Energy and Society

Revision of Homework set 5: Chapters 19 and 20 only.....

Exam 2
Chapters 10-20
November 3, 2011
Thorium: Is It the Better Nuclear Fuel?

What is special about thorium?

1. Weapons-grade fissionable material (uranium$^{233}$) is harder to retrieve safely and clandestinely from the thorium reactor than plutonium is from the uranium breeder reactor.

2. Thorium produces 10 to 10,000 times less long-lived radioactive waste than uranium or plutonium reactors.

3. Thorium comes out of the ground as a 100% pure, usable isotope, which does not require enrichment, whereas natural uranium contains only 0.7% fissionable U$^{235}$.

4. Because thorium does not sustain chain reaction, fission stops by default if we stop priming it, and a runaway chain reaction accident is improbable.
Preventing the Next Fukushima.....

Science Vol. 333 September 16, 2011 article...
How do we get energy from fossil fuels? Nuclear fuels?

Steam-powered Generator

One example....
A water turbine is a rotary engine that takes energy from moving water.
Boiling Water Reactor
In the boiling water reactor the same water loop serves as moderator, coolant for the core, and steam source for the turbine.

A typical operating pressure for such reactors is about 70 atm at which pressure the water boils at about 285°C. This operating temperature gives a Carnot efficiency of only 42% with a practical operating efficiency of around 32%, somewhat less than the pressure water reactor.
Pressurized Water Reactor

In the pressurized water reactor, the water which flows through the reactor core is isolated from the turbine.

In the pressurized water reactor (PWR), the water which passes over the reactor core to act as moderator and coolant does not flow to the turbine, but is contained in a pressurized primary loop. The primary loop water produces steam in the secondary loop which drives the turbine. The obvious advantage to this is that a fuel leak in the core would not pass any radioactive contaminants to the turbine and condenser. Another advantage is that the PWR can operate at higher pressure and temperature, about 160 atm and about 315 °C. This provides a higher Carnot efficiency than the BWR, but the reactor is more complicated and more costly to construct. Most of the U.S. reactors are pressurized water reactors.
Liquid-Metal Fast-Breeder Reactor

In the LMFBR, the fission reaction produces heat to run the turbine while at the same time breeding plutonium fuel for the reactor.

The most common breeding reaction is that of plutonium-239 from non-fissionable uranium-238. The term "fast breeder" refers to the types of configurations which can actually produce more fissionable fuel than they use, such as the LMFBR. This scenario is possible because the non-fissionable uranium-238 is 140 times more abundant than the fissionable U-235 and can be efficiently converted into Pu-239 by the neutrons from a fission chain reaction.

France has made the largest implementation of breeder reactors with its large Super-Phenix reactor and an intermediate scale reactor (BN-600) on the Caspian Sea for electric power and desalinization.
Breeding Plutonium-239
Fissionable plutonium-239 can be produced from non-fissionable uranium-238

Breeder or Converter?
Atoms of $^{239}$Pu per atom of U

The plutonium-239 breeder reactor is commonly called a fast breeder reactor, and the cooling and heat transfer is done by a liquid metal. The metals which can accomplish this are sodium and lithium, with sodium being the most abundant and most commonly used. The construction of the fast breeder requires a higher enrichment of U-235 than a light-water reactor, typically 15 to 30%. The reactor fuel is surrounded by a "blanket" of non-fissionable U-238. No moderator is used in the breeder reactor since fast neutrons are more efficient in transmuting U-238 to Pu-239. At this concentration of U-235, the cross-section for fission with fast neutrons is sufficient to sustain the chain-reaction. Using water as coolant would slow down the neutrons, but the use of liquid sodium avoids that moderation and provides a very efficient heat transfer medium.
**The Super-Phenix**
The Super-Phenix was the first large-scale breeder reactor. It was put into service in France in 1984.

The reactor core consists of thousands of stainless steel tubes containing a mixture of uranium and plutonium oxides, about 15-20% fissionable plutonium-239. Surrounding the core is a region called the breeder blanket consisting of tubes filled only with uranium oxide. The entire assembly is about 3x5 meters and is supported in a reactor vessel in molten sodium. The energy from the nuclear fission heats the sodium to about 500°C and it transfers that energy to a second sodium loop which in turn heats water to produce steam for electricity production. Such a reactor can produce about 20% more fuel than it consumes by the breeding reaction. Enough excess fuel is produced over about 20 years to fuel another such reactor. Optimum breeding allows about 75% of the energy of the natural uranium to be used compared to 1% in the standard light water reactors.
Example: Spontaneous Fission of $^{238}\text{U}$ results in $^{140}_{55}\text{Cs} + ^{92}_{37}\text{Rb} + \text{how many neutrons?}$

Example: What about $^{239}\text{Pu}$?

