Module 36: Nuclear Energy

Nuclear Energy

Recall that since the beginning of steam driven electrical power generation, all we needed was something hot (wood, coal, oil) to boil steam and push a fan (turbine) which turned a generator.

Nuclear power uses heat from a nuclear reaction.

Basics:

Fission is the splitting of heavy atoms into lighter ones.

Note heavy atoms (e.g. Uranium, Plutonium, Thorium) split into lighter ones (Krypton-kills Superman, Barium-what they do with dead people):



This happens quickly in an atomic bomb, slower in a nuclear power plant.

If you are into physics, the energy comes from the binding energy of the heavy nucleus, so we call it “nuclear energy”, E = mc2 is the famous formula for this energy released from the loss of mass (the mass of the smaller ones combined is less than the mass of the original atom, this missing mass is released as energy).

Important: count the number of neutrons in (1) and the number out (3). A nuclear chain reaction happens like this:



See how the number of neutrons increases with each collision? This happens in a fraction of a second, which is useful in a bomb, but hard to control with human reaction times in a reactor.

For this to be effective in a power plant, the neutrons need to be going slowly: (“thermal” neutrons).

In a nuclear power plant, to keep this reaction going, and control the speed (slow), we need to absorb some of the neutrons, (“criticality”, one neutron in, one out), and slow these down to make their collision with the next Uranium atom effective.

Moderators are how these neutrons are slowed and controlled, usually water in the reactor, graphite control rods or other materials.

Big picture:

Good: lowers carbon emissions (none), air pollution (mercury, sulfur, other heavy metals from coal or oil)

Bad: nuclear waste, accidents (“China Syndrome”), terrorism (dirty bombs)

Three critical (public) nuclear reactor accidents:

- Three mile island (PA) 1979
- Chernobyl (Ukraine) 1986
- Fukushima (Japan) 2011

Background:

Fission reactors were first used to power stuff in submarines (lots of cooling water). This design was not changed much when it was adapted to land-based power plants, usually situated near rivers or oceans for access to lots of cooling water. They were also made much larger using the same design, which makes for trouble.

We need to understand two main types of nuclear reactor:

PWR: Pressurized water reactor (most common)

BWR: Boiling water reactor (e.g. Fukushima)

PWR reactor diagrams:





This looks complex, here are the steps:

Fission happens when the neutrons from the fuel, slowed by the control rods and water, heat the water in the **primary loop.**

This hot, radioactive **pressurized** water passes through another **secondary water loop**, heating that water to make steam, which drives the **turbine**.

The “dead steam” is then **condensed** in **cooling towers** if on land, or using cooling river or ocean water to go back into the secondary loop.

Plus: Safer because the radioactive **primary loop** is contained in a **containment shell**

Minus: more complex, if the water boils out, the plant can meltdown, causing the China Syndrome, where the molten fuel would melt through the crust, supposedly “to China”. Some people never studied Geology.

This has happened several times: Three Mile Island in Pennsylvania, Chernobyl in the Ukraine, and Fukushima in Japan, which was a BWR reactor.

The spent fuel from both of these reactors, which is replaced every few years can also melt down if not cooled. This is still an issue in Fukushima where the cooling ponds are leaking into the ocean.

You might find it useful to think of a pressure cooker, which keeps water in a liquid state by being under PRESSURE, so PWR, Pressurized water reactor

BWR Reactors: (boiling water reactors)



n.b. one loop, everything else is similar.

Neutrons are slowed by the water flowing through, so as the water **boils**, the gaseous steam slows the neutrons less effectively, so the reaction slows down.

This sounds more automatic, but this can go crazy if the water pumping system fails, as it did in the tsunami that flooded the Fukushima plant in Japan after an earthquake, killing the generators that powered the gear that controlled the reactors as well as the pumps cooling the reactor, so it "melted down".

It is still molten, radioactive and spewing radioactive waste into the ocean (2023)

Plus: simpler, somewhat self regulating

Minus: lots of radioactive stuff to dispose of, e.g. everything (pumps, turbines, condensers, pipes, water, tools, equipment)

USSR tried using molten sodium as the coolant, the plant exploded taking a town with it. This was discovered by satellite photos when the town just disappeared.

Other types:

Breeder reactor: creates energy, but main purpose is to produce Plutonium for bombs by enriching other heavy elements with neutrons.

Gas reactor: also known as a VHTR or very high temperature reactor. These can either be next-generation pebble bed reactors like in the e2 video, or very high temperature reactors that skip the turbine step and instead use heat to split water (pyrolysis) into hydrogen and oxygen, which can be used as fuel. They often use carbon dioxide as the moderator, so as it heats up, it becomes less efficient, so is largely self-regulating.

Fusion energy (the other nuclear energy):

If fission is splitting heavy atoms into smaller ones, if you can push two light elements (Hydrogen, Helium) together, you can FUSE them, releasing huge amounts of energy:



This happens at high temperatures and pressures, like in the core of our sun or other stars.

