Read chapter 8 in text for tonight and next Tuesday.
Midterm exam, Thursday, February 26, will be like homework; it will include a mix of problems and essay questions. The exam will be open book and notes. It will cover up to and including material on electricity generation in the March 17 lecture and the March 24 homework.
Read chapter 8 for the March 3 lecture which is an overview of renewable energy technologies.
Nuclear energy now accounts for a significant fraction of electrical energy produced in the world. In France, the vast majority of electrical energy is produced by nuclear power. Since the accidents at Three Mile Island and Chernobyl there has been an increased public concern about the risks of nuclear energy. In addition, the costs of nuclear power are now higher than other power generation methods.

Recently there has been an increased interest in nuclear generation. In the deregulated power market several older nuclear power plants have been recently sold at a significantly higher price than their previous sale. Increasing concerns about global warming caused by emissions of CO₂ from combustion of fossil fuels have increased the attractiveness of nuclear power.

These notes present an overview of nuclear power generation starting from the basic physics, leading through nuclear plant designs and regulations of nuclear power.

Finally we will discuss the prospects for fusion power and some of the current thinking about the future of nuclear power generation in the US and in the world.
### Nuclear Electricity Share 2006

- **US and Canada**: 18.8%
- **Latin America**: 2.3%
- **Western Europe**: 29.4%
- **Eastern Europe and Former Soviet Union**: 18.2%
- **Middle East/South Asia**: 1.5%
- **Africa**: 2.4%
- **Far East**: 12.4%
- **World Total**: 15.5%

The slide shows the percent of a region’s total electrical energy that is produced by nuclear power, based on IAEA data obtained from the following web site on February 24, 2008:


The nuclear proportion of electrical energy for individual countries having the highest values for this figure is shown below. The percent of the world nuclear electrical energy is also shown for each country. The world total nuclear energy generation for 2006 was 2660 TWh. Data for each country with reactors during that year was taken from the following web site:


<table>
<thead>
<tr>
<th>Country</th>
<th>%nuclear</th>
<th>%world</th>
<th>Country</th>
<th>%nuclear</th>
<th>%world</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>78.1%</td>
<td>17.0%</td>
<td>Spain</td>
<td>19.8%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Lithuania</td>
<td>72.3%</td>
<td>0.3%</td>
<td>Taiwan, China</td>
<td>19.5%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Slovakia</td>
<td>57.2%</td>
<td>0.5%</td>
<td>U.S.</td>
<td>19.4%</td>
<td>27.0%</td>
</tr>
<tr>
<td>Belgium</td>
<td>54.4%</td>
<td>1.6%</td>
<td>U.K.</td>
<td>18.4%</td>
<td>2.8%</td>
</tr>
<tr>
<td>Sweden</td>
<td>48.0%</td>
<td>2.4%</td>
<td>Russia</td>
<td>15.9%</td>
<td>5.8%</td>
</tr>
<tr>
<td>Ukraine</td>
<td>47.6%</td>
<td>3.5%</td>
<td>Canada</td>
<td>15.8%</td>
<td>3.4%</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>43.7%</td>
<td>0.5%</td>
<td>Romania</td>
<td>9.0%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Armenia</td>
<td>42.0%</td>
<td>0.1%</td>
<td>Argentina</td>
<td>6.9%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Slovenia</td>
<td>40.3%</td>
<td>0.2%</td>
<td>Mexico</td>
<td>4.9%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Korea Rep.</td>
<td>38.6%</td>
<td>4.7%</td>
<td>South Africa</td>
<td>4.4%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Hungary</td>
<td>37.7%</td>
<td>0.5%</td>
<td>Netherlands</td>
<td>3.5%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Switzerland</td>
<td>37.4%</td>
<td>0.9%</td>
<td>Brazil</td>
<td>3.1%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Czech RP</td>
<td>31.5%</td>
<td>1.0%</td>
<td>Pakistan</td>
<td>2.7%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Germany</td>
<td>31.4%</td>
<td>5.5%</td>
<td>India</td>
<td>2.6%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Japan</td>
<td>30.0%</td>
<td>12.8%</td>
<td>China</td>
<td>1.8%</td>
<td>2.3%</td>
</tr>
<tr>
<td>Finland</td>
<td>28.0%</td>
<td>0.7%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Organizations

- **Nuclear Regulatory Commission (NRC)**
  - US agency responsible for nuclear power plant operations and regulations

- **International Atomic Energy Authority**
  - The IAEA describes itself as the “world's nuclear inspectorate” to prevent nuclear proliferation and illegal nuclear use

- **US Department of Energy Nuclear Energy Program for nuclear R & D**

Web sites for organizations on chart:
NRC: http://www.nrc.gov/
IAEA: http://www.iaea.org/
DOE/nuclear: http://www.doe.gov/energysources/nuclear.htm

Other organizations and web sites:
The NEI (Nuclear Energy Institute) is an organization of companies involved in the production of nuclear energy including plant operators, construction companies, uranium miners, etc. (http://www.nei.org/)
The WNA (World Nuclear Association) is another organization of companies engaged in all aspects of nuclear energy. (http://www.world-nuclear.org/)
The uranium information center of the Australian Uranium Association (http://www.uic.com.au/) is a useful site for information on uranium production and mining.
The American Nuclear Society (ANS) is the society for working professionals in the field of atomic energy. They have a web site for public information on nuclear issues: http://www.ans.org/pi/
The Federation of Atomic Scientists (http://www.fas.org/nuke/) is an international association of scientists concerned about weapons of mass destruction. Their site has good information on the interactions between nuclear power and potential nuclear proliferation.
The forecast is for a general downturn (or nearly constant level) in the percentage of electricity coming from nuclear energy in regions that already have large amounts. Regions with small amounts are forecast to increase. These forecasts are consistent with the data on nuclear power plants under construction, ordered or planned, and proposed shown on the next chart.

Chart taken from power point presentation downloaded from web site.
### World Reactors (GWe)

<table>
<thead>
<tr>
<th>Region</th>
<th>Current</th>
<th>Building</th>
<th>Planned</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>1.8</td>
<td>0.0</td>
<td>0.2</td>
<td>4.6</td>
</tr>
<tr>
<td>Asia</td>
<td>81.7</td>
<td>13.5</td>
<td>40.5</td>
<td>56.1</td>
</tr>
<tr>
<td>Eastern Europe</td>
<td>11.1</td>
<td>0.7</td>
<td>2.7</td>
<td>4.9</td>
</tr>
<tr>
<td>Former Soviet Union</td>
<td>36.0</td>
<td>2.7</td>
<td>11.5</td>
<td>23.9</td>
</tr>
<tr>
<td>Middle East</td>
<td>0.0</td>
<td>0.9</td>
<td>6.4</td>
<td>4.1</td>
</tr>
<tr>
<td>North America</td>
<td>112.2</td>
<td>2.7</td>
<td>4.7</td>
<td>26.0</td>
</tr>
<tr>
<td>South America</td>
<td>2.8</td>
<td>0.7</td>
<td>1.2</td>
<td>4.7</td>
</tr>
<tr>
<td>Western Europe</td>
<td>123.3</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>World</strong></td>
<td><strong>368.9</strong></td>
<td><strong>22.7</strong></td>
<td><strong>68.9</strong></td>
<td><strong>125.8</strong></td>
</tr>
</tbody>
</table>


This web site, which is now inactive, was maintained by the Australian Uranium Association, Ltd. According to that site, Australia provides about 20% of the world’s uranium although Australia itself does not have any nuclear power plants.

An alternative site for nuclear data is that of the World Nuclear Association. The site [http://world-nuclear.org/outlook/nuclear_century_outlook.html](http://world-nuclear.org/outlook/nuclear_century_outlook.html), has country-by-country forecasts for nuclear generation from now to 2100. According to this site, the current capacity is 367 GWe, similar to the figure stated above. Forecast ranges (low – high) for installed capacity in future years are shown in the following table:

<table>
<thead>
<tr>
<th>Year</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>602 to 1,289</td>
</tr>
<tr>
<td>2060</td>
<td>1,140 to 3,538</td>
</tr>
<tr>
<td>2100</td>
<td>2,062 to 11,046</td>
</tr>
</tbody>
</table>

The WNA forecast is based on the need to curb CO₂ emissions and use various forms of electricity generation, including nuclear, that do not generate such emissions. The web site has the following quote: “even if renewable and clean-fossil technologies meet extremely optimistic assumptions, a global clean-energy revolution adequate to avert catastrophic climate change will require an enormous contribution from nuclear power and extensive realization of its worldwide growth potential.”
<table>
<thead>
<tr>
<th>Country</th>
<th>Resources (Tonnes U)</th>
<th>World %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>1,143,000</td>
<td>24%</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>816,000</td>
<td>17%</td>
</tr>
<tr>
<td>Canada</td>
<td>444,000</td>
<td>9%</td>
</tr>
<tr>
<td>USA</td>
<td>342,000</td>
<td>7%</td>
</tr>
<tr>
<td>South Africa</td>
<td>341,000</td>
<td>7%</td>
</tr>
<tr>
<td>Namibia</td>
<td>282,000</td>
<td>6%</td>
</tr>
<tr>
<td>Brazil</td>
<td>279,000</td>
<td>6%</td>
</tr>
<tr>
<td>Niger</td>
<td>225,000</td>
<td>5%</td>
</tr>
<tr>
<td>Russian Fed.</td>
<td>172,000</td>
<td>4%</td>
</tr>
<tr>
<td>Other</td>
<td>699,000</td>
<td>14%</td>
</tr>
<tr>
<td>World total</td>
<td>4,743,000</td>
<td></td>
</tr>
</tbody>
</table>


As noted on the previous page for the web site has now been discontinued.
The web sites notes that the data were based on sources (OECD, NEA, and IAEA, *Uranium 2005: Resources, Production and Demand*) available on January 1, 2005. The cost of the uranium up to US$130/kg. However, recent US prices have been about $22 to $33 per kg over the last ten years. (EIA web site on uranium cost data, http://www.eia.doe.gov/cneaf/nuclear/umar/summarytable1.html, accessed February 24, 2008.

