Nuclear Energy: Then, Now, and the Future

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Professional Development Day
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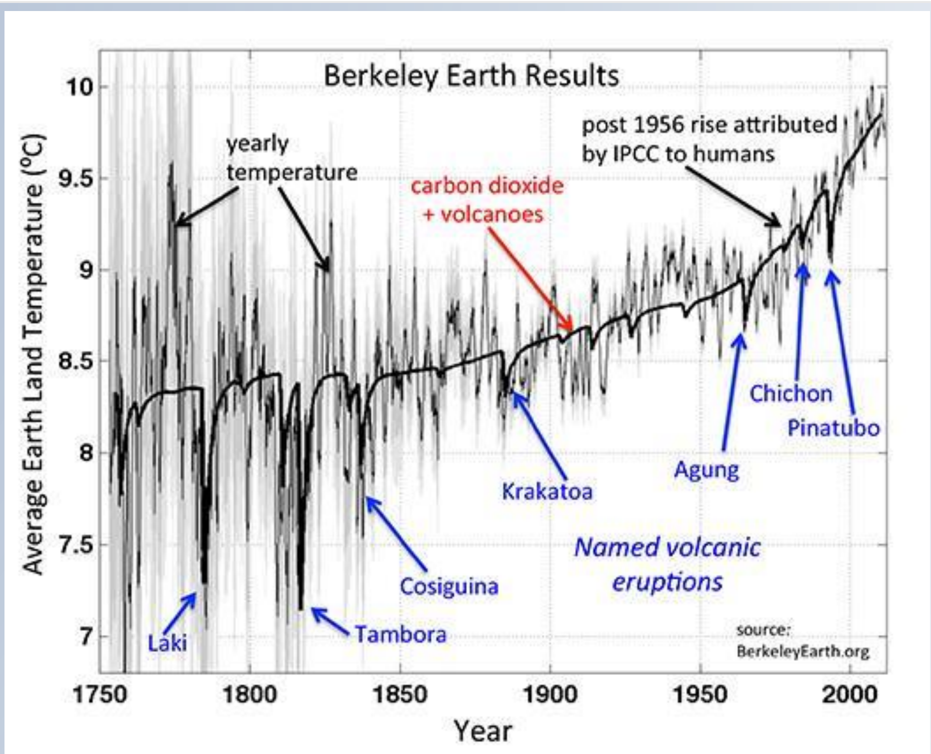
Outline

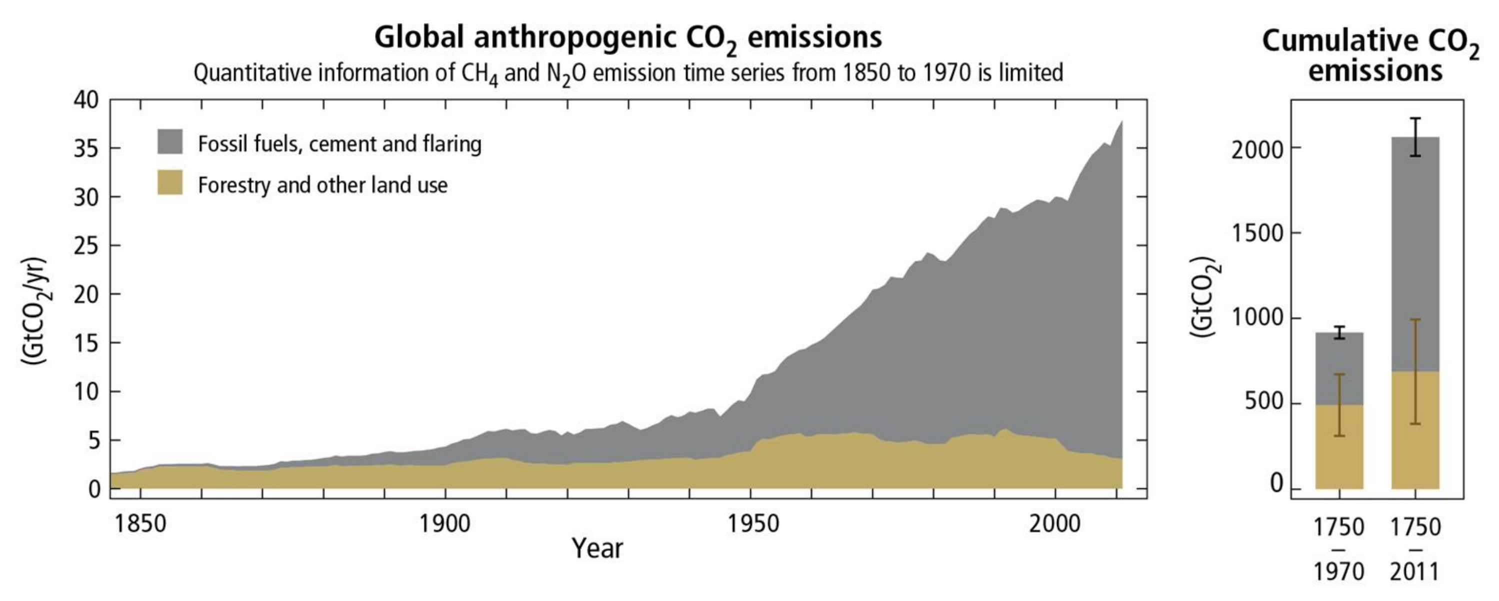
- Why nuclear power?
- Basic nuclear physics
- Nuclear power: Pros and Cons
  - Energy Yield
  - Emissions
  - Radiation
  - Waste
  - Proliferation
  - Future technologies

Why Nuclear Power?

The use of fossil fuels to produce energy is the leading cause of global climate change



