Nuclear Fuel Resource Demand and Supply

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Presentation Outline

• Introduction
  – Sustainability
  – INPRO Methodology

• Fuel Resource Demand
  – Static Demand
  – Projected Demand

• Fuel Resource Supply
  – Physical Supply
  – Economics of Supply

• Summary
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Sustainability

• Basic Concept –
  “The present generation should not compromise the ability of future generations to fulfill their needs.”

• Standard Approach - Limit depletion of non-renewable resources
  – Strict interpretation – Any use of non-renewable resources limits future generations
    • This interpretation is impractical, as it says “do nothing”
  – Lax interpretation – Use of non-renewable resources should be efficient
    • This interpretation says it is allowable to use non-renewable resources, as long as that use is not wasteful
    • This is the approach taken in the INPRO Methodology

• Application –
  – Nuclear Energy Systems consume fuel resources, so must do so efficiently
INPRO Methodology on Resource Depletion

• **Basic principle (Availability of resources):** A nuclear energy system (NES) shall be capable of contributing to the energy needs in the 21st century while making efficient use of non-renewable resources.

• **User Requirement 1 - Consistency with resource availability:** The NES should be able to contribute to the world’s energy needs during the 21st century without running out of fissile/fertile material and other non-renewable materials, with account taken of reasonably expected uses of these materials external to the NES. In addition, the NES should make efficient use of non-renewable resources.
  - Criteria 1.1, 1.2 and 1.3 address having sufficient material/power for 100 years
  - Criteria 1.4, 1.5 and 1.6 address the efficiency of use of U, Th, and other non-renewable resources

• **User Requirement 2 - Adequate net energy output:** The energy output of the NES should exceed the energy required to implement, operate and decommission the NES within an acceptably short period.
  - Criteria 2.1 addresses amortization time for energy return on investment
Sustainability – Another View

• **Basic Concept** –
  “The present generation should not compromise the ability of future generations to fulfill their needs.”

• Dynamic Approach - Develop and deploy technologies that allow future generations to better utilize non-renewable resources
  – If the resources and technologies left to future generations provide them the same or more capability to meet their needs, then they have not been limited

• Application –
  – Improve methods to obtain non-renewable resources
    • Makes more resources available to future generations
  – Improve methods to use non-renewable resources
    • Makes current resources go farther for future generations

• This presentation will address both of these approaches
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• Summary
Current Fuel Resources Utilization

- Current reactors are primarily LWRs with some HWRs, both using U
  - HWRs use ~ 150 t natural U per GWe-a (no enrichment)
  - LWRs use ~ 190 t natural U per GWe-a
- The LWR value can be reduced some by using more SWUs to reduce the U-235 content in the DU
- It also varies with burnup, but the impact is small. The lowest utilization is around 60-70 GWd/tHM (5-6% enrichment)
Potential Future Fuel Resource Utilization

• Several factors can significantly change resource utilization:
  – Higher thermal efficiencies could increase the electrical energy produced per unit of thermal energy by up to 50%.
    • Requires advanced reactors with much higher outlet temperatures, different coolants and different conversion systems
    • Note: The highest thermal efficiencies are projected for HTGRs, which actually can use more U per GWe-a because they require higher enrichments and have significant U-235 left in the spent fuel
  – Use of Th in once-through systems with LWR reactors does not save resources because significant U is needed to drive Th breeding
  – Limited recycle and use of MOX fuel could reduce LWR NU requirements by 10-25%, where the higher number also requires reenrichment of RU.
Potential Future Fuel Resource Utilization

- Breeding using full recycle or “breed and burn” systems can significantly reduce resource requirements
  - 3.3 t U / GWe-a for theoretical breed and burn once-through system (requires advanced cladding)
  - 1.1 t U / GWe-a for full recycle SFR at equilibrium (ignores start-up core) with minimal recycling losses
  - Similar values possible for Th-based full recycle systems (w/o startup core)
Summary of Static Resource Needs (per GWe-a)

• Once-through fuel cycles
  – 200 t U - HTGRs
  – 190 t U - LWRs (Mix of U, Th similar or higher)
  – 150 t U - HWRs
  – As low as 3.3 t U/Th for breed and burn (w/advanced cladding)

• Limited recycle fuel cycles
  – 170 t U – LWR UOX -> LWR MOX (no RU reenrichment)
  – 110 t U – HTGR -> LWR MOX
  – 8 t U/Th - MSR

• Continuous recycle fuel cycles
  – 160 t U – LWR MOX (with external fissile support)
  – 70 t U – HWR MOX
  – 1.1 t U – SFR
  – Th – MSR values similar to SFR
First Conclusions