Current usage is about 68,000 tonnes per year. The current resources are enough to last for about 70 years.

Other countries listed on the web site, but excluded from the table on the chart and their data are:

- Uzbekistan 116,000 2%
- Ukraine 90,000 2%
- Jordan 79,000 2%
- India 67,000 1%
- China 60,000 1%
- All others 287,000 6%

As noted previously, this web site is no longer operative.

The term reasonably assures resources sounds close to what would be called reserves. They are known and economical to recover at a certain price. (In this case the price may be slightly higher than the current market price, so they are not truly reserves.)

This chart shows that increasing the market price from $40/kg to $80/kg does not make a large increase in the available resources.

Here are some conversion factors: 1 mass unit of U₃O₈ contains 0.848001 mass units of uranium (with normal isotopic composition).

A cost of $100 per kg U is the same as $84.80 per kg U₃O₈, $45.36 per lb U, or $38.46 per lb U₃O₈.

As noted previously, this web site is no longer operative.

Between 1975 and 1983 the average annual spending for uranium exploration were about $4.5 \times 10^8$ US$ per year. From 1983 to 2005, the average annual spending has been about $1.3 \times 10^8$ per year. This decline in spending is obviously linked to the reduced need forecast for uranium use in power plants.

This is from the web site of the International nuclear Safety Center, which is operated by Argonne National Laboratory for the US Department of Energy.

The following information about California nuclear power plants would normally begin on the next notes page.

**Diablo Canyon** San Luis Obispo County, California. Construction of the units may have been the longest in U.S. history at 15 and 16 years due to regulatory concern for its ability to withstand seismic activity. Cooling water for the units is obtained from the Pacific Ocean.

**Operator:** Pacific Gas & Electric Company  
**Owner:** PG&E Corp. (100.0%)  
**Reactor Supplier:** Westinghouse Corporation

**Unit 1:** 1,073 net MWe PWR  
**Date of Operation:** November 1984  
**License Expiration Date:** 09/22/2021  
**2001:** 9.47 billion kWh  
**Average Capacity Factor:** 100.8%

**Unit 2 Capacity:** 1,087 net MWe PWR  
**Date of Operation:** August 1985  
**License Expiration Date:** 04/26/2025  
**2001:** 8.61 billion kWh  
**Average Capacity Factor:** 90.4%

**San Onofre** 3-unit site near San Clemente. Unit 1, shutdown in 1992, was a first generation Westinghouse commercial unit that operated for 25 years.

**Units 2 & 3 Operator:** Southern California Edison Co.  
**Owners:** Edison International (75.1%); San Diego Gas & Electric Co. (20%); Anaheim Public Utilities Dept. (3.2%); Riverside Utilities Dept. (1.8%)  
**Reactor Supplier:** Combustion Engineering, Inc.

**Unit 2 Capacity:** 1,070 net MWe PWR  
**Date of Operation:** September 1982  
**License Expiration Date:** 10/18/2022  
**2001:** 9.49 billion kWh  
**Average Capacity Factor:** 101.3%

**Unit 3 Capacity:** 1,080 net MWe PWR  
**Date of Operation:** September 1983  
**License Expiration Date:** 10/18/2022  
**2001:** 5.65 billion kWh  
**Average Capacity Factor:** 59.7%
US and Canada Plant Sites

http://www.insc.anl.gov/pwrmaps/map/united_states.html (accessed on February 24, 2008) is the source for this map and information below and on the previous notes page for California reactors.

Humboldt Bay 3 in Eureka is 63 MW(e) BWR that operated from 1963 to 1976 is permanently shut down.

Rancho Seco in Clay Station (near Sacramento), PWR 913 MW(e). operated from April 1975 to June 1989.

The location near San Francisco is called Vallecitos; this was a 5 MW experimental boiling water reactor that General Electric operated from 1957 to 1963. (Information downloaded from files.asme.org/ASMEORG/Communities/History/Landmarks/5654.pdf on February 16, 2009.)

The Palo Verde plant in Arizona has three PWRs each rated at 1,243 MW(e). This is the largest nuclear facility in the US. **Operator:** Arizona Nuclear Power Project  
**Owners:** Arizona Public Service Co. (29.1%); Salt River Project Agricultural Improvement & Power District (17.5%); Southern California Edison Co. (15.8%); El Paso Electric Co. (15.8%); Public Service Co. of New Mexico (10.2%); Southern California Public Power Authority (5.9%); Los Angeles Department of Water & Power (5.7%) **Reactor Supplier:** Combustion Engineering, Inc.

**Unit 1 in 2001:** 9.46 billion kWh **2001 Average Capacity Factor:** 86.9%  
**Unit 2 in 2001:** 9.98 billion kWh **2001 Average Capacity Factor:** 91.6%  
**Unit 2 in 2001:** 9.29 billion kWh **2001 Average Capacity Factor:** 85.0%

Data on San Onofre and Diablo Canyon are on the notes page for the previous chart.
Nuclear generation in the US has increased significantly without any increase in plant capacity. This has been done by improving the capacity factors for US nuclear plants.

Plot prepared from spreadsheet data downloaded from EIA site http://www.eia.doe.gov/emeu/aer/nuclear.html (Excel link to Nuclear Power Plant Operations) on February 24, 2008.

In some cases plants have made modifications so that they could operate for longer time periods between fuel replacement; such modifications have been subject to approval by the Nuclear Regulatory Commission. Other ways that plant capacity factors have increased is by using additional staff to ensure safe operations and reducing the need for more frequent shutdowns.

The capacity forecast calls for reductions in capacity before the end of this decade followed by some additions to capacity.
Basic Physics

- Einstein: $\Delta e = \Delta mc^2$
- $^{235}\text{U} + n \rightarrow ^{144}\text{Ba} + ^{89}\text{Kr} + 3n + 177\text{MeV}$
- Nuclear energy units
  - 1 atomic mass unit = $1.660 \text{ } 538 \text{ } 73 \times 10^{-27} \text{ kg}$
  - 1 eV = $1.602 \text{ } 176 \text{ } 462 \times 10^{-19} \text{ J}$
- Energy comparison
  - $^{235}\text{U}$ fission = $7.3 \times 10^{13} \text{ J/kg}$
  - Carbon combustion = $3.3 \times 10^7 \text{ J/kg}$

Einstein’s formula $e = mc^2$ can better be written in terms of $\Delta e$ and $\Delta m$. It is the change in mass in a nuclear reaction that produces a certain amount of energy. Atomic masses are measured in terms of the atomic mass unit or amu. One amu is exactly 1/12 the mass of a C$^{12}$ atom. (Recall that the atomic mass system is defined such that the atomic weight of of C$^{12}$ is exactly 12; one amu is approximately the mass of a proton or the mass of a neutron.) Since 12 grams of C$^{12}$ is exactly one mol with Avogadro's number $(6.02214199 \times 10^{23})$ of atoms, one atom of C$^{12}$ has a mass of $12g/(6.02214199 \times 10^{23})$. So the amu is $1/12^{th}$ of this mass or $1.66053873 \times 10^{-27} \text{ kg}$.

The energy unit of electron-volts is the energy generated when one electron moves through an electric field of one volt. The change on an electron is $1.60217426 \times 10^{-19} \text{ coulombs}$, and one coulomb-volt = 1 joule. (Recall that 1 ampere = 1 coulomb/s and the product of amps and volts is watts or joule-seCONDS.) Thus the energy in one eV is $1.602176462 \times 10^{-19} \text{ J}$. The speed of light is $299,792,458 \text{ m/s}$, so the annihilation of 1 emu of mass produces $(1.66053873 \times 10^{-27} \text{ kg}) \times (299,792,458 \text{ m/s})^2 = 1.49241778308056 \times 10^{-10} \text{ J} = 931495084.5 \text{ eV} = 931.4950845 \text{ MeV}$. In the fission of $^{235}\text{U}$ into $^{144}\text{Ba}$ and $^{89}\text{Kr}$, the mass difference is 0.19 amu producing the energy shown.

In this reaction the energy release per unit mass of $^{235}\text{U}$ is 177 MeV / $235.04394 \text{ amu}$; this is equivalent to $7.3 \times 10^{13} \text{ J/kg}$ compared to $3.3 \times 10^7 \text{ J/kg}$ for carbon combustion.
Mass Defect

- Isotopic mass, M, less than mass of constituents
- Difference is binding energy
- \( D = Z(m_p + m_e) + (A - Z)m_n - M \)
- Where \( D \) = mass defect, \( m_p \), \( m_e \), and \( m_n \) are masses of proton, electron and neutron, \( Z \) = protons, \( A - Z \) = neutrons
- Binding energy, \( BE = Dc^2 \)

M in this chart is the mass of the nucleus with \( Z \) protons and \( A - Z \) neutrons. M may be measured in any consistent mass units, amu, kg, etc.

