Radiation, Radioactivity, What’s the Difference and How do they relate to Nuclear Power?

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Much more detail in CEM 485, Spring/2010
http://www.chemistry.msu.edu/courses/CEM485/Index.html
What’s in a word?

Toast as compared to Toaster

Radio tower as compared to Radio Wave

Radioactivity as compared to Radiation?

Radioactive nucleus
- Will decay at its own rate
- It can’t be destroyed except by a nuclear reaction

Radiation
- Generally emitted at one time
- Moves in a straight line, at or near the speed of light
- Can be absorbed, depending on flavor
Part 1 – Power & Reactors

Nuclear Power, Nuclear Reactors
-- Background
--- Basics of Energy ( or Power ) Flow
--- Power in Michigan
--- Power in Japan
--- Reactor types
-- Nuclear Fission process
--- fissile nuclei
--- fission fragments
-- Nuclear Fission Operations
--- spent fuel
--- reactors in France

http://www.nrc.gov/info-finder/reactor/
Q: What’s a Quad in SI units?

1 Quad = 1 Quadrillion BTU
$10^{15}$ BTU * $10^{55}$ J/BTU ~ $1 \times 10^{18}$ J
(BTU = $\Delta E$ for 1 lb of water, 1° F)

Power = $94.6 \times 10^{15}$ BTU / $305 \times 10^6$ people = $310 \times 10^6$ BTU/person
(note that the US is only 5% of world population)

US Energy Consumption 2009, 94.6 Quads

http://www.eia.doe.gov/totalenergy/data/annual/diagram1.cfm

"US Total Energy Flow"
The non-electrical output at a CHP plant is called useful thermal output. Useful thermal output is thermal energy that is available from the plant for use in industrial or commercial processes or heating or cooling applications. In 2009, the industrial sector generated 1.2 quadrillion Btu of useful thermal output; the electric power and commercial sector generated much smaller quantities.

Q: What’s a kilowatt-hour in SI units?

\[
1 \text{kWh} = 10^3 \text{W hr} \times \frac{J}{W} \times \frac{3600 \text{s}}{\text{hr}}
\]

\[
1 \text{kWh} = 3.6 \times 10^6 \text{J} \approx 4 \text{MJ}
\]
Electrical Power in Japan

- Japan is only ~16% energy self-sufficient … 176 Million BTU/person
- The country's 50 main reactors provide some 30% of the country's electricity and this was expected to increase to at least 40% by 2017 with 2 more under construction.
- The destruction of Fukushima Units 1 to 4 will remove ~6% of capacity
- Japan has a full fuel cycle set-up, including enrichment and reprocessing of used fuel for recycle.

Japan Total Energy Consumption, 2008

- Nuclear 11%
- Natural Gas 17%
- Coal 21%
- Oil 46%
- Hydro 3%
- Other Renewables 1%

Primary Energy Consumption: 22.3 Quadrillion Btu

Source: EIA
http://www.eia.doe.gov/cabs/Japan/Full.html

http://www.world-nuclear.org/info/inf40.html
Michigan Nuclear Power Plants

Two D.C. Cook Power plants in Benton Harbor are pressurized water reactors, with 1,048 net megawatt-electrical (MWe) Unit 1 and 1,107 net MWe Unit 2.

N.B. MW-thermal is not MW-electrical.

Fermi 2 plant in Monroe, is a boiling water reactor with 1122 net MWe.

Palisades plant in South Haven, is a pressurized water reactor with 778 net MWe.
Pressurized Water Reactor (PWR)

(1) the reactor core creates heat from nuclear fission.
(2) pressurized-water in the primary coolant loop carries the heat to a steam generator.
(3) the steam generator uses the heat from the primary coolant loop to vaporize water in a secondary loop producing steam.

