Fundamentals of Nuclear Power
The Nuclear Fuel Cycle

Osher Lifelong Learning Institute
Spring 2012
Administrative Overhead

Topic for final (May 9) session?
“Once-Through” Fuel Cycle

- Enriching
- Fuel Fabrication
- Reactor
- Spent Fuel Storage
- Milling
- Exploration & Mining
- Geologic Disposal
Primary Energy Sources

- Fossil
  - Oil
  - Coal
  - Gas
- Solar
  - Hydroelectric
  - Wind
  - Biomass
  - Direct solar heat
  - Photovoltaics
- Non-solar "Renewable" – geothermal, waves, tides
- Nuclear
Secondary Energy Sources ("Carriers")

• Electricity

• Hydrogen – mainly from natural gas or electrolysis of water

• Alcohols – from wood or other plant material

• Oil and gas – from coal
Uranium Resources (RAR - $130/kg U)

World Total = 3296689 t

Canada 345200 t
USA 342000 t
Russia 131750 t
Kazakhstan 513897 t
Russia 131750 t
Mongolia 46200 t
Indonesia 42568 t (24)
Uzbekistan 76936 t
Jordan 30375 t
Ukraine 66706 t
Brazil 157700 t
Namibia 182556 t
South Africa 255593 t

(c) WISE Uranium Project

NA = Data not available

t = metric tonne
Coles Hill, VA

• 7th largest deposit in the world
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"There will be a dead zone with a 30 mile radius of the mine. Nothing will grow. Animals will die. The radiation genetically alters tissue. Animals will not be able to reproduce. We'll see malformed fetuses." -- Jack Dunavant, Southside Concerned Citizens
Mining Techniques

- Open cut or open pit (grade control usually achieved by measuring radioactivity as a surrogate for U concentration)
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• In Situ Leach (ISL) – popular in US and Kazakhstan – acid (sulfuric, phosphoric, etc.) or alkaline agent
Uranium (U₃O₈) Prices 1972 on annual basis

- Average Australian export value A$/kg
- Euratom long-term price US$/lb
- Spot price US$/lb
U in ground → Various forms

Mining and Milling → U₃O₈, etc. (Yellowcake)

Conversion → UF₆

Enrichment → UF₆

Fabrication → UO₂

Natural U Rx

UF₆
$\text{UF}_6$

- Gas at $\sim 60^\circ\text{C}$
- Fluorine has only one isotope
- $\text{UF}_6$ exposed to moist air reacts with the water in the air to produce $\text{UO}_2\text{F}_2$ and HF, both of which are highly soluble and toxic.
Natural Uranium (0.711% U\textsuperscript{235})

Enriched Uranium (>1.0% U\textsuperscript{235})

Depleted Uranium (Tails) (<0.7% U\textsuperscript{235})
UF₆ Storage

• About 95% of depleted U produced to date is stored as depleted UF₆ in steel cylinders in open air yards close to enrichment plants.

• Each cylinder contains up to 12.7 tons of solid UF₆.

• In the U.S. alone, 560,000 tons of depleted UF₆ had accumulated by 1993.

• In 2005, 686,500 tons in 57,122 storage cylinders were located near Portsmouth, Ohio, Oak Ridge, Tennessee, and Paducah, Kentucky

• Storage cylinders must be regularly inspected for signs of corrosion and leaks.

• The estimated life time of the steel cylinders is measured in decades.
Gaseous Diffusion

- Principal operating cost is electrical power required
- 1950s Oak Ridge, Portsmouth, OH and Paducah, KY plants
- Only US plant operating today is USEC's Paducah.
  - Transferred to private sector 1998
  - Capacity $8 \times 10^6$ SWU/y. US reactors need $12.7 \times 10^6$ SWU/y.
  - Expected to close once three new plants begin operation by 2020.
- 2009 – Russia's Tenex contracts with US utilities for enrichment services starting about 2014
U238 is heavier and collects on the outside walls (Depleted/Tails)

U235 is lighter and collects in the center (Enriched)

Feed to Next Stage
Centrifuges

9x10^6 SWU/y capacity plant:

- 90,000 to 100,000 centrifuges
- Requires high reliability (if mean time to failure is 3 y per unit $\rightarrow$ 90 machine failures per day)
- Speeds up to 600 m/sec $\rightarrow$ > 200,000 g
Stuxnet Worm

• A computer virus that appears to have been designed specifically to target Iran’s centrifuge machines so that they spin out of control.
• In November, 2010, Iran admitted that their centrifuges suffered partial sabotage by a computer virus
• U.S. or Israel seen as possible developers of Stuxnet—both governments denied responsibility.
Economics

- Gaseous Diffusion 2,500 kWh/SWU
- Centrifuge 50 kWh/SWU
- Laser ?

