Energy and Environment

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REFERENCES

The first textbook was always on my desk when I was preparing these lecture notes. I also list wikipedia, which was the source for many of the images and animations plus many useful tidbits of information.

Specific references are supplied on every slide except when the slide content is part of common mechanical engineering lore and can be found in any relevant textbook.

• Wikipedia, the free encyclopedia (http://en.wikipedia.org/wiki/Main_Page)
Is nuclear energy safe?

• As of 2003, the cumulative operating experience for the commercial nuclear power plants outside the former Soviet Union is about ______ reactor-years.
• In so many years, there have been ______ accidents causing the known death of any nuclear plant worker from radiation exposure.
• There have been ______ accidents exposing any member of the public to a substantial radiation dose.
Nuclear Energy

Nuclear energy is released from transformation of atomic nucleus, when the mass is converted into energy in accordance with Einstein’s famous relation $E=mc^2$.

The atomic nuclei may release its energy in two modes: **fusion** of light nuclei into larger nuclei; or **fission** of heavy nuclei into smaller ones.

Since the binding force per nucleon is greatest for elements in the middle of the periodic table, both the movement from the bottom end upwards to the middle (fusion) and from the heavy top end downwards to the middle (fission) generate energy.
Periodic Table

The periodic table of the elements

http://ccinfo.ims.ac.jp/periodic/

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Radioactivity

Radioactivity is the decay or slow fission of certain nuclei to lighter nuclei. There types of radiation are emitted by radioactive decay or fission: $\alpha$, $\beta$, and $\gamma$. Only the last one is electro-magnetic radiation. The first two are actually charged particles. The charged particles are relatively easier to stop. The $\gamma$-radiation is difficult to shield against and penetrates deep.

Alpha radiation consists of helium-4 nuclei and is readily stopped by a sheet of paper. Beta radiation, consisting of electrons, is halted by an aluminium plate. Gamma radiation needs very heavy shielding like thick lead walls.
Nuclear Energy Production

The energy released during nuclear fission has the following components:

- $E_f$ – kinetic energy of the fission products
- $E_n$ – kinetic energy of the fission neutrons
- $E_{\beta}$ – Energy in the $\beta$-radiation
- $E_{\gamma}$ – Energy in the $\gamma$-radiation
- $E_v$ – Neutrino radiation

The last one cannot be captured. The others are captured by the fuel element/reactor shielding and is converted to heat. This heat is what fuels the nuclear power plant.
# Nuclear Energy Release Data

<table>
<thead>
<tr>
<th>Target Nucleus</th>
<th>Incident Neutron, En₀</th>
<th>Fission Products, Ef</th>
<th>Energy in product neutrons, En</th>
<th>Beta Radiation Energy, E-β</th>
<th>Gamma radiation energy, E_γ</th>
<th>Neutrino energy, Ev</th>
<th>Total fission release</th>
<th>Thermal energy available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th-232</td>
<td>3.35</td>
<td>161.79</td>
<td>4.7</td>
<td>8.09</td>
<td>14.01</td>
<td>10.87</td>
<td>196.11</td>
<td>185.24</td>
</tr>
<tr>
<td>U-233</td>
<td>0</td>
<td>168.92</td>
<td>4.9</td>
<td>5.08</td>
<td>12.53</td>
<td>6.82</td>
<td>198.25</td>
<td>191.43</td>
</tr>
<tr>
<td>U-235</td>
<td>0</td>
<td>169.75</td>
<td>4.79</td>
<td>6.41</td>
<td>13.19</td>
<td>8.62</td>
<td>202.76</td>
<td>194.14</td>
</tr>
<tr>
<td>Pu-239</td>
<td>0</td>
<td>176.07</td>
<td>5.9</td>
<td>5.27</td>
<td>12.91</td>
<td>7.09</td>
<td>207.24</td>
<td>200.15</td>
</tr>
</tbody>
</table>

Notes:

(a) The incident neutron energy is zero for thermal neutrons (moderated neutrons).

