The Physics of Nuclear Reactors

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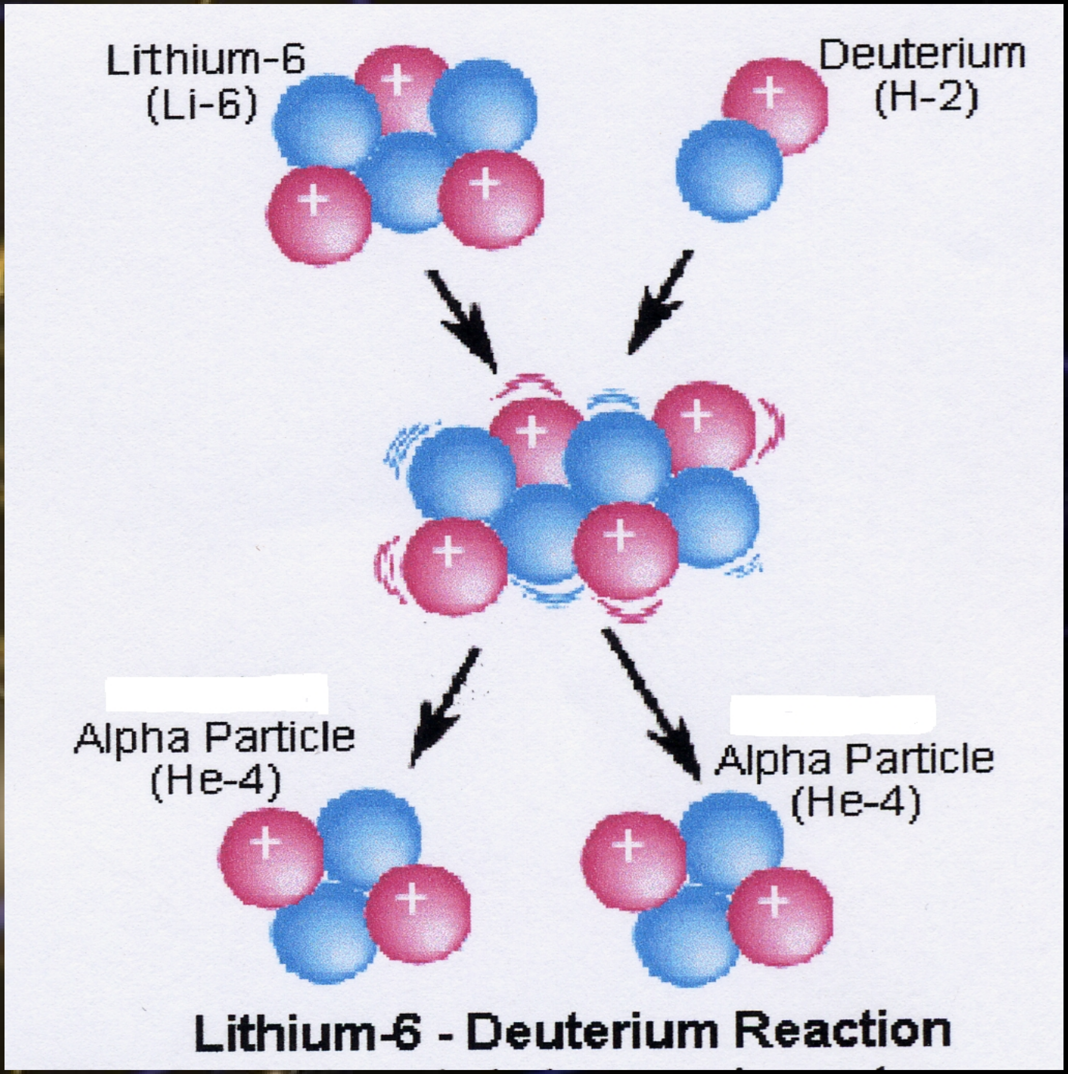
Physics 420

