Nuclear Power
Fission, Fusion and the Future
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We’ll cover

Basics of electricity

Generating electricity

- –Using steam, turbines, generator
- –Similarities of power plants

Atoms to electricity

- –Fission Process
- –Fusion Process

The future of nuclear

- –The clean energy mix

What is electricity?

Electricity is the flow of electrons.
Sometimes you see it in the sky in a lightning streak.
Sometimes you hear it crackle when you take off a sweater.

Generating Electricity

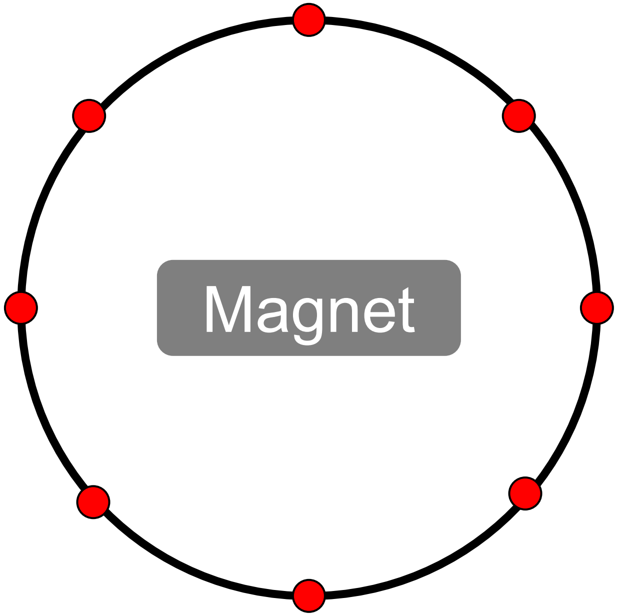
It takes energy to generate electricity.

In the United States, we convert energy from all these sources into electricity:

- Fossil fuel (coal, natural gas, and oil)
- Moving water (hydropower)
- Uranium (nuclear power)
- Wind, sunlight (solar power), biomass, geothermal heat, and even garbage.

Generator

Simply a magnet surrounded by conductors



Generator

You have to spin the generator.

- For a power plant, generators are huge and heavy.
- A lot of energy is needed to spin the generator.
- You have to create rotational motion.

Turbine

A turbine is a device that takes energy from a source and turns it into rotational motion, which turns the generator.

Basically, it is a large, fancy fan.

Steam turbine

Most power plants use steam to spin the turbine

- The turbine gets its energy from both the flow motion of the steam and the energy released from cooling the steam.

- Steam cycle advantages:
  - Well-understood technology
  - Water is relatively inexpensive and available
  - Burnable fuel is readily available

Where does the steam come from?