(b) Total Fission Release = Ef+En+Eβ+Eγ+Ev-En₀

(c) Thermal Energy Available = Ef+En+Eβ+Eγ-En₀

(d) 1 MeV = 10^6 electron-volts = 1.602x10^-13 J


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U-235 Fission

- One U-235 fission releases about $194 \text{ MeV}$
- One U-235 atom weighs roughly $235 \text{ amus}$
- $1 \text{ amu} = 1.66 \times 10^{-27} \text{ kg}$
- $1 \text{ kg U-235}$ contains $2.56 \times 10^{24} \text{ U-235 atoms}$
- Fission energy available from $1 \text{ kg of U-235}$
  - $4.97 \times 10^{26} \text{ MeV}$
  - $7.96 \times 10^{7} \text{ MJ}$ (compare with $32.76 \text{ MJ/kg}$ available from the combustion of carbon)
  - $2.21 \times 10^{4} \text{ kWh}$

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Avogadro’s Number

Avogadro's number, also called Avogadro's constant \((N_A)\), named after Amedeo Avogadro, is the number of atoms in a mole of a monatomic element or the number of molecules in a mole of a compound. Avogadro's number is formally defined in the SI as the number of carbon-12 atoms in 12 grams (0.012 kg) of unbound carbon-12 in its rest-energy electronic state. The accepted value is \(6.0221415 \times 10^{23}\) atoms/mole. In the nineteenth century physicists measured the mass of one atom of hydrogen to be about \(1/(6.023 \times 10^{23})\) grams; they were trying to evaluate how many molecules of an ideal gas would fit in 1 cubic centimeter [1]. Carbon-12 was chosen as the reference substance over hydrogen because its atomic mass could be measured more accurately.

A mole is defined in the SI as Avogadro's number of particles of any kind of substance (atoms, ions, molecules, or formula units). In the SI, this unit is abbreviated mol. The mole is the basic unit of amount of substance.

from wikipedia
An estimate for the fission energy release is given by the loss of mass during the reaction. For example, one of the several possible fission reactions for U-235 is,

\[ ^{235}U + n \rightarrow ^{144}Ba + ^{89}Kr + 3n \]

The masses on the LHS:
- U-235 = 235.04394 amu
- 1 neutron = 1.00867 amu

The masses on the RHS:
- Ba-144 = 143.92 amu
- Kr-89 = 88.9166 amu
- 3 neutrons = 3.026 amu

The mass defect (the mass “lost” during the fission reaction):

\[ 235.04394 + 1.00867 - (143.92 + 88.9166 + 3.026) = 0.19 \text{ amu} \]

or \( 0.19 \times 1.66 \times 10^{-27} = 3.15 \times 10^{-28} \text{ kg} \)

The energy released

\[ \Delta E = mc^2 = 3.15 \times 10^{-28} \times (2.9979 \times 10^8)^2 = 2.83 \times 10^{-11} \text{ J} \]
Atomic Mass Tables

The general practice is to use the mass of the atom when describing a nuclear species. The mass of the atom (M) is equal to the mass of the nucleus plus the mass of the electrons. This mass is close but not exactly equal to the mass number (A) of the atom.

For example, for U-238, A=238, and M=238.050788 amu. The difference between the two is referred to as the mass excess, ∆:

\[ \Delta = M - A \]

The mass excess, is usually expressed in terms of electron –volts. For U-238, for example, the mass excess is 47309 keV.

Note that 47309 keV is an energy unit and convertible to 0.050788 amu through the equation E=mc².

\[
0.050788 \times 1.66 \times 10^{-27} \times (2.9979 \times 10^8)^2 / (1.6022 \times 10^{-19}) = 47291876 \text{ eV} = 47293 \text{ keV}
\]

which is equal to the tabulated value of 47309 keV given above within rounding errors.

A list of atomic masses for different elements are provided as part of the supporting material for this course: [http://web1.boun.edu.tr/halimgurgenci/atomic_mass.htm](http://web1.boun.edu.tr/halimgurgenci/atomic_mass.htm)
"Isotope" – wikipedia definition

An isotope is any of several different forms of an element each having different atomic mass. Isotopes of an element have nuclei with the same number of protons (the same atomic number) but different numbers of neutrons. Therefore, isotopes have different mass numbers, which give the total number of nucleons—the number of protons plus neutrons. The term isotope comes from Greek and means "at the same place": all the different isotopes of an element are placed in the same location on the periodic table.