The concept of a mass defect recognizes that the binding energy of the nucleus, \( BE \), can be written in terms of this mass defect using Einsein’s formula that \( \Delta e = \Delta mc^2 \). In this case the energy change is the binding energy, \( BE \), and the mass change is \( \Delta m \); this gives the equation that \( BE = Dc^2 \). From the conversion factors on the previous chart, a mass defect of 1 amu is equivalent to a binding energy of 931.4950845 MeV.

With the units of amu, the mass of one atom or molecule is just the atomic or molecular weight expressed in amu. For example the mass of \(^{235}\text{U}\) is 235.04394 amu. The mass of a neutron is 1.008665 amu; the masses of a proton and an electron are 1.007276 amu and 0.000549 amu, respectively.

The binding energy is commonly expressed as the average binding energy, \( ABE \), is the binding energy, \( BI \), divided by the total “nucleons”, \( A \), which is the sum of protons and neutrons. The equation for the average binding energy is simply the equation on the chart divided by \( A \).

\[
ABE = \frac{Z}{A} \left( m_p + m_n \right) + \left( 1 - \frac{Z}{A} \right) m_n - \frac{M}{A}
\]

The binding energy is the energy produced in a hypothetical reaction where the all the protons and all the neutrons which are initially assumed to exist as free particles combine to form the particular isotope.
We see that the average binding energy per nucleon (ABE on previous notes page) is a maximum for iron. This chart allows us to see the effects of fission or fusion. We start with a certain binding energy in the initial element(s). When we have a nuclear reaction to another set of elements (with a certain average binding energy per nucleon), we have the possibility of releasing energy if the binding energy of the products is greater than the binding energy of the reactants.

This occurs because we can write, for example

92 protons + 143 neutrons → U-235 + 235(7.6 MeV)

For the average fission products we can write

92 protons + 143 neutrons → Fission products + 235(8.6 MeV)

Subtracting these two expression gives

U-235 → Fission products + 210 MeV

For elements lighter than iron, we can produce nuclear energy when we combine lighter elements into heavier ones. This is known as nuclear fusion. For elements heavier than iron, nuclear fission, the separation of a heavier element into two (or more) lighter ones will produce energy.
Nuclear Radiation

- Spontaneous decay of nuclei can yield other nuclei and radiation
  - Alpha particles $^{239}\text{Pu} \rightarrow ^{235}\text{U} + \alpha(^4\text{He})$
  - Beta particles $^{90}\text{Sr} \rightarrow ^{90}\text{Y} + \beta(^0\text{e})$
  - Gamma radiation $^{60}\text{Co} \rightarrow ^{60}\text{Co} + \gamma$

- The $\alpha$, $\beta$, and $\gamma$ radiation have different energy levels that affects their impact

- Major concern: health effects of radiation

In addition to nuclear fusion and fission, we can have a series of other nuclear reactions. In these reactions different kinds of radiation are released. Note that beta radiation, although it is equivalent to an electron, comes from the nucleus, not from the outer shell of the atom. Release of an electron from a nucleus with $Z$ protons and $A-Z$ neutrons increases the number of protons by one and decreases the number of neutrons by one. Decreasing the number of protons changes the chemical identity of the nucleus. Thus the beta decay of strontium-90 into yttirium comes because the number of protons in the nucleus has increased from 38 to 39.

Gamma radiation is high energy electromagnetic radiation. The wavelength region for gamma rays is between $10^{-10}$ and $10^{-12}$ meters. Gamma radiation does not change the chemical identity of the atom.

An alpha particle is a helium nucleus; release of an alpha particle does change the chemical identity of the atom.

In a nuclear reaction a complex series of changes can occur. Not only does the basic fission reaction take place, but products from the original fission, called daughter products can under go other reactions. The complexity of the reaction schemes produces a large amount of different isotopes, with varying degrees of radioactivity in the spent fuel from the nuclear reactor.
Chain Reactions

- $^{235}\text{U} + n \rightarrow ^{144}\text{Ba} + ^{89}\text{Kr} + 3n + 177\text{MeV}$
- Product neutrons, called fast neutrons, have MeV range energies
- Slow or thermal neutrons energies are in the eV range
- In a nuclear reactor the fast neutrons may be moderated into slow neutrons

The equation at the top of the page is taken from a previous slide. It shows the basic notion of a chain reaction. The reaction not only produces energy, but it also produces additional neutrons to carry on the reaction.

Some of the neutrons may be absorbed and some may leave the reactor. A critical mass is one in which the chain reaction can be sustained.

Additional reactions can take place in a nuclear reactor from the product neutrons. One of these is the production of plutonium-239 by the reaction of a neutron with U-238 that is usually present. Here is the sequence that produces plutonium

$^{238}\text{U} + n \rightarrow ^{239}\text{U} + \gamma$

$^{239}\text{U} \rightarrow \beta + ^{239}\text{Np}$

$^{239}\text{Np} \rightarrow \beta + ^{239}\text{Pu}$

The first reaction in this sequence changes the number of neutrons in the nucleus, but it does not change the number of protons; thus we still have element the element with 92 protons in the nucleus, uranium. In the second reaction, the $^{239}\text{U}$ releases an electron from the nucleus. This does not affect the total number of nucleons in the nucleus; instead it converts a neutron to a proton. We thus have 93 protons in the nucleus so we have formed element 93 which is called neptunium. The neptunium then undergoes a subsequent beta decay with the same effect. The number of protons in the nucleus is increases giving element 94 which is Plutonium.

Plutonium is the main element used in nuclear weapons. The design of nuclear reactors depends on their purpose. Reactors to produce nuclear weapons are designed to produce significant amounts of plutonium. Civilian reactors are designed to avoid the production of plutonium.
Radioactive Decay

- Decay proportional to amount present
- Gives first order differential equation for radioactive decay \( N = \text{amount} \)
- \( \frac{dN}{dt} = -kN \) so \( N = N_0 e^{-kt} \)
- \( t = \frac{-1}{k} \ln\left(\frac{N}{N_0}\right) \)
- Half life, \( t_{1/2} \), is point where \( N/N_0 = \frac{1}{2} \)
- \( t_{1/2} = \frac{-1}{k} \ln\left(\frac{1}{2}\right) = \frac{\ln(2)}{k} \)
- \( N = N_0 e^{-\ln(2)t/t_{1/2}} \)

The decay rate of spontaneous radiation is directly proportional to the amount present. The time required for half of the initial radiation to decay is known as the half life. Half lives for various isotopes can range from centuries to microseconds.

The calculation of how much of the original amount of a radioactive isotope is present after a certain period of time is computed in terms of half lives:

- \( \frac{1}{2} \) present after one half life
- \( \frac{1}{4} \) present after two half lives
- \( \frac{1}{8} \) present after three half lives
- \( \frac{1}{16} \) present after four half lives
- \( \frac{1}{1024} \) present after ten half lives
- \( \frac{1}{1048476} \) present after twenty half lives

The proposed nuclear waste storage facility in Ward Valley Nevada is designed to store the nuclear waste that will be radioactive for a long time.
Radiation Measurements

- Units for rate of decay
  - becquerel (Bq) = 1 disintegration per sec
  - curie (Cu) – older unit; 1 Cu = 3.72x10^{10} Bq

- Units for energy deposited in matter
  - 1 gray (Gy) = 1 J/kg in water
  - 1 roentgen (R) = .008 J/kg in air (approx)
  - 1 rad = .01 Gy (radiation absorbed dose)

The curie is defined as the amount of radiation from one gram of radium. Thus one gram of radium has 3.72x10^{10} disintegrations per second.

The gray is defined as the amount of energy absorbed in water, where water is used as a surrogate for human tissue. The gray is really trying to measure the amount of energy absorbed in human tissue.

The roentgen (R) is a measure of radiation intensity of X-rays or gamma rays. It is formally defined as the radiation intensity required to produce and ionization charge of 0.000258 coulombs per kilogram of air. It is one of the standard units for radiation dosimetry, but is not applicable to alpha, beta, or other particle emission and does not accurately predict the tissue effects of gamma rays of extremely high energies. The roentgen has mainly been used for calibration of X-ray machines. (Quoted from http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html.)
Biological Effectiveness

- The sievert (Sv) is the new measure of effective radiation dose
  - Replaces the former unit of rem (roentgen equivalent man)
- Biological equivalence coefficient, Q, accounts for different radiation effects
  - 1 rad delivers Q rem
  - 1 Gy delivers Q Sv

There are two approaches to defining standards. The first uses direct measures of the radiation in terms of grays (or the older units of rads). The other uses the notion of biological effective dose described here. Again, there is a new unit, the sievert, and an old unit, the rem. The conversion between these two is the same as the conversion between grays and rads:

1 gray = 100 rads or 1 rad = 0.01 gray
1 sievert = 100 rem or 1 rem = 0.01 sievert

The Q factor is not constant. For alpha particles it is about 20. For X-rays it is defined to be one.

Although the sievert is now the preferred unit for radiation exposures, there is still a large amount of data in rems and, more commonly, millirems.
These data were taken from Table 4-1, page 89 in the book *Megawatts and Megatons*, by Garwin and Charpak. Recall that 1 sievert = 100 rem so these numbers would be multiplied by 100 to get the doses in millirem.

This chart shows the normal exposure that the typical US resident has to radiation from natural and medical sources. This is an average and there are large differences in the various exposures depending on your individual living situation.

People in Denver get more cosmic rays than people in Los Angeles. (So do people who fly a lot compared to people who don’t.)