BerkeleyEarth.org



IPCC AR5

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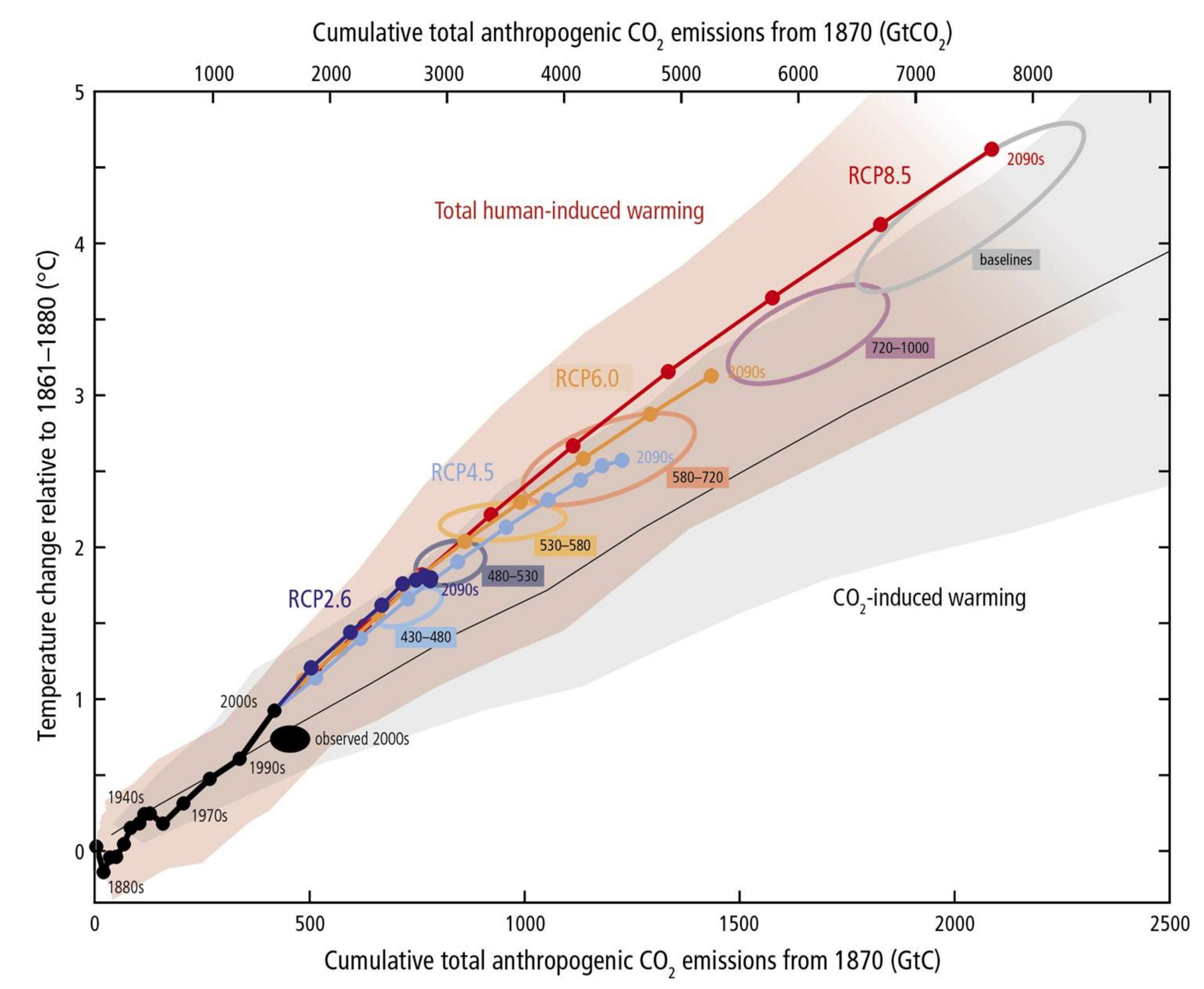
Intergovernmental Panel on Climate Change



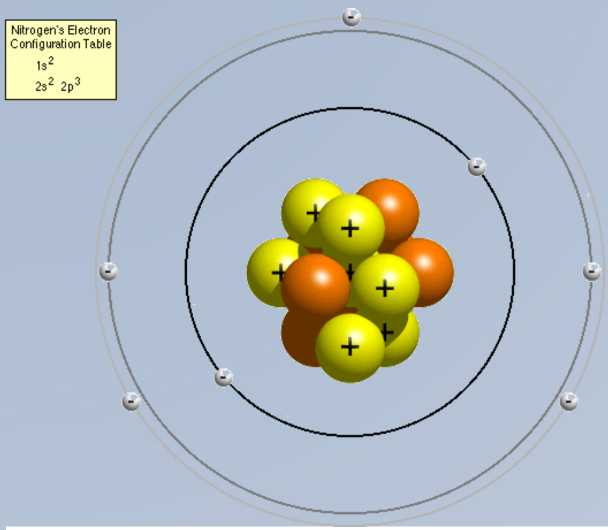
IPCC AR5

RPC stands for **R**epresentative **C**oncentration **P**athway. These are different scenarios for future greenhouse gas emissions by humanity.

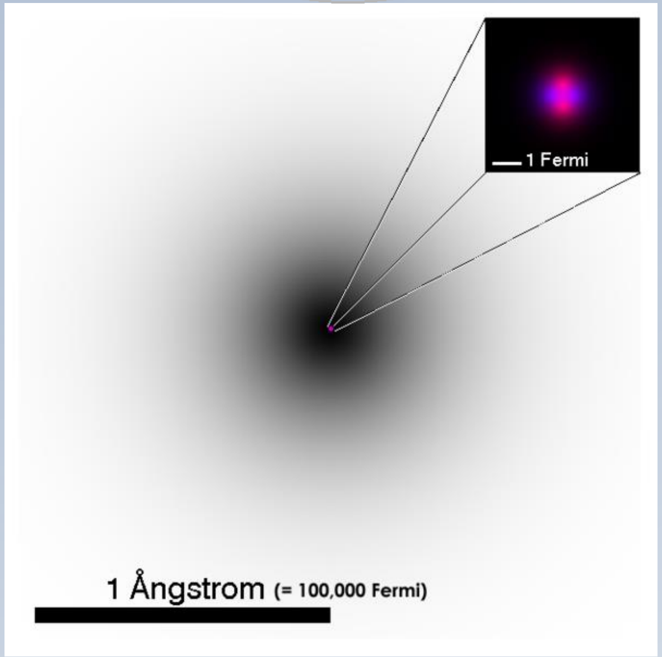
Nuclear Physics

- Most people are afraid of the images and concepts brought to mind by the words **nuclear** or **radiation** or **radioactive**.
- How dangerous are these things?
- Should you be scared or worried?
- What should you know about nuclear physics in this day and age of nuclear power and nuclear weapons?

The Atom



- This is the picture of an atom that most students first learn about. It is made of
    - Electrons (-)
    - Protons (+)
    - Neutrons (0)
    - With the electrons orbiting the nucleus.