• **Sustainability challenges** –
  – *Improve methods to obtain non-renewable resources*
    • Makes more resources available to future generations
  – *Improve methods to use non-renewable resources*
    • Makes current resources go farther for future generations

• **Adopting continuous recycle can:**
  – Convert existing depleted U from a waste to a fuel
    • Makes more resources available to future generations
  – Improve the use of U/Th by up to 17,000 % ($190 / 1.1 = 172$)
    • Makes current resources go much farther for future generations
Projected Demand – From GAINS

Global primary energy
IPCC SRES scenarios

Reference – Global primary energy is from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES)

Global nuclear electricity

GAINS Moderate and High Growth Cases

- GAINS split the world into three non-geographic nuclear strategy groups for purposes of heterogeneous analysis of fuel cycle evolution
  - NG1 – Countries involved in development of innovative nuclear systems and ready to deploy them when commercially available
  - NG2 – Countries with significant nuclear energy experience, but not planned to change fuel cycles
  - NG3 – Countries incorporating nuclear energy in the future

<table>
<thead>
<tr>
<th>Nuclear energy strategy groups (NGs)</th>
<th>GW(e)/a</th>
<th></th>
<th></th>
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<td>2030 Moderate</td>
<td>2030 High</td>
<td>2050 Moderate</td>
<td>2050 High</td>
<td>2100 Moderate</td>
<td>2100 High</td>
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<td>NG1</td>
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<td>285</td>
<td>333</td>
<td>455</td>
<td>682</td>
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<td>2000</td>
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<td>285</td>
<td>333</td>
<td>455</td>
<td>682</td>
<td>1000</td>
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<td>34</td>
<td>90</td>
<td>136</td>
<td>500</td>
<td>1000</td>
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<tr>
<td>WORLD TOTAL</td>
<td>298</td>
<td>600</td>
<td>700</td>
<td>1000</td>
<td>1500</td>
<td>2500</td>
<td>5000</td>
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</table>
Transition to a New Fuel Cycle - GAINS

Business as Usual Case
- Continue with LWRs/HWRs
- High growth case
- Reaches 5000 GWe-a by 2100

BAU + FR Case
- Same growth rate
- LWRs replaced by FRs after 2030
- FR growth limited by Pu availability
Uranium Usage – GAINS BAU, BAU-FR Cases

Key Indicator 2 - BAU
- Energy per Natural U mass
- HWRs outperform LWRs
- System average driven by LWRs

Key Indicator 2 – BAU-FR
- Same HWR and LWR performance
- FR performance off the chart
- Systems average improves slowly
Uranium Total Used – GAINS BAU, BAU-FR Cases

**Cumulative Uranium**
- Energy per Natural U mass
- Total U by 2100 ~50 Million t
- Well above known resources

**Cumulative Uranium**
- Same growth rate
- Total U by 2100 ~32 Million t
- Still above known resources

![Cumulative U demand (ktHM) - High case](chart.png)
More Conclusions?

- Transition to a closed fuel cycle may take many decades to accomplish.
- Uranium resource usage during transition may challenge known resources.
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Attribution

• Most of the uranium information in the supply section of this talk came from work by Dr. Erich Schneider (University of Texas at Austin), some funded by the U.S. Department of Energy via subcontracts with the INL.

• All of the thorium information and some of the uranium information in the supply section of this talk came from work under the direction of Dr. Rod Eggert (Colorado School of Mines), funded by the U.S. Department of Energy via subcontracts with the INL.
Will we run out of uranium?

Perception of Imminent Scarcity 1972-1979

Example: 1979 projection of demand in 1994

Uranium Consumption [1000 t/year]; (Pre-1993 Forecasts exclude former East Bloc nations)


OECD Uranium Demand Forecasts - 15 Year Forward Projections

(Year of Forecast Shown in Italics)
History of U Prices & Exploration Expenditures

- **Historical perspective:** the long-term average cost of discovery is ~ $6/kgU. Hence $1B has led on average to discovery of 150,000 tonnes of resources.
Redbook Resources: Historical Perspective

The known conventional resource base (RAR+EAR-I) has increased over the four decades of OECD recordkeeping, from 3 MT to 7 MT, even as 2 MT of U have been extracted.

Identified resources increased by nearly 800,000 tU between 2009 and 2011.
Understanding Production

Production in a given region is the sum of individual mines
• Current mines may “play out”, continue, or increase production
• Announced mines may or may not come into production
• The time horizon is limited - It always looks like we are running out of ore because the data doesn’t include future mine announcements
Understanding Potential Production

Potential production includes properties that currently may not be economical to develop

- Lower grade ores
- More overburden to be removed
- New areas not supported by existing infrastructure
Deffeyes and MacGregor (Scientific American, 1980) illustrated the distribution of uranium in the Earth’s crust.