Steam comes from boiling water

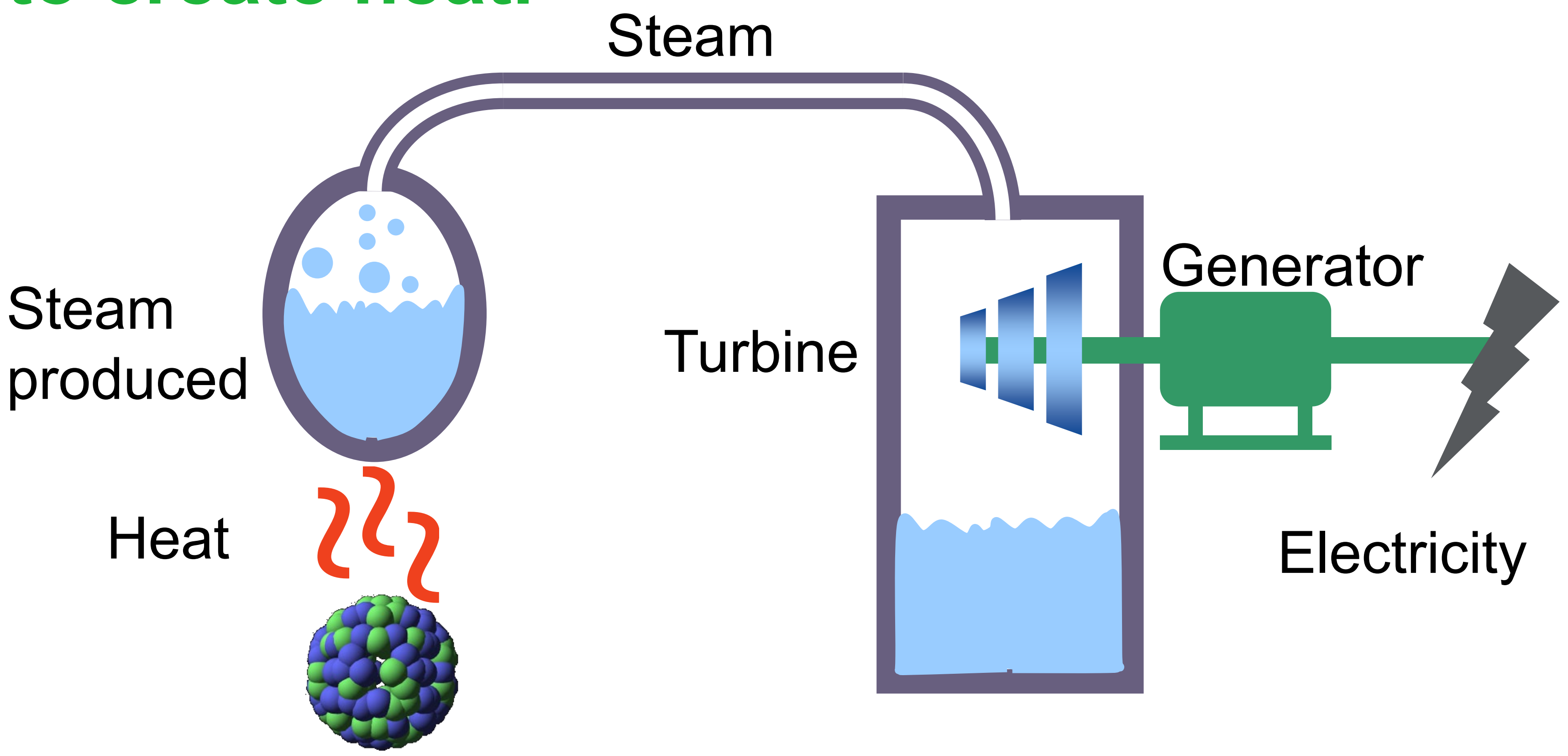
- Just like a tea kettle

Boiling occurs in the boiler

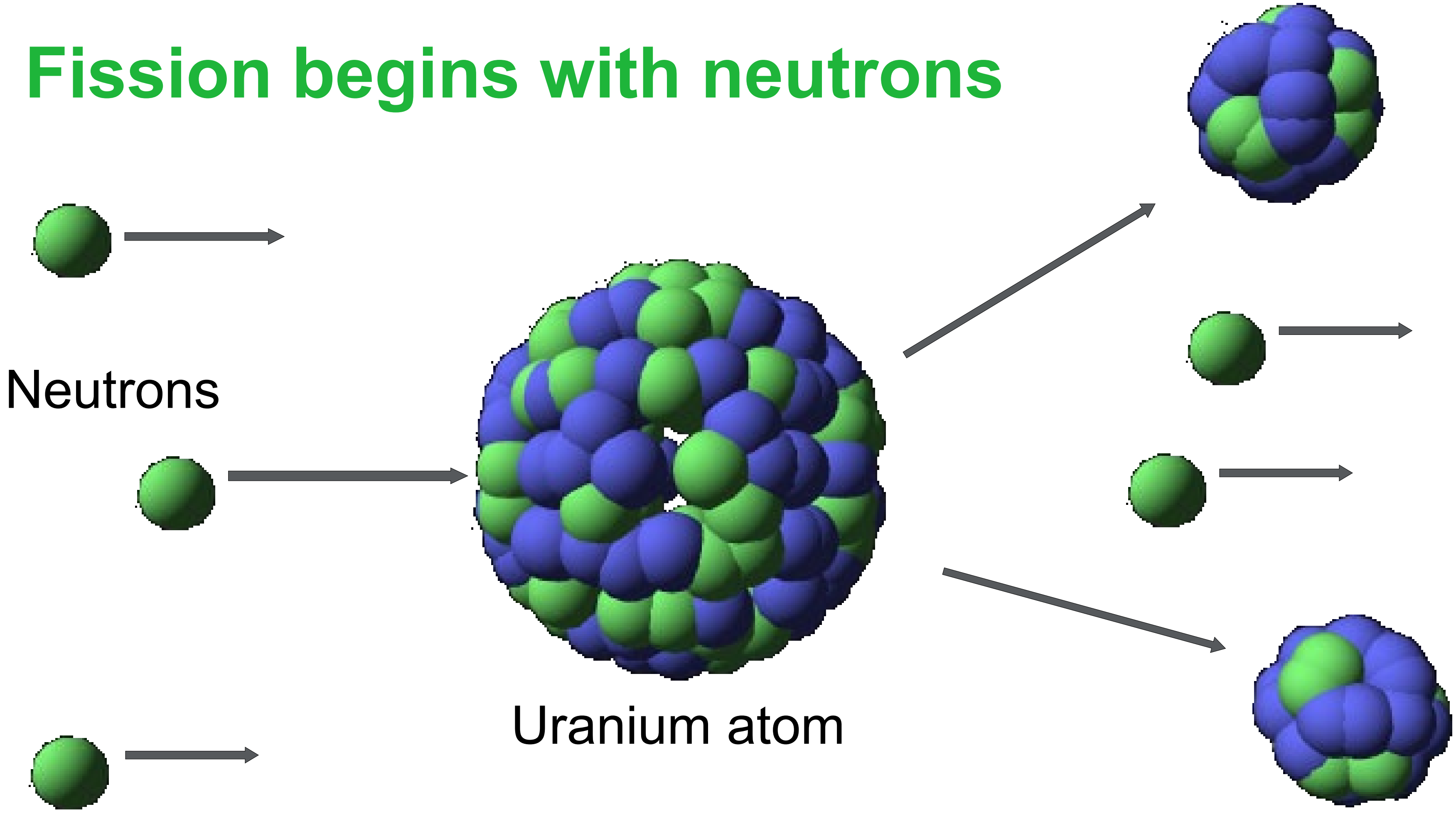
- Any heat source can be used
  - Coal, Oil, Natural Gas
  - Wood, Trash, Biomass
  - **Nuclear Fission**

