Lecture 17

May 26, 2011

Nuclear Energy

- Vast possibilities
- Much worry about safety, partly based on experience
- Further ideas for safer harvesting
- Need to know the basics:

$$^{236}_{92}U \rightarrow ^{90}_{36}Kr + ^{143}_{56}Ba + 3n + \ 199Mev$$

Fission reaction: Need to understand the symbols and concepts.

Nucleus

A nucleus consists of Z protons and N neutrons.

Its mass is close to (but not exactly) (A+Z) u.

Their nomenclature is as follows:

$^{A}_{Z}(\text{Symbol})_{N}$

A= Mass number

N= Neutron number

Z= Atomic (or proton) number

or sometimes simply as

$^{A}_{Z}(\text{Symbol})$

Example of abundant oxygen

$^{16}_{8}O_{8}$ or more simply $^{16}_{8}O$

In nature we also find other "isotopes" of Oxygen

$^{17}_{8}O_{9}$

$^{18}_{8}O_{10}$

$^{14}_{6}C_{8}$

A few important nucleii, and their isotopes

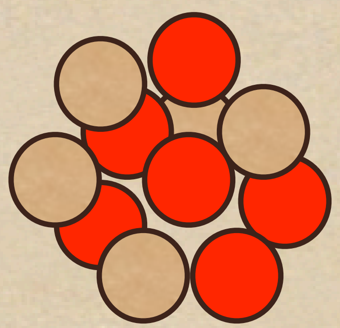
$Hydrogen\ ^1_1H$ Stable hydrogen

$Deuterium\ ^2_1H$ Stable heavy hydrogen

$Tritium\ ^3_1H \quad halflife = \ 12\ years$

Helium	$^{4}_{2}He$ $^{3}_{2}He$	
Carbon	$^{12}_{6}C$ $^{14}_{6}C$	- Carbon dating 5600 yrs
Uranium	$^{238}_{92}U$ $^{235}_{92}U$	Both isotopes occur in nature.
Plutonium	$^{244}_{94}Pu$ $^{239}_{94}Pu$	Both isotopes occur in nature.

Radius of a nucleus ~ 10^{-15} m, i.e. a fermi



Strong interaction forces bind the nucleons together, overcoming their Coulomb repulsion by an even stronger attraction.

Binding energy and mass defect.

The reason a nucleus is stable is due to the binding energy. We can say:

$E_{nucleus} = E_{nucleons} - E_{Binding}$

or

$E_{Binding} = E_{nucleons} - E_{nucleus}$

$M_{defect} = E_{Binding} / C^2$

$$E_{Binding} = (Total\ energy\ of\ Z\ protons\ and\ N\ neutrons) - (total\ energy\ of\ nucleus)$$

$$\Delta m = (total\ mass\ nucleons) - (mass\ nucleus)$$

Example of $^{14}{}_{7}N$ nitrogen nucleus:

Nuclear Mass - 7 electron mass= 13.9992 u

Mass of nucleii (7 p + 7 n)= (.112356+ 13.9992)u

Mass defect = .112356 u

Binding energy = 1.004 10^{13} J

10 tons of this substance gives 98 QBTU !!!!

Radioactivity:

Nuclear reactions accompanied by small particles of various types that emerge and potentially damage the surroundings.