Deposit types that are currently being mined are shown in white.

A line drawn tangent to the distribution can approximate the relationship between the amount of uranium available \([Q, \text{ tonnes}]\) and its concentration in ore \([K, \% \text{ uranium}]\).

At currently mined grades, the local slope of the distribution is \(~3.5\)
- A factor of 10 improvement in economical ore grade provides \(10 \times 3.5 = 35\) times more accessible U

Note – Extraction of U from seawater is also being researched
What is the minimum ore grade?

Chapman (1975) calculated the ore grade where front-end energy used > energy produced, at around 20 ppmU.

Steps to lower the minimum ore grade

Reduce energy used - In-situ leaching, a new technique, bypasses the first steps in the process.

Increase energy produced - Advanced fuel cycles could produce much more energy per tonne U mined

Cutoff Grade: Perspectives

- The model (curves) is plotted against contemporary mine data (purple data points) and selected historical data
  - Dotted line represents 10% of electricity output from reference cycle
Ore Grade in Existing Mines

The extraction of uranium from ores of grade 0.1% is currently economically attractive.

Hematite breccia mines (like Olympic Dam) often produce Au, Ag, Cu and Fe as well as U so that recovery of lower grade U is cost effective.
More on mining economics

- The crustal models always predict that the long-term price of uranium will increase.

- This is true if everything else (time, technological progress) is held fixed – lower ore grades are more expensive to extract.

- Is this borne out by reality?
  - Consider the history of extraction of other elements . . .
Quantifying Historical Price Trends: Regressions For Individual Minerals: $P = K e^{Mt}$

- **Aluminum**: $y = 8E+20e^{-0.0204x}$
- **Vanadium**: $y = 5E+14e^{-0.0121x}$
- **Bromine**: 1915 and 1916 prices: $35.6k$ and $43.2k$ per tonne, $M = -0.0283$
- **Chromium**: $y = 0.0002e^{0.0077x}$

1900 to 2000

*Images of graph plots for each mineral*
Results: $M$ Coefficient: $P = Ke^{Mt}$

<table>
<thead>
<tr>
<th>M</th>
<th>Aluminum</th>
<th>Antimony</th>
<th>Arsenic</th>
<th>Bauxite</th>
<th>Beryllium</th>
<th>Bismuth</th>
<th>Boron</th>
<th>Bromine</th>
<th>Cadmium</th>
<th>Chromium</th>
<th>Cobalt</th>
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</thead>
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<tr>
<td></td>
<td>-0.0204</td>
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<td>-0.0210</td>
<td>-0.0015</td>
<td>-0.0283</td>
<td>-0.0243</td>
<td>0.0077</td>
<td>-0.0049</td>
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</table>

<table>
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<tr>
<th>Copper</th>
<th>Germanium</th>
<th>Gypsum</th>
<th>Indium</th>
<th>Iodine</th>
<th>Iron Ore</th>
<th>Lead</th>
<th>Lithium</th>
<th>Magnesium</th>
<th>Manganese</th>
<th>Mercury</th>
<th>Molybdenum</th>
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<tr>
<td>-0.0064</td>
<td>-0.0212</td>
<td>0.0041</td>
<td>-0.0407</td>
<td>-0.0153</td>
<td>0.0029</td>
<td>-0.0052</td>
<td>-0.0254</td>
<td>-0.0232</td>
<td>0.0033</td>
<td>-0.0124</td>
<td>-0.0075</td>
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<table>
<thead>
<tr>
<th>Nickel</th>
<th>Platinum</th>
<th>Pumice</th>
<th>Rhenium</th>
<th>Silver</th>
<th>Tantalum</th>
<th>Thorium</th>
<th>Tin</th>
<th>Titanium</th>
<th>Tungsten</th>
<th>Vanadium</th>
<th>Zinc</th>
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<tr>
<td>-0.0043</td>
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<td>-0.0013</td>
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<td>0.0013</td>
<td>-0.0395</td>
<td>-0.0019</td>
<td>-0.0121</td>
<td>-0.0038</td>
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</tbody>
</table>

Distribution of $M$ Coefficients:

- **Most Negative**: Rhenium, -0.0499
- **Most Positive**: Chromium, 0.0077
- **Mean**: -0.0118
- **Standard Dev.**: 0.0136
- **$2\sigma$ Confidence Interval**: [-0.0390, +0.0153]

For most elements, costs have declined as total extraction has increased.
Historical Prices For 34 Mineral Commodities

Fit to data for 34 commodities:
PR = exp(-8.43E-3 t)

t is elapsed time
Resource depletion tends to push prices up. Other factors act in the opposite direction. The amount of uranium extracted by one miner working for one year increased sixfold (Australia and Canada) between 1980 and 2003.
What about Thorium?