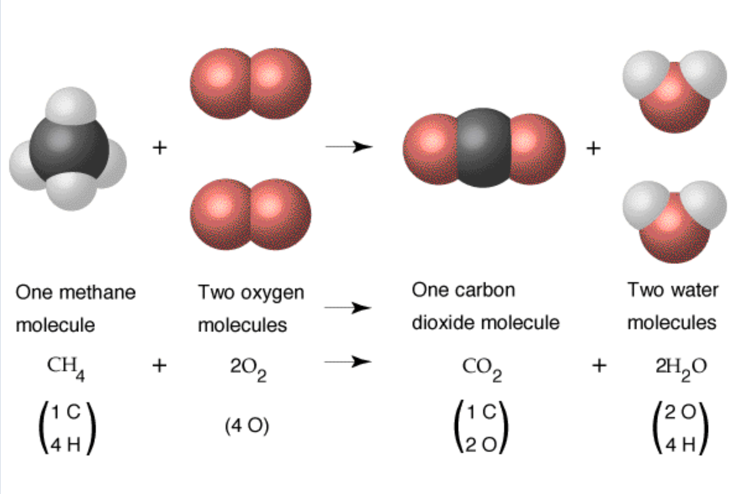
- This is a much more realistic picture of an atom, with a “cloud” of electrons taking up 99.9% of the space in the atom, and a tiny nucleus with 99.9% of the mass of the atom.

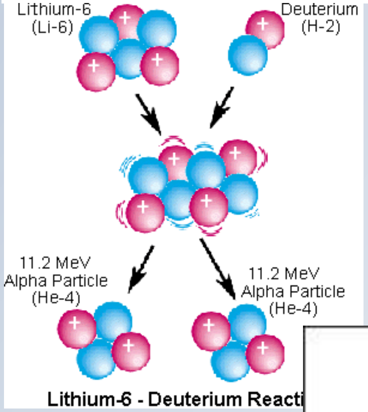
Energy and Nuclear Physics

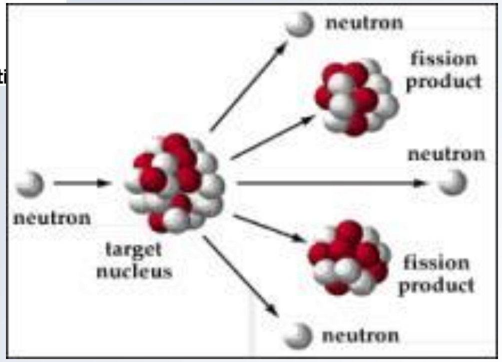
- Most of the sources of energy we use in our lives comes from chemical interactions that involve the electrons in atoms.
- Nuclear reactions involve only the nuclei of atoms.
- Where does this energy come from in these reactions? Mass!!

$$E = mc^2$$

- Since there is thousands of times more mass in the nucleus, nuclear reactions can involve thousands of times more energy!







Nuclear Radiation

- An **element** is defined by how many protons are in the nucleus.
- While an **isotope** is defined by how many neutrons. ${}_{8}^{16}O$, ${}_{8}^{19}O$
- Not all isotopes of an element have stable nuclei, these unstable nuclei will **decay** at some time.
- When a nucleus decays, it emits **energy** in the form of particles. There are many different types of nuclear decay, and different particles can be emitted.... alpha particles, beta particles, gamma rays, and etc.
- We call these particles **ionizing radiation**. They can penetrate your body and deposit their energy, damaging your cells.

- How Radioactive is it?
  - https://youtu.be/XTIvoTiTTSU if you don’t have the equipment

Nuclear Radiation

- You cannot see, feel, hear, smell, or taste these particles, which is probably why people are so afraid of radioactivity and "radiation".

- Your body can repair the damage done by ionizing radiation, and does so on a daily basis, since you are constantly exposed to a very low natural dose of ionizing radiation.

- Every once in a while, when some DNA in a cell is damaged, errors occur in the repairs, and you get cancer. But considering how much natural ionizing radiation you are exposed to in your life, this is **very** rare!

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Nuclear Safety

- It is actually difficult for most ionizing radiation to make another nucleus unstable. This means just being exposed to ionizing radiation usually does not make something radioactive.

- How can be safe from radioactivity? There are two basic ways.
  - **Shielding**... put lots of stuff between you and something radioactive, the ionizing radiation will interact in the stuff, and not in you.
  - **Distance**.... the farther away you are, the less likely the ionizing radiation will hit you in the first place.

- The most dangerous place for something radioactive to be is in you!

Nuclear Safety

Usually radioactive contamination means dust, water, or air that is radioactive. These workers wear suits not to protect themselves from direct radiation, but to prevent them from breathing or picking up radioactive dust.

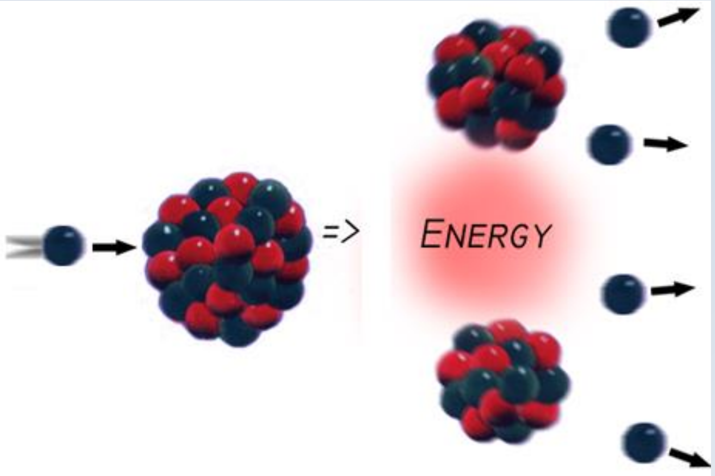
- Half Life Lab
  - https://youtu.be/214cwT4v3D8 to be able to collect data without buying the equipment

Nuclear Fission

- There are two basic nuclear reactions used to create energy from mass.
  - **Fusion** - what occurs in the Sun
  - **Fission** - used in nuclear power plants.
- Some very large nuclei can decay by the process of **fission** - they split almost in half.

$$U_{235} \rightarrow Sr_{97} + Cs_{136} + 2n$$

- When this happens the mass of the “daughters” is less than the mass of the original nucleus, and the missing mass is released as energy!



Nuclear Fission

Fission process occur very rarely - it would take several billion years to release most of the energy in a 50 kg (110 lb) lump of uranium.

This would not be good for a reactor!