α- rays Ionized Helium atoms ($^{4}_{2}He^{++}$): Stopped e.g. by human hand

β- rays e^- electrons : Pass through humans stopped by thinnest concrete

γ- rays light (photons) : Stopped by heavy concrete

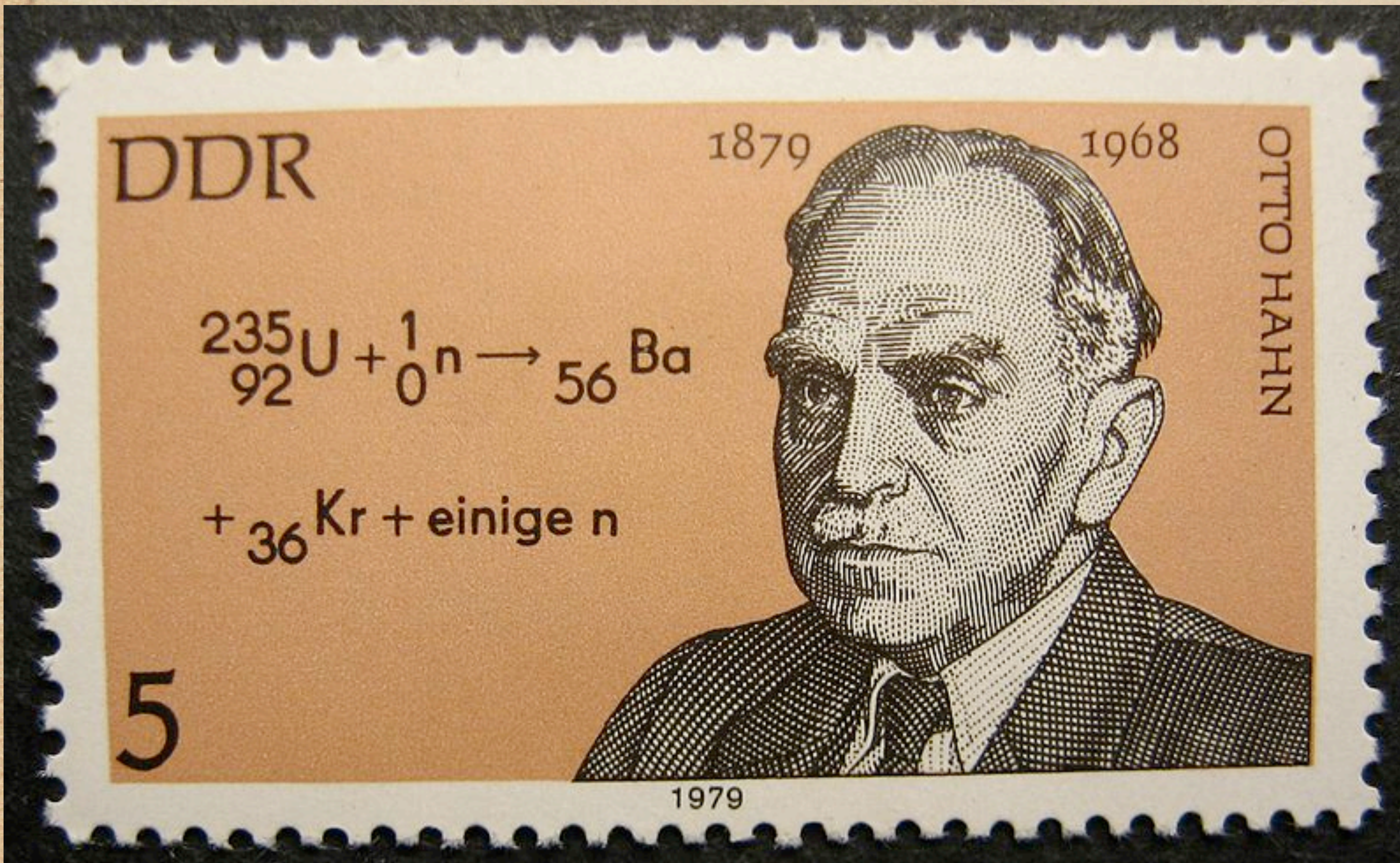
Fission: Not clean, radioactive products formed.

Fusion: Clean, i.e. no radioactive products formed

Fission first demonstrated by Hahn, Strassman, explained by Frisch- Meitner (~ 1938)
Leads to either runaway growth (bombs) (Manhattan project...)
or can be put into a steady state. (power reactors) First shown by E Fermi in Chicago 1942
First reactor 1957 (Shippingport, Pennsylvania)

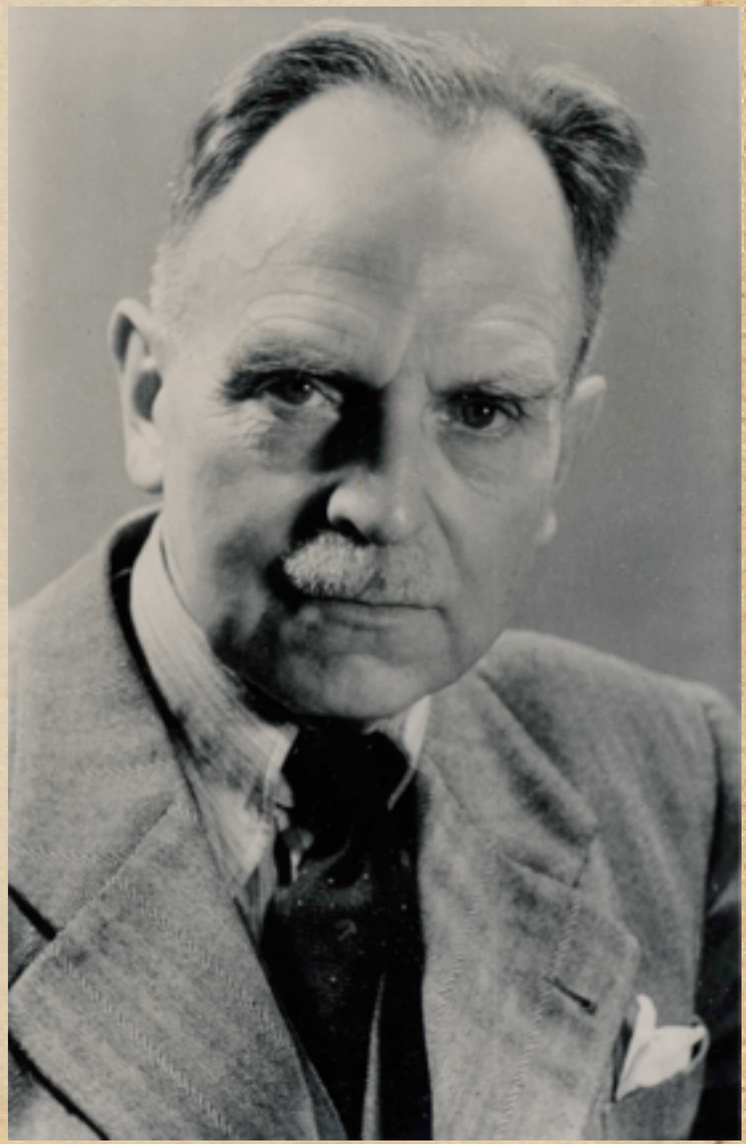
Currently nuclear reactors produce 114 GW (about 17% of total)
France ~ 78% of total is nuclear reactors

einige ≈ many or a few



Fission: neutron production energy release and growth.