Nuclear Fission

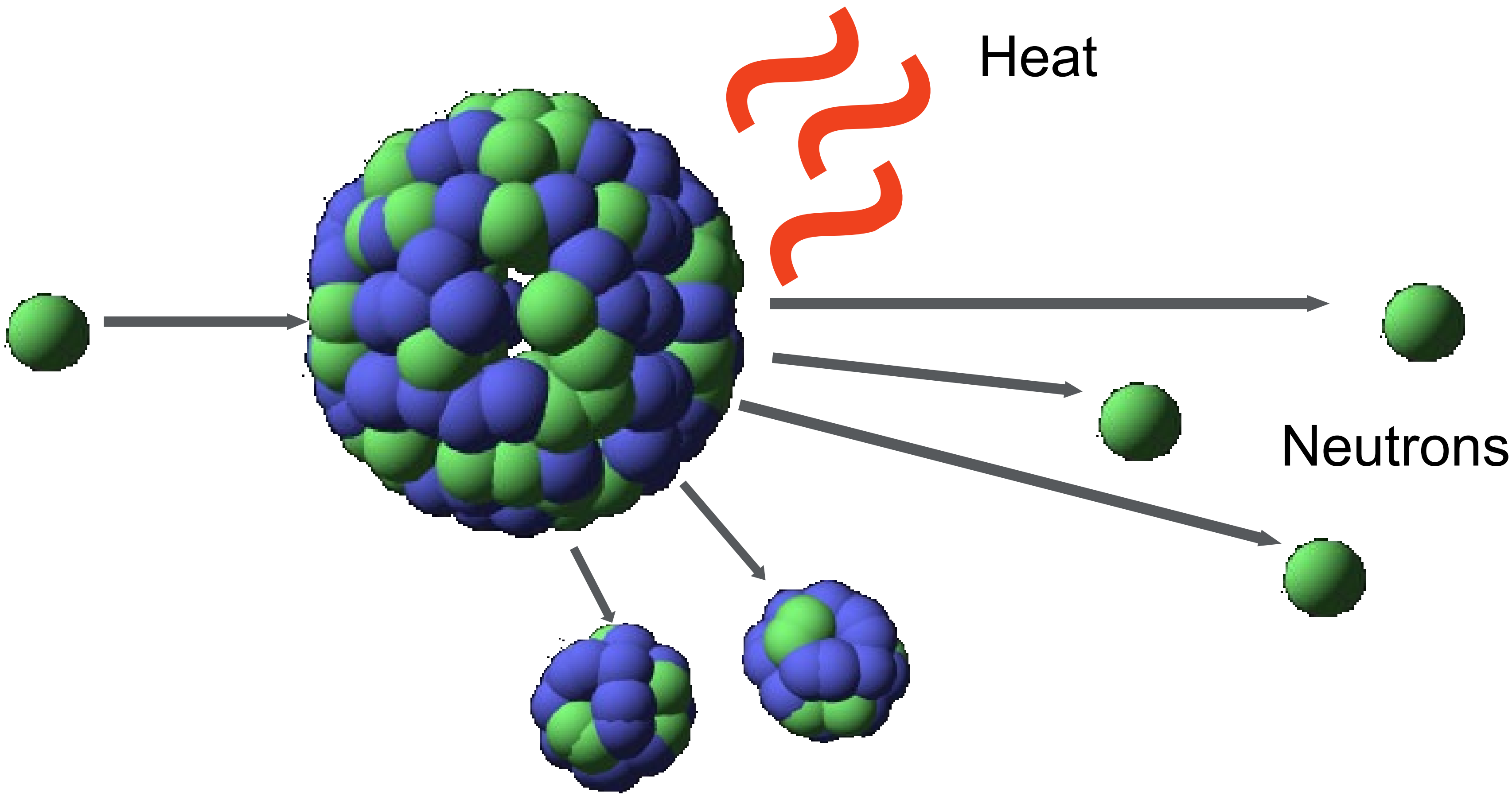
A nuclear power plant uses fission to create heat.