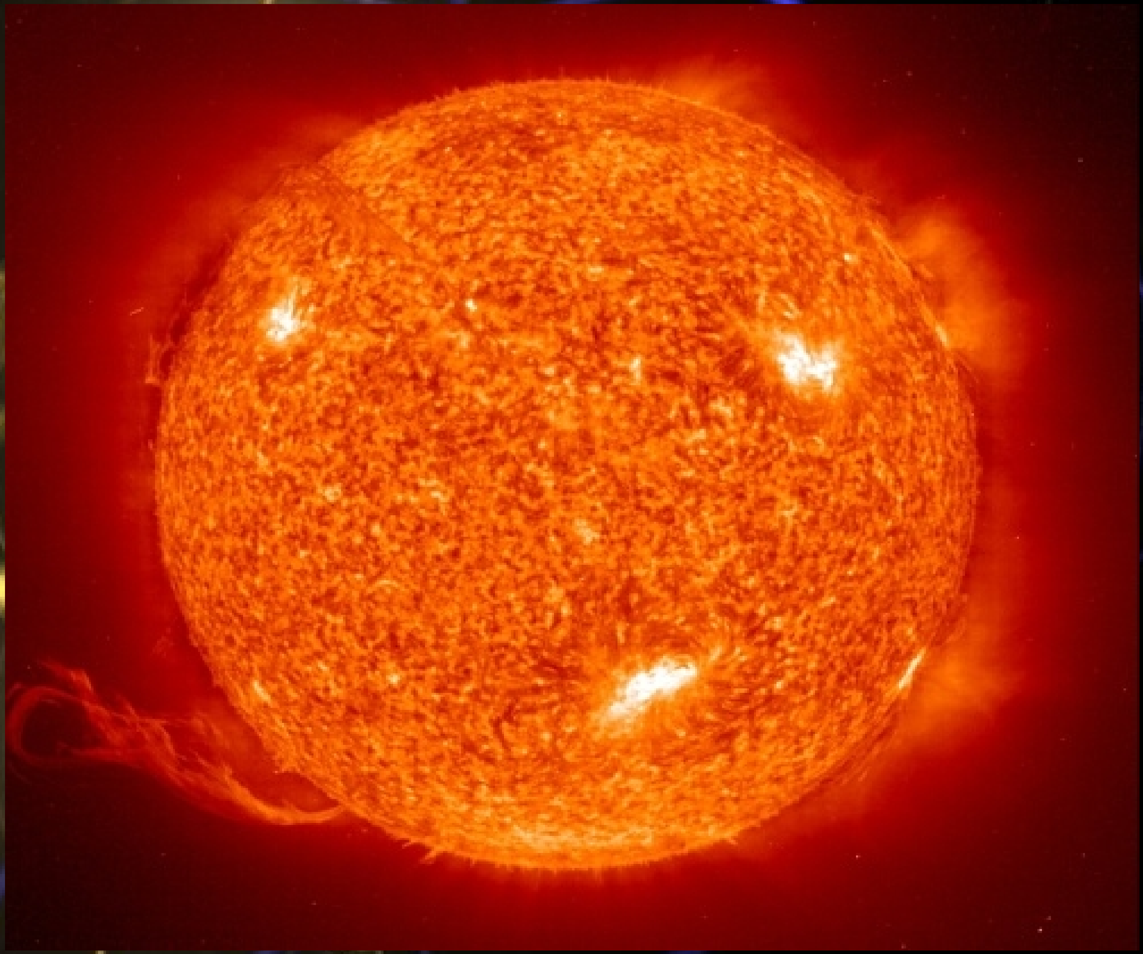
Nuclear Reactions

- A nuclear reaction is a reaction that involves atomic nuclei, or nuclear particles (protons, neutrons), producing products different than the initial particles.
- There are two types of nuclear reactions we will talk about: fission, and fusion.