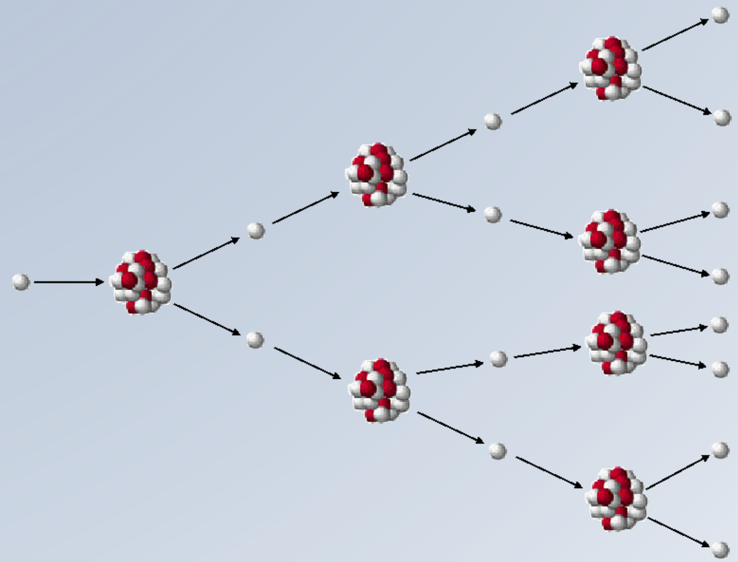
What we need is for one uranium fission to cause two or more other fissions to occur. This would create a **chain reaction** - an exponential growth in the number of decays - lots of energy very quickly!

Chain Reaction

Answer: Neutrons!
If you hit an uranium nucleus with a neutron it can cause it to fission.

If you use the right isotope of uranium (U_{235}) you also get 2 new neutrons from each fission!

If these new neutrons also cause fission to occur you get a **chain reaction**!



Critical Mass

- If the neutrons leave the uranium the chain reaction stops.
- So you need enough uranium - a critical mass - around the initial fission for the neutrons to hit more uranium nuclei.
- Unfortunately, other uranium atoms (U_{238}) absorb neutrons, stopping the process.
- Bad news - U_{238} is 99% of all naturally occurring uranium!

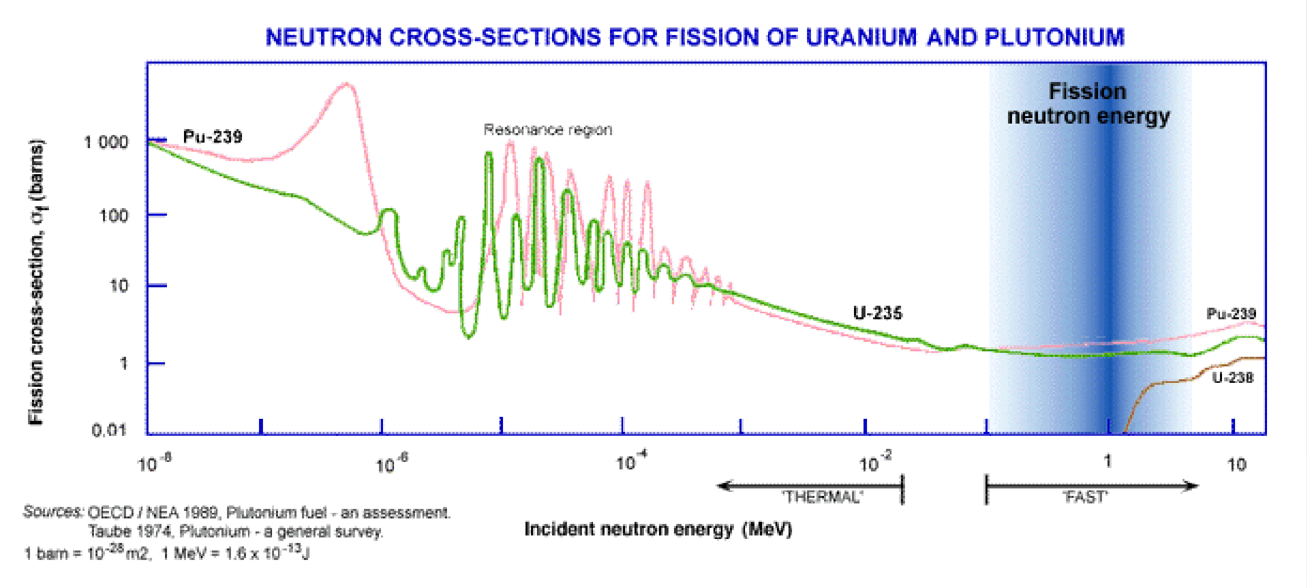
- Critical Mass Simulation
  - http://blog.nuclearsecrecy.com/2015/04/10/critical-mass/
  - http://blog.nuclearsecrecy.com/misc/criticality/

Refinement

- Uranium has to be **enriched** to have enough U_{235} to sustain a chain reaction.
- Use giant centrifuges to separate
  - Reactor-grade (enriched) uranium is from 3-19% U_{235}
  - Weapons-grade (highly enriched) uranium is about 90-95% U_{235}
- Note that weapons-grade uranium can be made from reactor-grade

Moderators

- U_{238} does not absorb slow neutrons, only fast ones
- A moderator (water, graphite) slows down neutrons so they are only absorbed by U_{235}, not U_{238}



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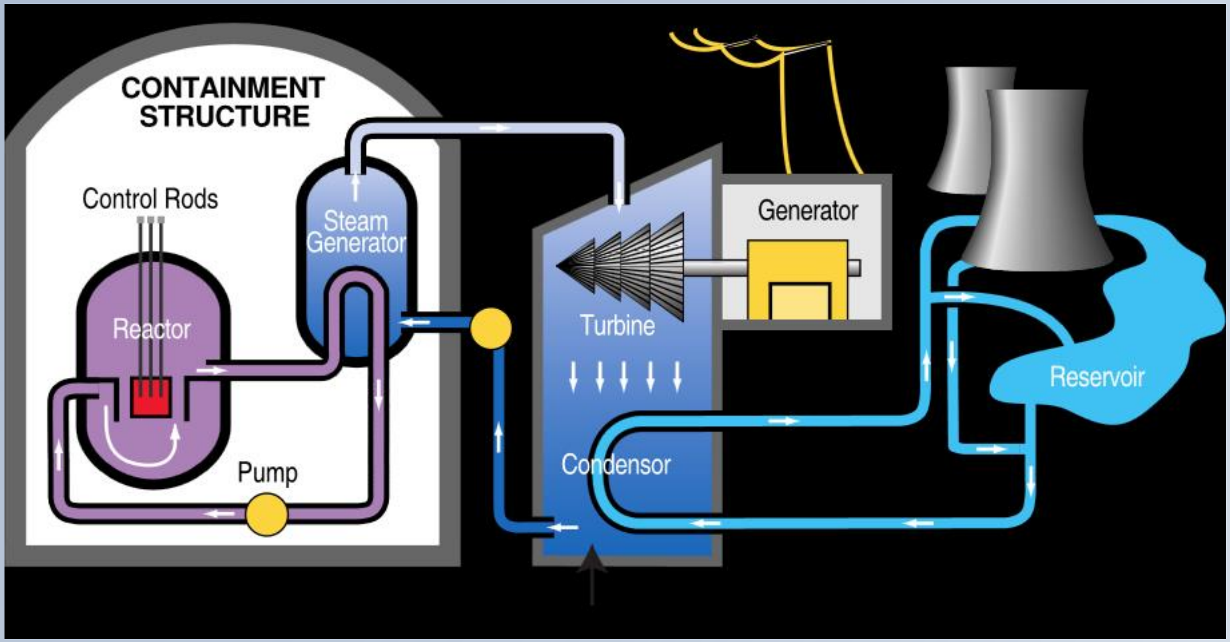
Nuclear power plants