A nuclide is any particular atomic nucleus with a specific atomic number \( Z \) and mass number \( A \); it is equivalently an atomic nucleus with a specific number of protons and neutrons. Collectively, all the isotopes of all the elements form the set of nuclides. The distinction between the terms isotope and nuclide has somewhat blurred, and they are often used interchangeably. Isotope is best used when referring to several different nuclides of the same element; nuclide is more generic and is used when referencing only one nucleus or several nuclei of different elements. For example, it is more correct to say that an element such as fluorine consists of one stable nuclide rather than that it has one stable isotope.

In scientific nomenclature, isotopes and nuclides are specified by the name of the particular element, implicitly giving the atomic number, followed by a hyphen and the mass number (e.g. helium-3, carbon-12, carbon-14, iodine-131 and uranium-238). In symbolic form, the number of nucleons is denoted as a superscripted prefix to the chemical symbol (e.g. 3He, 12C, 14C, 131I and 238U).

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Decay Rates and Half Lives

The progressive fission of a collection of radioactive nuclei is governed by the following differential equation:

$$-\frac{dN}{dt} = kN$$

where $N$ is the number of decaying nuclei and $k$ is the decay rate (constant). The solution to this differential equation is

$$N = N_0 e^{-kt}$$

The period in which the number of nuclei drops to half of the original number is called the half-life

$$t_{1/2} = \frac{\log_e 2}{k}$$
Some Isotopes in the Nuclear Fuel Cycle

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half Life</th>
<th>Radioactive emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kr-87</td>
<td>76 min</td>
<td>β</td>
</tr>
<tr>
<td>H-3</td>
<td>12.3 y</td>
<td>β</td>
</tr>
<tr>
<td>Sr-90</td>
<td>28.1 y</td>
<td>β</td>
</tr>
<tr>
<td>Cs-137</td>
<td>30.2 y</td>
<td>β</td>
</tr>
<tr>
<td>Xe-135</td>
<td>9.2 h</td>
<td>β, γ</td>
</tr>
<tr>
<td>Ba-139</td>
<td>82.9 m</td>
<td>β, γ</td>
</tr>
<tr>
<td>Ra-223</td>
<td>11.4 d</td>
<td>α, γ</td>
</tr>
<tr>
<td>Ra-226</td>
<td>1600 y</td>
<td>α, γ</td>
</tr>
<tr>
<td>Th-232</td>
<td>1.4e10 y</td>
<td>α, γ</td>
</tr>
<tr>
<td>Th-233</td>
<td>22.1 m</td>
<td>β</td>
</tr>
<tr>
<td>U-233</td>
<td>1.65e5 y</td>
<td>α, γ</td>
</tr>
<tr>
<td>U-235</td>
<td>7.1e8 y</td>
<td>α, γ</td>
</tr>
<tr>
<td>U-238</td>
<td>4.5e9 y</td>
<td>α, γ</td>
</tr>
<tr>
<td>Np-239</td>
<td>2.35 d</td>
<td>β, γ</td>
</tr>
<tr>
<td>Pu-239</td>
<td>2.44e4 y</td>
<td>α, γ</td>
</tr>
</tbody>
</table>

from Table 6.1 of Fay & Golomb
Measuring Radioactive Emissions

The SI unit for radioactivity is becquerel (Bq). One becquerel is 1 disintegrations per second. This is a very small amount of radioactivity. A more practical unit is curie(Ci):

\[ 1\text{Ci} = 3.7 \times 10^{10} \text{Bq} \]

These units are aptly named as Henri Becquerel, and Pierre and Marie Curie shared the 1903 Nobel Physics prize for the discovery of radioactivity.

Ci or Bq may be used to refer to the amount of radioactive materials released into the environment. For example, during the Chernobyl power plant accident, an estimated total of 81 million Ci of radioactive cesium was released (www.bt.cdc.gov/radiation/pdf/measurement.pdf).

Henri Becquerel detected radioactivity by observing its effect on photographic plates. The modern instruments rely on the charged particles ionising an inert gas and then detecting the effect of ionisation.

