INTRODUCTION TO SUSTAINABLE ENERGY

Prof. Michael W. Golay
Nuclear Engineering Dept.
NUCLEAR ENERGY BASICS AND STATUS
GOALS

- To Understand the Situation and Prospects of the Nuclear Power Enterprise Within the Overall Energy Context
  - Domestically
  - Internationally
NUCLEAR POWER TECHNOLOGIES

GOALS OF NUCLEAR POWER DISCUSSION: To Answer the Following Questions

• Who used nuclear power today?
  Answer: Most industrialized countries.

• Who is likely to use nuclear power in the future?
  Answer: East Asian and developing countries, countries wanting energy supply diversity.

• What are the important nuclear power technologies
  ■ Today? Answer: LWRs – pressurized and boiling water reactors.
  ■ Future? Answer: Maybe LWRs near term, gas-cooled reactors medium term, breeder reactors long term.

• How could nuclear power relieve global warming?
  Answer: Most likely with large-scale, high-temperature breeder reactors.

• What are the future prospects for nuclear power?
  Answer: That depends upon how concerned people are about the problems of other energy technologies and what nuclear power can produce in addition to electricity.
TYPES OF STEAM-ELECTRIC GENERATING PLANTS

- **Fossil fuel**
  - Fuel
  - Boiler
  - Turbine
  - Condenser
  - Steam
  - Generator
  - Water
  - Pump

- **Nuclear BWR**
  - Fuel
  - Reactor
  - Turbine
  - Condenser
  - Steam
  - Generator
  - Water
  - Pump

- **Nuclear PWR**
  - Fuel
  - Reactor
  - Steam generator
  - Turbine
  - Condenser
  - Steam
  - Generator
  - Water
  - Pump

- **Nuclear LMFBR**
  - Fuel
  - Reactor
  - Liquid sodium
  - Intermediate heat exchanger
  - Steam generator
  - Turbine
  - Condenser
  - Steam
  - Generator
  - Water
  - Pump

Image by MIT OpenCourseWare.
PWR FUEL ASSEMBLY AND CUTAWAY OF OXIDE FUEL FOR COMMERCIAL LWR POWER PLANTS

Reactor Fuel Assembly

## RANGE OF RADIATION IN TISSUE

<table>
<thead>
<tr>
<th>Particle Name</th>
<th>Range (m)</th>
<th>Particle Type and Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission Product</td>
<td>$10^{-6}$</td>
<td>Fragment of Nucleus</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$10^{-4} - 10^{-5}$</td>
<td>Helium Nucleus++, 2 protons, 2 neutrons</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$10^{-3}$</td>
<td>Electron$^-$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$0.1 - 10$</td>
<td>Photon$^0$</td>
</tr>
<tr>
<td>$n$</td>
<td>$0.1 - 10$</td>
<td>Neutron$^0$</td>
</tr>
</tbody>
</table>

### TRANSMUTATION

$A^m + n \rightarrow A^{m+1}$
FISSION

\[ n + {^{235}}U \rightarrow {^{236}}U \rightarrow 2 \text{ Fission Products} \]

\[ + \nu (\approx 2.5)n \]
\[ + 6 \beta \]
\[ + 10 \gamma \]
\[ + \text{neutrinos} \]
\[ + \text{kinetic energy (} \approx 200 \text{ MeV)} \]
TWO REPRESENTATIVE FISSION-PRODUCT DECAY CHAINS*

Flowchart of decay chains for Br-90 and Xe-143 removed due to copyright restrictions.
### ENERGY BALANCE FOR AN AVERAGE FISSION

<table>
<thead>
<tr>
<th>Source of Energy</th>
<th>Kinetic Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy of fission fragments (2 nuclei: A Å95, A Å140)</td>
<td>165 ± 5</td>
</tr>
<tr>
<td>Prompt γ rays (5 γ rays)</td>
<td>6 ± 1</td>
</tr>
<tr>
<td>Beta decay of fragments (7 β rays)</td>
<td>8 ± 1.5</td>
</tr>
<tr>
<td>Neutrinos related to above</td>
<td>12 ± 2.5</td>
</tr>
<tr>
<td>Gamma rays related to above (7 γ rays)</td>
<td>6 ± 1</td>
</tr>
<tr>
<td>Kinetic energy of neutrons (2 to 3 neutrons)</td>
<td>5</td>
</tr>
</tbody>
</table>
**NEUTRONIC PROPERTIES OF NUCLEAR FUELS**