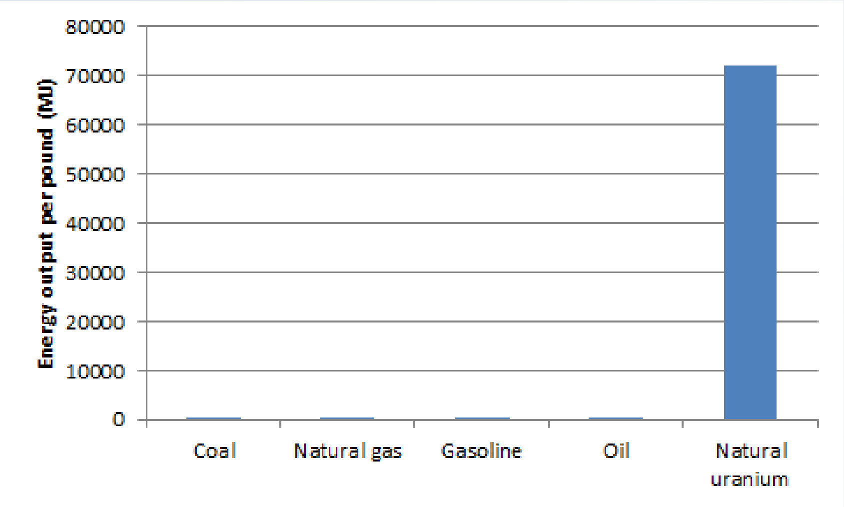
- Generate a sustained, controlled fission reaction
- Use heat to boil water
- Use steam to turn turbine to run generator
- Radiation does not escape the enclosure!

- Radiation and Shielding Project
  - Handouts
  - https://www.spenvis.oma.be/intro.php

Nuclear power: a comparison

A comparison: Energy yield

Fuel	Energy per pound (MJ)
Coal	16
Natural gas	20
Gasoline	22
Crude oil	24
Natural uranium	72,000
Uranium-235	37,000,000



Source: https://www.ocean.washington.edu/courses/envir215/energynumbers.pdf
www.ct.gov/deep/lib/deep/energy/energyprice/energy_conversion_factors.pdf

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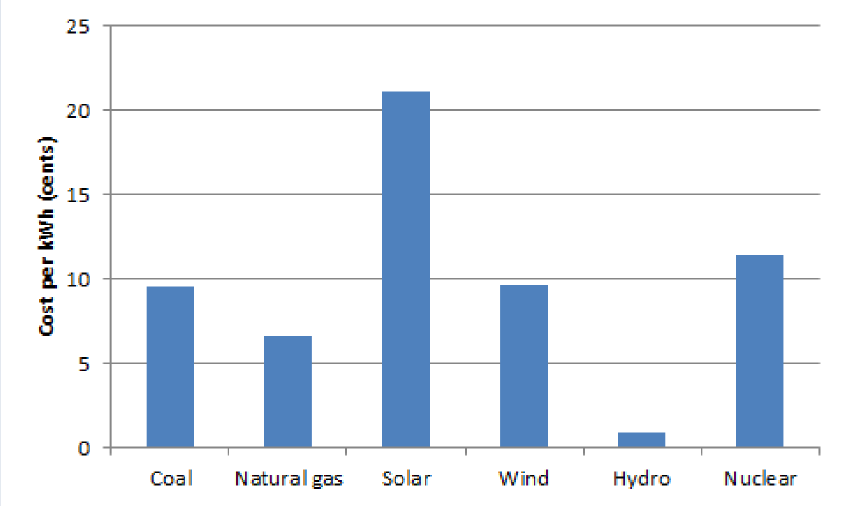
A comparison: Cost

Method	Cost per kilowatt hour
Coal	9.5¢
Natural gas	6.6¢
Solar	21.1¢
Wind	9.7¢
Hydro	0.9¢
Nuclear	11.4¢



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2011*

Life cycle CO_2 equivalent (including albedo effect) from selected electricity supply technologies.[2][3] Arranged by decreasing median (gCO_2eq/kWh) values.

Technology	Min.	Median	Max.
Currently commercially available technologies			
Coal – PC	740	820	910
Biomass – Cofiring with coal	620	740	890
Gas – combined cycle	410	490	650
Biomass – Dedicated	130	230	420
Solar PV – Utility scale	18	48	180
Solar PV – rooftop	26	41	60
Geothermal	6.0	38	79
Concentrated solar power	8.8	27	63
Hydropower	1.0	24	2200
Wind Offshore	8.0	12	35
Nuclear	3.7	12	110
Wind Onshore	7.0	11	56

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A comparison: Power

Method	Amount needed for 1 GW (about 300,000 homes)
Coal	800 pounds (a 1.5-foot sphere) per hour
Natural gas	3.5 million cubic feet per hour
Solar	18 million PV cells - about 12 square miles
Wind	500 turbines - about 75 square miles
Hydro	½ of Hoover Dam
Nuclear	75 pounds uranium (a 3-inch sphere) per hour

Source: https://www.energy.gov/eere/articles/how-much-power-1-gigawatt
Richard Muller, *Energy for Future Pesidents*

- Nuclear Power Plant Simulation
  - http://www.nuclearpowersimulator.com
- Simpler introduction
  - https://phet.colorado.edu/en/simulation/nuclear-fission

The problem of renewables

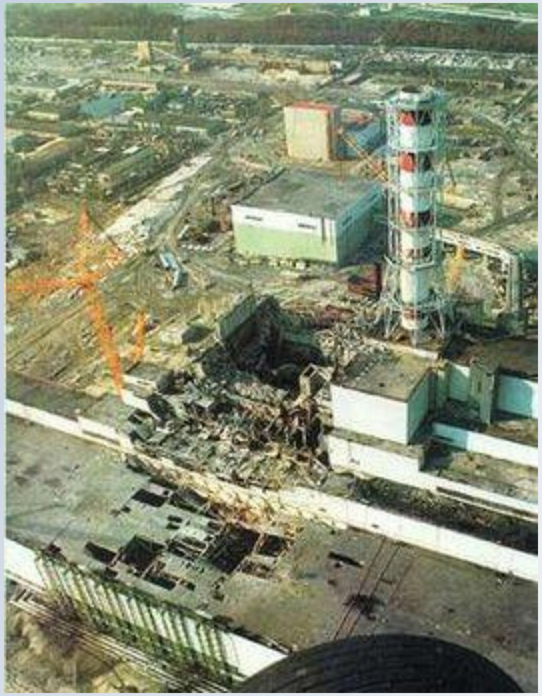
- Solar: Only works during sunny days - storage currently impractical
- Wind: Only works in windy areas and windy days - transfering power inefficient and expensive
- Hydroelectric: Only works in large rivers - with environmental impacts

What’s the catch?