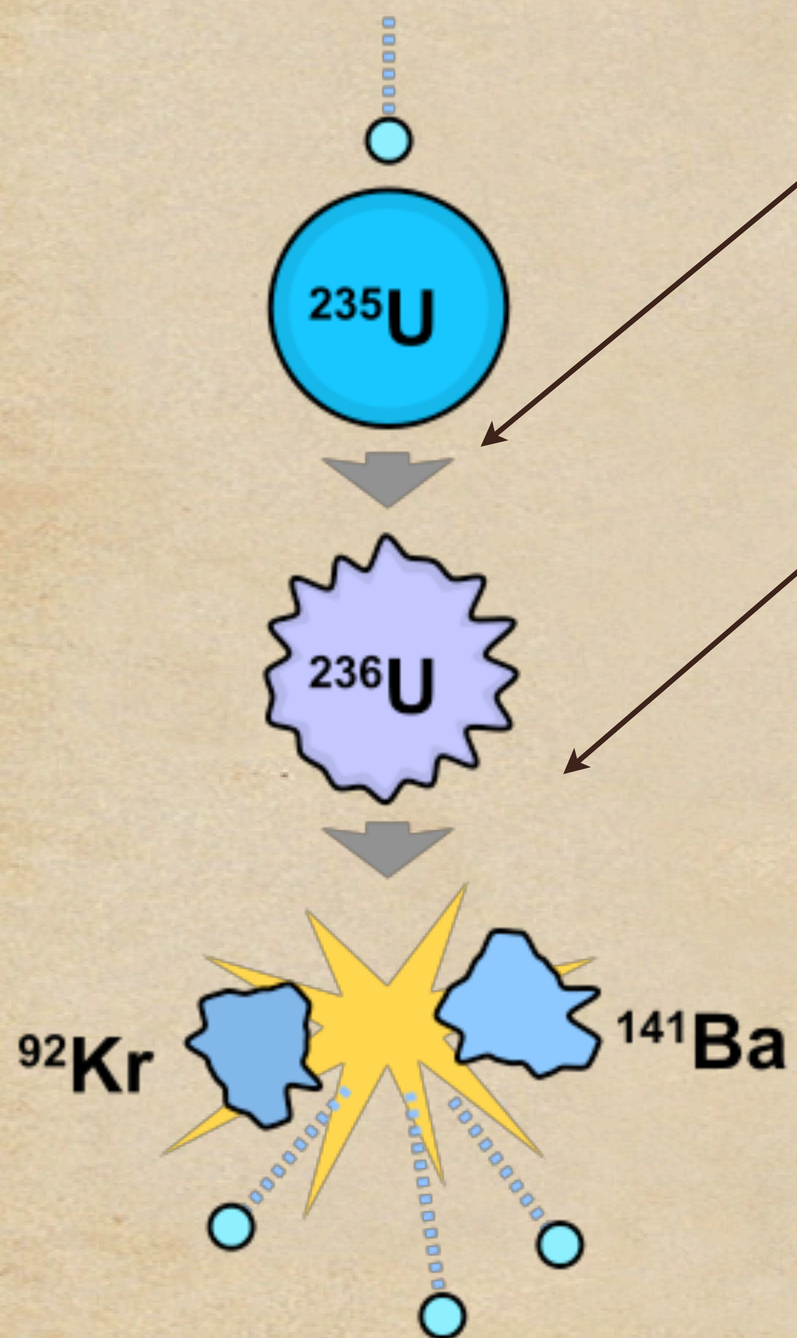
$$^{236}_{92}U \rightarrow ^{90}_{36} Kr + ^{143}_{56} Ba + 3n$$
$$+199 \ Mev$$



The extra energy comes about due to the mass defect.

Thus we put in one neutron + a stable nucleus and end up getting three neutrons.
These can go off in a big way unless we control them.
Taming the nuclear reaction leads to safe reactors.

Liquid drop model of Bohr



$${}^{235}_{92}U + n \rightarrow {}^{236}_{92}U$$

$${}^{236}_{92}U \rightarrow {}^{90}_{36}Kr + {}^{143}_{56}Ba + 3n$$
$$+199\ Mev$$

Chain reaction:

Examples of Radioactive decay

$$^{137}_{55}Cs_{82} \rightarrow ^{137}_{56}Ba_{81} + \beta^- + \overline{\nu} \qquad T_{\frac{1}{2}} = 30yrs$$

$$^{239}_{94}Pu_{145} \rightarrow ^{235}_{92}U_{143} + ^{4}_{2}He_{2} \qquad T_{\frac{1}{2}} = 24,000yrs$$

Cobalt radioisotopes in medicine

Cobalt-60 (Co-60 or 60Co) is a radioactive metal that is used in radiotherapy. It produces two gamma rays with energies of 1.17 MeV and 1.33 MeV. Cobalt-60 has a radioactive half-life of 5.27 years. This decrease in activity requires periodic replacement of the sources used in radiotherapy and is one reason why cobalt machines have been largely replaced by linear accelerators in modern radiation therapy.