It is not naturally occurring.....has to be made in a reactor.....
Example: Problem 33 from Chapter 19

Heat of combustion for TNT is 15MJ/kg

a. How much energy is released in complete combustion of 1 ton of TNT?
   1000 kg x 15 MJ/kg = 15,000 MJ

b. What about in a 1 kiloton explosion?

c. How many Uranium fissions would it take to supply this much energy?
   15000 MJ
   Each fission yields 200 MeV
   200 MeV = 200 MeV x 1.602x10^{-13} J/MeV = 3.20x10^{-11} J per fission
   15000 MJ x 10^6 J/MJ = 1.5x10^{10} J

4.7 x10^{20} fissions

4.7 x10^{20} fissions / 6x10^{23} fissions/mole = 0.78 x 10^{-3} moles
0.78x10^{-3} moles x 235g/mole = 183.3 mg

Conversion Factors
1 eV = 1.602e-19 J
1 MeV = 1.602e-13 J
1 amu = 1.66043e-31 J
= 931.4812 MeV
Example: Problem 37 from Chapter 20

\(^{236}\text{Pu}\) alpha decays with a \(t_{1/2} = 3.9\) yrs.

Energy of alpha particles is 5.75 MeV

If \(4 \times 10^{-9}\) kg of \(^{236}\text{Pu}\) is inhaled and lodges in the lungs of a 75 kg man For 50 years...

a. how much energy is transferred?  
b. What dose has been delivered?

How much energy is transferred?  
\(4 \times 10^{-6} \text{ g/[236g/mole]} = 1.69 \times 10^{-8} \text{ moles}\)  
\(1.69 \times 10^{-8} \text{ moles} \times (6.02 \times 10^{23} \text{ atoms/mole}) = 1.02 \times 10^{16} \text{ atoms}\)

Activity is atoms decaying  
\(N = N_0 e^{-\lambda t}: t_{1/2} = \ln (2)/\lambda\)

\(\tau = 0.693/t_{1/2} = 0.693/3.9\) yrs = 0.1777 /yr; 50 yrs  
Activity: \(\lambda N_0 = 0.177/\text{yr} \times [1.02\times10^{16} \text{ atoms}] = 0.18 \times 10^{16} \text{ atoms/yr}\)

\[0.18 \times 10^{16} \text{ atoms/yr} \times 50 \text{ yrs} \times 5.75 \text{ MeV/alpha} = 51.75 \times 10^{16} \text{ MeV}\]

Convert MeV to J  
\[51.75 \times 10^{16} \text{ MeV} \times [1.602 \times 10^{-13} \text{ J/MeV}] = 82.9 \text{ kJ}\]

Alpha Quality factor = 20  
\(\text{J/kg} = \text{Gy}\)

Exposure = 82.9 kJ/75 kg = 1105 Gy

Dose = Exposure \times \text{Quality factor}  
\[= 1105 \text{ Gy} \times 20 = 22,100 \text{ Sv}\]

Lethal Dose = 25 Sv
Nuclear accidents...

Three Mile Island
March 28, 1979
Loss of coolant and partial core meltdown

Chernobyl
April, 1983
Loss of coolant and partial core meltdown
The accident at the Three Mile Island Unit 2 (TMI-2) nuclear power plant near Middletown, Pa., on March 28, 1979, was the most serious in U.S. commercial nuclear power plant operating history, even though it led to no deaths or injuries to plant workers or members of the nearby community. But it brought about sweeping changes involving emergency response planning, reactor operator training, human factors engineering, radiation protection, and many other areas of nuclear power plant operations. It also caused the U.S. Nuclear Regulatory Commission to tighten and heighten its regulatory oversight. Resultant changes in the nuclear power industry and at the NRC had the effect of enhancing safety.

The sequence of certain events - equipment malfunctions, design-related problems and worker errors - led to a partial meltdown of the TMI-2 reactor core but only very small off-site releases of radioactivity.
The Chernobyl accident in 1986 was the result of a flawed reactor design that was operated with inadequately trained personnel.

The resulting steam explosion and fires released at least 5% of the radioactive reactor core into the atmosphere and downwind.

Two Chernobyl plant workers died on the night of the accident, and a further 28 people died within a few weeks as a result of acute radiation poisoning.

UNSCEAR says that apart from increased thyroid cancers, "there is no evidence of a major public health impact attributable to radiation exposure 20 years after the accident."

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation

Resettlement of areas from which people were relocated is ongoing.

The Chernobyl disaster was a unique event and the only accident in the history of commercial nuclear power where radiation-related fatalities occurred. However, the design of the reactor is unique and the accident is thus of little relevance to the rest of the nuclear industry outside the then Eastern Bloc.
March 11, 2011

The Fukushima Daiichi nuclear disaster is a series of equipment failures, nuclear meltdowns, and releases of radioactive materials at the Fukushima I Nuclear Power Plant, following the Tōhoku earthquake and tsunami on 11 March 2011. The plant comprises six separate boiling water reactors designed and built by General Electric (GE), and maintained by the Tokyo Electric Power Company (TEPCO). The Fukushima disaster is the largest of the 2011 Japanese nuclear accidents and is the largest nuclear accident since the 1986 Chernobyl disaster, but it is more complex as multiple reactors and spent fuel pools are involved.
Recent Events in Japan

My Experiences and Radiation Concerns

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