A RENAISSANCE OF U.S. NUCLEAR ELECTRIC POWER?

SC 212

May 10 and 17, 2011
PHASES IN DEVELOPMENT TO DATE

- Commercial use started: Dec. 1951, Arco, Idaho, 100 KW
- Development and growth period: mid 1950s – mid 1970s
- Current status and possible renaissance for the future
HISTORY OF DEV. & GROWTH PERIOD
Mid 1950s – mid 1970s

KEY ACTIVITIES AND ACCOMPLISHMENTS:
- Dev. & Refinement of reactor & plant tech. & designs
- Dev. of our Industrial base & world wide leadership
- Dev. & growth of post-grad. Nuclear engr. Education
- Evolution of regulatory bodies and procedures
- Establish basis for consumer confidence in capability
PROBLEMS THAT OCCURRED (1950-1970s)

- Fear due to rumors and public emotionalism
- Over played minor accident (TMI) & Chernobyl disaster
- Major cost growth and schedule delays

  -- Competition from incumbent power gen. technologies

  -- Growing questions about long term economic viability without continued government subsidies

- Increasing terrorism leads to proliferation concerns

  -- Failure to define & start building waste handling sys.
GLOBAL NUCLEAR REACTOR CONSTRUCTION
(annually, 1954–2009)

Construction peaked in 1976 following the 1973 oil crisis

Source: International Atomic Energy Agency
Nuclear Power Today

• 104 reactors provide 20% of our electricity
  • 2/3 of carbon-free electricity
• Excellent safety record
• One nuclear power plant can power a city about the size of Sacramento or Long Beach
• Lowest production costs
Nuclear Energy: Good for the Environment

• Produces no greenhouse gases
  – California’s use of nuclear power as an alternative to coal is equivalent to about 539,000 passenger cars.

• Conserving Natural Resources
  – Reduces dependence on coal, natural gas and oil
  – Each plant’s electrical production during the course of a year is equal to that of 1.4 billion gallons of oil or 912 train loads of coal
Top 10 Nuclear Generating Countries
2009, Billion kWh

<table>
<thead>
<tr>
<th>Country</th>
<th>kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>798.7</td>
</tr>
<tr>
<td>France</td>
<td>390</td>
</tr>
<tr>
<td>Japan</td>
<td>260.1</td>
</tr>
<tr>
<td>Russia</td>
<td>153</td>
</tr>
<tr>
<td>Korea Rep.</td>
<td>141.1</td>
</tr>
<tr>
<td>Germany</td>
<td>127.6</td>
</tr>
<tr>
<td>Canada</td>
<td>85.3</td>
</tr>
<tr>
<td>Ukraine</td>
<td>77.5</td>
</tr>
<tr>
<td>China</td>
<td>70.1</td>
</tr>
<tr>
<td>UK</td>
<td>62.9</td>
</tr>
</tbody>
</table>

Source: International Atomic Energy Agency, U.S. is from Energy Information Administration
Updated: 5/10
# TOP 10 NUCLEAR-POWER-GENERATING COUNTRIES

**ELECTRIC POWER GENERATED, 2009**

<table>
<thead>
<tr>
<th>RANK/COUNTRY</th>
<th>Nuclear (billion kWh)</th>
<th>As a percentage of total electric gen.</th>
<th>REACTORS OPERABLE</th>
<th>REACTORS UNDER CONSTRUCTION</th>
<th>REACTORS PLANNED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 United States</td>
<td>798.7</td>
<td>20.2%</td>
<td>104</td>
<td>101,216</td>
<td>2</td>
</tr>
<tr>
<td>2 France</td>
<td>391.7</td>
<td>75.2</td>
<td>58</td>
<td>63,236</td>
<td>1</td>
</tr>
<tr>
<td>3 Japan</td>
<td>263.1</td>
<td>28.9</td>
<td>55</td>
<td>47,348</td>
<td>2</td>
</tr>
<tr>
<td>4 Russia</td>
<td>152.8</td>
<td>17.8</td>
<td>32</td>
<td>23,084</td>
<td>10</td>
</tr>
<tr>
<td>5 South Korea</td>
<td>141.1</td>
<td>34.8</td>
<td>20</td>
<td>17,716</td>
<td>6</td>
</tr>
<tr>
<td>6 Germany</td>
<td>127.7</td>
<td>26.1</td>
<td>17</td>
<td>20,339</td>
<td>—</td>
</tr>
<tr>
<td>7 Canada</td>
<td>85.3</td>
<td>14.8</td>
<td>18</td>
<td>12,679</td>
<td>2</td>
</tr>
<tr>
<td>8 Ukraine</td>
<td>77.9</td>
<td>48.6</td>
<td>15</td>
<td>13,168</td>
<td>—</td>
</tr>
<tr>
<td>9 China</td>
<td>65.7</td>
<td>1.9</td>
<td>12</td>
<td>9,624</td>
<td>24</td>
</tr>
<tr>
<td>10 Spain</td>
<td>50.6</td>
<td>17.5</td>
<td>8</td>
<td>7,448</td>
<td>—</td>
</tr>
<tr>
<td><strong>World total</strong></td>
<td><strong>2,560.0</strong></td>
<td><strong>14</strong></td>
<td><strong>440</strong></td>
<td><strong>375,805</strong></td>
<td><strong>59</strong></td>
</tr>
</tbody>
</table>

