Energy on this world and elsewhere

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Course web site available at www.phys.virginia.edu, click on classes and find Physics 1110.
or at http://people.virginia.edu/~gdc4k/phys111/fall11

Lecture 24, November 22, 2011
Breeding plutonium
The vast majority of natural uranium is U-238, which for all practical purposes, is not fissionable.
Breeding plutonium

In a reactor, however, U-238 is slowly (or not so slowly) converted into plutonium. This process is referred to as breeding.
Beta decay

- The neutron mass is slightly more than the proton mass.
- When a neutron turns into a proton, some energy is released, so the system settles into a lower energy state (as far as nuclear forces are concerned).
- The net result is that the mass number stays the same, but the atomic number (the number of protons) goes up by one.
Example of Beta Decay

Total number of nucleons or the “mass number”

\[
\begin{align*}
\frac{137}{55} \text{Cs} & \rightarrow \frac{137}{56} \text{Ba} + \beta^- + \bar{\nu}
\end{align*}
\]

Number of protons or “atomic number”

This is a beta particle, which is really just an electron.

Thick cardboard or a small amount of metal will stop beta particles.
How plutonium is made

• U-238 captures a neutron, becoming U-239

• U-239 Beta decays (half-life of 23 minutes) into neptunium-239

• Np-239 beta decays (half-life of 2.4 days) into plutonium-239

\[
\begin{align*}
_{92}^{238}U + n &\rightarrow _{92}^{239}U \\
23 \text{ minutes} &\rightarrow _{93}^{239}Np \\
&\beta^- + \bar{\nu} \\
&\rightarrow _{94}^{239}Pu \\
2.4 \text{ days}
\end{align*}
\]
Clicker question

Why is plutonium more dangerous than uranium?

A. It is easier to make a bomb out of plutonium.
B. Plutonium can be separated out using chemical techniques.
C. The centrifuges needed to separate out plutonium are simpler than what is used for uranium.
D. Plutonium is not a greater danger than uranium.
What is a “Fast Breeder Reactor” (FBR)

- Conventional reactors burn the U-235 almost exclusively.
- Fast breeders are designed to convert large amounts of the U-238 into Pu-239 in the process of burning the U-235.
- In principle, a fast breeder can make more fuel than it burns (at least until the U-238 runs out).
- Early in the “atomic age”, there was great enthusiasm for fast breeders, and it was almost assumed that we would go in that direction.
- Today, fast breeding is used only very little. Among other things, people aren’t too enthused over manufacturing huge quantities of plutonium.
- Fast breeding may never come into its own, but it is worth remember that if it did, we would have energy for many many centuries, if not millenia.
Example of a “Generation IV reactor” FBR design

SFR
Sodium-Cooled Fast Reactor
How an FBR works

- Conventional reactors use water as a moderator. It slows down the neutrons produced during fission reactions.
- Slower neutrons are more likely to cause the fission of U-235. Conventional reactors typically use 3-5% enriched U.
- Fast Breeder reactors typically use liquid metal as a moderator. The neutrons are not slowed down nearly as much and are thus “fast”.
- The fast neutrons are readily captured by U-238, which converts to plutonium.
- To make up for the fast neutrons, the reactors use a richer mixture of fissionable fuel. This also makes them less stable.
How long would the world’s uranium last if it were the only source of energy?

<table>
<thead>
<tr>
<th>Technology</th>
<th>Reserves in Gtoe’s</th>
<th>Reserves in Quads (@ 411 Quads/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>conventional reactor</td>
<td>260</td>
<td>9,620</td>
</tr>
<tr>
<td>Fast Breeder Reactor (FBR)</td>
<td>15,540</td>
<td>575,000</td>
</tr>
</tbody>
</table>

- If only conventional reactors were used, something like 23 years.
- If fast breeder reactors were used (and around half the the U-238 were converted into plutonium), around 1,400 years.
What if we used nuclear energy at the rate it was being used in 2005?