### NEUTRON ENERGIES

<table>
<thead>
<tr>
<th>Parameter</th>
<th>U$^{233}$</th>
<th>U$^{235}$</th>
<th>Pu$^{239}$</th>
<th>U$^{233}$</th>
<th>U$^{235}$</th>
<th>Pu$^{239}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>0.123</td>
<td>0.2509</td>
<td>0.38</td>
<td>0.1</td>
<td>0.15</td>
<td>0.1</td>
</tr>
<tr>
<td>η</td>
<td>2.226</td>
<td>1.943</td>
<td>2.085</td>
<td>2.45</td>
<td>2.3</td>
<td>2.7</td>
</tr>
<tr>
<td>ν</td>
<td>2.50</td>
<td>2.43</td>
<td>2.91</td>
<td>2.7</td>
<td>2.65</td>
<td>3.0</td>
</tr>
</tbody>
</table>

\[ \eta = \frac{\nu}{1 + \alpha} \text{, n's produced} \div \text{absorption} ; \quad \alpha = \frac{\text{captures}}{\text{fissions}} ; \quad \nu = \frac{\text{n's produced}}{\text{fission}} \]

Conversion Reactions:

- \( U^{238} + n \rightarrow U^{239} + \gamma \rightarrow Np^{239} + \beta^- \rightarrow Pu^{239} + \beta^- \)
- \( Th^{232} + n \rightarrow Th^{233} + \gamma \rightarrow Pa^{233} + \beta^- \rightarrow U^{233} + \beta^- \)
SELF-SUSTAINED CHAIN REACTION

1 neutron + U$^{235}$ → $\eta$ neutrons ⇒

1 neutron for subsequent fission, and
$(\eta - 1)$ neutrons for leakage, parasitic absorption, and conversion

Necessary Condition for Breeding: for each fissile nucleus consumed another is produced via conversion of fertile material, e.g., a U$^{235}$ nucleus is consumed and replaced by production of a new Pu$^{239}$ nucleus, via the reaction –

$$n + U^{238} \rightarrow U^{239} + \gamma$$
$$\rightarrow Np^{239} + \beta^- + \gamma$$
$$\rightarrow Pu^{239} + \beta^- + \gamma$$

Conversion Ratio ≡ Number of new fissile nuclei produced as a result of fission of a single nucleus

Conversion Ratio:

\[\begin{align*}
\geq 1 & \text{ for breeding} \\
< & \text{ for burning}
\end{align*}\]
<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Fundamental Nuclear Energy Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>Gravitationally confined solar fusion reactions transmitted via photons</td>
</tr>
<tr>
<td>Fossil Fuels</td>
<td>Gravitationally confined solar fusion reactions transmitted via photons and stored in biomass</td>
</tr>
<tr>
<td>Geothermal</td>
<td>Naturally-occurring radioactive decays of materials within the Earth and Gravitational Work</td>
</tr>
<tr>
<td>Tidal</td>
<td>Nuclear reactions following the Big Bang</td>
</tr>
<tr>
<td></td>
<td>Sustaining Current Gravitational Work</td>
</tr>
<tr>
<td>Nuclear Fission</td>
<td>Neutron-induced fission reactions of heavy nuclei</td>
</tr>
<tr>
<td>Nuclear Fusion</td>
<td>Nuclear fusion reactions of light nuclei</td>
</tr>
</tbody>
</table>
# ENVIRONMENTAL EFFECTS OF ENERGY SOURCES