For example, a Geiger counter is basically a tube filled with an inert gas such as Argon. When a charged particle (\(\alpha\) or \(\beta\)) enters the tube and hits one of the gas molecules, it removes electrons from the gas and thus creates ions. These ions are detected as an electrical current. This current is amplified and displayed and recorded. An audible click is also emitted for each charged particle hit. Geiger counters can effectively measure \(\alpha\) or \(\beta\) radiation but not \(\gamma\).
Radioactivity Detectors

Marie Curie used an electroscope. An electrostatic charge lifts the foil leaves. They slowly close down discharging to the air. The rate at which they close depend on the level of ionisation in the air (and hence the concentration of charged particles generating free ions)

www.ndt-ed.org/EducationResources/HighSchool/Radiography/detectionmeasurement.htm
Measuring Radioactive Exposure

The SI unit to measure radioactive energy absorption is J/kg also called gray (Gy),

\[ 1 \text{ Gy} = 1 \text{ J/kg} \]

named after the British physicist Louis Harold Gray (1905-1965), founder of radiobiology.

A different unit called sievert (Sv) is used to measure the harmful effect of radioactive exposure. The potential of damaging biological tissue is different for different particles (α, β, and γ). Each of these emission types is assigned a quality factor Q.

\[ 1 \text{ Sv} = Q \times 1 \text{ Gy} \]

Alternative units used in the past were rad (1 Gy = 100 rad) and rem (1 Sv = 100 rem).

Fay & Golomb gives examples of exposure levels: 0.1 mSv for one chest X-ray; 0.7 mSv for one mammogram, and 3 mSv for one year’s exposure to natural radiation. A short-term dose of 1 Sv causes temporary radiation sickness; 10 Sv kills. The wikipedia suggests that 1 sievert dose has a 5% chance of causing cancer and a 1% chance of causing a mutation in a gamete (e.g. egg) or a gamete forming cell such as those in the testis which can be passed to the next generation.

The US Nuclear Regulatory Commission (NRC) limits for exposure to man-made radioactivity are 50 mSv/year for nuclear power plant workers and 1 mSv/y for general public.
Chernobyl

On April 26, 1986, the fourth reactor of the Chernobyl Nuclear Power Plant, exploded at 01:23 AM local time.

The 2005 report prepared by the Chernobyl Forum, led by the International Atomic Energy Agency (IAEA) and World Health Organization (WHO), attributed 56 direct deaths (47 accident workers, and nine children with thyroid cancer), and estimated that as many as 9,000 people among the approximately 6.6 million most highly exposed, may die from some form of cancer (one of the induced diseases).

Neutrons are normally too fast to capture

A neutron born from natural fission is fast at a speed of 4400 km/s (which corresponds to a kinetic energy of about 1MeV). Fast neutrons cannot be captured by the U-235 atoms. In a thermal reactor, the chain reaction is maintained by neutrons slowed down by repeated collisions with the moderator nuclei until they come into thermal equilibrium with the moderator hence the name thermal reactor. The moderator is either graphite or the hydrogen in water. Fast reactors contain no moderator.
Nuclear Chain Reaction

n  Neutron
FP  Fission Product

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A nuclear reactor is a pressure vessel in which a self-sustained chain reaction takes place. In a nuclear-fueled power plant the heat generated by this chain reaction is removed by boiling water, pressurised water, a liquid metal (e.g. sodium) or a gas (e.g. He or CO₂) and then used in a power plant cycle like any other heat source.

The fuel is $^{235}\text{U}$ and/or $^{239}\text{Pu}$. The natural uranium is mostly $^{238}\text{U}$, which is not fissile. The amount of $^{235}\text{U}$ in naturally-found uranium is less than 1%.

To sustain a chain reaction, a nuclear reactor fuel must contain about 3-4% of $^{235}\text{U}$.

The function of the moderator is to slow down the neutrons. Otherwise, the neutrons would not be absorbed by other $^{235}\text{U}$ atoms and the reaction would not be sustained.

Control rods are natural neutron absorbers and they stop the reaction absorbing the neutrons when inserted into the reactor.
Calder Hall, UK

The world's first commercial scale nuclear power station began generation on October 17, 1956, in Calder Hall, UK.

Calder Hall was a gas-cooled nuclear reactor with a graphite reactor. At its peak, Calder Hall generated four times as much electricity as it did in 1956, although by modern standards its size - 196 megawatts - is considered small.