Fission begins with neutrons



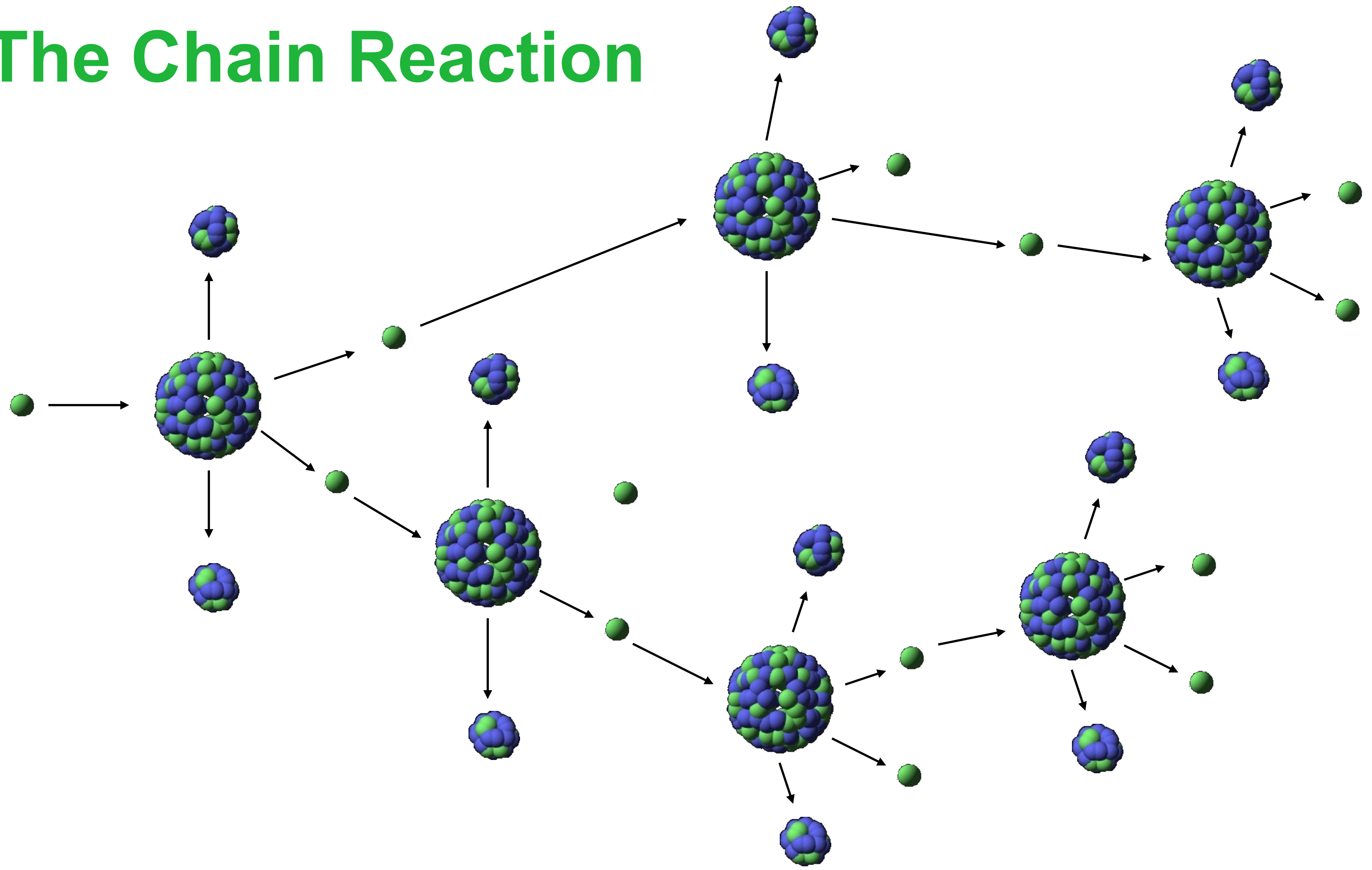
Fission releases energy in the form of heat