Data for the U.S. is from the Energy Information Administration and was not included in World Nuclear Association totals as of August 2010. Sources: World Nuclear Association (reactor data); International Atomic Energy Agency (generation)
<table>
<thead>
<tr>
<th>Reactor type</th>
<th>Main Countries</th>
<th>Number</th>
<th>GWe (GWatt)</th>
<th>Fuel</th>
<th>Coolant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurized Water Reactor (PWR)</td>
<td>US, France, Japan, Russia, China</td>
<td>265</td>
<td>251.6</td>
<td>enriched UO₂</td>
<td></td>
</tr>
<tr>
<td>Boiling Water Reactor (BWR)</td>
<td>US, Japan, Sweden</td>
<td>94</td>
<td>86.4</td>
<td>enriched UO₂</td>
<td></td>
</tr>
<tr>
<td>Heavy Water Reactor 'CANDU'</td>
<td>Canada</td>
<td>44</td>
<td>24.3</td>
<td>natural UO₂</td>
<td></td>
</tr>
<tr>
<td>Graphite Reactor (AGR &amp; Magnox)</td>
<td>UK</td>
<td>18</td>
<td>10.8</td>
<td>natural U (metal), enriched UO₂</td>
<td></td>
</tr>
<tr>
<td>Graphite Reactor (RBMK)</td>
<td>Russia</td>
<td>12</td>
<td>12.3</td>
<td>enriched UO₂</td>
<td></td>
</tr>
<tr>
<td>Fast Breeder Reactor (FBR)</td>
<td>Japan, Russia</td>
<td>2</td>
<td>1.0</td>
<td>PuO₂ and UO₂</td>
<td></td>
</tr>
<tr>
<td>Russia</td>
<td>4</td>
<td>0.05</td>
<td></td>
<td>enriched UO₂</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>439</td>
<td>386.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

GWe = capacity in thousands of megawatts (gross)

Source: Nuclear Engineering International Handbook 2010
GLOBAL ELECTRIC PRODUCTION

GENERATING TECHNOLOGY

- Nuclear
- Fossil Fuels
  - Coal
  - Coal + CCS
  - Gas
  - Gas + CCS
  - Oil
- Renewables
  - Hydro
  - All others*

2005

- Nuclear: 2%
- Fossil Fuels: 40%
- Renewables: 15%

2050 (Projected)

- Business as usual
  - Nuclear: 3%
  - Fossil Fuels: 52%
  - Renewables: 6%
- Blue Map scenario
  - Nuclear: 23%
  - Fossil Fuels: 34%
  - Renewables: 13%

Electricity Generation

Nuclear Energy Supplies 20% of U.S. Power

Source: Ventyx Velocity Suite / Energy Information Administration and Energy Information Administration's Monthly Review
May 10
AVERAGE LEVELIZED COST TO GENERATE POWER
($ per megawatt-hour in the United States)

Transmission investment
Variable operations and maintenance (including fuel)
Fixed operations and maintenance
Levelized capital cost

*Carbon capture and storage; **Conventional combined cycle; ***Advanced combined cycle.
Source: U.S. Energy Information Administration
Pressurized Water Reactor

Containment Structure

Pressurizer - Steam Generator

Control Rods - Reactor Vessel

Turbine - Condenser

Generator - Grid

Cooling
Steam Cycle (BWR)

BWR – Boiling Water Reactor
Nuclear Reactor Levels of Containment

**Containment Vessel**
1.5-inch thick steel

**Bio Shield**
4 foot thick leaded concrete with 1.5-inch thick steel lining inside and out

**Reactor Vessel**
4 to 8 inches thick steel

**Reactor Fuel Cladding**
Fuel Storage

Container Transport to Storage Area
Nuclear Energy: Good for the Environment

• Produces no greenhouse gases
  – California’s use of nuclear power as an alternative to coal is equivalent to about 539,000 passenger cars.