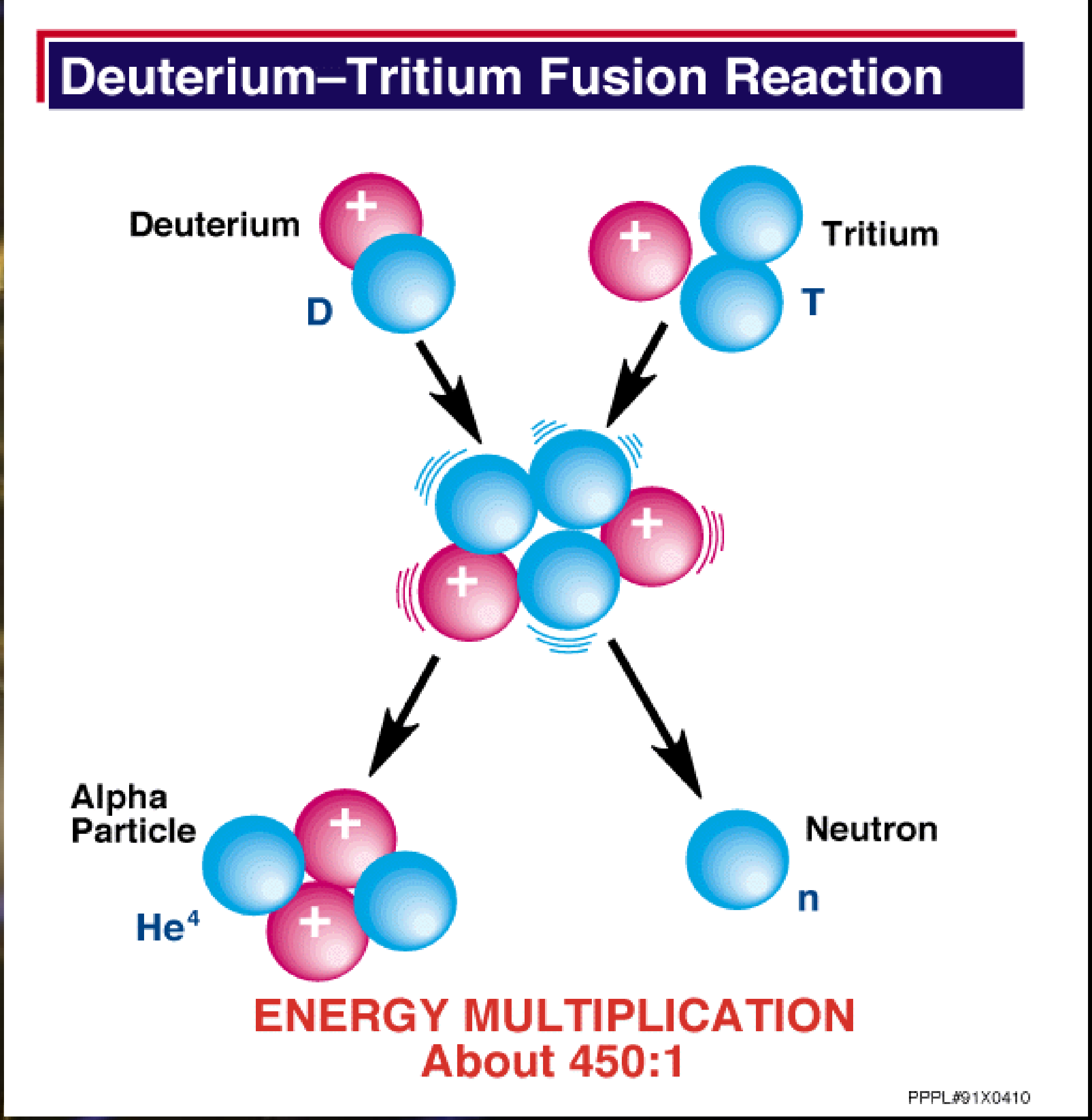
Nuclear Fusion

- Fusion is the process by which smaller nuclei combine to form larger nuclei.
- Fusing nuclei lighter than iron or nickel usually absorbs energy, the fusion of heavier nuclei releases energy.
- Fusion reactions power stars, fusion reactions in stars are the reason that we have elements heavier than hydrogen and helium!