The products of nuclear fission

- Two lighter elements
- 2-3 neutrons
- Gammas
- ≈200 MeV per fission

The Chain Reaction



Nuclear reactor
Essential components

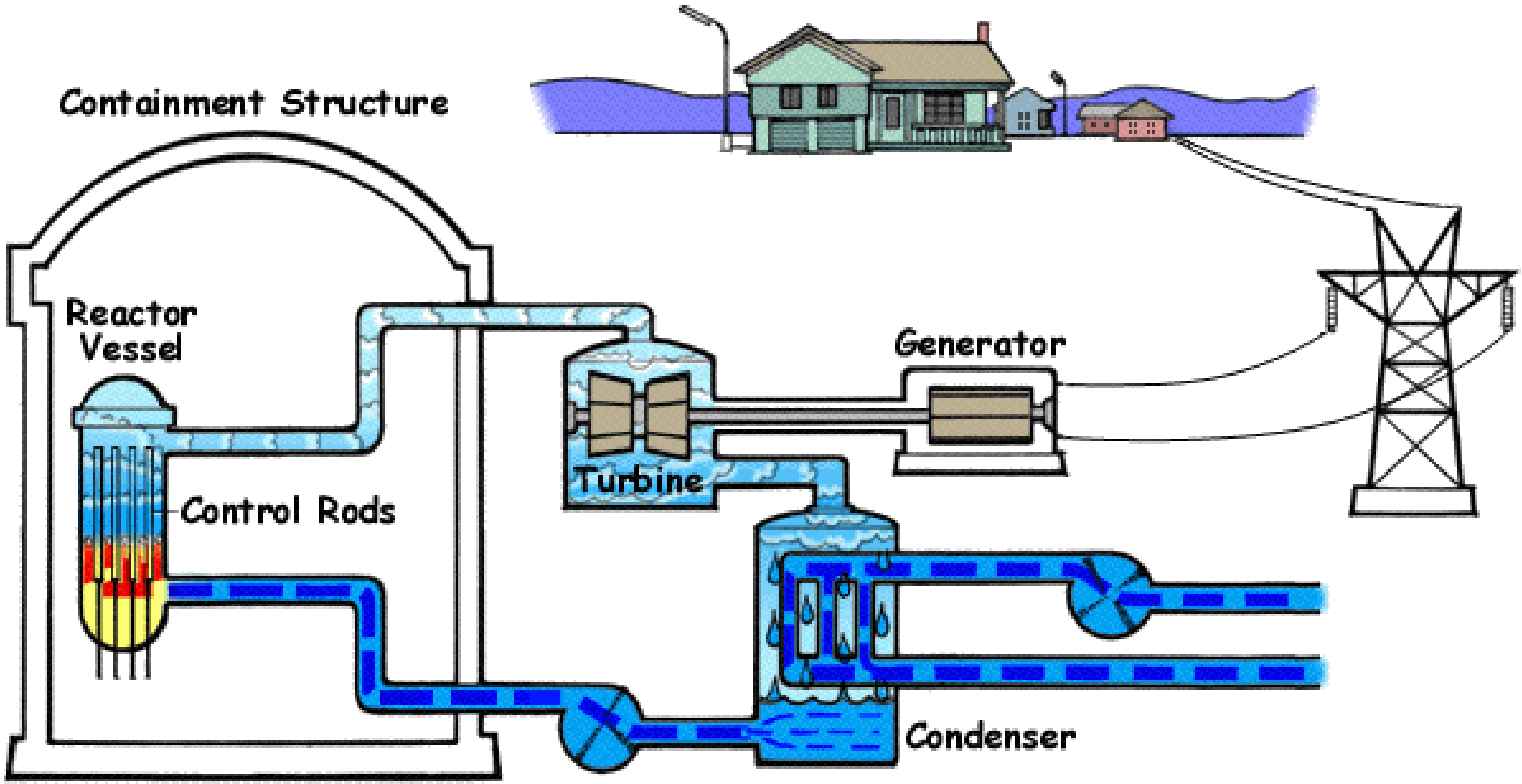
1. Fissile Fuel (usually enriched uranium)
   Fissions upon absorption of thermal neutron to create heat

2. Moderator
   - To moderate, or slow, the speed of the fast neutrons
   - Made of a material that will scatter neutrons
   - H_2O and graphite most common