Most elements have isotopes that decay or remain stable.

To find them on earth need either longer life time than age of earth, or be formed by decay of long lived isotopes, or be continuously produced,

e.g.

^{14}C Life time 5730 years. This is produced by collisions with cosmic rays in the atmosphere.

$$\Delta N = -\lambda N \Delta t$$

λ > 0 implies decay
λ<0 implies growth
λ=0 implies steady state

$$T_{\frac{1}{2}} = \frac{constant}{\lambda}$$

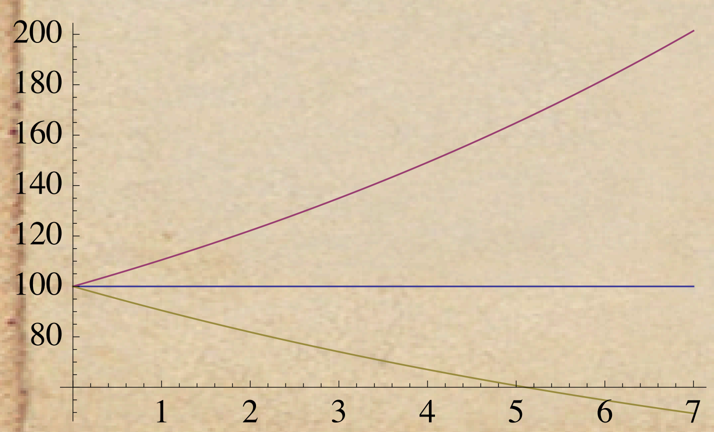
Here N(t) is the number of somethings (neutrons/dollars...) and ΔN is the change in N during a time period Δt.

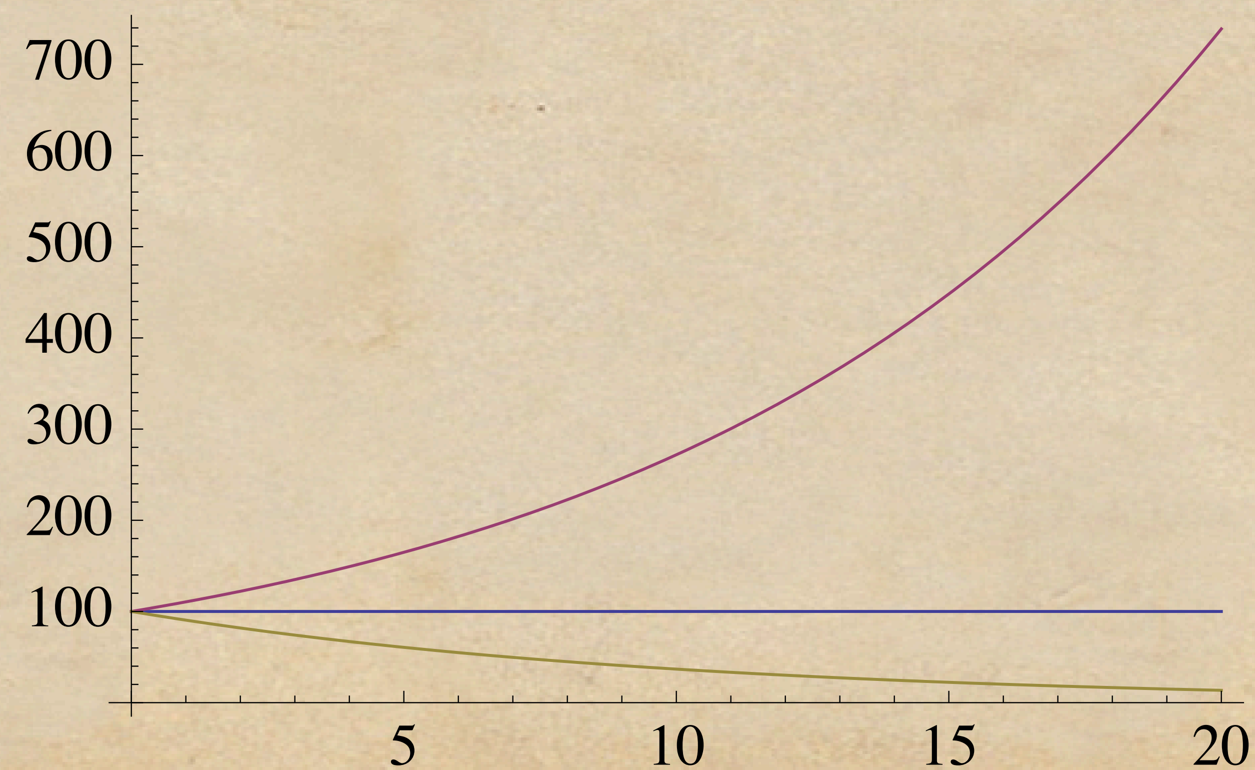
λ	t=0	1	2	3	4	5	6	7
0	100	100	100	100	100	100	100	100
0.1	100	90	81	72.9	65.6	59.05	53	47.8
-0.1	100	110	121	133	146.4	161	177	195

Half life:

$$N(t) = N(0)\ (\frac{1}{2})^{\frac{t}{t^*}}$$

In last problem t* is 7 years.