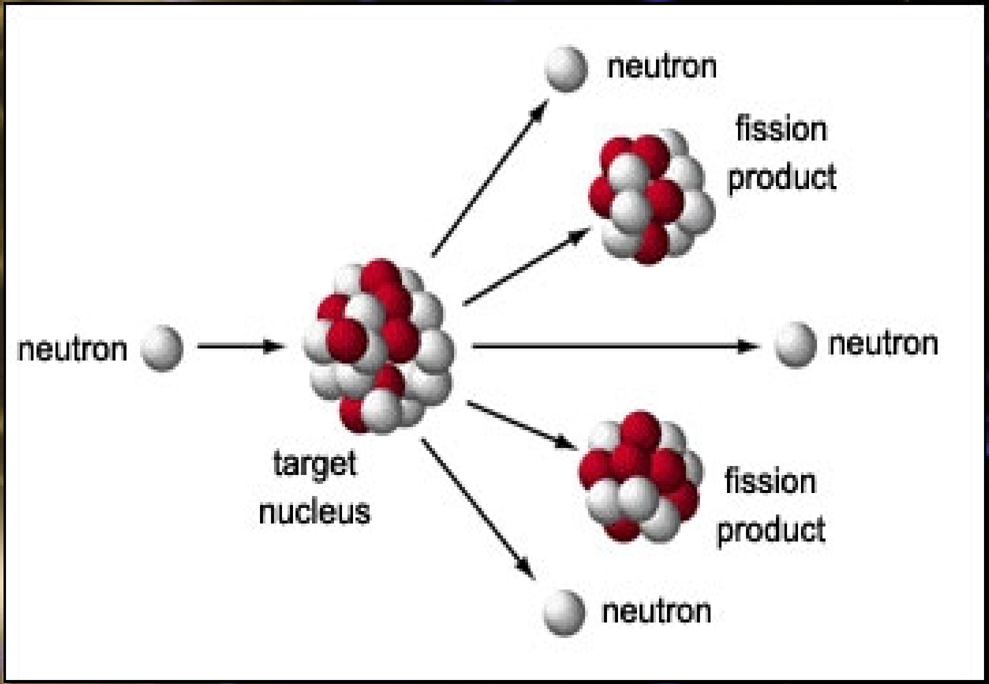
Nuclear Fusion cont.

- So why don't we use fusion for energy production?
- Answer: Energy
- We have to overcome the repulsion of protons vs. protons, this is called electrostatic repulsion.
- Need to get over the **Coulomb barrier** to bring nuclei into contact with each other.
- The temperatures of fusion reactions are so hot, that we need massive B fields to contain them, so massive that the field takes more energy to maintain than we are getting out!
- Only time people have used fusion reactions that have resulted in energy production is the H-bomb.



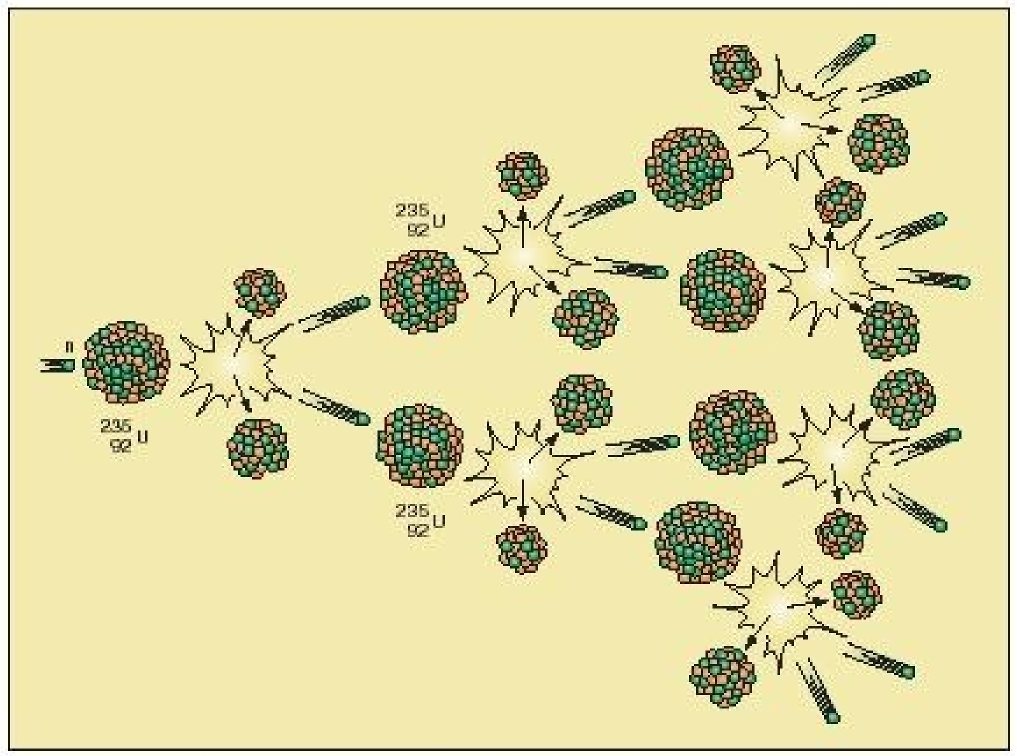
Nuclear Fission

- Fission is a process whereby the nucleus of an atom is split into two or more smaller nuclei, as well as some by-product particles (protons, photons etc.)
- Energy release occurs for fission of heavy nuclei, absorbtion for light nuclei.
- So we can use fission of heavy nuclei to produce energy.