Estimated Trend

<table>
<thead>
<tr>
<th>Supply Source</th>
<th>2007</th>
<th>2017</th>
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<tbody>
<tr>
<td>Diffusion</td>
<td>25%</td>
<td>0</td>
</tr>
<tr>
<td>Centrifuge</td>
<td>65%</td>
<td>93%</td>
</tr>
<tr>
<td>Laser</td>
<td>0</td>
<td>3%</td>
</tr>
<tr>
<td>HEU ex weapons</td>
<td>10%</td>
<td>4%</td>
</tr>
</tbody>
</table>
## World Enrichment Capacity – Operational and Planned (1000 SWU/y)

<table>
<thead>
<tr>
<th>Country</th>
<th>2005</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>10,800</td>
<td>7,000</td>
</tr>
<tr>
<td>Germany-Holland-UK</td>
<td>8,100</td>
<td>12,200</td>
</tr>
<tr>
<td>Japan</td>
<td>150</td>
<td>750</td>
</tr>
<tr>
<td>USA (USEC Paducah)</td>
<td>11,300</td>
<td>3,800</td>
</tr>
<tr>
<td>USA (Urenco, NM)</td>
<td>0</td>
<td>5,900</td>
</tr>
<tr>
<td>USA (Areva, ID)</td>
<td>0</td>
<td>&gt;1,000</td>
</tr>
<tr>
<td>Russia</td>
<td>20,000</td>
<td>33,000</td>
</tr>
<tr>
<td>China</td>
<td>1,000</td>
<td>3,300</td>
</tr>
</tbody>
</table>
SOURCE ENERGY EQUIVALENTS

1 Uranium Fuel Pellet, without being reprocessed and recycled, has about as much energy available in today’s light water reactor as...

3 Barrels of Oil (42 gal. each)
1 Ton of Coal
17,000 Cubic Feet of Natural Gas
Once Through Nuclear Fuel Cycle
Coal vs. Nuclear Waste Comparison

• Coal-primary waste output
  – 400+ tons of ash per day
  – 35,000 tons of CO$_2$ per day
  – 250 tons of SO$_2$ per day
  – 20 tons of NO$_x$ per day

• Nuclear-primary waste output
  – 300 m$^3$ low level and mixed waste per YEAR
  – 25 tons worth of radioactive spent nuclear fuel assemblies per YEAR
Coal-Fired Plant

• 1000 MWe coal-fired plant burns 10,000 tons of fuel (110 rail cars) per day
• 5% of burned coal $\rightarrow$ ash
• In mass terms, 20,000 times more coal is needed than U.
Reaction in standard UO₂ fuel

U-235 4%
U-238 96%
Pu 3%
U-235 1%
U-238 93%

Fission Products 5%
Pu 1%
65% fissile Pu to MOX
Waste
Reprocessed U for recycle

Basis: 45,000 MWd/t burn-up, ignores minor actinides
Reaction in MOX fuel

Pu (65% fissile) 7%

Fission Products 5%

U-238 93%

Pu (55% fissile) 5%

Pu 3%

Fission Products 5%

U-238 90%

3% 2% 4% 1%

Basis: 45,000 MWd/t burn-up, ignores minor actinides
Nuclear Cask Crash Tests

http://www.youtube.com/watch?feature=player_detailpage&v=1mHtOW-OB04#t=9s
Sandia National Laboratory Test
Sandia National Laboratory Test
F-4 Containment Wall Test - 1988
Complete Nuclear Fuel Cycle
• Once-through fuel cycle uses only 5% of energy in the fuel.
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• After 5 to 10 years in spent fuel pool, fuel can be moved to dry cask storage.
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• After 5 to 10 years in spent fuel pool, fuel can be moved to dry cask storage.
• 50 years of US used fuel would occupy football field 22 ft deep. If recycled, its waste would occupy football field 9 inches deep.
Thorium

• Insignificant production of long-lived minor actinides compared to uranium

• Proliferation resistance due to hard gamma emitters in U233
Advantages of Thorium (cont.)