<table>
<thead>
<tr>
<th>FUEL PHASE</th>
<th>Coal</th>
<th>Petroleum</th>
<th>Natural Gas</th>
<th>Nuclear</th>
<th>Hydro</th>
<th>Solar Terrestrial Photovoltaic</th>
<th>Solar Power Tower</th>
<th>Wind</th>
<th>Fusion</th>
<th>Geothermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction</td>
<td>Mining Accidents</td>
<td>Drilling-Spills (off-shore)</td>
<td>Drilling</td>
<td>Mining Accidents</td>
<td>Construction</td>
<td>Mining Accidents</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>He, H(^2), Li Production</td>
</tr>
<tr>
<td>Refining</td>
<td>Refuse Piles</td>
<td>Water Pollution</td>
<td>- -</td>
<td>Milling Tails</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
</tr>
<tr>
<td>Transportation</td>
<td>Collision</td>
<td>Spills</td>
<td>Pipeline Explosion</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
</tr>
<tr>
<td>On-Site</td>
<td>Thermal High Efficiency</td>
<td>High Efficiency</td>
<td>High Efficiency</td>
<td>Low Efficiency</td>
<td>- -</td>
<td>Low Efficiency Ecosystem Change</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>Low Efficiency H(_2)S</td>
</tr>
<tr>
<td></td>
<td>Air Particulates-(\text{SO}_2), (\text{NO}_x)</td>
<td>(\text{SO}_2), (\text{NO}_x)</td>
<td>(\text{NO}_x)</td>
<td>BWR Radiation Releases</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
</tr>
<tr>
<td></td>
<td>Water Water Treatment Chemicals</td>
<td>Water Treatment Chemicals</td>
<td>Water Treatment Chemicals</td>
<td>Water Treatment Chemicals</td>
<td>Destroys Prior Ecosystems</td>
<td>Water Treatment Chemicals</td>
<td>Water Treatment Chemicals</td>
<td>- -</td>
<td>Tritium in Cooling Water</td>
<td>Brine in Streams</td>
</tr>
<tr>
<td></td>
<td>Aesthetic Large Plant Transmission Lines</td>
<td>Large Plant Transmission Lines</td>
<td>Large Plant Transmission Lines</td>
<td>Small Plant Transmission Lines</td>
<td>Poor Large Area</td>
<td>Poor Large Area</td>
<td>Large Area Large Towers</td>
<td>- -</td>
<td>Small Area</td>
<td>Poor Large Area</td>
</tr>
<tr>
<td></td>
<td>Wastes Ash, Slag</td>
<td>Ash</td>
<td>- -</td>
<td>Spent Fuel Transportation Reprocessing Waste Storage</td>
<td>- -</td>
<td>Spent Cells</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>Irradiated Structural Material</td>
</tr>
<tr>
<td>Special Problems</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>- -</td>
<td>Construction Accidents</td>
<td>- -</td>
<td>Bird, Human Injuries</td>
<td>- -</td>
<td>Occupational Radiation Doses</td>
<td>- -</td>
</tr>
<tr>
<td>Major Accident</td>
<td>Mining</td>
<td>Oil Spill</td>
<td>Pipeline Explosion</td>
<td>Reactor Cooling</td>
<td>Dam Failure</td>
<td>Fire</td>
<td>- -</td>
<td>- -</td>
<td>Tritium Release</td>
<td>- -</td>
</tr>
</tbody>
</table>
PUBLIC MOOD MORE FAVORABLE TO NUCLEAR POWER

- Global Warming Concerns
  - Popular belief
  - IPCC reports and 2007 Nobel Peace Prize
- Fossil fuel costs/supply security
- Middle-East Wars
- Better Nuclear Power Technology – Mainly Concerning Safety
- Good Operational Record of Existing Nuclear Plants
World Electricity Generation

- Nuclear: 14.7%
- Coal: 40.8%
- Gas: 20%
- Oil: 5.8%
- Hydro: 16.4%
- Other: 2.3%

Image by MIT OpenCourseWare. Source: OECD/IEA 2006.
INTERNATIONAL NUCLEAR POWER GROWTH – End of 2010

- 441 Units Operating in 30 Countries, with 376,000 MWe of total capacity
- 7 New Units Expected to Start Up in 2010
- 60 New Units Under Construction, 11 Started in 2009
- 150 New Units Planned
- 340 New Units Proposed
- China Plans 50 Units Over Next 10 Years
- UK “White Paper” Encourages New Nuclear Power Plants (1/08)
- New Units in South Korea, China, Finland, France, India, Japan, Russia—most growth is in Asia
Fuel for Electricity Generation 2006

Width of each bar indicative of gross power production


http://www.world-nuclear.org/info/inf01.html
## Number of Reactors in Operation Worldwide as of Oct. 1, 2010