Fission cont. : Chain Reactions

- So why use fission?
- Because we can create a **sustainable chain reaction**!
- A neutron colliding with the nuclei of an atom can result in a fission reaction, which in turn releases more neutrons (as well as lots of usable energy!).
- Most common fuels: ^{235}U and ^{239}Pu (some Canadian reactors use ^{238}U)
- Spontaneous fission: very rare.
- In bombs and reactors, we induce fission by bombarding the material with neutrons, or by getting lots of fuel in one place.



Fission cont.

• What do we need to have a sustainable chain reaction? We need generated neutrons to outnumber the escaping neutrons

• When we get to this level it is called a **critical assembly**, or **critical mass**

•So why use nuclear fission instead of chemical fuels like gasoline?

• Energy! A typical fission event produces energy on a scale of hundreds of MeVs. Burning chemical fuels? Only tens of eVs! That means that a typical fission reaction produces about **10 million times more energy** than its chemical counterpart!

An uncontrolled chain reaction results in a bomb!

Energy production : Chemical vs. Nuclear fuels

A sample calculation:

$C + O_2 \Rightarrow CO_2 + 4.1$ eV
or : $H_2 + ½\, O_2 \Rightarrow H_2O + 3.0$ eV
$^{235}U + n \Rightarrow {}^{137}Ba + {}^{97}Kr + 2n + Q$

Q – some energy. How much?

A ~ 240 => Binding energy ~ 7.5 MeV
A ~ 120 => Binding energy ~ 8.5 MeV

There is an increase in binding energy of ~1 MeV/nucleon

When binding energy increases, mass decreases and is converted to heat.

So Q is approximately 200 MeV!

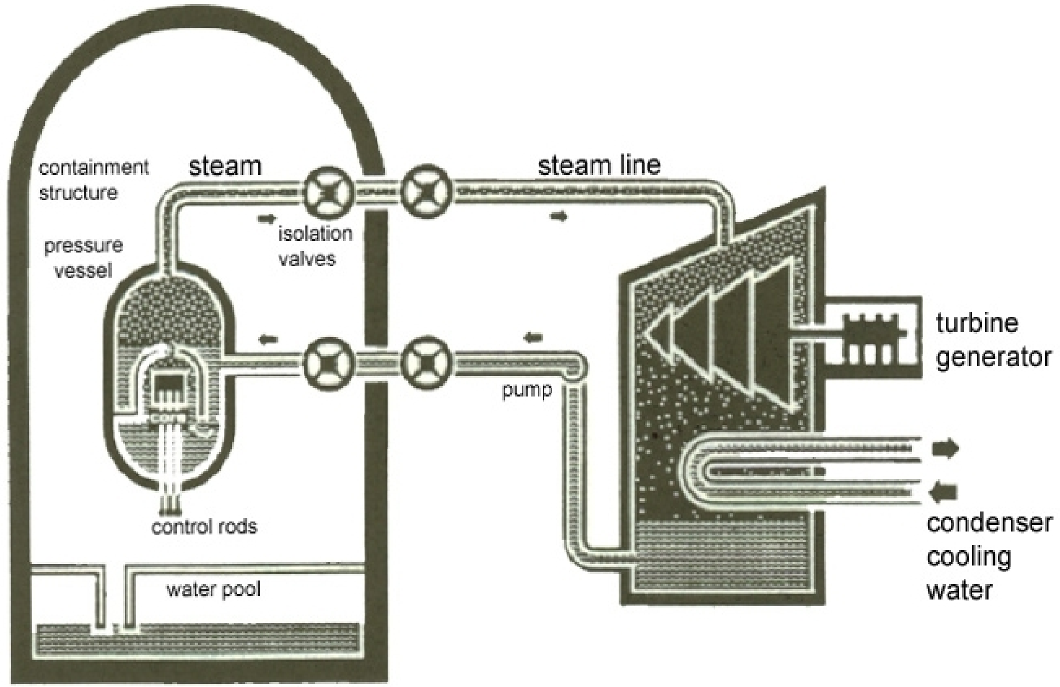
Fission cont: How do we control it?

