr>
<td>21 Mt limit</td>
<td>2124</td>
<td>After 2150</td>
</tr>
<tr>
<td>39 Mt limit</td>
<td>2148</td>
<td>After 2150</td>
</tr>
</tbody>
</table>

**Expected date of all U consumed**
(No more PWR production)

**Expected date of all U engaged**
(No more nuclear construction (PWR))

<table>
<thead>
<tr>
<th>Scenario</th>
<th>A3</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 Mt limit</td>
<td>2032</td>
<td>2042</td>
</tr>
<tr>
<td>21 Mt limit</td>
<td>2065</td>
<td>2097</td>
</tr>
<tr>
<td>39 Mt limit</td>
<td>2089</td>
<td>2143</td>
</tr>
</tbody>
</table>

When the limit drops from 39 Mt to 21 Mt, the shortage occurs:

- **25 years earlier**
- **45 years earlier**
FR deployment - Assumptions

- From 2040, building Fast Reactors (FR) will be given a top priority.
  - **Self-sufficient** reactors
  - **Breeder** reactors with a Breeding Gain (BG) of 0.3

- All the spent fuel can be reprocessed

- No geopolitical consideration (the World is a whole unit)

- If there is an insufficient stock of available Pu but still a sufficient supply of U, PWRs are built.

- If both U and Pu are lacking, no reactors will be built.
Possible deployment of FR from 2040 (1/3)

Breeding gain has no effect yet (Time in reactor + time for reprocessing)

Demand not satisfied
All U engaged PU insufficient

Breeding gain allows increase

21 Mt limit

Start of FR

PWR + FR (BG=0.3)

PWR + FR (BG=0)

PWR
Possible deployment of FR from 2040 (1/3)

- A3 - PWR
- A3 - PWR + FR (BG=0)
- A3 - PWR + FR (BG=0.3)

Breeding gain has no effect yet
(Time in reactor + time for reprocessing)

Demand not satisfied
All U engaged Pu insufficient

Breeding gain allows increase

Start of FR

21 Mt limit

Stable installed capacity
Possible deployment of FR from 2040 (2/3)

7 Mt: Identified conventional uranium resources
21 Mt: 17 Mt of conventional resources (7 Mt of identified + 10 Mt of undiscovered) + 4 Mt from phosphate rocks
39 Mt: 17 Mt of conventional resources (7 Mt of identified + 10 Mt of undiscovered) + 22 Mt from phosphate rocks
90 Mt: very optimistic view rather than an evaluation
Possible deployment of FR from 2040 (3/3)

Dates when nuclear power requirements are no longer satisfied

<table>
<thead>
<tr>
<th>U limit</th>
<th>Breeding gain</th>
<th>A3</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 Mt</td>
<td>0</td>
<td>2032</td>
<td>2052</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>2032</td>
<td></td>
</tr>
<tr>
<td>21 Mt</td>
<td>0</td>
<td>2072</td>
<td>2128</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>2075</td>
<td></td>
</tr>
<tr>
<td>39 Mt</td>
<td>0</td>
<td>2102</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>2121</td>
<td></td>
</tr>
</tbody>
</table>

Regardless of the level of resources
- the transition to FRs is necessary
- the FRs should be breeder
Conclusion

A large-scale deployment of nuclear reactors will require more Uranium

U resources are limited and not well known:
- U from Seawater : Major technical breakthrough needed
- U from phosphate rocks : 4 Mt, an upper bound limit

=> Mining exploration is necessary
=> What about the annual production capacity?

If only PWRs are deployed in this century:
- All the U identified resources are engaged before 2050 and consumed before the end of the century

=> The deployment of PWR only is not sustainable in the long term
=> The FR deployment is inescapable for a long term development of nuclear power

But the installation rate of the FR fleet is limited by the Pu availability…