Composition and concept of a reactor

Enrico Fermi was the designer of the first reactor

Chain reaction — Most nuclear reactors use a chain reaction to induce a controlled rate of nuclear fission in fissile material, releasing both energy and free neutrons.

Moderators
Control Rods — A reactor consists of an assembly of nuclear fuel (a reactor core), usually surrounded by a neutron moderator such as regular water, heavy water, graphite, or zirconium hydride, and fitted with mechanisms such as control rods that control the rate of the reaction.

Controlled Process — Nuclear reactor physics is the branch of science that deals with the study and application of chain reaction to induce controlled rate of fission for energy in reactors.

Abundance Issues: Naturally occurring Uranium (as an Oxide) is 99.7% of ^{238}U (that doesnot undergo fission), and only .3% of ^{235}U, (which does undergo fission.)

Enrichment is all about creating enough bulk of ^{235}U by centrifugal separation.
For weapons grade material need 90% of ^{235}U.
However for reactors need much less concentration, just 3% of ^{235}U is enough.
We produce more as we go along- breeder reactors.

Reactor Issues:

Chain reaction: neutrons + U produces more neutrons
Controlled Chain reaction is a Reactor and is desirable for energy purposes

$$^{236}_{92}U \rightarrow ^{90}_{36} Kr + ^{143}_{56} Ba + 3n$$
$$+199\ Mev$$

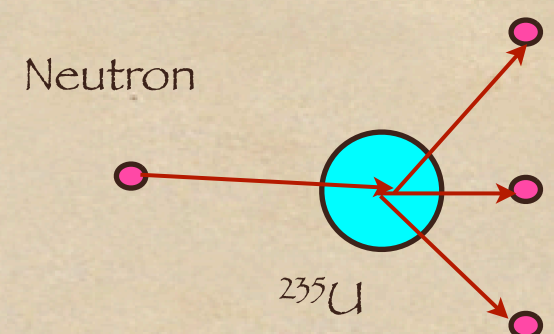
Some decays do not produce neutrons but give photons i.e. gamma rays instead.

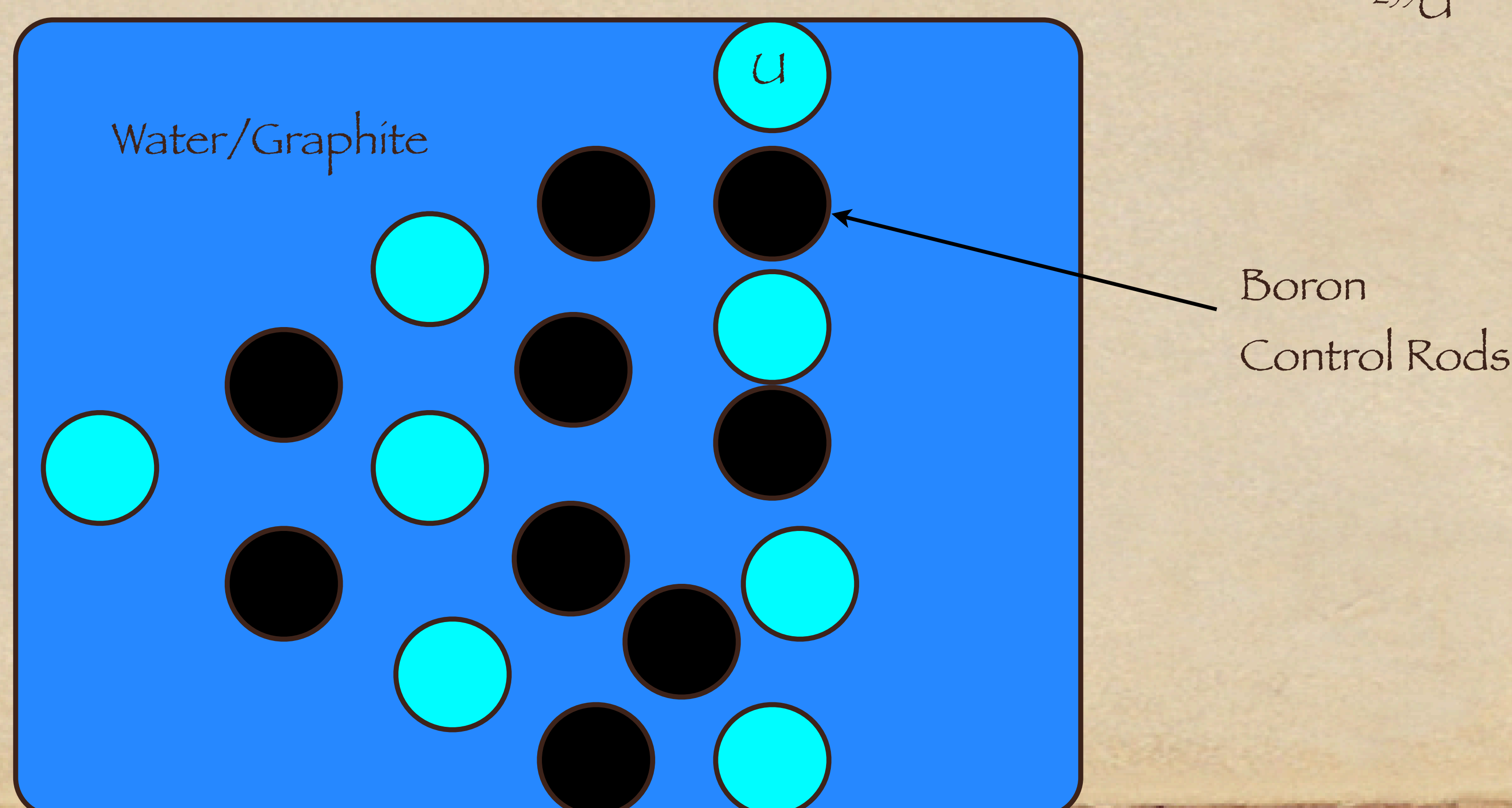
A few crucial facts are important to assimilate here:

1. Slow neutrons have a greater chance of fissioning ^{235}U. The probability of fissioning is 1000 times larger for neutrons with energy .025 eV (300K) than with 1 Mev. Therefore the importance of "thermal neutrons".
2. The emitted neutrons are very fast, with energy of O(Mev) and these need to be slowed down, in order to create next generations of fission.
3. Slowing down happens with the help of "moderators". Moderators are material such as heavy water or graphite where the fast neutrons rattle around to get thermalized.
4. Need control rods to absorb neutrons that are produced, to prevent a reactor from blowing up.

1. A moderator is a tank of some material that scatters neutrons without absorbing them. Good candidates are water, graphite, heavy water.

2.Control rods are inserted to soak up neutrons and to stop the processes. Control rod materials are good neutron absorbers- Boron compound work well





What about the neutrons that do not slow down? And the *97%* of ^{238}U?

Breeder processes.

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

$$^{239}U \rightarrow ^{239}Np + \beta^- + \overline{\nu} \quad T_{1/2} = 24min, \quad \rightarrow ^{239}Pu + \beta^- + \overline{\nu} \quad T_{1/2} = 2.3days.$$

^{239}Pu is stable with regard to radioactive decay. However, it is fissionable just like ^{235}U, and hence it leads to secondary fission as it builds up in the core. This is called breeder technology, since the initial reactor is breeding fuel for the next gen.

Criticality:

Need a certain amount of ^{235}U to sustain a chain reaction.

$$^{235}_{92}U + n \rightarrow ^{236}_{92}U$$

$$^{236}_{92}U \rightarrow ^{90}_{36}Kr + ^{143}_{56}Ba + 3n + 199\ Mev$$

In breeder tech reactors we also get into

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

$$^{239}_{92}U + n \rightarrow ^{239}_{94}Pu + \text{stuff}$$

$$n + ^{239}_{94}Pu \rightarrow \text{fission products} + \text{energy}$$

Different uses weapons or reactors have different requirements of enrichment and criticality.