- So how do we control fission so we can harness the energy and use it to do other things besides blowing stuff up?
- We need to control the number of neutrons that are available to create more fission reactions.
- When we do this we have a **nuclear fission reactor**
- There are 3 main types of fission reactors: power, research and breeder reactors. We will be talking about power reactors.

Diablo Canyon fission reactor

Power Reactors

- Energy resulting from fission reactions is mainly in the form of kinetic energy of the fission products.
- Power reactors convert this kinetic energy into heat. The fission products heat the **working fluid** (usually water, or heavy water), which in turn is used to drive a heat engine.
- Voila! Usable energy! The heat engine can generate mechanical or electrical energy.



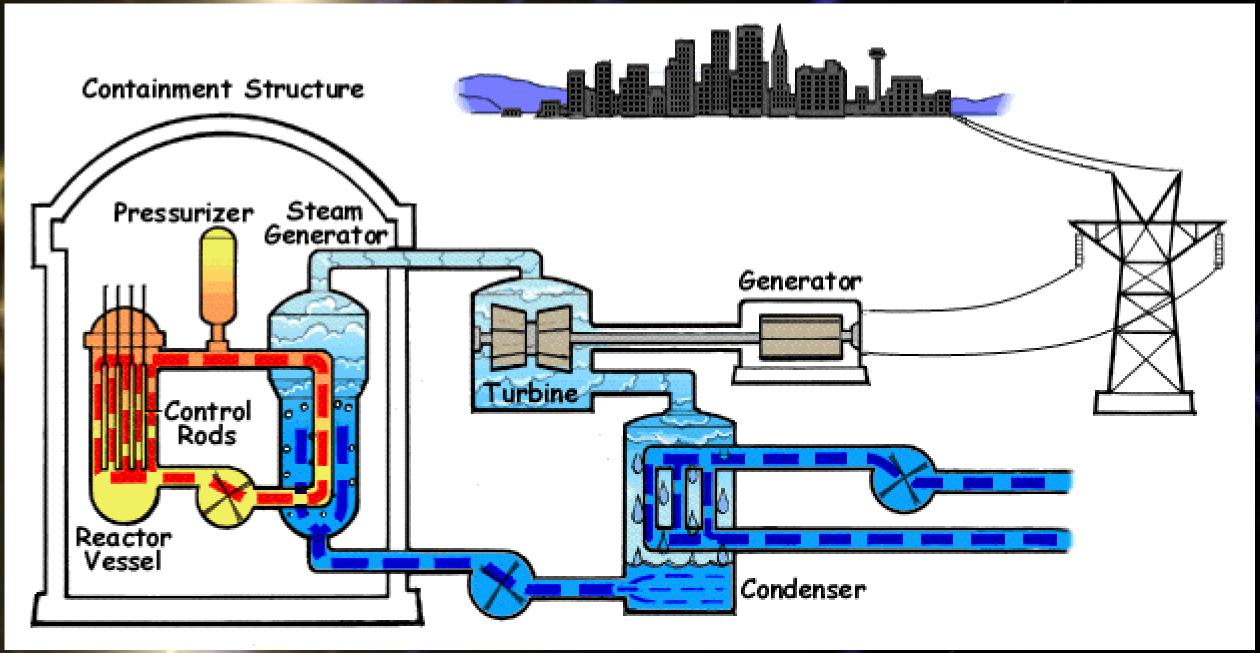
Boiling water reactor (BWR)

Power Reactors Cont.

- So what's the difference between a nuclear bomb and a nuclear reactor?
- Time! A bomb's goal is to release as much energy as possible in a very short amount of time. A reactor **controls** and **sustains** the nuclear reactions.
- A reactor can be either a fast neutron reactor, or a slow thermal neutron reactor. Power reactors are usually the latter.
- The most common type of power reactor today is called a Pressurized Water Reactor or a PWR.