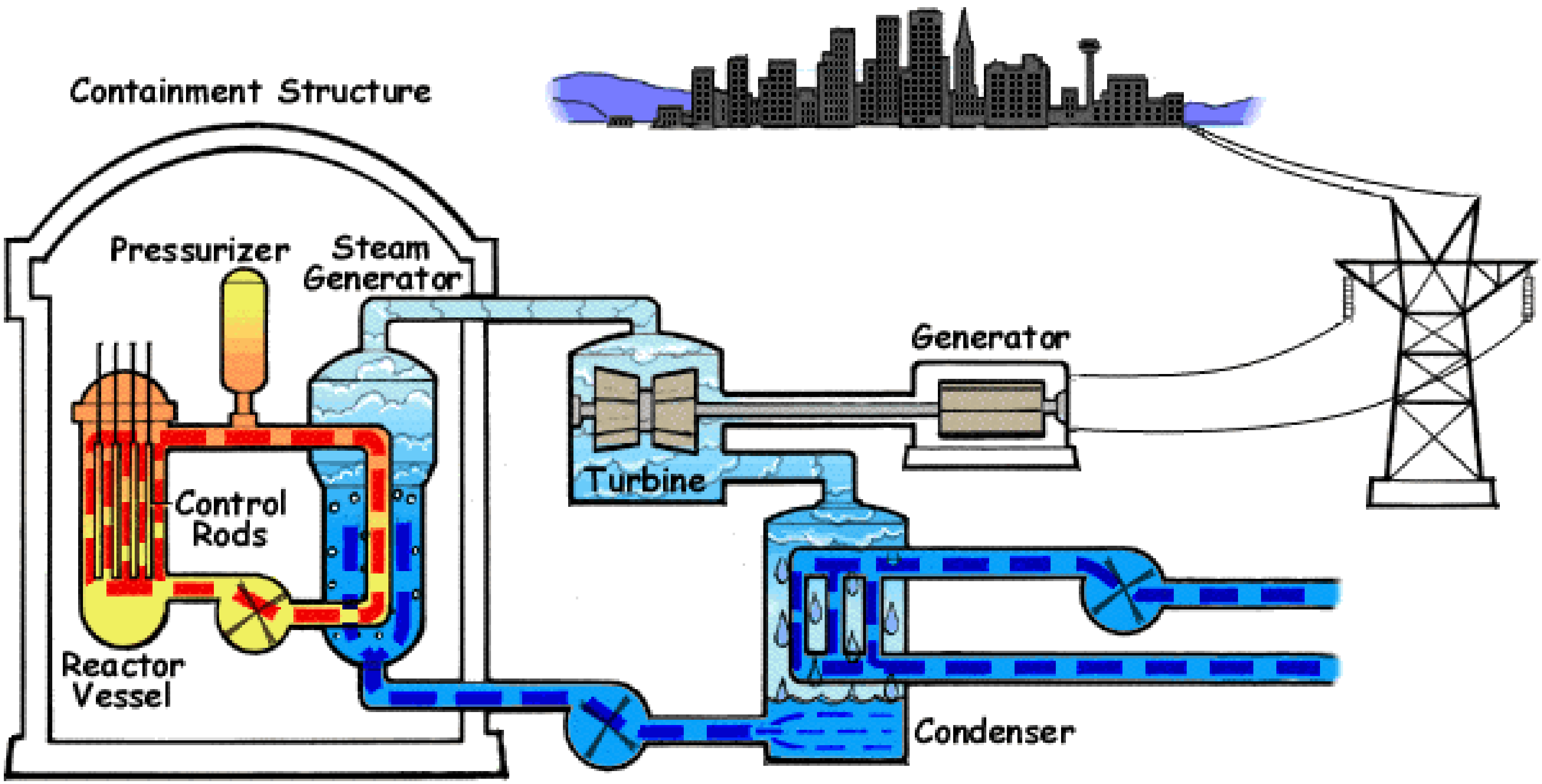
3. Coolant
   Takes heat from reactor fuel core to make steam to make electricity