Boiling water reactor

BWR

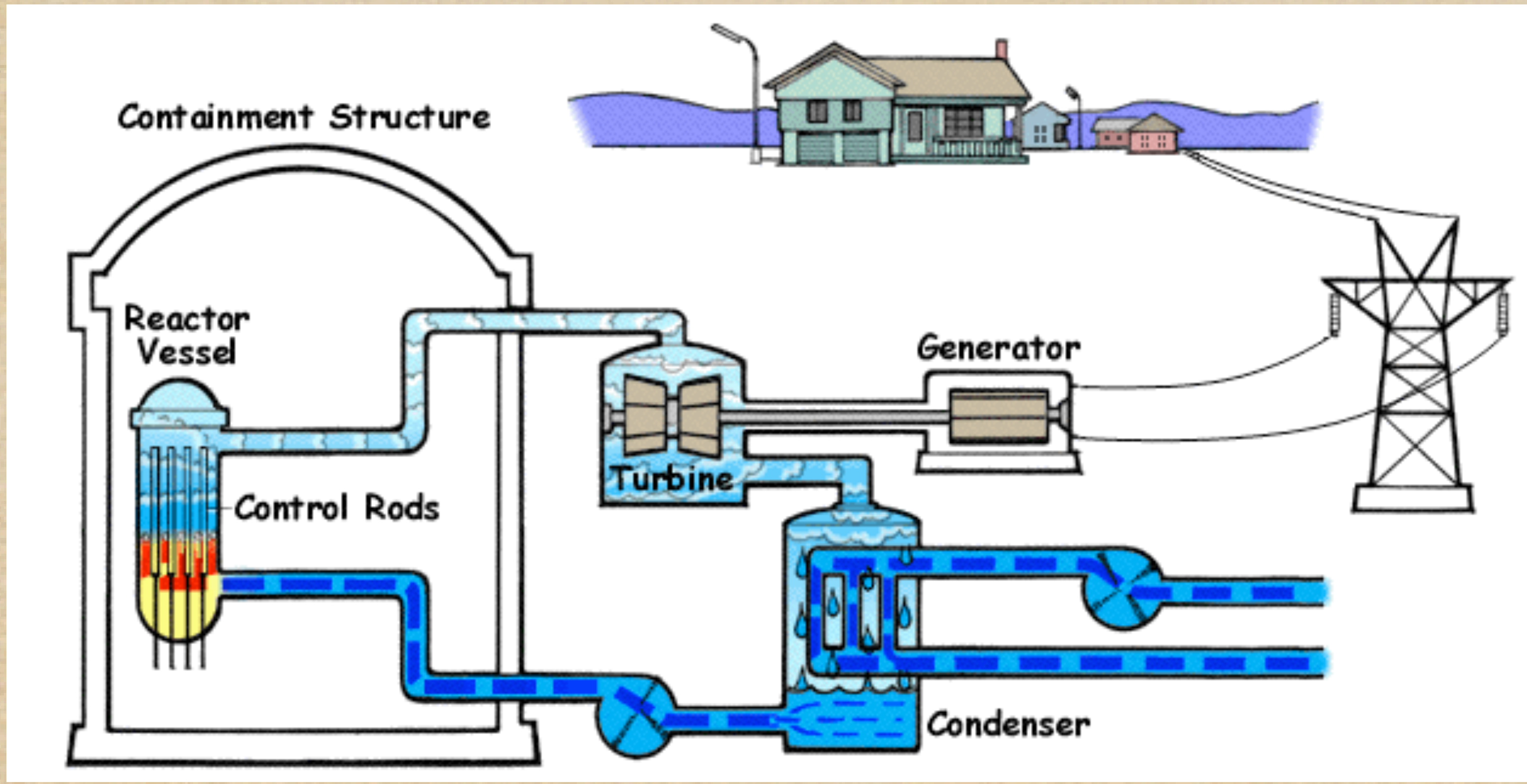
versus

Pressurized Water Reactor

PWR (submarines)

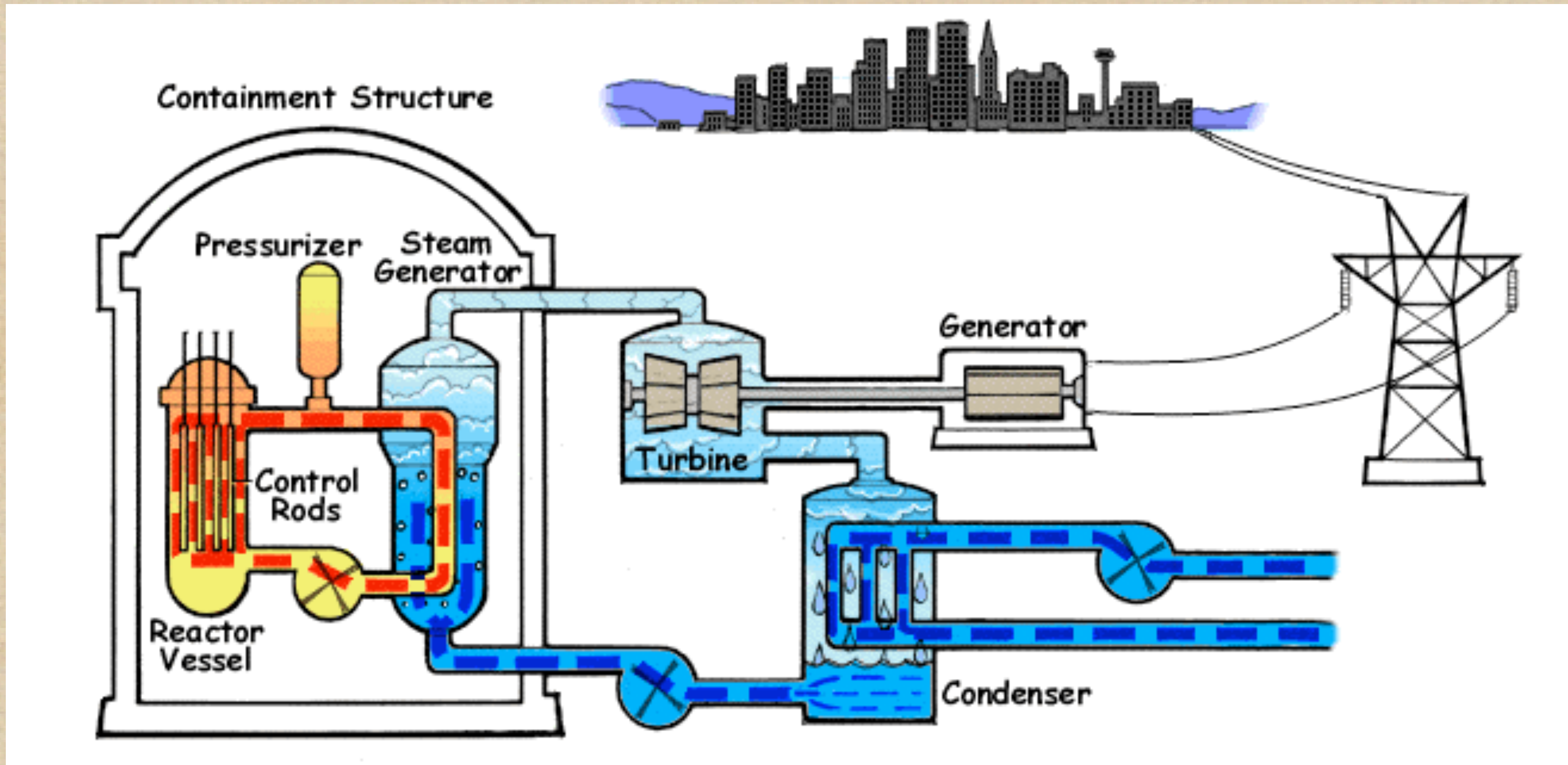
In PWR's water is pressurized to prevent it from boiling. Water gets superhot and outside the reactor, it heats up and boils unpressurized water. Pipes needed to carry this high pressure water around.