<table>
<thead>
<tr>
<th>Country</th>
<th>Reactors</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States of America</td>
<td>104</td>
</tr>
<tr>
<td>France</td>
<td>58</td>
</tr>
<tr>
<td>Japan</td>
<td>32</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>21</td>
</tr>
<tr>
<td>Republic of Korea</td>
<td>54</td>
</tr>
<tr>
<td>India</td>
<td>19</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>19</td>
</tr>
<tr>
<td>Canada</td>
<td>17</td>
</tr>
<tr>
<td>Germany</td>
<td>15</td>
</tr>
<tr>
<td>Ukraine</td>
<td>13</td>
</tr>
<tr>
<td>China</td>
<td>10</td>
</tr>
<tr>
<td>Sweden</td>
<td>8</td>
</tr>
<tr>
<td>Spain</td>
<td>7</td>
</tr>
<tr>
<td>Belgium</td>
<td>6</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>5</td>
</tr>
<tr>
<td>Switzerland</td>
<td>4</td>
</tr>
<tr>
<td>Finland</td>
<td>4</td>
</tr>
<tr>
<td>Hungary</td>
<td>4</td>
</tr>
<tr>
<td>Slovak Republic</td>
<td>4</td>
</tr>
<tr>
<td>Argentina</td>
<td>2</td>
</tr>
<tr>
<td>Brazil</td>
<td>2</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>2</td>
</tr>
<tr>
<td>Mexico</td>
<td>2</td>
</tr>
<tr>
<td>Pakistan</td>
<td>2</td>
</tr>
<tr>
<td>Romania</td>
<td>2</td>
</tr>
<tr>
<td>South Africa</td>
<td>2</td>
</tr>
<tr>
<td>Armenia</td>
<td>1</td>
</tr>
<tr>
<td>Netherlands</td>
<td>1</td>
</tr>
<tr>
<td>Slovenia</td>
<td>1</td>
</tr>
</tbody>
</table>

World Total: 441 Reactor units

Note: Long-term shutdown units (5) are not counted

Image by MIT OpenCourseWare. Source: International Atomic Energy Agency.

http://www.iaea.org/cgi-bin/db.page.pl/pris.oprconst.htm
NUCLEAR ELECTRICITY PRODUCTION AND SHARE OF TOTAL ELECTRICITY PRODUCTION

Image by MIT OpenCourseWare. Adapted from the World Nuclear Association.

http://www.world-nuclear.org/info/inf01.html
NUCLEAR ELECTRICITY GENERATION 2007

Nuclear Electricity Generation 2007

Bar width is indicative of the amount of electricity in each country

Image by MIT OpenCourseWare. Adapted from the World Nuclear Association.

http://www.world-nuclear.org/info/inf01.html
NUCLEAR ENERGY

Share of Total Electricity Production in OECD Countries, 2009

Image by MIT OpenCourseWare. Source: OECD.

Source: [http://www.oecd.org](http://www.oecd.org), Nuclear Energy Data, 2010
### EXISTING NUCLEAR POWER PLANTS
(Approximately 441 Worldwide)

<table>
<thead>
<tr>
<th>Country</th>
<th>Fraction of Electricity</th>
<th>Units Under Construction</th>
<th>Operating Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>75.2</td>
<td>1</td>
<td>59</td>
</tr>
<tr>
<td>Belgium</td>
<td>51.7</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>35.9</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>S. Korea</td>
<td>34.8</td>
<td>6</td>
<td>21</td>
</tr>
<tr>
<td>Switzerland</td>
<td>39.5</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Japan</td>
<td>28.9</td>
<td>2</td>
<td>55</td>
</tr>
<tr>
<td>UK</td>
<td>17.9</td>
<td>0</td>
<td>19</td>
</tr>
<tr>
<td>USA</td>
<td>20.2</td>
<td>1</td>
<td>104</td>
</tr>
<tr>
<td>Russia</td>
<td>17.8</td>
<td>10</td>
<td>32</td>
</tr>
<tr>
<td>S. Africa</td>
<td>4.8</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Netherlands</td>
<td>3.7</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>China</td>
<td>1.9</td>
<td>23</td>
<td>13</td>
</tr>
</tbody>
</table>

Sources: world-nuclear.org & euronuclear.org, 10/10
## SUMMARY OF TYPES OF POWER REACTORS USED WORLDWIDE