People who live in brick houses get radon exposure. Other get significantly less.

The exposure to environmental minerals depends to a large degree on where you live. At one time there were attempts to mine uranium in the Antelope Valley; I would guess that there may be larger mineral background radiation in parts of the Antelope Valley than there are in the Los Angeles Basin.

X-ray exposure is obviously dependent on the amount of X rays one receives. This is a risk benefit calculation that all individuals subconsciously make to have the benefits of medical diagnosis traded against the risks of radiation exposure.

Note that all such data are subject to approximations and the data here differ from those on the next slide taken from a different source.

<table>
<thead>
<tr>
<th>Natural Radiation Doses</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic rays</td>
<td>0.38 mSv/yr</td>
</tr>
<tr>
<td>Internal to human body</td>
<td>0.19 mSv/yr</td>
</tr>
<tr>
<td>Environmental minerals</td>
<td>0.46 mSv/yr</td>
</tr>
<tr>
<td>Radon and daughters</td>
<td>1.3 mSv/yr</td>
</tr>
<tr>
<td>Medical/dental X-rays</td>
<td>0.54 mSv/yr</td>
</tr>
<tr>
<td>Total natural plus medical</td>
<td>2.87 mSv/yr</td>
</tr>
</tbody>
</table>

In this chart medical X-rays are said to contribute 80 millirems which is equivalent to 0.8 mSv in contrast the estimate of 0.54 mSv on the previous chart. Similarly the total exposure to natural and medical radiation is listed here as 200 millirems per year as compared to 2.87 mSv = 287 millirems on the last chart.

http://www.nrc.gov/what-we-do/radiation/sources.html#member says that the total natural dose is about 360 millirems/year or about 3.6 mSv/yr. Of this total, natural sources of radiation account for about 81% of all public exposure, while man-made sources account for the remaining 19%. Natural and artificial radiations are not different in any kind or effect. Above this background level of radiation exposure, the NRC requires that its licensees limit maximum radiation exposure to individual members of the public to 100 mrem (1 mSv) per year, and limit occupational radiation exposure to adults working with radioactive material to 5,000 mrem (50 mSv) per year. (NRC regulations and radiation exposure limits are contained in Title 10 of the Code of Feral Regulations under Part 20).
Health Risks

- Cumulative risk of getting a disease at any time is lifetime risk (0.25 for cancer)
- Relative risk: ratio of incidence from some cause to normal incidence
  - Relative risk of smoking for lung cancer 9.9
  - Cohort studies measure relative risk
  - Case control studies measure odds ratio
  - Excess relative risk = relative risk minus 1

Health risks are measured in the terms shown here.

The difference between an odds ratio and a relative risk is a formal one which recognizes the differences in two kinds of studies. In a cohort study, sometimes called a prospective study, two groups are selected. One group receives a “treatment” and a second group does not. The groups are followed for some period of time and the incidence of the disease under study is measured in both groups. The incidence rate of some disease in the group with the “treatment” is then compared to the incidence rate in the group which did not receive the treatment. The cohorts are designed to have similar activity patterns so the differences in the disease rate will be due to the treatment.

The second kind of study, the case control study, sometimes called a retrospective study, is one in which two groups are selected (e.g. people who worked with radiation and those who did not). The incidence rate of certain diseases is then compared for the two groups. Other factors which may affect the results are controlled for in the study.

Both types of studies are known as epidemiological studies. These are studies on human populations. Ethical issues govern these studies and limit the kinds of exposures that can be provided.

Other types of studies, known as toxicological studies, use laboratory animals. In such studies it is possible to use exposures to large doses that would not be used on humans. The problem is in extrapolating results to humans. This is usually done by studying the effect in terms of units like grams of dose per kilogram of body weight. The easiest subjects to use are mice, but these have a metabolism that is not like humans. Studies on larger animals are more expensive and usually not done.

My favorite quote from an epidemiologist is the following: “Epidemiology uses the right species but does not always have accurate dose data; toxicology uses the wrong species but has accurate dose data. I'll take the right species any time.”
Reference: http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html which attributes the chart to the Atlanta Journal, March 20, 1993, page F1.

The health effects associated with exposures to radiation are uncertain. Although we know that large doses have the results shown in the table below, we do not know what the long term effects to low does of radiation over long times are. The standards for radiation exposure are based on a linear, no-threshold hypothesis. This means that high does exposures for which we have data are extrapolated to zero effect at zero dose, without assuming a threshold. Some health scientists have argued that this is too conservative, but it has been used to provide protection to the public.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Dose (rems)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No observable effect</td>
<td>0-25</td>
</tr>
<tr>
<td>Slight blood changes</td>
<td>25-100</td>
</tr>
<tr>
<td>Significant reduction in blood platelets and white blood cells (temporary)</td>
<td>100-200</td>
</tr>
<tr>
<td>Severe blood damage, nausea, hair loss, hemorrhage, death in many cases</td>
<td>200-500</td>
</tr>
<tr>
<td>Death in less than two months for over 80%</td>
<td>&gt;600</td>
</tr>
</tbody>
</table>
Nuclear Reactors

- Classified by neutron energy
  - Fast versus slow
- Moderators reduce neutron energy
- Fast breeder reactors
- Light water reactors
- Gas cooled rectors
- CANDU reactors

Nuclear reactors have fissile fuel that undergoes nuclear fission and produces energy. Once a chain reaction is started many different reactions can take place in the reactor. If the majority of the fission reactions are done by fast neutrons, the reactor is called a fast reactor. When moderators are used to absorb the energy of the fast neutrons, most of the fissions are done by slow (or thermal) neutrons. Such reactors are called thermal reactors (because they use thermal neutrons).

All nuclear reactors have the following an active core in which fissile fuel undergoes fission. The core may also contain a fertile material that can be converted to a fissile material. If the reactor is to use slow or thermal neutrons, a moderator is required. The core is surrounded by a reflector to prevent neutrons from escaping from the core.

The heat produced in the core is removed by a coolant. The energy added to this coolant is then used to produce useful power from the reactor.

The reaction is controlled by rods inserted into the core that absorb neutrons. Such rods, called control rods, are neutron poisons such as boron or cadmium.

Fast breeder reactors use both a fertile and a fissile material. Such a reactor can produce more fuel from the fertile material than it consumes from the fissile material.

Most commercial reactors are light-water reactors in which H₂O, with its natural isotopic composition acts as both the moderator and the coolant. Such reactors have a fuel that is about 2% to 4% U-235.

The CANDU reactor uses natural uranium as the fuel with heavy-water (deuterium oxide or D₂O) as the moderator.
This diagram shows a pressurized water reactor. In this reactor there is a separate coolant loop of high pressure water that receives heat from the reactor and then exchanges heat with the working fluid in the steam generator (SG). Both the reactor and the steam generator are located within the containment vessel that is designed to contain the debris from a nuclear accident. Steam produced in the steam generator then is used in a steam turbine as in a fossil-fueled power plant.

In this diagram RCP is the reactor coolant pump and PZR is the pressurizer, a tank or vessel that acts as a head tank (or surge volume) to control the pressure in a pressurized water reactor.

The diagram was found at http://eia.doe.gov/cneaf/nuclear/page/nuc_reactors/pwr.html in September 2001.

In the US 69 units are pressurized water reactors (PWRs) totaling 65,100 net megawatts (electric) and 35 units are boiling water (BWR) totaling 32,300 net megawatts (electric).
This detailed diagram of a reactor vessel for a pressurized water reactor was found at http://eia.doe.gov/cneaf/nuclear/page/nuc_reactors/pwr.html in September 2001.

Recall that the purpose of this vessel is to establish a controlled nuclear reaction that transfers heat to high pressure water. The high pressure water, which does not boil in a PWR, then transfers heat in a separate loop to the actual working fluid in the steam cycle.

This chart shows the detailed requirements for the reactor vessel, particularly the ability to insert and withdraw control rods from the reactor. These control rods absorb neutrons and their removal allows the reaction to proceed. Inserting the control rods into the reactor decreases the amount of the nuclear reactions, which, in turn, reduces the heat produced.
Boiling Water Reactor


In the boiling water reactor, the heat from the reactor core is transferred to the working fluid, producing steam. The steam from the reactor goes directly to the steam turbine to produce electricity. In order to keep the core cooled, additional water circulation is used.
CANDU Reactors


CANDU (a registered trademark) stands for "Canada Deuterium Uranium". It is a pressurized-heavy-water, natural-uranium power reactor designed first in the late 1950s by a consortium of Canadian government and private industry. All power reactors in Canada are of the CANDU type (of varying vintage). It is also the power-reactor product marketed by Canada abroad.

The CANDU reactor uses natural uranium fuel and heavy water (D₂O) as both moderator and coolant (the moderator and coolant are separate systems). It is refueled at full-power, a capability provided by the subdivision of the core into hundreds of separate pressure tubes. Each pressure tube holds a single string of natural uranium fuel bundles (each bundle is half a meter long and weighing about 20 kg) immersed in heavy-water coolant, and can be thought of as one of many separate "mini-pressure-vessel reactors" - highly subcritical of course. Surrounding each pressure tube a low-pressure, low-temperature moderator, also heavy water, fills the space between neighboring pressure tubes.

Heavy water is about eight times worse than light water for slowing down ("moderating") neutrons, but its macroscopic absorption cross-section (i.e. probability of absorption) is over 600 times less, leading to a moderating ratio (the ratio of the two parameters, a useful measure of a moderator's quality) that is 80 times higher than that of light water.

