Future of Nuclear Energy

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Presented at
The Clark School of Engineering Sustainability Workshop
April 22, 2009
Quick Overview of Nuclear Energy Today

- 104 US reactors (20% of electricity), 440 World reactors in 30 countries.
- 34 new reactors in various stages of construction Worldwide.
- In 2007 highest ever nuclear energy production in the US.
- 51 reactor licenses extended, from 40 years to 60 years of operation, 17 more reactors in process.
- 2 orders (4 units total) for new reactor construction signed, 17 license applications (26 units total) filed with NRC, 10+ more units expected.
“We made the mistake of lumping nuclear energy in with nuclear weapons, as if all things nuclear were evil. I think that’s as big a mistake as if you lumped nuclear medicine in with nuclear weapons” Patrick Moore, former Director of Greenpeace International
Worldwide Nuclear Power Usage and Total Electric Usage Per Capita (kWh/day per person)

<table>
<thead>
<tr>
<th>Country</th>
<th>Nuclear</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>19.6</td>
<td>40.63</td>
</tr>
<tr>
<td>France</td>
<td>19.0</td>
<td>20.45</td>
</tr>
<tr>
<td>Belgium</td>
<td>12.2</td>
<td>21.82</td>
</tr>
<tr>
<td>Finland</td>
<td>11.8</td>
<td>46.07</td>
</tr>
<tr>
<td>Switzerland</td>
<td>9.7</td>
<td>22.01</td>
</tr>
<tr>
<td>South Korea</td>
<td>7.7</td>
<td>21.12</td>
</tr>
<tr>
<td>USA</td>
<td>7.5</td>
<td>35.06</td>
</tr>
<tr>
<td>Canada</td>
<td>7.4</td>
<td>45.86</td>
</tr>
<tr>
<td>Slovenia</td>
<td>7.4</td>
<td>19.09</td>
</tr>
<tr>
<td>Japan</td>
<td>5.7</td>
<td>20.84</td>
</tr>
</tbody>
</table>

Norway 0 (67.54)
China: 0.12 (5.95)
India: 0.04 (1.21)
Reactor Generations

**Generation I**
- Early Prototype Reactors
  - Shippingport
  - Dresden, Fermi I
  - Magnox

**Generation II**
- Commercial Power Reactors
  - LWR-PWR, BWR
  - CANDU
  - VVER/RBMK

**Generation III**
- Advanced LWRs
  - ABWR
  - System 80+

**Generation III+**
- Evolutionary Designs Offering Improved Economics for Near-Term Deployment

**Generation IV**
- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

Timeline:
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030
Five Advanced Reactor Designs Used in the US

- **ABWR (GE-Hitachi)**
- **US-APWR (Mitsubishi)**
- **US-EPR (AREVA)**
- **AP1000 (Toshiba: Westinghouse)**
- **ESBWR (GE-Hitachi)**
Key Features of New Designs

- **Improved economics**
  - Increased plant life (60-80 years)
  - Shorter construction time (24-48 months)
  - Low capital cost (~$1000-2000/kWe)
  - Low cost of electricity (~ 3-5¢/kWh)
  - High Burnup

- **Improved safety and reliability**
  - Reduced need for operator action
  - Passive Safety Features
  - Reduced core damage and release frequency

**Core Damage Frequency Per Year**

- **U.S. NRC Safety Goal**
  - $1 \times 10^{-4}$

- **Current U.S. LWR Plants**
  - $5 \times 10^{-5}$

- **EPRI Utility Requirement**
  - $1 \times 10^{-6}$

- **EPRI EPRI**
  - $4 \times 10^{-7}$

- **NuScale**
  - $1 \times 10^{-5}$

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Public Health, Safety & Environment: Comparing Options

Source: Center for Innovation in Carbon Capture and Storage, University of Nottingham
The Concerns

• **Capital intensity**
  – New nuclear plants remain very expensive to build
  – Loan guarantees in 2005 energy bill help the financial risk (2008 applications totaled $122M vs. $18M allocation)

• **Nuclear Waste**
  – Geological repository is the current approach in the U.S.
  – Yucca Mountain site selected, license application submitted to the NRC, its future is uncertain

• **Proliferation**
  – Technical features of fuel cycle can hinder proliferation (e.g., high burnup, use of thorium, modular sealed reactors, etc.)
  – Ultimately it is a political issue; New IAEA treaty?
Capital Intensity/Needs

- Capital cost comes to $1000-$2500/ KWhr
- With “Cap and Trade” this would be competitive, otherwise subsidies would be needed
Nuclear Waste

- Interim storage at plants (storage pools and dry casks, successfully implemented for 22 years)
  - Pu+U recycled in (sodium-cooled) fast reactors (being reconsidered in Russia, Japan, France and US under GNEP umbrella)
  - Separated Pu is recycled in LWRs (MOX approach, done in France and Japan)
## Fuel Cycle: Known recoverable Sources of Uranium

### Million tons in Ground
- Australia 1.14
- Kazakhstan 0.82
- Canada 0.44
- USA 0.34
- South Africa 0.34
- Namibia 0.28
- Brazil 0.28
- Russian Federation 0.17
- Uzbekistan 0.12

**World total** 4.7

### Million tons Elsewhere
- Phosphate deposits 22
- Seawater 4,500
- Uranium in wastes due to previous activities 1.3
At today’s rate of consumption, once-through fuel cycle could keep going for a hundred years.

At 40-fold increase worldwide, in order to compensate for all fossil fuels, once-through nuclear is not a sustainable option unless seawater Uranium recovery is used.

Japanese have a technique for extracting uranium from seawater at a cost of $200–500/Kg (current cost is ~$20/kg for ore).
Fuel Cycle: Sustainability, Fast Breeder & Reprocessing Option

• With Recycling (Reprocessing) and re-use in fast breeder reactors the fuel-cycle will be sustainable without reliance on seawater
• Reprocessing plus fast breeder increases the resources by 80 folds
• Beside Uranium, Thorium can be used with ground reserves 4 time larger than Uranium
Conclusions

• A renaissance in new nuclear plants underway in the US and the World for first time in 30 years
• New plants feature offer far higher levels of safety through increased redundancy and use of passive safety features
• Nuclear is available (today!) to reduce reliance on fossil fuel and slow carbon emissions
• The most challenging issue is the long-term disposal of spent fuel