• Thorium crustal abundance is 3-4 times higher than Uranium
  – Limited current uses
  – Few deposits identified due to lack of demand
    • Redbook values probably incomplete
  – Can be a nuisance waste when mining for other minerals (radioactivity)

• Thorium primarily makes sense for continuous recycle fuel cycles
  – After initial core, mostly interchangeable with uranium
    • For breeding, better in softer spectrums
    • Can’t achieve as high of breeding ratios (growth scenarios)
  – Very little Th needed per GWe-a (same as U)
  – Fuel and reprocessing technologies less mature
# World Thorium Resources by Deposit Type

<table>
<thead>
<tr>
<th>Major Deposit Type</th>
<th>Australia Mines Atlas Resource Estimate</th>
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<tbody>
<tr>
<td>Carbonatite</td>
<td>1,900,000</td>
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<tr>
<td>Placer Deposits</td>
<td>1,500,000</td>
</tr>
<tr>
<td>Vein-type Deposits</td>
<td>1,300,000</td>
</tr>
<tr>
<td>Alkaline Rocks</td>
<td>1,120,000</td>
</tr>
<tr>
<td>Other</td>
<td>258,000</td>
</tr>
<tr>
<td>Total</td>
<td>6,078,000</td>
</tr>
</tbody>
</table>
Thorium Mining Options

- As a main product
- As a by-product of main product rare earth production
- Twice By-product of heavy mineral sand mining
  - Titanium and other HMS mined as main product
    - Monazite also recovered for rare earth content
      - Thorium recovered from rare earth processing
Potential Global Thorium Cost Curve

Estimated Unit Cost ($/kg)

- Steenkampskraal, South Africa (By-Product)
- Richard’s Bay, South Africa (By-Product)
- Murry Basin, Australia (By-Product)
- Jocelin Ambrosia, Australia (By-Product)
- Orissa, India (By-Product)
- Iluka Virginia, USA (By-Product)
- Hall Mountain, USA
- Wet Mountain Pass, USA (By-Product)
- Lephi Pass, USA
- Palmer, USA
- Bear Lodge, USA (By-Product)
- Mt. Weld, Australia (By-Product)
- Araxa, Brazil (By-Product)
- Bald Mountain, USA
- Conway Granite, USA

Potential Annual Production Capacity (‘000 kgs ThO₂)
Supply Conclusions

• Additional sources of U/Th are available
  – More prospecting has easily identified more reserves
  – U from phosphates has significant potential if prices rise
  – U from seawater could provide a ceiling on prices

• More non-renewable resources can be made available by making lower grade ores more economical
  – New mining technologies – improves the efficiency of extraction
  – U/Th as a co-product or by-product – improves the economics of individual mines
  – New reactor and fuel cycle technologies – could significantly improve the energy generated per unit of natural resource consumed
Summary

• “The present generation should not compromise the ability of future generations to fulfill their needs.”

• Approach–
  – Improve methods to obtain non-renewable resources
    • Makes more resources available to future generations
  – Improve methods to use non-renewable resources
    • Makes current resources go farther for future generations

• More non-renewable resources can be made available by making lower grade ores more economical
  – New mining technologies
  – U/Th as a co-product or by-product

• Adopting continuous recycle can:
  – Convert existing depleted U from a waste to a fuel
  – Improve the use of U/Th by over 2 orders of magnitude

• Fuel cycle transition will likely take many decades to complete
**Summary - INPRO Methodology on Resource Depletion**

- **Basic principle (Availability of resources):** A nuclear energy system (NES) shall be capable of contributing to the energy needs in the 21st century while making efficient use of non-renewable resources.

- **User Requirement 1 - Consistency with resource availability:** The NES should be able to contribute to the world’s energy needs during the 21st century without running out of fissile/fertile material and other non-renewable materials, with account taken of reasonably expected uses of these materials external to the NES. In addition, the NES should make efficient use of non-renewable resources.
  - Criteria 1.1, 1.2 and 1.3 address having sufficient material/power for 100 years
  - Criteria 1.4, 1.5 and 1.6 address the efficiency of use of U, Th, and other non-renewable resources

- **The Basic Principle, User Requirement and Criteria are consistent with the summary findings in this presentation**
  - Improve the efficiency of use of U/Th
  - Ensure resources are not exceeded in the near- to mid-term
Thank you for your attention!