Heavy water's low absorption cross-section permits the use of natural uranium, which is low in fissile content and would not attain criticality in a light-water lattice. The lower slowing-down power of heavy water requires a much larger lattice than in light-water cores; however, the larger lattice allows space at the core end faces for on-line refueling, as well as space between channels for control rods, in-core detectors, and other non-fuel components.
Reference:

High temperature gas (cooled) reactors HTGR or HTGCR uses graphite as the moderator and some gas such as helium as the coolant. The power conversion uses a closed Brayton cycle. (Typical Brayton cycle engines that use the combustion gases as the working fluid simply dump the waste heat in the form of exhaust gas to the atmosphere.

This diagram shows the GT-MHR development program has started in 1993 in a venture involving MINATOM of Russia and General Atomics (GA) of the US, together with Framatome of France and Fuji Electric of Japan. The proposed plant, rated at 600 MWt/293 Mwe will be utilized for weapons Plutonium destruction with a long-term goal of commercial development. The final design is expected in 2005, with construction planned for 2009.

Claimed efficiencies for the advanced reactor types are of the order of 50%.
Nuclear Reactor Fuel

- Light water reactors require enriched uranium fuel
- Natural uranium has about 0.7% $^{235}\text{U}$
- Power plants require enrichment to about 5% $^{235}\text{U}$ or less
- Gaseous diffusion phasing out in favor of centrifuge separation
- Separative work units (SWU)


In order to start and sustain a chain-reaction in a light water reactor, the uranium isotope $^{235}\text{U}$ ($^{235}\text{U}$) in nuclear fuel must have a concentration of up to 5% depending on reactor-type and design. $^{235}\text{U}$ is the only isotope of uranium which can be split by thermal neutrons. However, naturally occurring uranium, contains only 0.71% of the $^{235}\text{U}$ isotope. The remaining portion is overwhelmingly made up of the $^{238}\text{U}$ isotope which cannot be split. The enrichment of the somewhat lighter $^{235}\text{U}$ is thus a technically necessary step in the manufacture of nuclear fuel from natural uranium. For the annual reload of a standard pressurized water reactor of 1300 MW electrical capacity some 24 tonnes of uranium with an average $^{235}\text{U}$ concentration of 3.95% are required.

Assuming depletion to 0.3% $^{235}\text{U}$ some 213 tonnes of natural uranium must be used and some 124 tonnes of separative work are required for the enrichment. Separative work is a measure of the amount of effort required for enriching uranium. For the enrichment of uranium a number of separation processes have been invented and in part further developed. The main processes used today are gaseous diffusion and centrifugation. Both of these take advantage of the differences in mass between the uranium isotopes.

Recall that CANDU reactors, which use heavy-water as the moderator, do not require enriched uranium.
Complete fuel cycle from mining to disposal requires several steps to get uranium ore from mines to reactor fuel and disposal.


Mined uranium ore typically has between 0.1% uranium (low grade) and 2% uranium (high grade). The ore must be processed to remove the uranium prior to the conversion step shown in the diagram. As mined, uranium is in the compound U₃O₈, commonly known as yellowcake because of its color. Separation processes for enriching the uranium use the gaseous uranium compound, uranium hexafluoride (UF₆). Prior to conversion to UF₆, the uranium is converted to UO₂ which is used in reactors that do not require enriched uranium.

The enriched uranium is then converted from gaseous UF₆ to solid UO₂, which is then sintered at temperatures above 1400°C and formed into fuel pellets. The pellets are then placed in fuel rods, typically about 4 m long, which are used in the actual reactors.

These preparation steps leave two waste streams. The first is the mine tailings from which the uranium has been removed. These are other compounds, with a trace of the original uranium that cannot be removed economically. These will constitute about 99% of the original ore and will have a residual radioactivity. The second waste stream (shown above as depleted uranium) comes from the enrichment process. This stream will be uranium with a reduced content of U²³⁵. Again, because of the low initial concentration of this isotope, most of the feed to the enrichment plant will wind up as depleted uranium.
Uranium Hexafluoride UF₆

- Triple point at 1516.5 mbar: 64.02 °C
- Density (solid) at 20.7°C: 5.09 g/cm³
- Density (liquid) at 64.02°C: 3.668 g/cm³
- Density (liquid) at 148.9°C: 3.043 g/cm³
- Heat of sublimation at 64.02°C: 11.4 kcal/mol
- Melting heat at 64.02°C: 4.5 kcal/mol
- Vaporizing heat at 64.02°C: 6.8 kcal/mol
- Reaction heat with water at 25°C: 50.4 kcal/mol
- Critical pressure: 45.6 bar
- Critical temperature: 230.2 °C
- Vapor pressure at 20°C: 106.7 mbar
- Molecular weight: 352.07 kg/kmol
- Sublimation point at 1013.5 mbar: 56.4°C


The following information was accessed on February 28, 2008 from the site http://www.uic.com.au/nip33.htm

**World Conversion supply and demand** (thousand tonnes U as UF6)

<table>
<thead>
<tr>
<th>Supplier</th>
<th>2007</th>
<th>2010</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cameco (Canada &amp; UK)</td>
<td>13.7</td>
<td>15.5</td>
<td>15.5</td>
</tr>
<tr>
<td>Areva</td>
<td>14.0</td>
<td>14.0</td>
<td>15.0</td>
</tr>
<tr>
<td>ConverDyn</td>
<td>12.0</td>
<td>14.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Rosatom</td>
<td>5.0</td>
<td>5.5</td>
<td>10.0</td>
</tr>
<tr>
<td>China</td>
<td>1.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>UF6e inventories</td>
<td>20.1</td>
<td>20.8</td>
<td>11.0</td>
</tr>
<tr>
<td>Total supply</td>
<td>66.3</td>
<td>72.3</td>
<td>72.0</td>
</tr>
<tr>
<td>Requirements (ERI)</td>
<td>59</td>
<td>62-65</td>
<td>67-77</td>
</tr>
<tr>
<td>Requirements (WNA)</td>
<td>61</td>
<td>61-64</td>
<td>70-77</td>
</tr>
</tbody>
</table>

In a dry process uranium trioxide is reduced hydrogen to uranium dioxide which is further reacted with gaseous hydrogen fluoride (HF) to form uranium tetrafluoride. The tetrafluoride is reacted with gaseous fluorine to produce UF₆. An alternative wet process produces the tetrafluoride from uranium oxide by reaction with hydrofluoric acid (HF in solution with water).
Separative Work Unit

- Have feed, product and tails streams
  - Feed mass flow rate $F$ (kg/s)
  - Feed $^{235}\text{U}$ concentration, $N_F = 0.0071$
  - Similar data for product stream ($P$ and $N_P$) and waste (tail) stream ($T$ and $N_T$)
- Mass balance $F = P + T$
- Balance on $^{235}\text{U}$: $F N_F = P N_P + T N_T$
- $\text{SWU} = PV(N_P) + TV(N_T) - FV(N_F)$
- $V(N)$ is the value function

Note that uranium costs for a nuclear operator are a combination of the cost of the raw uranium (with a natural $^{235}\text{U}$) content and the cost of enrichment. A higher material cost justifies a higher enrichment cost that will produce more useful uranium fuel, per unit cost of the raw material.

In 2006 the average cost per SWU for US nuclear power plant operators was $106 per SWU. (reference http://www.eia.doe.gov/cneaf/nuclear/umar/table16.html, accessed February 25, 2008).

Earlier cost data (unreferenced notes by L. S. Caretto) show a spot market price for uranium enrichment of $98.00 per separative work unit (SWU) in mid-1996. By mid-1998 the spot market prices was $86 per SWU and in June 1999 the price was $84 per SWU. During this period the US dollar was appreciating against most European currencies decreasing the dollar cost of foreign enriched uranium. European enrichers Urenco and Cogema could sell more competitively in the U.S. market, were they were able to gain additional market share. European enrichers also made additional inroads to the Japanese market.

During the mid 1990s, Urenco, a European-based enricher, expanded its production capabilities with modern centrifuges that could produce lower cost per SWU and this also contributed to a decline in costs.
Calculating SWU

- Value function defined and tabulated

\[ V(N) = (2N - 1) \ln \left( \frac{N}{1-N} \right) \]

<table>
<thead>
<tr>
<th>N</th>
<th>V(N)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>6.892941</td>
<td>0.999</td>
</tr>
<tr>
<td>0.002</td>
<td>6.187756</td>
<td>0.998</td>
</tr>
<tr>
<td>0.005</td>
<td>5.240372</td>
<td>0.995</td>
</tr>
<tr>
<td>0.01</td>
<td>4.503217</td>
<td>0.99</td>
</tr>
<tr>
<td>0.02</td>
<td>3.736147</td>
<td>0.98</td>
</tr>
<tr>
<td>0.05</td>
<td>2.649995</td>
<td>0.95</td>
</tr>
<tr>
<td>0.1</td>
<td>1.75778</td>
<td>0.9</td>
</tr>
<tr>
<td>0.2</td>
<td>0.831777</td>
<td>0.8</td>
</tr>
<tr>
<td>0.5</td>
<td>0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The value function is a measure of the work involved in obtaining pure components from a binary mixture. It depends only on the concentrations. The work is defined to be zero for a 50:50 mixture. As the degree of purity of the components in the separated stream increases, the separative work increases.