Figure 6-7  Years of uranium availability for nuclear power

Source: IAEA, 2007

<table>
<thead>
<tr>
<th>Reactor/fuel cycle</th>
<th>Years of 2005 world nuclear electricity generation with identified resources</th>
<th>Years of 2005 world nuclear electricity generation with total conventional resources</th>
<th>Years of 2005 world nuclear electricity generation with total conventional and unconventional resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current once-through fuel cycle with light water reactors</td>
<td>85</td>
<td>270</td>
<td>675</td>
</tr>
<tr>
<td>Pure fast reactor fuel cycle with recycling</td>
<td>5000 – 6000</td>
<td>16000 – 19000</td>
<td>40000 – 47000</td>
</tr>
</tbody>
</table>
France’s Superphoenix - example of breeder reactor

Rocket attack

Against a background of ongoing protest and low-level sabotage,[1] on the night of January 18, 1982 a rocket attack was launched against the unfinished plant by an "eco-pacifist group". Five rockets were launched using a Russian rocket launcher. The incomplete containment building was damaged by two of the rockets, which narrowly missed the reactor's empty core.

On May 8, 2003, Chaim Nissim, who in 1985 was elected to the Geneva cantonal government for the Swiss Green Party, admitted carrying out the attack. He claimed that the weapons were obtained from Carlos the Jackal via the Belgian terrorist organisation Cellules Communistes Combattantes (Communist Combatant Cells).[2]

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Average annual generation (last 5 years):</td>
<td>797 GWh</td>
</tr>
<tr>
<td>Net generation</td>
<td>3,392 GWh</td>
</tr>
<tr>
<td>As of:</td>
<td>July 27, 2007</td>
</tr>
</tbody>
</table>
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Dealing with nuclear waste
All waste is not equal.

With the exception of technetium, the byproducts of fission are relatively short lived. The actinides, however, that result from neutron capture and subsequent decay, are very long lived.
The concept of the half-life of an isotope

The half-life of a nucleus is the time it takes for one half of the original amount of that substance to decay. Radioactive decay is an exponential process.
Calculating what’s left

If you are interested in an integral number of half-lives, it is particularly easy. Let us say that you want to know what is left after “n” half-lives. You simply take the initial quantity of the substance and multiply by \((1/2)^n\)

For example, consider
\(^{137}\text{Cs}\), a fission fragment with a half-life of 30 years. How much would be left after 90 years?

First we note that \(90/30=3\)

Further assume we have a quantity of \(^{137}\text{Cs}\) \(N_0\) at \(t=0\)

\(N(t=90 \text{ years}) = (1/2)(1/2)(1/2) N_0 = (1/2)^n N_0 = (1/8) N_0\)
Calculating what’s left

If you prefer, you can also use the equation:

\[ N(t) = N_0 e^{-\left( \frac{\ln 2}{t_{1/2}} \right) t} \]

In this way, you can also deal with an arbitrary time period.
All waste is not equal.

<table>
<thead>
<tr>
<th>Fission Products</th>
<th>Actinides</th>
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<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>Nuclide</td>
<td>Half-Life (Years)</td>
</tr>
<tr>
<td>$^{90}$Sr</td>
<td>28.8</td>
</tr>
<tr>
<td>$^{99}$Tc</td>
<td>$2.1 \times 10^5$</td>
</tr>
<tr>
<td>$^{106}$Ru</td>
<td>1.0</td>
</tr>
<tr>
<td>$^{125}$Sb</td>
<td>2.7</td>
</tr>
<tr>
<td>$^{134}$Cs</td>
<td>2.1</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>30</td>
</tr>
<tr>
<td>$^{147}$Pm</td>
<td>2.6</td>
</tr>
<tr>
<td>$^{151}$Sm</td>
<td>90</td>
</tr>
<tr>
<td>$^{155}$Eu</td>
<td>1.8</td>
</tr>
</tbody>
</table>


With the exception of technetium, the byproducts of fission are relatively short lived. The actinides, however, that result from neutron capture and subsequent decay, are very long lived.
Sub-critical accelerator driven reactors

- The reactor core is SUB-CRITICAL. This means it is not capable of sustaining a chain reaction on its own.
- A sub-critical reactor core produces FEWER THAN ONE CAPTURED NEUTRON per fission that occurs.
- To make up the difference, a particle accelerator is used to produce more neutrons.
The accelerator can be TURNED OFF at any time.
Run-away chain reactions (more possible in breeder reactors) is not a serious danger.
Cooling is still needed even when everything is turned off.
All transuranic elements and actinides can be separated out, put into new fuel, and burned up.
The only wastes are the shorter-lived, but still very radioactive fission fragments.
Comments on FBR’s

• A technology already exists that could probably provide human kind with energy for more than 1,000 years.
• Unfortunately, the technology WILL put bomb-grade material into many people’s hands.
• Despite early enthusiasm and some reasonably successful prototypes, FBR’s have never made it to the main stream.
• The jury is still out rearding the future of this technology.