- Danger of meltdown or radiation leakage
- Waste
- Nuclear Weapon Proliferation

Nuclear accidents

- Some perspective on past nuclear accidents:
  - The Chernobyl accident killed about 30 people directly, perhaps 4000 total due to cancer deaths
  - The much smaller Fukushima accident killed none from direct radiation and may cause 300 cancer deaths eventually
  - The Three Mile Island accident caused no harm except for increased stress



Source: http://www.who.int/mediacentre/news/releases/2005/pr38/en/

Compared to other sources

	Deaths from accidents		Air pollution-related effects		
	Among the public	Occupational	Deaths*	Serious illness†	Minor illness‡
Lignite[30]	0·02 (0·005–0·08)	0·10 (0·025–0·4)	32·6 (8·2–130)	298 (74·6–1193)	17 676 (4419–70 704)
Coal[31]	0·02 (0·005–0·08)	0·10 (0·025–0·4)	24·5 (6·1–98·0)	225 (56·2–899)	13 288 (3322–53 150)
Gas[31]	0·02 (0·005–0·08)	0·001 (0·0003–0·004)	2·8 (0·70–11·2)	30 (7·48–120)	703 (176–2813)
Oil[31]	0·03 (0·008–0·12)	··	18·4 (4·6–73·6)	161 (40·4–645·6)	9551 (2388–38 204)
Biomass[31]	··	··	4·63 (1·16–18·5)	43 (10·8–172·6)	2276 (569–9104)
Nuclear[31,32]	0·003	0·019	0·052	0·22	··

Data are mean estimate (95% CI). *Includes acute and chronic effects. Chronic effect deaths are between 88% and 99% of total. For nuclear power, they include all cancer-related deaths. †Includes respiratory and cerebrovascular hospital admissions, congestive heart failure, and chronic bronchitis. For nuclear power, they include all non-fatal cancers and hereditary effects. ‡Includes restricted activity days, bronchodilator use cases, cough, and lower-respiratory symptom days in patients with asthma, and chronic cough episodes. TWh=10^{12} Watt hours.

Table 2: **Health effects of electricity generation in Europe by primary energy source (deaths/cases per TWh)**

Source: *Lancet* 2007; 370: 979–90

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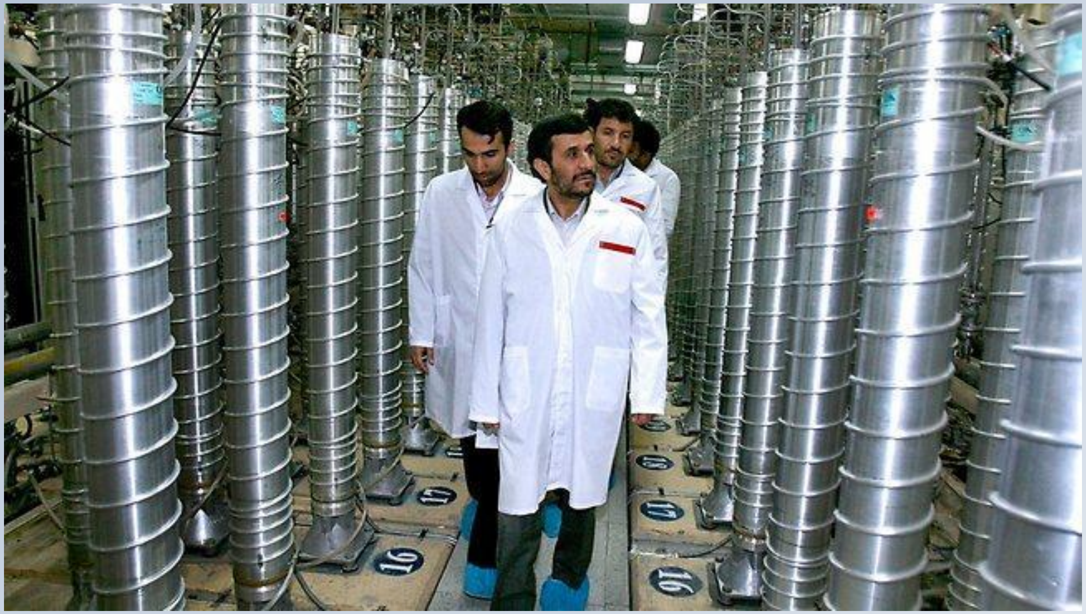
Nuclear waste

- Nuclear waste is extremely dangerous
  - Residual radioactivity
  - Temperature
  - Use in "dirty bombs"
- The best solution: store it in Yucca Mountain
  - This is a political problem, not an engineering problem
- Nuclear waste is the *only* industrial waste with a disposal plan
  - Coal and natural gas expel their waste into the atmosphere and water

Proliferation

- Nuclear reactors are closely related to nuclear weapons.
- If you can refine fuel for a reactor, you can refine fuel for a bomb.
- Uranium bombs are unfortunately easy to build.
- **Breakout** - the conversion of a civilian program to a military one - is a real problem



Proliferation - plutonium

- Plutonium is a more fissile material than uranium.
- Plutonium is naturally produced in nuclear reactors from U_{238}.
- Fortunately, plutonium bombs are much harder to build.

Proliferation - solutions

- Heavy-water reactors work on unrefined uranium, due to the highly effective moderator
- Some proposed small modular reactors can be buried underground, preventing unauthorized access
- Hope may lie in future technologies

Future technologies - Thorium

- Thorium reactors use a neutron source to turn thorium into uranium, which then fissions.
- Thorium is more abundant and easier to mine than uranium.
- Because the uranium is produced and used on the spot, proliferation is much more difficult.
- Much less waste (as much as 1000 times less) is produced.