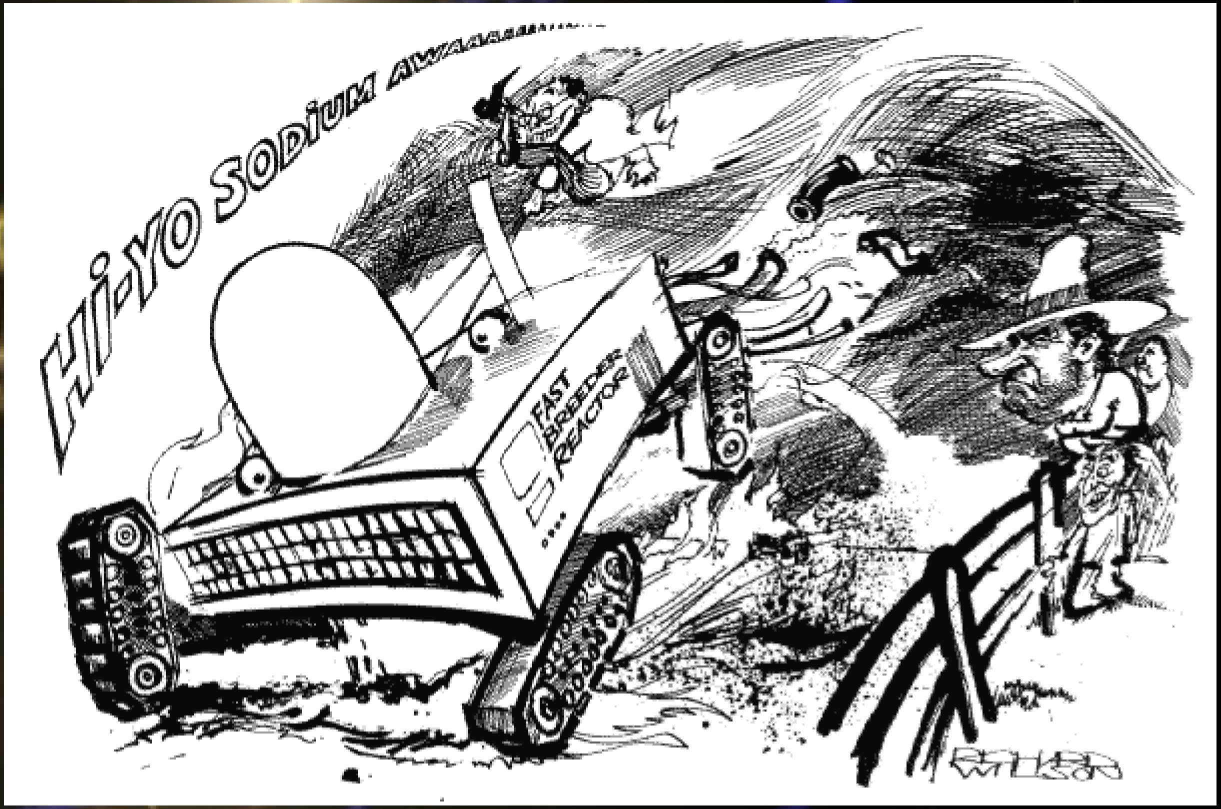
PWRs : Pressurized Water Reactors

- PWRs use regular or 'light' water as a coolant and moderator (to slow down neutrons, making them easier for Uranium atoms to absorb).
- Fission reactions heat the water in the primary coolant loop, but the water does not boil because it is under high pressure.
- The hot water is pumped through a steam generator, which allows the water in the secondary loop to heat up.
- The steam generator turns a turbine which produces electricity.



Breeder Reactors

• This is just what it sounds like!
• Breeder reactors 'breed' nuclear fuel.
• A breeder reactor creates more **fissile** material than it consumes.
• How? One way this can occur is by bombarding ^{238}U with neutrons, this transforms into ^{239}U. The neutron then undergoes beta decay. This changes the neutron into a proton, and releases and electron and a neutrino, changing ^{239}U into ^{239}Pu. Voila! Fissile fuel!
• In order to prevent the possibility of using the ^{239}Pu for nuclear weapons, there are often impurities added that will make it very difficult to use thisPlutonium for a bomb.