Calder Hall closed in 2003, after more than 40 years providing electricity (from BBC archives- http://news.bbc.co.uk/onthisday).
A current nuclear power plant

Byron Bay Power Plant, Ogle County, Illinois. The nuclear reactors are inside the two cylindrical containment buildings in the foreground—behind are the cooling towers (venting water vapor).
## World Installed Nuclear Power Generation Capacity

### Table A4-1: Number and Power (in MW) of Reactors, by Type and Continent

<table>
<thead>
<tr>
<th>Code</th>
<th>Type</th>
<th>Europe</th>
<th>Africa</th>
<th>Americas</th>
<th>Asia</th>
<th>Total</th>
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<tr>
<td></td>
<td></td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
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<tr>
<td>AGR</td>
<td>Advanced Gas Cooled Reactor</td>
<td>14</td>
<td>36</td>
<td>34</td>
<td>14</td>
<td>90</td>
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<tr>
<td></td>
<td></td>
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<td>(31,639)</td>
<td>(28,156)</td>
<td>(8,360)</td>
<td>(77,056)</td>
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<td>BWR</td>
<td>Boiling Water Reactor</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>24</td>
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<tr>
<td></td>
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<td>(261)</td>
<td>(1,054)</td>
<td>(1,054)</td>
<td>(19,315)</td>
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<td>FBR</td>
<td>Fast Breeder Reactor</td>
<td>2</td>
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<td>4</td>
<td></td>
<td>6</td>
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<tr>
<td></td>
<td></td>
<td>(793)</td>
<td></td>
<td>(1,054)</td>
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<td>(1,054)</td>
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<td>GCR</td>
<td>Gas Cooled Reactor</td>
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<td>20</td>
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<td>(3,125)</td>
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<td>(3,125)</td>
<td>(3,125)</td>
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<td>HWLWR</td>
<td>Heavy-Water-Moderated, Light-Water-Cooled</td>
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<td>1</td>
<td></td>
<td>1</td>
<td>3</td>
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<tr>
<td></td>
<td></td>
<td>(148)</td>
<td>(148)</td>
<td></td>
<td>(148)</td>
<td>(148)</td>
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<td>LWGR</td>
<td>Light Water Cooled Graphite Reactor</td>
<td>18</td>
<td></td>
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<td>20</td>
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<tr>
<td></td>
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<td>(12,594)</td>
<td></td>
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<td>(12,594)</td>
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<td>PHWR</td>
<td>Pressurized Heavy Water Reactor</td>
<td>1</td>
<td></td>
<td>22</td>
<td>16</td>
<td>39</td>
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<tr>
<td></td>
<td></td>
<td>(650)</td>
<td></td>
<td>(14,436)</td>
<td>(4,815)</td>
<td>(20,001)</td>
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<td>Pressurized Water Reactor</td>
<td>109</td>
<td>2</td>
<td>71</td>
<td>40</td>
<td>222</td>
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<tr>
<td></td>
<td></td>
<td>(106,560)</td>
<td>(1,842)</td>
<td>(65,917)</td>
<td>(32,093)</td>
<td>(206,412)</td>
</tr>
<tr>
<td>WWER</td>
<td>Water Cooled Water Moderated Power Reactor</td>
<td>32</td>
<td></td>
<td>1</td>
<td>33</td>
<td>34</td>
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<tr>
<td></td>
<td></td>
<td>(18,553)</td>
<td></td>
<td>(376)</td>
<td>(18,929)</td>
<td>(18,929)</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>215</td>
<td>2</td>
<td>129</td>
<td>94</td>
<td>440</td>
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<tr>
<td></td>
<td></td>
<td>(167,896)</td>
<td>(1,842)</td>
<td>(119,992)</td>
<td>(65,849)</td>
<td>(347,679)</td>
</tr>
</tbody>
</table>

Boiling Water Reactor (BWR)

Water moderates the reaction and also removes the heat by boiling. The fuel is usually 3-4% enriched $^{235}\text{U}$. The steam at about 300 °C and 7 MPa is taken away to run a steam turbine in a Rankine cycle. The thermal efficiency is high (about 33%) based on the inherent heat in the $^{235}\text{U}$ consumed.

Although control rods are used, the reaction itself is self-controlling. If the chain reaction gets too intense, it would boil all the water. This would remove the moderator and stop the reaction.