• Conserving Natural Resources
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THE FUTURE OF NUCLEAR REACTORS

• NEW LIGHT WATER REACTORS

• SMALL MODULAR REACTORS

• RELATIVELY FAR OUT NEW DESIGNS-GENERATION IV

• OTHER RELATED EFFORTS (incl. THORIUM)
AP-1000 (WESTINGHOUSE)
Improved PWR Design

- Design Approved by US NRC
- Passive Safety features (air flow, Pressure Change, gravity)
- 4 Now Being built in China
- 6 Planned in US after final approval
EUROPEAN EVOLUTIONARY REACTOR EPR (from French firm AREVA)

- A STANDARD PWR DESIGN BUT LARGER
- HIGHER EFFICIENCY—REDUCED DOWNTIME
- WASTE IS MORE RADIOACTIVE
- 4 UNDER CONSTRUCTION (FRANCE, FINLAND, 2 IN CHINA)
- POSSIBLE PLANS TO USE IN THE US
NEXT GENERATION (GEN IV) REACTORS

- Fast Reactors
- May be cooled by helium/graphite moderator
- TOSHIBIA 4S (unattended for up to 30 years)
  - liquid sodium coolant
  - reduced volume of waste to store
- TERRAPOWER TP-1
  - doesn’t require enrichment or reprocessing
  - one fuel load can last several decades
  - need to build and test one
Why Modular Nuclear

• Baseload
• Non carbon emitting
• Potentially lower cost than large nuclear
• Scalable – build as you need
• Easier to finance
• Meets or exceeds safety standards
SMALL MODULAR REACTORS

- **NUSCALE**
  - A passive version of a traditional PWR using convection cooling
  - Scalable (1-24 units). Off-site manufacturing

- **HYPERION POWER MODULE**
  - A fast reactor using liquid metal coolant
  - Design not yet used commercially
Modular Nuclear Examples

• Babcock & Wilcox

• NuScale

Four B&W mPower™ nuclear reactors configured as a 500 megawatt nuclear power plant.
<table>
<thead>
<tr>
<th>Technology</th>
<th>Capital Cost $/KW</th>
<th>Capacity Factor %</th>
<th>Install MWe for 500MWea</th>
<th>Capital Cost for 500MWea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>$3300</td>
<td>80</td>
<td>625</td>
<td>$2.1B</td>
</tr>
<tr>
<td>Gas-CT</td>
<td>$1200</td>
<td>50</td>
<td>1000</td>
<td>$1.2B</td>
</tr>
<tr>
<td>Modular Nuclear</td>
<td>$4000</td>
<td>90</td>
<td>550</td>
<td>$2.2B</td>
</tr>
<tr>
<td>Wind</td>
<td>$2200</td>
<td>33</td>
<td>1500</td>
<td>$3.3B</td>
</tr>
<tr>
<td>Solar</td>
<td>$4000</td>
<td>25</td>
<td>2000</td>
<td>$8.0B</td>
</tr>
</tbody>
</table>
# Economic Comparison

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capital Cost 500MWA</th>
<th>Debt Cost 20yr/5%</th>
<th>O&amp;M Costs $/MWhr</th>
<th>Fuel Cost $/MWhr</th>
<th>Carbon Costs $/MWhr</th>
<th>Total Costs $/MWhr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>$2.1B</td>
<td>38</td>
<td>8</td>
<td>25</td>
<td>25</td>
<td>96</td>
</tr>
<tr>
<td>Gas-CT</td>
<td>$1.2B</td>
<td>22</td>
<td>5</td>
<td>55</td>
<td>10</td>
<td>92</td>
</tr>
<tr>
<td>Modular Nuclear</td>
<td>$2.2B</td>
<td>40</td>
<td>20</td>
<td>6</td>
<td>0</td>
<td>66</td>
</tr>
<tr>
<td>Wind</td>
<td>$3.3B</td>
<td>60</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>75</td>
</tr>
<tr>
<td>Solar</td>
<td>$8.0B</td>
<td>145</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>147</td>
</tr>
</tbody>
</table>
Coated fuel particle
0.92 mm diameter

Fuel compact
39 mm tall

Fuel sphere
60 mm diameter

Prismatic block
580 mm tall

[3] Fuel goes into prismatic blocks that...

[4] Many thousands of fuel spheres fill...