4. Control
   Typically composed of neutron absorbers e.g. boron and cadmium

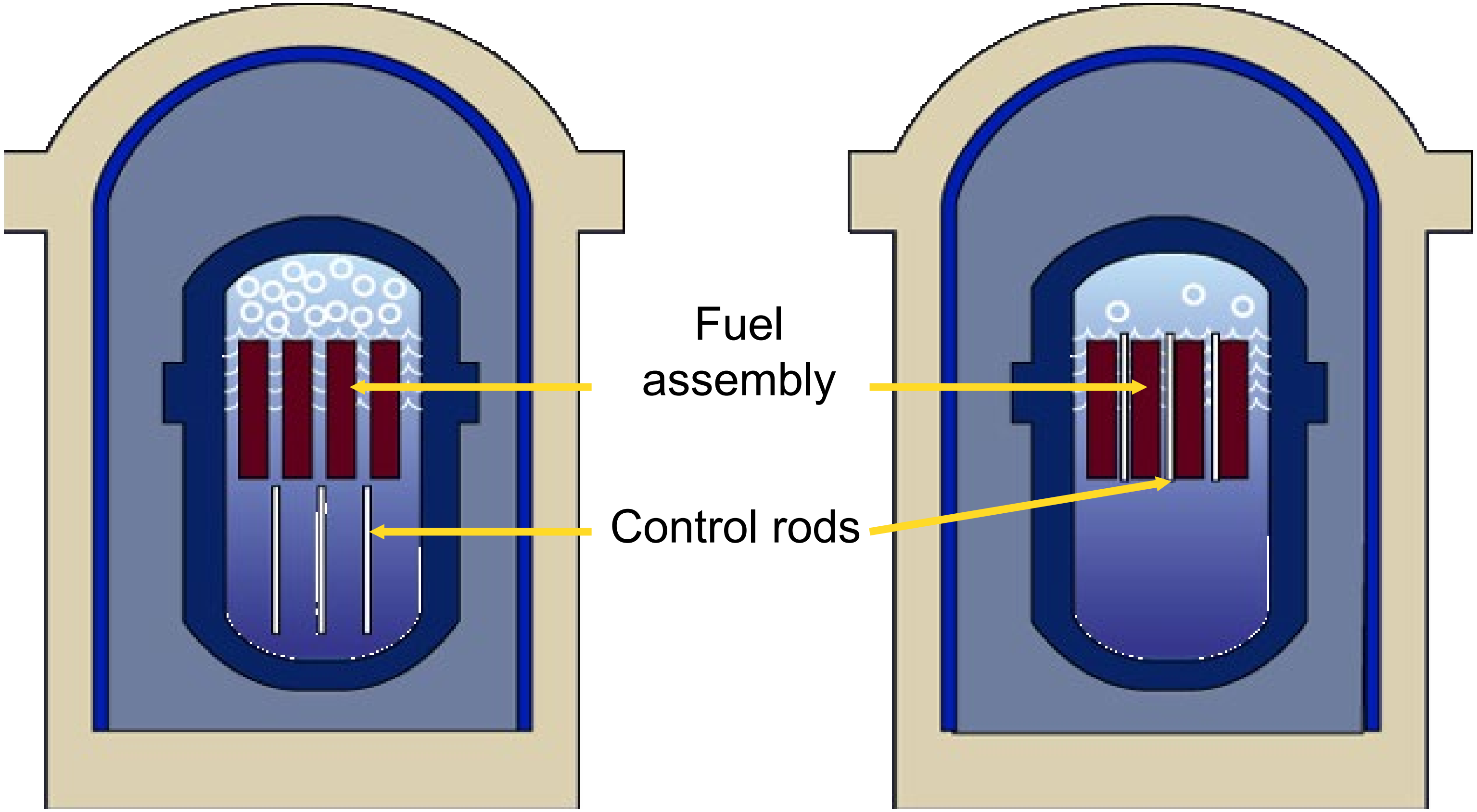
Boiling water reactor



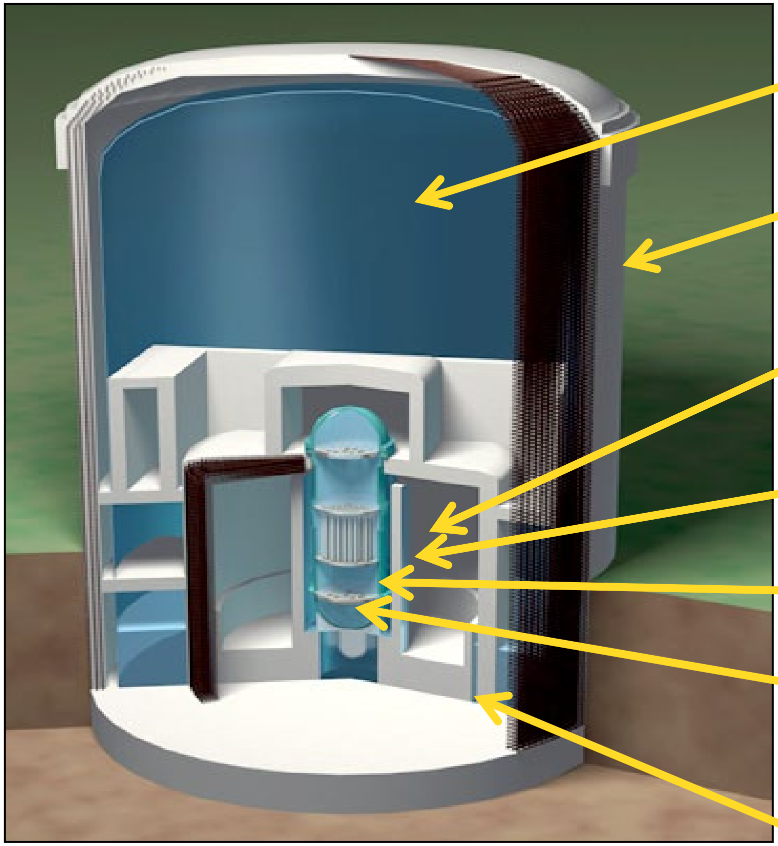
Pressurized water reactor



Controlling the chain reaction



Safety is engineered into reactor designs



Containment vessel
1.5-inch thick steel

Shield building wall
3 foot thick reinforced concrete

Dry well wall
5 foot thick reinforced concrete

Bio shield
4 foot thick leaded concrete with
1.5-inch thick steel lining inside and out

Reactor vessel
4 to 8 inches thick steel

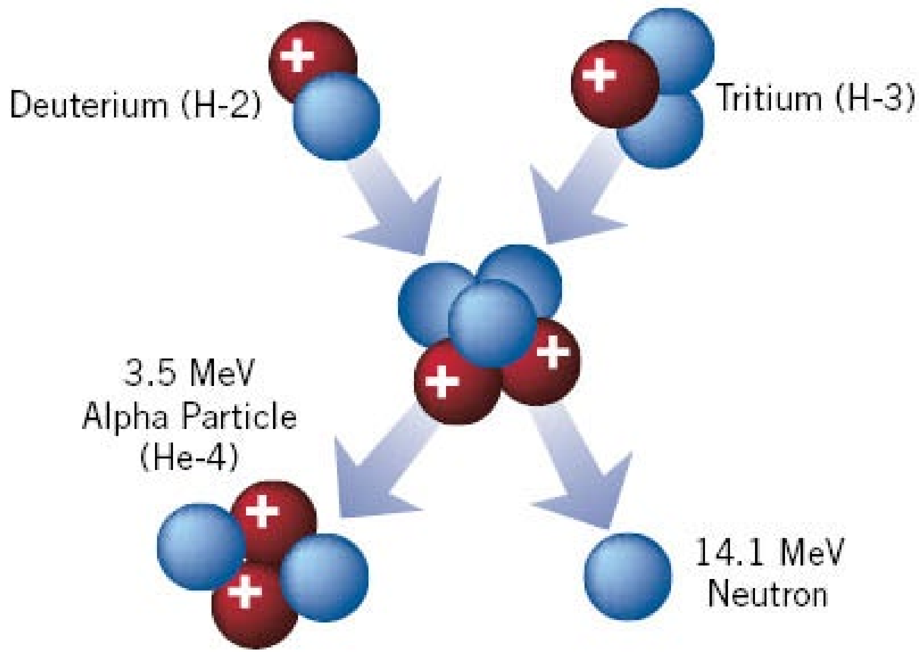
Reactor fuel weir wall
1.5 foot thick concrete