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Pressurised Water Reactor (PWR)

The PWR was originally designed to power nuclear submarines. It is the most common reactor in the USA. It needs enriched fuel the same as a BWR. The water again acts as both the moderator and the coolant. Pressurised at 20 MPa, it remains as liquid at temperatures maintained around 340-350°C. The steam is generated at a secondary circuit at 7 MPa. This steam powers a Rankine cycle. Compared to BWRs, the moderation is more precise because water does not boil away. Another advantage is the confinement of the coolant water radioactivity into the primary circuit, which remains within the containment structure. The thermal efficiency is about 30%, lower than a BWR because of the additional heat exchanger.

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CANDU® stands for "CANada Deuterium Uranium". It's a Canadian-designed power reactor of PHWR type (Pressurized Heavy Water Reactor) that uses heavy water (deuterium oxide) for moderator and coolant, and natural uranium for fuel. It has two main advantages over PWR:

- The heavy water (D\textsubscript{2}O or deuterium oxide) used as a moderator in a CANDU reactor does not absorb neutrons and therefore all neutrons are available to sustain the chain reaction.

CANDU reactor does not need a fuel enrichment facility.

- The CANDU reactor, due to its mechanical design, can be refuelled while in operation. Since a nuclear reactor has to be fuelled every 2-3 years, not having to stop the reactor while refuelling means a significant increase in availability.

The CANDU design has been adopted by India in its nuclear energy program although this is happening in isolation from the original CANDU program since Canada stopped all interactions with the Indian nuclear program after that country exploded an atomic bomb.

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Each string of fuel bundles is in its own cylindrical pressure vessel, or "fuel channel", made of a special zirconium alloy (zircaloy) that is relatively transparent to neutrons. The individual fuel channels are in turn suspended in a low-pressure "calandria" which does not need to be as thick walled as a pressure vessel.

The calandria-based design allows individual fuel bundles to be removed without taking the reactor off-line, improving overall duty cycle or "capacity factor". To make this task easier, the calandria is mounted horizontally, allowing a pair of remotely-controlled fuelling machines to visit each end of an individual fuel string, one machine inserting new fuel while the other receives discharged fuel.
Gas-Cooled Reactor

This type of reactor was developed in Britain. The fuel could be normal or enriched uranium. The moderator is graphite and the coolant is either CO₂ or helium. The core temperature (e.g. 655 °C in the Hinkley Point reactor) is higher than water-cooled reactors. The thermal efficiency is therefore higher at >40%. However, the fuel also burns faster and the overall fuel efficiency is lower.

Control rods penetrate the moderator and a secondary shutdown system involves injecting nitrogen into the coolant or releasing boron ball shutdown devices.

The gas-cooled reactor as shown above is an obsolete design but the R&D is continuing.
Pebble-Bed Reactors

This is an advanced reactor design which is lately attracting considerable attention around the world (but not in the places where it was invented). It is a marriage of a novel fuel packaging invented in Germany and the British GCR concept. The uranium, thorium or plutonium nuclear fuels are contained within spherical pebbles made of pyrolytic graphite, which also acts as the primary neutron moderator. Each sphere is effectively a complete "mini-reactor".

The advantages are

(a) Self-control - the reaction stops when the core gets too hot (neutrons get absorbed by $^{238}\text{U}$ instead of $^{235}\text{U}$)

(b) Continuous refuelling – one pebble at a time

The main disadvantage is the volume of the nuclear waste - larger because the whole pebble is the waste.

There are no operating plants but Pebble Bed Modular Reactor Pty. Ltd. (PBMR) in South Africa is the current technology leader, developing a modular pebble-bed reactor.
Breeder Reactors

A breeder reactor produces fuel, i.e. fissile nuclei while it is producing power. This can happen by conversion of $^{238}\text{U}$ to $^{239}\text{Pu}$:

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

More than half the $^{239}\text{Pu}$ “fissions” again to $^{235}\text{U}$ and $^{240}\text{Pu}$ but the rest accumulates in the spent fuel. It can be reused either as a thermal nuclear reactor fuel or for building nuclear weapons. The second use has been the main driver for most breeder reactor construction.