• Since U233 has lower mass # compared to U235 and U238, amount of higher actinides (Np, Pu, Am, Cm) produced per unit of energy generated is insignificant compared to uranium-based fuels.

• Plutonium is completely absent from thorium fueled reactor waste.
(Reasonably assured and inferred resources recoverable at up to $80/kg)

<table>
<thead>
<tr>
<th>Country</th>
<th>Tonnes</th>
<th>% of total</th>
</tr>
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<tbody>
<tr>
<td>Australia</td>
<td>489,000</td>
<td>19</td>
</tr>
<tr>
<td>USA</td>
<td>400,000</td>
<td>15</td>
</tr>
<tr>
<td>Turkey</td>
<td>344,000</td>
<td>13</td>
</tr>
<tr>
<td>India</td>
<td>319,000</td>
<td>12</td>
</tr>
<tr>
<td>Venezuela</td>
<td>300,000</td>
<td>12</td>
</tr>
<tr>
<td>Brazil</td>
<td>302,000</td>
<td>12</td>
</tr>
<tr>
<td>Norway</td>
<td>132,000</td>
<td>5</td>
</tr>
<tr>
<td>Egypt</td>
<td>100,000</td>
<td>4</td>
</tr>
<tr>
<td>Russia</td>
<td>75,000</td>
<td>3</td>
</tr>
<tr>
<td>Greenland</td>
<td>54,000</td>
<td>2</td>
</tr>
<tr>
<td>Canada</td>
<td>44,000</td>
<td>2</td>
</tr>
<tr>
<td>South Africa</td>
<td>18,000</td>
<td>1</td>
</tr>
<tr>
<td>Other countries</td>
<td>33,000</td>
<td>1</td>
</tr>
<tr>
<td><strong>World total</strong></td>
<td><strong>2,610,000</strong></td>
<td><strong>-</strong></td>
</tr>
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Present Energy Demand and Supply

- Typical US household wired for 24 kW (120 V x 200 A), peak ~15 kW (electric stove/dryer ~ 5 kW each)
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- Electricity demand growing faster than overall energy demand.
Economics

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  – sustainable,
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- **Green** is a relative, not an absolute.
- All energy sources have advantages and disadvantages.
Economics (cont.)

- All energy sources impact the environment, and none are indefinitely sustainable.
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- An energy source that is “economically competitive” does not require taxpayer subsidies.
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- *negative externalities* – costs of production that are shifted to non-producers; e.g., factory air pollution.
Economics (cont.)

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• Nuclear is the only energy source wherein the industry accounts for and is held responsible for all associated costs.
Green Energy

• *Small Is Beautiful: Economics As If People Mattered* – E. F. Schumacher, 1973 (associate of Keynes and Galbraith)

• US average solar flux \( \approx 200 \text{ W/m}^2 \)

• Wind farm – 1000 MWe \( \approx 600 \text{ mi}^2 \) (25% efficiency assumed)
• Nuclear less costly than renewables.
• Equivalent solar plant requires
  – 15×concrete
  – 75×steel
  – 2,530×land
Rancho Seco

- Nuclear plant 1975-1989, 913 MWe, 39% capacity factor, closed by public referendum

- 2 MWt (?) solar plant (PV1 and PV2)
The set came with four types of uranium ore, a beta-alpha source (Pb-210), a pure beta source (Ru-106), a gamma source (Zn-65?), a spinthariscope, a cloud chamber with its own short-lived alpha source (Po-210), an electroscope, a geiger counter, a manual, a comic book (Dagwood Splits the Atom) and a government manual "Prospecting for Uranium."
The Shoreham Saga

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- 1985-1989 low power testing
- Once completed, officials in Suffolk County refused to cooperate with emergency response exercise, making it impossible to comply with NRC requirement.
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• Total amount of commercial power generated by Shoreham = **ZERO**