<table>
<thead>
<tr>
<th>Type</th>
<th>Coolant</th>
<th>Moderator</th>
<th>Coolant Temperature (°C)</th>
<th>Deployment</th>
<th>Current Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurized Water (PWR)</td>
<td>Light Water</td>
<td>Light Water</td>
<td>300</td>
<td>Most nuclear countries</td>
<td>265</td>
</tr>
<tr>
<td>Boiling Water (BWR)</td>
<td>Light Water</td>
<td>Light Water</td>
<td>300</td>
<td>Most nuclear countries</td>
<td>94</td>
</tr>
<tr>
<td>RBMK</td>
<td>Light Water</td>
<td>Graphite</td>
<td>300</td>
<td>Former USSR*</td>
<td>16</td>
</tr>
<tr>
<td>Pressurized Heavy Water (PHWR)</td>
<td>Heavy Water</td>
<td>Heavy Water</td>
<td>300</td>
<td>Canada, Korea, China, Argentina, India, Pakistan</td>
<td>44</td>
</tr>
<tr>
<td>Gas-Cooled (GCR)</td>
<td>Carbon Dioxide, Helium</td>
<td>Graphite</td>
<td>600</td>
<td>UK, Russia</td>
<td>18</td>
</tr>
<tr>
<td>Liquid Metal-Cooled (LMFBR)</td>
<td>Sodium, Lead, Lead-Bismuth</td>
<td>None</td>
<td>600</td>
<td>France, UK, Japan, Russia; former USSR, China and India</td>
<td>2</td>
</tr>
</tbody>
</table>

*Union of Soviet Socialists Republics
French Electricity Output

10^3 GWh

- Coal
- Oil
- Nuclear
- Hydro
- Other

Image by MIT OpenCourseWare. Source: International Energy Agency database.
**INTERNATIONAL TRENDS**

- Deregulation originated in the United Kingdom, went well until natural gas prices fell (≈ 2002); British Energy was near bankruptcy and depended upon government loans.

- Deregulation is also being tried in United States, Canada, Chile, Japan, South Korea, Australia, and European Community.

- Consolidation among nuclear equipment vendors is occurring: Areva, Siemens, British Nuclear Fuels Ltd/Toshiba, General Electric, Hitachi, Mitsubishi Heavy Industries.

- New reactor manufacturers from S. Korea, Russia, perhaps China next, entering international competition.
REGIONAL FACTORS

EUROPE

• Electricité de France is a big exporter and owner
• Nuclear power shutdowns have been mandated in Sweden, Germany and Belgium; now being revoked or reconsidered
• Fifth Finnish nuclear unit (EPR) plant is proceeding

AFRICA

• South Africa was developing the pebble bed modular reactor (PBMR), has shut down the project
ASIA

• China has 9 units under construction, 41 more planned

• Japan has 11 units planned and 2 units under construction; is in recovery from 7 units of TEPCO taken off-line following 2007 earthquake and are slowly returned to service

• South Korea has privatized KEPCO, is planning a new series of LWRs, has 6 units under construction and two planned

• Taiwan is completing 2 BWRs; nothing is planned beyond them
EMERGING NUCLEAR ENERGY COUNTRIES

- 45 Countries Considering New Nuclear Power Programs; some can be classified according to how far their plans have progressed
  - Iran: Power reactors under construction
  - UAE, Turkey: Contract signed, legal and regulatory infrastructure well-developed
  - Vietnam, Jordan, Italy: Committed plans, legal and regulatory infrastructure developing
  - Thailand, Indonesia, Egypt, Kazakhstan, Poland, Belarus, Lithuania: Well-developed plans but commitment pending
  - Saudi Arabia, Israel, Nigeria, Malaysia, Bangladesh, Morocco, Kuwait, Chile: Developing plans
  - Namibia, Kenya, Mongolia, Philippines, Singapore, Albania, Serbia, Estonia & Latvia, Libya, Algeria, Azerbaijan, Sri Lanka: Discussion as serious policy option
  - Australia, New Zealand, Portugal, Norway, Ireland: Officially not a policy option at present
ELECTRICITY NET GENERATION, TOTAL (ALL SECTORS)

By Sector, 1989-2009

- Total (All Sectors)
- Commercial and Industrial
- Electric Power

By Source Category, 2009

- Fossil Fuels: 2.7 Twh
- Nuclear Electric Power: 0.8 Twh
- Renewable Energy: 0.4 Twh

By Source, 2009

- Coal: 45%
- Natural Gas: 23%
- Nuclear Electric Power: 20%
- Hydroelectric Power: 7%
- Other 1%

By Source, 1949-2009

- Coal
- Natural Gas
- Nuclear Electric Power
- Hydroelectric Power

Footnotes:
1 Wind, petroleum, wood, waste, geothermal, other gases, solar thermal and photovoltaic, batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, miscellaneous technologies, and non-renewable waste (municipal solid waste from non-biogenic sources, and tire-derived fuels).
2 Conventional hydroelectric power and pumped storage.
Sources: Tables 8.2a, 8.2b, and 8.2d.