Future technologies - Fusion

- The same process that powers stars and hydrogen bombs.
- Requires extremely high temperature to fuse light particles into heavier ones, releasing energy.
- Releases ten times the energy, per pound, as fission.
- Ideally, uses hydrogen (water) as its fuel, and helium as its waste
- The perfect energy source!

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Future technologies - Fusion

- We have worked on fusion for a long time.
- Still a long way away.
- The ITER experiment should produce sustained fusion some time in the 2030s.
- Commercial fusion will be a while after that.

Conclusion

- Nuclear power sounds scary, but is much less dangerous than fossil fuel alternatives.
- Nuclear power can provide a large amount of energy, especially useful in countries with few fossil fuel resources.
- As with all power sources, it has advantages and disadvantages.
- There is always a shortage of nuclear engineers - in terms of job security, this is a good field!

Thank you!

- https://www.youtube.com/watch?v=ciStnd9Y2ak
- https://www.youtube.com/watch?v=ZwY2E0hjGuU
- https://www.youtube.com/watch?v=uU3kLBo_ruo
- “Energy For Future Presidents the science behind the headlines” by Richard A Muller

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Useful references

Backup slides

Nuclear Fission

Fission process occur very rarely - it would take several billion years to release most of the energy in a 50 kg (110 lb) lump of uranium.

This would not be good for a bomb or a reactor!

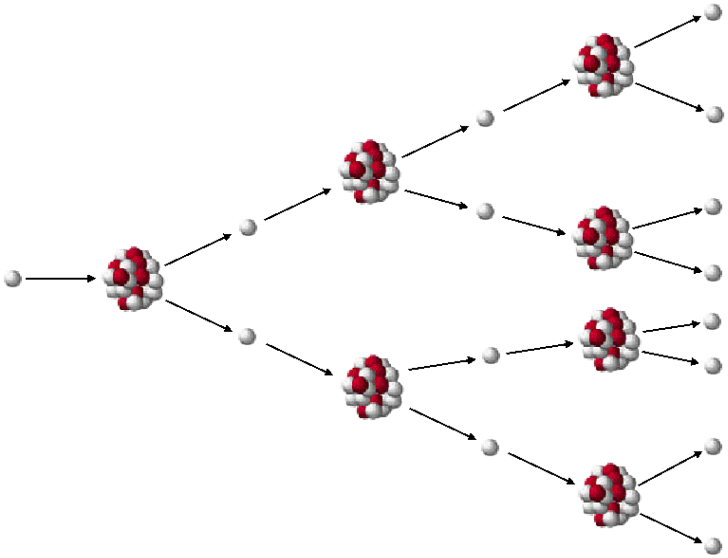
What we need is for one uranium fission to cause two or more other fissions to occur. This would create a **chain reaction** - an exponential growth in the number of decays - lots of energy very quickly!

Boom!!!

Answer: Neutrons!
If you hit an uranium nucleus with a neutron it can cause it to fission.

If you use the right isotope of uranium (U_{235}) you also get 2 new neutrons from each fission!

If these new neutrons also cause fission to occur you get a **chain reaction**!



Critical Mass - the big IF

If the neutrons leave the uranium the chain reaction stops.

So you need enough uranium - a critical mass -around the initial fission for the neutrons to hit more uranium nuclei.

If you have a sub-critical mass, there are two ways to make it go critical.
1) just add more mass (easy to do, but slow)
2) squeeze it to get a higher density (hard to do, but fast)

Critical Mass

One key achievement of the Manhattan project was to develop the formulas needed to calculate what the critical mass is for uranium.

Nowadays these formulas and solutions can be found on the web, and be used by anyone.

For a bomb you need to make a greater than critical mass of uranium, and make sure it stays critical until most of the uranium has fissioned. This has to be done fast..... or it will fizzle.

Uranium

Over 99% of the uranium found in ores is U_{238} and only 0.7% is U_{235}. To be useful it needs to be “enriched”. This is a long and difficult process using centrifuges, gas diffusion, or other methods.

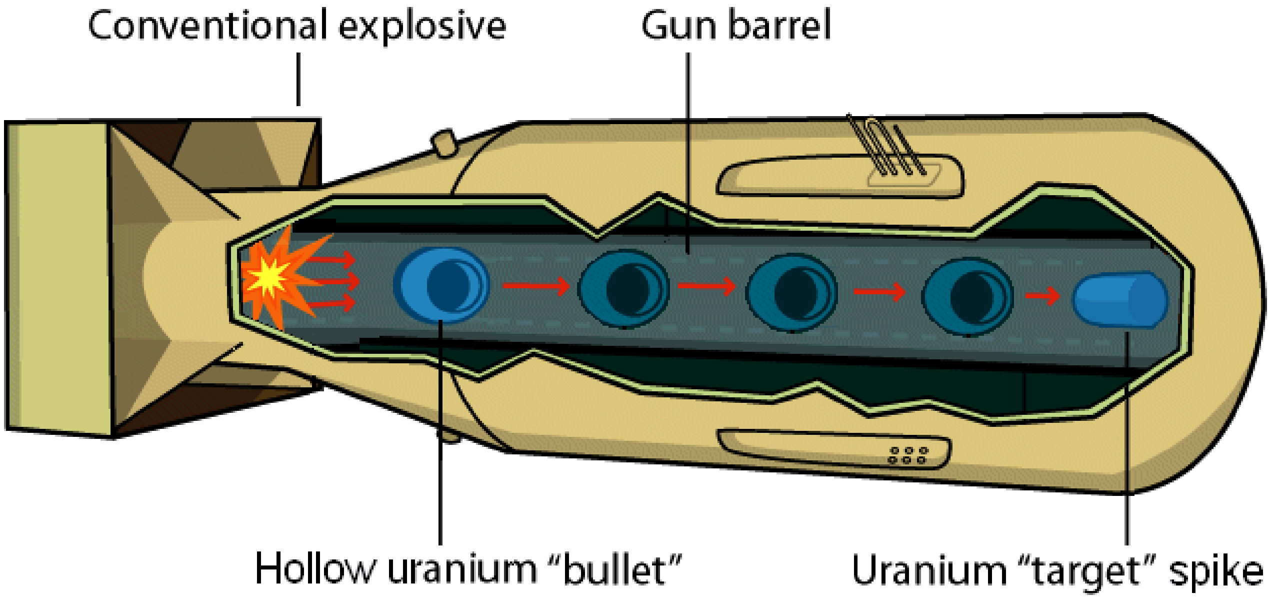
To be used in power plants uranium needs to be enriched so that it is 3 - 5% U_{235}.