Boiling water reactor



Efficiency 34%
Power 1220 MW
342 tons /year
UO_2

Pressurized Water Reactor



Submarines: Can provide power for more that 15 years without refueling due to enriched Uranium fuel.

A few interesting facts:
1. Uranium oxide is sintered into pellets and placed in Zirconium alloys to give fuel rods.
2. A fuel rod remains in a reactor for appxly 3 years
3. Every year a third of the fuel rods are removed and replaced.
4.Nuclear waste problem is: how to deal with spent fuel rods, also proliferation issues crop up.

Direct fission

Uranium as fuel: Availability / costs aspect.
1.Available $3x10^6$ Tons U_3O_8
2.To produce 1 GW.yr need 1Ton ^{235}U or 200 Tons mined U_3O_8
3.Total capacity in USA 97 GW.yr ..Available for 155 years

Breeder tech

Plutonium as fuel:
1. 4200 years
2.Lower grade Uranium is also useful therefore more....
3.Win-Win from this view point. Liquid sodium leaks.+ proliferation issues......

Costs of electricity from nuclear power versus other fuels

Type of fuel	$ per MWH	Market share 2009
Nuclear Power	51	20.3%
Coal	37	44.9%
Gas turbine combo	35	23.4%
Solar cells	202	
Solar Thermal	158	
Wind	55	
Hydro electric	48-86	7%

Waste disposal. Big issue at present. Perhaps creative solutions exist such as deep space or dumping into the burning sun

Chernobyl:

Poor design: Read details in RK. Operator errors + design errors. No containment room since they wanted to extract Pu from a RUNNING reactor!!

Need negative feedback design: Europe & US designs seem fine with this.

The **Fukushima Daiichi nuclear disaster** is a series of fires, equipment failures and releases of radioactive materials at the Fukushima I Nuclear Power Plant, following the 9.0 magnitude Tōhoku earthquake and tsunami on 11 March 2011. The plant comprises six separate boiling water reactors maintained by the Tokyo Electric Power Company (TEPCO).

At the time of the quake, reactor 4 had been de-fueled while 5 and 6 were in cold shutdown for planned maintenance. The remaining reactors shut down automatically after the earthquake, with emergency generators starting up to run the control electronics and water pumps needed to cool reactors. The plant was protected by a seawall designed to withstand a 5.7 m (19 ft) tsunami but not the 14 m (46 ft) maximum wave which arrived 41–60 minutes after the earthquake. The entire plant was flooded, including low-lying generators and electrical switchgear in reactor basements and external pumps for supplying cooling seawater. The connection to the electrical grid was broken. All power for cooling was lost and reactors started to overheat, owing to natural decay of the fission products created before shutdown. The flooding and earthquake damage hindered external assistance.

Evidence soon arose of partial core meltdown in reactors 1, 2, and 3; hydrogen explosions destroyed the upper cladding of the buildings housing reactors 1, 3, and 4; an explosion damaged the containment inside reactor 2; multiple fires broke out at reactor 4. Despite being initially shutdown, reactors 5 and 6 began to overheat. Fuel rods stored in pools in each reactor building began to overheat as water levels in the pools dropped. Fears of radiation leaks led to a 20 km (12 mi) radius evacuation around the plant while workers suffered radiation exposure and were temporarily evacuated at various times. One generator at unit 6 was restarted on 17 March allowing some cooling at units 5 and 6 which were least damaged. Grid power was restored to parts of the plant on 20 March, but machinery for reactors 1 through 4, damaged by floods, fires and explosions, remained inoperable. Flooding with radioactive water continues to prevent access to basement areas where repairs are needed. However, on 5 May, workers were able to enter reactor buildings for the first time since the accident.