NUCLEAR GENERATING UNITS

U.S. Commercial Nuclear Power Reactors—Years of Operation

Years of Commercial Operation

- ▲ 0-9
- ▲ 10-19
- ▲ 20-29
- ▲ 30-39

Number of Reactors

- 0
- 10
- 42
- 52

Source: U.S. Nuclear Regulatory Commission

http://www.nrc.gov/reactors/operating/map-power-reactors.html
HISTORICAL AND PROJECTED US NUCLEAR ELECTRIC GENERATION CAPACITY, 1960-2055

Source: DOE-ONEST (c. 1997).

Fig. 5.3 in "Report to the President on Federal Energy Research and Development for the 21st Century."
President's Committee of Advisors on Science and Technology, Panel on Energy Research and Development, November 1997.
### EXISTING USA NUCLEAR POWER INDUSTRY

<table>
<thead>
<tr>
<th>Utilities</th>
<th>NRC Office of New Reactors</th>
<th>Vendors</th>
</tr>
</thead>
<tbody>
<tr>
<td>¥ Power capacity increases continuing</td>
<td>¥ Reactor oversight process continues in force</td>
<td>¥ General Electric</td>
</tr>
<tr>
<td>¥ Operating record is good but not improving</td>
<td>¥ Risk-informed regulation has stalled</td>
<td></td>
</tr>
<tr>
<td>¥ Restructuring of economic regulation has stalled</td>
<td>¥ 17 new plant licenses under application for 28 reactors</td>
<td></td>
</tr>
<tr>
<td>¥ Consolidation has slowed</td>
<td>¥ Three new plants being built</td>
<td>✯ In alliance with Hitachi</td>
</tr>
<tr>
<td>✯ Exelon-PSEG merger failed</td>
<td></td>
<td>✯ Nuclear operations are now in North Carolina</td>
</tr>
<tr>
<td>✯ Constellation-FPL merger failed</td>
<td></td>
<td>✯ ESBWR cancelled</td>
</tr>
<tr>
<td>¥ Plant purchases have stopped</td>
<td></td>
<td>✯ Westinghouse purchased by Toshiba</td>
</tr>
<tr>
<td>¥ Restructuring of economic regulation has stalled</td>
<td></td>
<td>✯ (who also make BWRs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>✯ Areva in alliance with Constellation Energy, EDF, Mitsubishi in UniStar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>✯ Mitsubishi entering US market</td>
</tr>
</tbody>
</table>
OTHER PROJECTS

• Yucca Mountain HLW Repository (in Nevada)
  ■ License application submitted 2008, effectively withdrawn 2010
  ■ Earliest opening 2020
  ■ Will federal government take back spent fuel?
    ◆ Several successful utility lawsuits
• Private Fuel Storage Interim Facility (in Utah) approved
  ■ Transportation access blocked
• Louisiana Enrichment Services (in New Mexico)
  ■ Urenco, Areva
• U.S. Enrichment Corp. (USEC) (in Ohio)
• Mixed Oxide (UO₂, PuO₂) Fuel Fabrication Plant (in Savannah River, South Carolina)
CURRENT/SHORT TERM

Light Water Reactors (LWRs)
  • Pressurized Water Reactor (PWR)
  • Boiling Water Reactor (BWR)
Heavy Water Reactor (PHWR)
  • Pressurized Heavy Water Reactor (CANDU)

INTERMEDIATE TERM (>20 years)

  Brayton Cycle Gas (He or CO₂) Cooled Reactor (GCR-GT)

LONG TERM (>50 years)

  Fast Breeder (²³⁸U ⇀ ²³⁹Pu-based)
  Thermal Breeder (²³²Th ⇀ ²³³U-based)
MHTGR SIDE-BY-SIDE ARRANGEMENT WITH PRISMATIC FUEL

Image by Emoscopes on Wikimedia Commons.
FACTORS LIKELY TO AFFECT FUTURE USE OF NUCLEAR POWER

Operational Safety Record

Utility, Critical Elite, Public, Investor Attitudes

End of Cold War

Degree of Nuclear Weapons Proliferation

Nuclear Waste Disposal Success

Global Warming and Air Pollution Worries

Ability of Nuclear Power to Produce More than Electricity