The symmetry about \( N = \frac{1}{2} \) can be expressed by the following equation

\[ V\left(\frac{1}{2}+x\right) = V\left(\frac{1}{2} - x\right) \]

Note that there are two effects taking place here, concentration and recovery. For a given concentration of \( \text{U}^{235} \) in the product stream, it takes more work to produce a lower concentration in the tailings. This recovers more of the uranium, reducing the initial material cost. The optimum tailing concentration is a trade off between the material cost and the separation costs.
Enrichment

- For $N_P = 3\%$, 3.8 SWU required if $N_T = 0.25\%$, or 5.0 SWU if $N_T = 0.15\%$
  - $N_T = 0.15\%$ requires only 5.1 kg of natural U; (6.0 kg of natural U for $N_T = 0.25\%$)
- About 100-120,000 SWU for annual fuel loading in 1000 MWe light water reactor
- Gaseous diffusion 9000 MJ per SWU; gas centrifuge 180 MJ per SWU.
- Enrichment ~5% of the electricity cost


Gaseous diffusion was developed by the Manhattan project during World War II as the shortest path to providing enriched uranium. More recently centrifuge technology has proven more economical and is the preferred technology. Older gaseous diffusion plants are being phased out.

In 2007 gaseous diffusion accounted for about 25% of the total enrichment. Another 10% came from conversion of weapons grade materials into reactor fuel. The remaining 65% of enriched uranium came from centrifuge operations. The forecast for 2017 is that 96% of the enriched uranium will come from centrifuge operations with the remaining 4% coming from conversions of weapons grade materials into reactor fuels.

Other separation processes including electromagnetic separation and aerodynamic separation are possible, but are more costly than centrifuge separation. A new laser process is currently being developed.

The following data for a “typical” 1000 MWe reactor were accessed on February 26, 2008 from http://www.world-nuclear.org/info/inf03.html: (t stands for tonnes) 20,000 t of uranium ore with 1% uranium produces 230 t of $U_3O_8$ which is converted to 288 t of $UF_6$ (both have 195 t uranium). The enrichment process produces 35 t of $UF_6$ with 24 t of enriched uranium (4% $U^{235}$ content). The remaining 253 t of $UF_6$ is the tails with a $U^{235}$ content of 0.24%. This process requires 140,000 SWU.

*(continued on next notes page)*
US Uranium Costs

- $10 per pound of U₃O₈ equals $11.79 per pound of uranium


Note the steady increase in uranium costs over time. Using the previously stated conversion factors for the cost per pound of uranium (a cost of $100 per kg U is the same as $84.80 per kg U₂O₈, $45.36 per lb U, or $38.46 per lb U₃O₈) shows that a cost of $10 per pound of U₃O₈ is the same as a cost of $11.79 per pound of uranium.

(Continued from previous notes page)

The 35 t of UF₆ is converted into 27 t of UO₂ (still with 24 t of enriched uranium) for fuel fabrication. This 24 t or enriched uranium is 1/3 of the reactor’s total load of 72 t, 1/3 of which is replaced annually. The reactor can produce 7.75 TWh of electricity (assuming a capacity factor of 88.5%).

When the 27 t of UO₂ fuel are removed from the reactor, it will contain 23 t of uranium with a U²³⁵ concentration of 0.5%. It will also contain 240 kg of plutonium and 720 kg of fission products.

The performance of this reactor is rated as 45,000 MW·day/t. This is called the burn-up rate.
Most US SWU from foreign sources


<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>France - Areva</td>
<td>10,800</td>
<td>10,800</td>
<td>7500</td>
</tr>
<tr>
<td>Germany-Netherlands-Urenco</td>
<td>5850</td>
<td>9000</td>
<td>11,000+</td>
</tr>
<tr>
<td>Japan - JNFL</td>
<td>900</td>
<td>1050</td>
<td>1500</td>
</tr>
<tr>
<td>USA - USEC</td>
<td>8,000</td>
<td>11,300</td>
<td>3500+</td>
</tr>
<tr>
<td>USA - Urenco &amp; Areva</td>
<td>0</td>
<td>0</td>
<td>4000+</td>
</tr>
<tr>
<td>Russia - Tenex</td>
<td>20,000</td>
<td>25,000</td>
<td>33,000+</td>
</tr>
<tr>
<td>China - CNNC</td>
<td>1,000</td>
<td>1000</td>
<td>1000+</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>total</td>
<td>~46,500</td>
<td>48,450</td>
<td>61,800+</td>
</tr>
<tr>
<td>Requirements (WNA)</td>
<td>&lt; &gt;</td>
<td>48,428</td>
<td>57,000 - 63,000</td>
</tr>
</tbody>
</table>
This chart shows the balance between the price of the natural uranium and the price of the enrichment.

The purchaser of enriched uranium seeks to minimize the cost of enriched uranium, plotted on the vertical axis (after being divided by the original cost of the natural uranium.) The parameter in the plot is the ratio of the enrichment cost to the feed cost. The chart shows the amount of U^{235} that should be left in the tails (waste) stream to minimize the overall cost.

The curves have a very gradual slope so the location of the optimum tails assay (the fraction of U^{235} remaining in the waste stream) is not that critical. As expected it is more efficient to have a lower tails assay as the ratio of enrichment cost to natural uranium cost decreases.

For example, if the cost of natural uranium is $20 per pound of U_3O_8 and the ratio of enrichment cost to natural uranium cost is ($2/SWU)/($/lb U_3O_8), then the optimum tails assay is about 0.2 %wt and the total cost of enriched uranium (in $/kg) is about 27 times the original uranium cost of $20 per pound of U_3O_8 for a total cost of $540 per kg of enriched uranium. If the ratio of enrichment cost to natural uranium cost is ($20/SWU)/($/lb U_3O_8) then the optimum tails assay is about 0.45 %wt and the total cost of enriched uranium (in $/kg) is about 97 times the original uranium cost of $20 per pound of U_3O_8 for a total cost of $1,840 per kg of enriched uranium.

The Tricastin gaseous diffusion plant in Southern France produces enriched uranium for the operation of French nuclear reactors. The actual gaseous diffusion plants are in the four dark buildings in the center of the picture. In the foreground are the four nuclear reactors required to produce the electricity for the plant.
Nuclear Energy Regulation

- Nuclear Regulatory Commission (NRC)
- International Atomic Energy Agency (IAEA)
- Environmental Protection Agency (EPA)
- Department of Energy (DOE)
  - Responsible for design of national nuclear waste facility
  - Must get approval of NRC for actual plans for disposal site

NRC has responsibility for regulating the use of—
Source material (uranium and thorium)
Special nuclear material (enriched uranium and plutonium)
Byproduct material (material made radioactive in a reactor, and residues from the milling of uranium and thorium)
The NRC regulates the use of radioactive materials through 10 CFR Part 20, "Standards for Protection Against Radiation." Part 20 includes agency requirements for Dose limits for radiation workers and members of the public Monitoring and labeling radioactive materials, Posting radiation areas, Reporting the theft or loss of radioactive material,
Part 20 also includes Penalties for not complying with NRC regulations and tables of individual radionuclide exposure limits.
The IAEA is responsible for setting international programs for nuclear energy. Much of their effort is directed towards a comprehensive program of nuclear safety and avoiding the diversion of nuclear materials from civilian reactors into weapons programs.
The EPA has responsibility for environmental radiation standards and one of their major efforts has been in addressing the problem of radon exposure in homes and offices.
The DOE, NRC, and EPA share responsibility for the development of the Ward Valley Waste Disposal Site.
Waste Disposal

- Ward Valley (NV) waste site
  - Permanent repository for high-level nuclear waste initially scheduled to open in 2010
  - Designed for 10,000 year storage
- Waste Isolation Pilot Plant (WIPP)
  - Presently operating in New Mexico for low-level waste from DOE sites
- 10,000 year standard

Reference: http://www.epa.gov/radiation/wipp/faq.htm#general_1

**What is the WIPP?**

"WIPP" is the abbreviation for the Waste Isolation Pilot Plant, a U.S. Department of Energy (DOE) facility located in southeastern New Mexico, 26 miles southeast of Carlsbad. The site chosen for the 2,150-foot-deep WIPP is a 16-square-mile tract of federal land that consists of a thick layer of rock salt deposited about 225 million years ago. The facility is the nation's first geological repository for permanent disposal of transuranic (TRU) radioactive waste. Congress authorized the development of WIPP in 1980 to demonstrate the safe disposal of radioactive waste resulting from defense programs of the United States.

**What is Transuranic Radioactive Waste?**

The term "transuranic" is derived from trans, meaning beyond, and uranic, meaning uranium. TRU waste, which contains manmade elements heavier than uranium (and therefore "beyond uranium" on the periodic chart) is produced during nuclear fuel assembly, nuclear weapons research, productions, and cleanup, and as a result of reprocessing spent nuclear fuels. The waste generally consists of protective clothing, tools, glassware, and equipment contaminated with radioactive materials.

TRU waste consists of materials containing alpha-emitting radio-isotopes, with half-lives greater than twenty years and atomic numbers greater than 92, in concentrations greater than 100 nano-curies per gram of waste. The WIPP Land Withdrawal Act specifically excludes high-level waste and spent nuclear fuel from the definition, as neither is allowed to be disposed of at the WIPP.