New fissile nuclei are created in the core of any reactor while others are being destroyed. The breeding ratio, $BR$, is defined as the ratio of the fissile nuclei produced to those destroyed. In a breeder reactor, $BR > 1$. 
Fast Breeder Reactors

Breeder reactors using the $^{238}\text{U}$ cycle are called fast breeder reactors because $^{238}\text{U}$ can only capture fast neutrons. Therefore, there is no need for a moderator. Because of the high amount of heat generated, an efficient coolant is required and liquid sodium has been used for this purpose effectively in the past in the so-called Liquid Metal Fast Breeder Reactors or LMFBR.

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Thermal breeders

It is also possible to use Thorium instead of uranium through the following reaction in a thermal reactor

\[ ^{232}Th + n + \gamma \rightarrow ^{233}Th + \beta \rightarrow ^{233}U \]

This technology is currently under pursuit in India. India is interested in developing this technology because it has large thorium reserves.

These are called thermal breeders because the \(^{232}\)Th can effectively capture only the “slow” or so-called thermal neutrons. Water is proposed as moderator to slow the neutrons down in a thorium-fuelled nuclear reactor.

Total worldwide resources of thorium exceed those of uranium, so in the long term this technology may become of more general interest.
Uranium ore leaves the mine in 200-l drums filled with yellow cake ($\text{U}_3\text{O}_8$ concentrate – 99.3% $^{238}\text{U}$ and 0.7% $^{235}\text{U}$). Unless using CANDU, the $^{235}\text{U}$ content must be enriched to above 3-4% for use as nuclear fuel.

$\text{U}_3\text{O}_8$ is converted to gaseous UF$_6$ first and then can be enriched in two ways:

(a) Diffusion through membranes (past method)

(b) Centrifuge to separate heavier $^{238}\text{UF}_6$ from lighter $^{235}\text{UF}_6$ (present method)

The enriched UF$_6$ is converted to ceramic-like UO$_2$ pellets and loaded into fuel rods - metal (usually steel) containers.

About 85% of the original UF$_6$ is rejected as depleted uranium. Currently, this is stored as possible fuel for future FBRs.

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Spent Fuel Processing

The fuel rods need to be replaced every 18-36 months. The retrieved fuel rods are first kept in the containment vessel until the short-term high-level radiation dies away.

In most countries, the fuel rods are then processed. U and Pu are separated from the rest. U is sent to enrichment. Pu is mixed with natural uranium into a type of fresh fuel called mixed oxide (MOX).

Liquid waste is generated in leaching U and Pu out. This waste is eventually calcined (evaporated to dry powder) and then vitrified (encased in molten glass). The molten glass is poured into stainless steel canisters. In UK, France, Belgium and Sweden, these canisters are stored in deep silos – pending permanent storage.

A satisfactory permanent storage procedure and storage location have yet to be found.
Spent Fuel in US

• Depending upon the type and size of the reactor, a fuel assembly can weigh up to 1,500 pounds.
• Until a disposal or long-term storage facility is operational, most spent fuel is stored in water pools at the reactor site where it was produced. The water removes leftover heat generated by the spent fuel and serves as a radiation shield to protect site workers.
• In most other countries, the fuel rods are processed.
Synroc

Synroc, a portmanteau from "synthetic rock", is a possible means of safely storing and disposing of radioactive waste. It was invented in 1978 by a team led by Dr Ted Ringwood at the Australian National University, with further research being undertaken in collaboration with ANSTO.

It is an advanced ceramic comprising geochemically stable natural titanate minerals which have immobilised uranium and thorium for billions of years. Unlike borosilicate glass, which is amorphous, Synroc is a ceramic that incorporates the radioactive waste into its crystal structure.

Although it has not yet experienced commercial use, in April of 2005, the process was chosen for a multi-million dollar "demonstration" contract to eliminate five tonnes of plutonium-contaminated waste at British Nuclear Fuel's Sellafield plant, on the northwest coast of England. (wikipedia)
Synroc Development

From issue 2546 of New Scientist magazine, 08 April 2006, page 25
Pauline Newman Sydney, New South Wales, Australia

“Your correspondent Rosemary Campbell asks what happened to Synroc, the Australian project for sealing radioactive waste (25 March, p 25). I reported on the continuing, albeit slow, progress of this project in an episode of The Science Show on ABC Radio National a few months ago. There is a transcript at www.abc.net.au/rn/science/ss/stories/s1494179.htm.”