To be used in a bomb uranium needs to be highly enriched so that it is about 90% U_{235}.

Uranium

Once you know the critical mass and have that much highly enriched uranium, it is straight forward to make a nuclear bomb.

Use high explosives to ram two pieces of sub-critical U_{235} together to make a super-critical mass.



Plutonium

The other material that can be used for a bomb is plutonium (Pu_{239}).

Pu_{239} is readily made in nuclear reactors, and is much easier to purify than U_{235}.

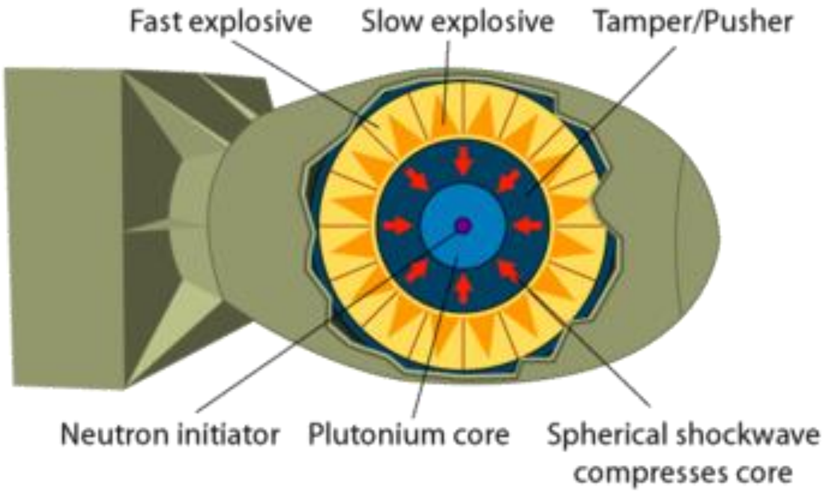
When Pu_{239} fissions it releases 3 new neutrons instead of 2 like U_{235}. There are two important consequences of this.
1) the chain reaction proceeds much faster
2) the critical mass is much less (11 kg vs 56 kg)

Plutonium

Because the chain reaction proceeds faster in Pu_{239} you need to have a different bomb design.

Plutonium weapons need to reach critical mass by compression - squeezing the plutonium to higher density.

This is technically very challenging, and these bombs are much more complex than uranium weapons.



Plutonium vs Uranium

Pu_{239} is relatively easy to produce in nuclear reactors

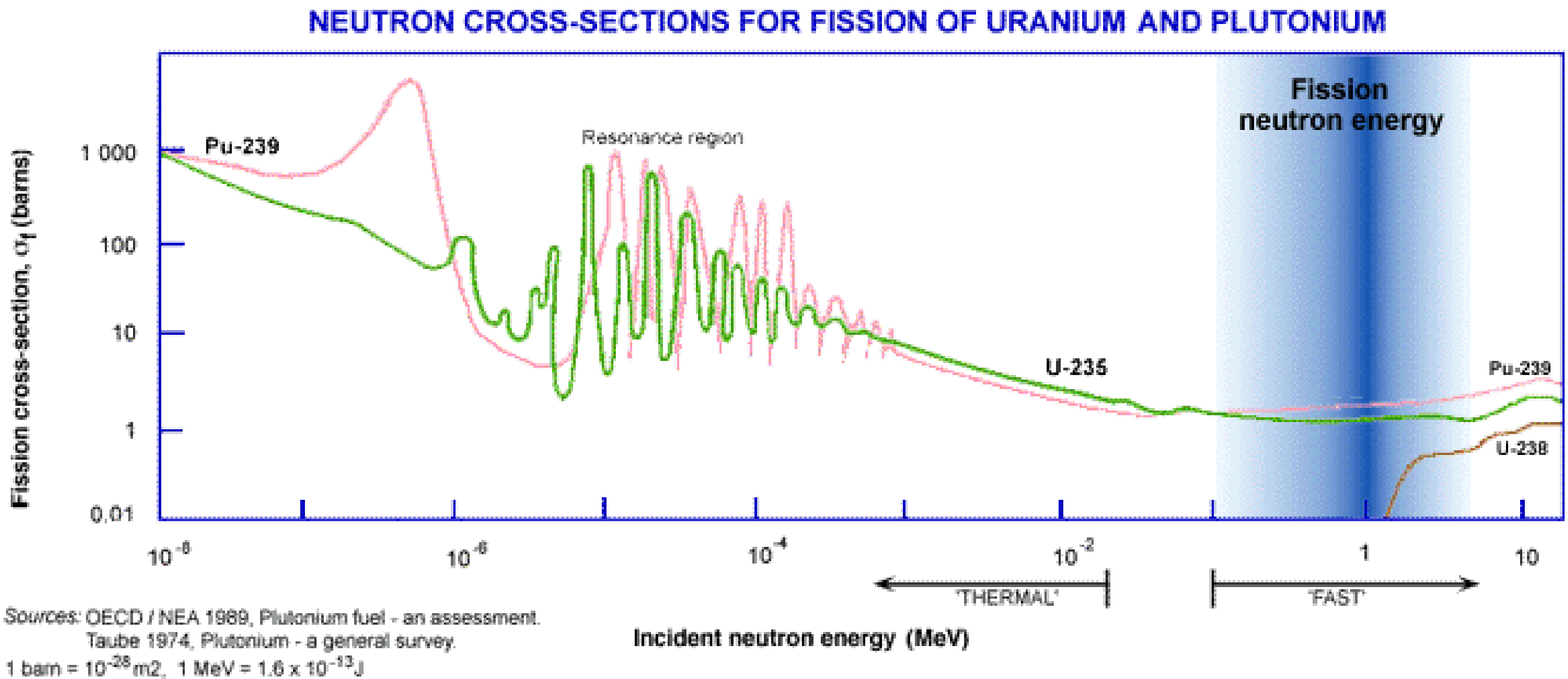
Uranium is difficult to enrich to bomb purity

Smaller critical mass

Larger critical mass

More difficult to make a weapon

Relatively simple to make a weapon


NEUTRON CROSS-SECTIONS FOR FISSION OF URANIUM AND PLUTONIUM
Fission neutron energy
Resonance region
Pu-239
U-235
Pu-239
U-238
Fission cross-section, σ_f (barns)
1 000
100
10
1
0.01
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10
'THERMAL'
'FAST'
Incident neutron energy (MeV)
Sources: OECD / NEA 1989, Plutonium fuel - an assessment.
Taube 1974, Plutonium - a general survey.
1 barn = 10^{-28} m2, 1 MeV = 1.6 x 10^{-13} J