**EPA and the WIPP**

First, EPA was required to finalize regulations which apply to all sites -- except Yucca Mountain -- for the disposal of spent nuclear fuel, transuranic and high level radioactive waste. The regulations, located at Subparts B and C of 40 CFR Part 191 (disposal regulations), limit the amount of radioactive material which may escape from a disposal facility, and protect individuals and ground water resources from dangerous levels of radioactive contamination.
EPA Process for WIPP

- Set environmental standards
- Monitor DOE activities
- DOE runs WIPP
- DOT is responsible for setting transportation standards
- Ward Valley site continues to be controversial

EPA’s final certification of compliance will allow the emplacement of radioactive waste in the WIPP to begin, provided that all other applicable health and safety standards, and other legal requirements, have been met at waste generator sites.

Panel Closure System - Condition 1 of the certification relates to the panel closure system, which is intended over the long term to block brine flow between waste panels in the WIPP.

Waste Characterization and Quality Assurance - Conditions 2 and 3 of the final rule relate to activities conducted at waste generator sites that produce the transuranic waste proposed for disposal in the WIPP. The compliance criteria require DOE to have in place a system of controls to measure and track important waste components, and to apply quality assurance ("QA") programs to waste characterization activities.

Passive Institutional Controls - Condition 4 of the certification relates to passive institutional controls ("PICs"). The compliance criteria required DOE to use both records and physical markers to warn future societies about the location and contents of the disposal system to deter inadvertent intrusion into the WIPP.

Throughout its operation of the WIPP, DOE must submit a recertification application to EPA every five years, documenting the WIPP’s In the immediate future, EPA will conduct inspections at waste generator sites in order to implement Conditions 2 and 3 of the compliance certification.

There is worldwide scientific consensus that 10,000 years is a time over which we can reasonably predict geology, hydrology and climatology (we extrapolated backwards to the last ice age, 10,000 years ago). If WIPP can meet the standards for 10,000 years, then it is highly likely that it will survive beyond that.

The current defense-generated transuranic waste is temporarily stored at federal government facilities in California, Colorado, Idaho, Illinois, Nevada, New Mexico, Ohio, Tennessee, South Carolina, and Washington.

Regulations issued by the Department of Transportation set guidelines for routing waste to the WIPP, but give the states and Indian tribes authority to designate routes within their borders. Different departments make the decision in each state, ranging from the Department of Health in Texas to the Public Service Commission in Indiana.
Fusion Power

- D = Duterium (\(^2\text{H}\))
- T = Tritium (\(^3\text{H}\))
- D + T → \(^4\text{He} + n\)
- For first generation fusion reactors
- \(n + \text{Li}^6 \rightarrow \text{He}^4 + \text{T}\) generates T


Energy-Releasing Reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Chemical</th>
<th>Fission</th>
<th>Fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td>Coal</td>
<td>(\text{U}^{235} \rightarrow \text{Ba}^{143} + \text{Kr}^{91})</td>
<td>Deuterium &amp; Lithium</td>
</tr>
<tr>
<td>Temp(K)</td>
<td>700</td>
<td>1000</td>
<td>10^8</td>
</tr>
<tr>
<td>Energy(J/kg)</td>
<td>(3.3 \times 10^7)</td>
<td>(2.1 \times 10^{12})</td>
<td>(3.4 \times 10^{14})</td>
</tr>
</tbody>
</table>

The "D-T" reaction has the highest reaction rate at the plasma temperatures which are currently achievable; it also has a very high energy release. These properties make it the easiest reaction to use in a man-made fusion reactor. As the figure shows, the products of this reaction include an alpha particle (Helium-4 nucleus) with 3.5 MeV energy, and a neutron with 14.1 MeV energy. The neutron escapes from the plasma (it has no charge and is not confined) and can be trapped in a surrounding "blanket" structure, where the \(n + \text{Li}^6 \rightarrow \text{He}^4 + \text{H}^3\) reaction can be used to "convert" the neutrons back into tritium fuel.

The site contains the following description of plasmas:

“Plasmas consist of freely moving charged particles, i.e., electrons and ions. Formed at high temperatures when electrons are stripped from neutral atoms, plasmas are common in nature. For instance, stars are predominantly plasma. Plasmas are the "Fourth State of Matter" because of their unique physical properties, distinct from solids, liquids and gases. Plasma densities and temperatures vary widely.

One approach to fusion reactions is to create a magnetically confined plasma in which the fusion reactions take place. The magnetic field allows the high temperature reactions to take place without melting the walls of the reaction chamber.”
Both inertial and magnetic confinement fusion research have focused on understanding plasma confinement and heating. This research has led to increases in plasma temperature, \( T \), density, \( n \), and energy confinement time, \( \tau \). Future power plants based on fusion reactors are expected to produce about 1 GW of power, which requires plasma parameters of \( n\tau \sim 2\times10^{20} \text{ s/m}^3 \) and \( T \sim 120 \text{ million K} \).
Reference: http://fusedweb.pppl.gov/

In this diagram for a fusion power plant, the deuterium-tritium (D-T) mixture is placed in an evacuated reactor chamber where it is ionized and heated to thermonuclear temperatures, creating a plasma. Magnetic forces hold the ionized fuel away from the chamber walls.

The deuterium tritium reaction forms charged helium nuclei. These nuclei transfer energy to the deuterium and tritium which are injected to the reactor. This energy transfer then sustains the fusion reaction.

The neutrons that are formed in the reaction move out of the plasma because they have no charge. They move through the walls of the vacuum chamber and are absorbed in a lithium blanket that surrounds the fusion chamber.

Collisions between the neutrons and the lithium nuclei creates the heat that is transferred to the steam in a conventional steam power cycle. The neutrons react with the lithium to generate tritium which is separated and fed back into the reactor as a fuel.

The successful operation of a fusion power plant will require the use of materials resistant to energetic neutron bombardment, thermal stress and magnetic forces. Additional work also needs to be done on the design of fuel injection systems and systems for removing spent gas.

The web site describes work at Oak Ridge National Laboratory as follows: “Tritium will be a fuel at future fusion reactors, but health risks for tritium differ between its form as T$_2$ gas and its form as HTO. Because tritium in the water form is about 25,000 times more hazardous than in the gas form, evaluation of human health risks for a number of situations around future fusion reactor plants depends on knowledge of how tritium converts from T$_2$ to HTO.

A series of experimental and theoretical studies were undertaken to measure needed parameters and to calculate others. This effort resulted in the development of validated rate equations, which spanned more than seven orders of magnitude in tritium concentration. Health risks from a wide variety of possible situations can now be calculated. These calculations provide input for future design and siting requirements for tritium-fueled fusion reactors.”
Nuclear Power Concerns

- Costs per kWh for new plants
- Production of fuel that can be diverted for use in weapons
  - Rouge states or terrorists
- Long-term waste disposal
- Possibility of accidents
- Terrorist attacks against power plants

Cost analyses continue to show nuclear as a costly option for electric power due to high construction costs. The uncertainty about nuclear power leads electric utilities to be concerned enough to consider other options even if nuclear power were costs competitive.

The possibility of diversion to weapons led the US to halt reprocessing of spent nuclear materials from power plants in 1977. (An action attributed to President and former nuclear engineer Carter.) The technology to handle high-level wastes means that such diversion would probably be limited to rouge nations who have large resources.

At present the US has not implemented the proposed Ward Valley facility for storage of nuclear wastes. High level wastes are initially stored in the water ponds and later in dry storage within the containment vessels of nuclear power plants.

Before Chernobyl, Edward Teller called the problem of nuclear accidents the “zero-infinity” dilemma. He felt that the probability of a very large accident with was vanishingly small. Hence the estimated effect of the accident – the probability of occurrence times the impact – was like the product of zero and infinity: indeterminate. Other than accidents at experimental facilities the two best known accidents have been Three-Mile Island (TMI) and Chernobyl. At TMI there was a core meltdown, but no release of radiation.

Continued on next notes page
Accidents and Terrorism

- Three Mile Island and Chernobyl
- Risks from transportation
  - Special concerns over high level waste transport to Ward Valley
  - Containers designed to contain radioactivity in case of accident
- Terrorism – Containment structures said to be able of airplane strike


The Chernobyl accident was based on a Russian reactor design that was known to have problems. It had poor response of increasing power when its moderator turned to steam in contrast to design of other reactors in which the power decreased when this occurred. At the time of the accident it was being tested under low power and operator errors coupled with a poor design caused an explosion that released part of the reactor fuel to the atmosphere.

This most serious nuclear accident directly caused 30 deaths (28 from radiation exposure). An additional 209 individuals were treated for radiation poisoning. (Most of these were workers who handled the cleanup operations.)

About 371,000 people were relocated at various times following the accident.


According to this publication, there has been an increase in childhood thyroid cancer among children exposed to the accident, but there have been no other “clearly demonstrated increase in the incidence of solid cancers or leukemia due to radiation in the most exposed populations.”
Breeder Reactors

- Nuclear reactions can transform atoms that do not readily undergo nuclear transformations into ones that do

\[
\begin{align*}
^{238}_{92}U + n & \rightarrow ^{239}_{92}U \\
^{239}_{92}U & \rightarrow ^{239}_{92}Np + e \\
^{239}_{92}Np & \rightarrow ^{239}_{92}Pu + e
\end{align*}
\]

- This overall path transforms \(U^{238}\) into \(Pu^{239}\)


It is also possible to have a breeder cycle based on thorium. The amount of thorium present on the earth is estimated to be about the same as that of uranium. In a nuclear reactor, Thorium, \(Th^{232}\), can absorb a neutron and undergo beta decay to produce \(Po^{233}\) (protoactinium) and then \(U^{233}\). This isotope of uranium, that is not naturally occurring, is also fissile and can be used as a fuel in nuclear reactors. India, which has large supplies of thorium is building a breeder reactor based on thorium.