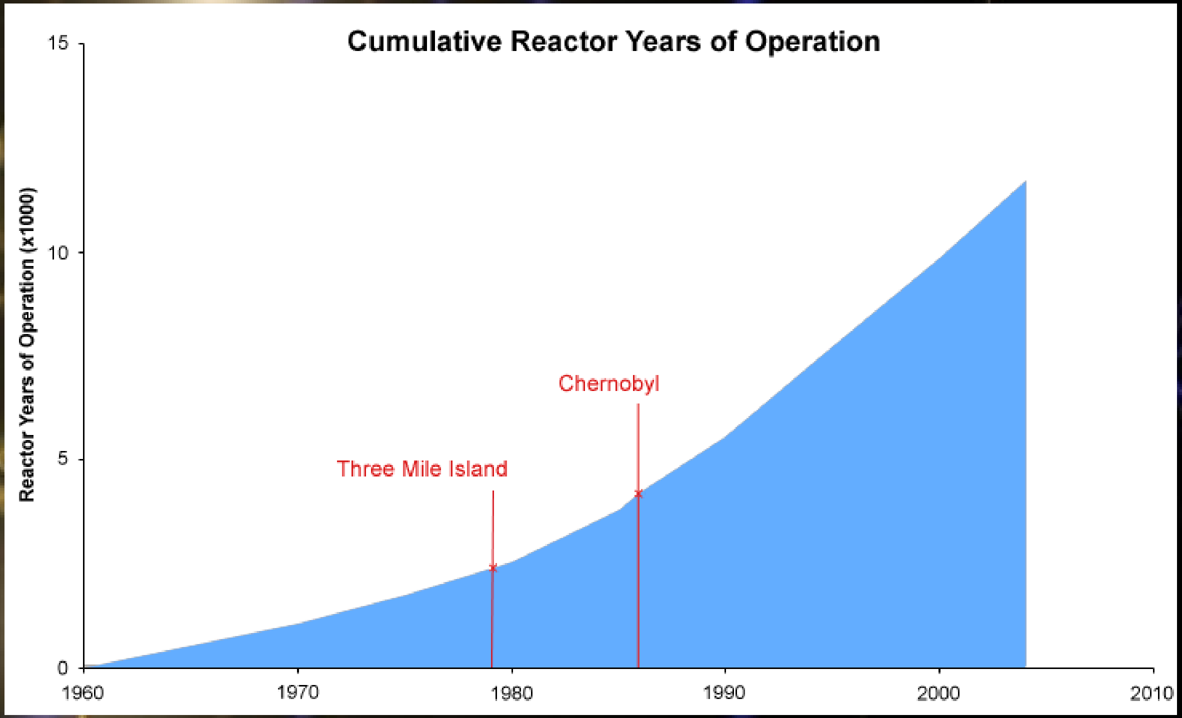


But aren't nuclear reactors dangerous?

- Although it's true that this technology is controversial, a lot of this is politics!
- Nuclear power has gotten a bad reputation because of its use in weapons, but it is really quite safe.
- It does not produce greenhouse gases or any other air pollution.
- We need a comparitively small amount of fuel.
- Energy production is much better!
- There are lots of fail safes in place to prevent a meltdown. You have to try really hard to have another Chernobyl!
- The main problem with nuclear reactors is nuclear waste. It takes a long time to become non reactive, and we need to store it somewhere.

Safety Cont.

- There have been only 2 major accidents since we have been using nuclear power plants.
- Chernobyl is the only accident that has resulted in any members of the public/workers dying from exposure to radiation.
- The second major accident, Three Mile Island, resulted in severe damage to the reactor, but was entirely contained to the facility, and no lives were lost.
- Over 12,000 cumulative years of reactor use in 32 countries has only resulted in these two accidents!



Conclusion

Points to come away with:

• A nuclear reactor requires a controlled, **sustainable chain reaction**, which we currently produce using **nuclear fission**

• Fission involves the splitting of atomic nuclei into two or more smaller nuclei, releasing lots of kinetic energy in the process.

• A single fission event produces about **10 million** times more energy than an equivalent chemical event (burning fuel)!

• The most common type of reactor in use today is the Pressurized Water Reactor or **PWR**, which uses water under high pressure to then drive a steam generator which in turn drives a turbine to create electricity!

• Nuclear power is actually quite **safe** to use, and it is much **better for the environment** than the burning of chemical fuels as it doesn't release any greenhouse gases or other air pollutants.