(4) The steam turns the main turbine and generator, which produces electricity. The “used” steam is exhausted to the condenser where it is condensed into liquid water. The resulting water is pumped out of the condenser, reheated, and sent back to the steam generator (another loop).
(5) The reactor's core contains fuel assemblies which are cooled by liquid water under high pressure (~1000 psi), which is force-circulated by electrically powered pumps. Not shown: Emergency cooling water is supplied by other pumps which can be powered by onsite diesel generators.
Boiling Water Reactor (BWR)

1. The reactor core creates heat from nuclear fission.
2. All the water is in one common loop. A steam-water mixture is produced when water moves through the hot core.
3. The steam-water mixture leaves the top of the core and enters the two stages of moisture separation where water droplets are removed.
4. The steam line directs the steam to the main turbine causing it to turn the turbine generator, which produces electricity. The “used” steam is exhausted to the condenser where it is condensed into liquid water.
5. The reactor's core contains fuel assemblies which are cooled by liquid water, which is also force-circulated by electrically powered pumps. Not shown: Emergency cooling water is supplied by other pumps which can be powered by onsite diesel generators.
Overall Schematics

Nuclear Regulatory Commission Graphics
Part 2 – Fission Process

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All chemical elements have a range of isotopes, i.e. a variable number of neutrons (mass) for a fixed number of protons. Of all of the possible nuclei, only three undergo fission after low energy neutron capture that can be obtained in quantity, and are called ‘fissile’ nuclei.

$^{235}$U ... natural
$^{239}$Pu ... make from $^{238}$U
$^{233}$U ... make from $^{232}$Th
Mass and Charge of FF’s

\[ ^{1}n + ^{235}U \rightarrow (^{236}U_{144})^* \rightarrow \text{Mass}^{1}Z_{1} + \text{Mass}^{2}Z_{2} + ^{1}n’s \]

Mass\(_{1} = \text{Mass}\(_{2} = 236/2 \) – rare split
Mass\(_{1} \sim 140\), Mass\(_{2} = (236-140) \) – common split

Unchanged Charge Ratio
Protons/Mass = 92/238

1/100
1/1000
1/10,000
1/100,000
The Fission Fragments are produced with an excess of neutrons simply because the stable uranium nuclei have many more neutrons than protons ...

\[ ^1n + ^{235}U \rightarrow (^{236}U_{144})^* \rightarrow (\text{Mass}_1Z_1)^* + (\text{Mass}_2Z_2)^* + ^1n's \]

\[ \text{Mass}_1 \sim 138, \text{Mass}_2 \sim 96 \text{ e.g., } 2n + ^{137}\text{Te}_85 + ^{97}\text{Zr}_57 \]

\[ T_\frac{1}{2} = 2.5 \text{ s} \]

\[ 137\text{I}_84 \]

\[ T_\frac{1}{2} = 24 \text{ s} \]

\[ 137\text{Xe}_83 \]

\[ T_\frac{1}{2} = 3.8 \text{ min} \]

\[ 137\text{Cs}_82 (T_\frac{1}{2} = 30\text{yr}) \]

\[ T_\frac{1}{2} = 17 \text{ hr} \]

\[ 97\text{Nb}_56 \]

\[ T_\frac{1}{2} = 71 \text{ min} \]

\[ 97\text{Mo}_55 \]

\[ 137\text{Ba}_81 \]
The Fission Fragments are produced with an excess of neutrons simply because the stable uranium nuclei have many more neutrons than protons ...

\[ ^1\text{n} + ^{235}\text{U} \rightarrow (^{236}\text{U}_{144})^* \rightarrow (^{A1}Z_1)^* + (^{A2}Z_2)^* + ^1\text{n}'s \]

Mass_1 \approx 131, \text{ Mass}_2 \approx 103 \text{ e.g., } 2n + ^{131}\text{Sn}_{81} + ^{103}\text{Mo}_{61}
Part 3 – Fission Operation

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Nuclear Fuel Rods, Before & After

Spent fuel in holding pool, before reprocessing at LaHague, France
Temporary storage in the US

NRC Website on Storage www.nrc.gov

“Fuel that has been stored for at least five years in water has cooled sufficiently, and its radioactivity decreased enough, for it to be removed from the spent fuel pool and loaded into casks to free up additional space in the pool for storing spent fuel newly removed from the reactor.”
France derives over 75% of its electricity from nuclear energy with 59 reactors. This is due to a long-standing policy based on energy security.

France is the world's largest net exporter of electricity due to its very low cost of generation.

France has been very active in developing nuclear technology. Reactors, fuel products and fuel processing services are a major export.

~62 Million people (~1/5 of USA)
Major Modifications and Upgrades to U.S. Boiling Water Reactors with Mark I Containment Systems.

1. Added spare diesel generator and portable water pump – 2002
2. Added containment vent – 1992
3. More batteries in event of station blackout – 1988
4. Strengthened torus – 1980
5. Control room reconfiguration – 1980