These reactions are the basis for the operation of a nuclear reactor that will produce more fuel than it consumes. This is not a new idea. These nuclear reactions have been used for many years to produce plutonium that is used in nuclear weapons.

One of the key concerns of breeder reactors is the production of plutonium that can be used for weapons. When the nuclear fuel in the reactor is replenished, the fuel withdrawn from the reactor has to be reprocessed. This allows for the possibility that plutonium in the fuel can be withdrawn for weapons use. This would have to be done by a rogue nation. It is unlikely that a terrorist group would have the resources to reprocess fuel.
According to the report, “the specific numerical mass flows and enrichments in Figure A-4.1 are for a burnup of 33 GWd/MTIHM, which was the average burnup for U.S. reactors about 2 decades ago. In the rest of this section, we use a burnup of 50 GWd/MTIHM, which is currently the average for U.S. PWRs.”

MTIHM is an abbreviation for metric tons of initial heavy metal.

The cycle is called a once-through cycle in that there is no reprocessing of the waste materials to recover potential materials for additional fuel or weapons.

Definition of terms: B = burnup = Q/M where Q = Annual thermal energy output (GW-days per year) and M = Mass of fuel loaded per year (MTIHM/yr)

Q = P_e CF 365/η where P_e = installed electrical capacity GWs, CF = capacity factor, and η = thermal efficiency

Calculations assume η = 33% and CF = 90%
Fuel Cycle with Fast Reactors


Abbreviations: FP – Fission Products
FR – Fast Reactor
MA – Minor actinides (elements heavier than U except Pu)

This chart, like the last one, examines the different approaches to developing a new set of nuclear power reactors that would total 1500 GWe capacity by 2050. Although this is a far off time frame, the report examines the opportunities and barriers to the development of such a large amount of nuclear power in a 50-year time frame.

By comparison, the total world installed summer electrical capacity in 2007 was 372 GWe.

Although the report describes this cycle, it does not recommend its use because of concerns over proliferation.
MIT 2003 Report

Identifies four areas of concern about possible expansion of nuclear power

- Cost – not currently competitive
- Safety – need better information about safety of entire fuel cycle
- Waste – geological deposition technically feasible but not demonstrated in practice
- Proliferation – inadequate safeguards


Cost. In deregulated markets, nuclear power is not now cost competitive with coal and natural gas. However, plausible reductions by industry in capital cost, operation and maintenance costs, and construction time could reduce the gap. Carbon emission credits, if enacted by government, can give nuclear power a cost advantage.

Safety. Modern reactor designs can achieve a very low risk of serious accidents, but “best practices” in construction and operation are essential. We know little about the safety of the overall fuel cycle, beyond reactor operation.

Waste. Geological disposal is technically feasible but execution is yet to be demonstrated or certain. A convincing case has not been made that the long-term waste management benefits of advanced, closed fuel cycles involving reprocessing of spent fuel are outweighed by the short-term risks and costs. Improvement in the open, once through fuel cycle may offer waste management benefits as large as those claimed for the more expensive closed fuel cycles.

Proliferation. The current international safeguards regime is inadequate to meet the security challenges of the expanded nuclear deployment contemplated in the global growth scenario. The reprocessing system now used in Europe, Japan, and Russia that involves separation and recycling of plutonium presents unwarranted proliferation risks.
MIT 2003 Recommendations

- Continue DOE R&E efforts to lower cost
- Production tax credit for new plants
- Incentives for carbon-free energy should include nuclear
- DOE should broaden waste program
  - Specific technical recommendations
  - Develop international standards


We support the Department of Energy (DOE) 2010 initiative to reduce costs through new design certification, site banking, and combined construction and operation licenses.

The government should also share “first mover” costs for a limited number of power plants that represent safety-enhancing evolutionary reactor design. We propose a production tax credit for up to $200/kWe of the plant’s construction cost. This mechanism creates a strong incentive to complete and operate the plant and the mechanism is extendable to other carbon-free technologies. The government actions we recommend aim to challenge the industry to demonstrate the cost reductions claimed for new reactor construction, with industry assuming the risks and benefits beyond first-mover costs.

Federal or state portfolio standards should include incremental nuclear power capacity as a carbon free source.

The DOE should broaden its long-term waste R&D program, to include improved engineered barriers, investigation of alternative geological environments, and deep bore hole disposal. A system of central facilities to store spent fuel for many decades prior to geologic disposal should be an integral part of the waste management strategy. The U.S. should encourage greater harmonization of international standards and regulations for waste transportation, storage, and disposal.
MIT 2003 Recommendations

- Expand authority of IAEA to inspect suspect faculties
  - Develop a system that goes beyond accounting
- DOE R&D recommendations
  - Focus on open, once-through fuel cycle
  - Establish a program in simulation and modeling of fuel cycles


The International Atomic Energy Agency should have authority to inspect all suspect facilities (implement the Additional Protocol) and should develop a worldwide system for materials protection, control, and accountability that goes beyond accounting, reporting, and periodic inspections. The U.S. should monitor and influence developments in a broad range of enrichment technologies.

The DOE R&D program should be realigned to focus on the open, once-through fuel cycle. It should also conduct an international uranium resource assessment; establish a large nuclear system analysis, modeling, and simulation project, including collection of engineering data, to assess alternative nuclear fuel cycle deployments relative to the four critical challenges; and halt development and demonstration of advanced fuel cycles or reactors until the results of the nuclear system analysis project are available.
EPAct 2005

- Energy policy act of 2005 covers several different areas
- Nuclear areas
  - Expand Price-Anderson act to provide government insurance to nuclear power plants for longer term
  - Establish next-generation nuclear plant project
- No nuclear provisions in 2007 act


The pdf file referenced above has 551 pages – one measure of the complexity of the act. The following list gives the act’s titles (and subtitles).

Title I – Energy Efficiency (A. Federal programs, B. Energy assistance and state programs, C. Energy efficient products, D. Public housing)

Title II – Renewable Energy (A. General, B. Geothermal energy, C. Hydroelectric, D. Insular energy)

Title III – Oil and Gas (A. Petroleum reserve and home heating oil, B. Natural gas, C. Production, D. Naval petroleum reserve, E. Production, F. Access to Federal lands, G. Miscellaneous, F. Refinery revitalization.)

Title IV – Coal (A. Clean coal power initiative, B. Clean power projects, C. Coal and related programs, D. Federal coal leases.)

Title V – Nuclear Matters (A. Price-Anderson Act Amendments, B. General nuclear matters, C. Next generation nuclear power project, D Nuclear security.)

Title VI – Vehicles and Fuels (A. Existing programs, B. Hybrid vehicles, advanced vehicles and fuel cell buses, C. Clean school buses, D. Miscellaneous, E. Automobile efficiency, F. Federal and state procurement, G. Diesel emissions reduction.)

(continued on next notes page)
EPAct 2005 Nuclear Areas II

- Expand nuclear security to consider a series of threats listed in the Act
- Federal insurance against delay costs for first six companies to build new plants
- DOE Nuclear Power 2010 program to demonstrate new regulatory procedures
- Global Nuclear Energy Partnership to provide fuel to countries without processing


The following list gives the act’s titles (and subtitles) is continued from the previous notes page.

Title VIII – Hydrogen

Title IX – Research and Development (A. Energy efficiency, B. Distributed energy and electrical systems, C. Renewable energy, D. Agricultural biomass research and development programs, E. Nuclear energy, F. Fossil energy, G. Science, H. International cooperation, I. Research administration and operations, J. Ultra-Deepwater and unconventional natural gas and other petroleum resources.)

Title X – Department of energy management

Title XI – Personnel and training

Title XII – Electricity (A. Reliability standards, B. Transmission infrastructure modernization, C. Transmission operation improvements, D. Transmission rate reform, E. Amendments to PURPA, F. Repeal of PUHCA, G. Market transparency, enforcement and consumer protection


(continued on next notes page)
EPAct 2005 Nuclear Areas III

- Expand nuclear security to consider a series of threats listed in the Act
- Federal insurance against delay costs for first six companies to build new plants
- $0.018/kWh tax credit for qualified advanced nuclear facilities (Title XIII)
  - Limited to first 6000 MWe constructed
- Global Nuclear Energy Partnership to provide fuel to countries without processing


XIV – Miscellaneous (A. In General, B. Set America Free)

XV – Ethanol and motor fuels (A. General Provisions, B. Underground Storage Tank Compliance, C. Boutique Fuels)

XVI – Climate change (A. National Climate Change Technology Development, B. Climate Change Technology Development in Developing Countries)

XVII – Incentives for innovative technologies.

XVIII – Studies.

The 2007 energy act, signed by President Bush in December 2007 was found at the following web site on February 27, 2008:
http://thomas.loc.gov/cgi-bin/query/D?c110:8::/temp/~c110z7pwNA:

This act had no provisions on nuclear energy.
Future Prospects

• Current nuclear reactors will continue to operate
• Plans underway for deployment of new nuclear reactors in the US by 2010
• Certify designs in advance to reduce regulatory burden
• Improve design safety

## Capacity (thousand SWU/yr)

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<tr>
<td>France - Areva</td>
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<tr>
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Transporting Nuclear Waste

Geological Challenges in Radioactive Waste Isolation
Third International Review
edited by
P.A. Witherpoon
G.S. Bodvarsson
Earth Sciences Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720 U.S.A.
December 2001
DE-AC03-76SF00098
LBNL-49767
on LSC’s home desktop computer