First ever "break even" was achieved in 2022, when more energy was released than was needed to trigger the reaction

- H2/1 is an isotope of hydrogen, called Deuterium.
- H3/1 is another isotope called Tritium.
- Both have extra neutrons, but the same number of protons (recall that protons define the identity of the atom).
- You may also see the notation n1/0, which means neutron, one thing in the nucleus, no protons.

To do this here on earth, we can do one of two things:

1. Heat and pressure from lasers aimed at a drop of Deuterium (H2/1) can fuse at a temperature of 1,000,000°C (SHIVA at NIF, TOKOMAK)
2. Use atom bombs (fission) around deuterium (H2/1) or Tritium (H3/1) to make a “hydrogen bomb” or "thermonuclear weapon" (thermo=heat).

- The bombs you have heard of at Trinity (first atomic bomb test), Hiroshima and Nagasaki were all fission “A-bombs”.

- Nagasaki used Plutonium (easy to produce, hard to explode), the others used Uranium (hard to produce, easy to explode).
- We only had enough Uranium for two tests, we had lots of Plutonium.
- Both of these released huge amounts of radioactive fallout, covered below.

Fusion “Hydrogen bombs" or "H-bombs” are hundreds of times more powerful and destructive "thermonuclear" weapons.

The ones you see in tests on the ocean are H-bombs.

Present use of A-bombs is only in small cases, or in “neutron bombs” which are designed to release neutron radiation, killing people, leaving buildings intact (banned in the 1970's as inhumane, developed to defend Europe if the USSR invaded).

Fusion power would be great, as the oceans have lots of Deuterium. It is also much cleaner. Ignition is the toughest part, check this out:

National Ignition Facility-SHIVA

Radiation and Fallout:

Recall four main types of nuclear radiation:

- **Alpha particle/rays:** slow, heavy Helium nucleus (He), charged, stopped by your skin, but if it gets inside (lungs or blood) they are fatal.
- **Beta particle/rays:** faster (137,000 mph), lighter, charged electrons, stopped by metal foil, can knock electrons off of DNA, so these are called “ionizing radiation”.
- **Gamma particle/rays:** speed of light (675,000,000 mph), no charge, no mass, ionizes DNA, stopped by lots of lead or concrete. Very dangerous.
- **Neutron radiation:** heavy, uncharged particles destroy cell membranes, make steel brittle, passes through many meters of lead of concrete.

Radiation comes from anything radioactive. Fallout is the name for dust or particles of this radioactive material.

Two main cases:

1. Bombs: release radioactive materials from the bomb, but mainly lots of dust from vaporized islands/desert/other stuff. “Dirty bombs” are just explosives with lots of

radioactive stuff wrapped around them (e.g. plutonium, cobalt, cesium, radioactive waste)
2. Reactor accidents: usually much more radioactive material involved (1000 kg vs. 10 kg), less of an explosion vaporizing stuff, more a matter of radioactive fuel exploding and going into the atmosphere.

Hiroshima, Nagasaki: radioactive dust, Plutonium (Nagasaki), many mutations from radiation: direct (alpha, beta, gamma, neutron) and fallout (usually alpha, beta, gamma).

Pacific bomb tests:

- US tests obliterated some of the Marshall islands.
- The French tests near Tahiti released lots of radioactive Strontium 90, which radiated dairy products in NZ (look up Strontium and Calcium on the periodic table).
- The French are not popular in that region.
- Side note: the French later bombed a Greenpeace ship, the Rainbow Warrior in Auckland Harbor in 1985 which was protesting these French bomb tests. Again, not very popular.

Three mile island: 1979:

- A water valve malfunctioned, due to human error the core was uncovered, the core then melted down, radioactive gas was released from the containment dome, no deaths, but a 5/7 on the total nuclear disaster scale.
- This happened the same weekend a movie about the same accident opened: The China Syndrome

Chernobyl: 1986:

- During a rogue test (more human error), the graphite/uranium core exploded, radioactive core materials, Iodine 131 and other radioactive isotopes were released, many tons of highly radioactive dust were released all over Europe (detected even here in Hawaii).
- Toll: 28 dead on scene, 200,000 estimated cancer deaths all over Europe.
- The USSR hid the disaster for days, which was finally detected at a nuclear facility in Sweden.



Fukushima: 2011:

- The 9.0 Tohoku earthquake offshore caused a tsunami that flooded and disabled the power plant pumping the BWR reactor cooling water, the core melted down, then exploded, the core is still molten today
- TEPCO (Tokyo electric power company, the power utility) continuously lied about the accident, and is still trying to contain the leakage into the ocean and groundwater.
- All fish and produce from the area is still banned.



Smaller accidents:

- Sweden: Forsmark,
- Japan: Tokaimura,
- SL-1 Reactor Idaho Falls (three victims were buried in lead coffins they were so radioactive)

Make sure you understand radioactive half life:

At = A0 (1/2)n or At = A0/2n

At is the amount later at some time t

A0 is the amount at time zero

n is the number of half lives

Common misconception about half life: 2x half-life does not make zero

Can also use population formula if you want to show off:

At = A0e-kt if you know k (the decay rate)

k = 0.693/t1/2 n.b. as t1/2 is larger, k is smaller (slower decay)

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