Nuclear Fusion

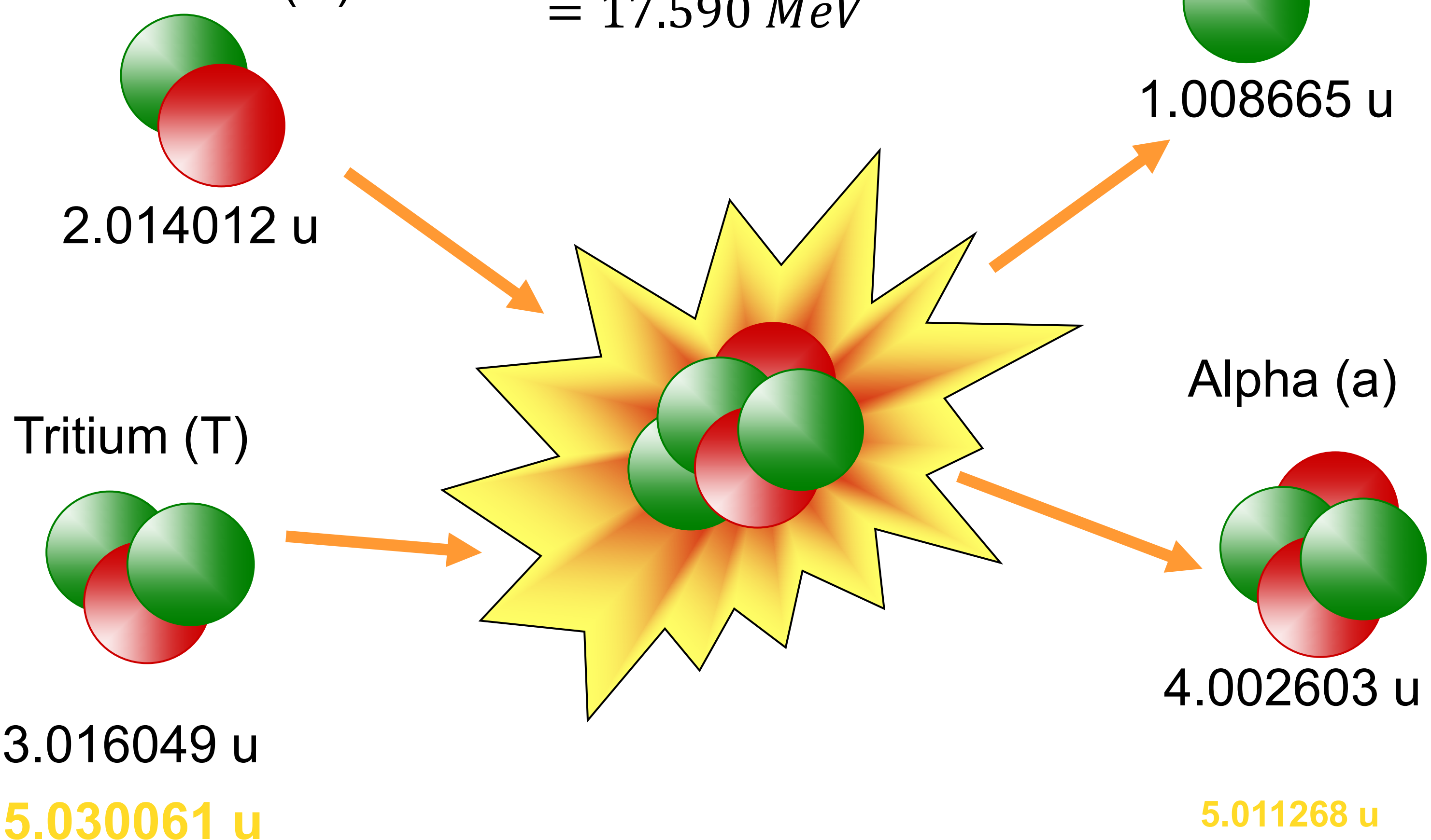
Fusion

- Opposite of fission
- Combines light nuclei elements
- Powers the sun and stars
- Hard to achieve on Earth

Basic fusion reaction



$$
\begin{aligned}
E &= \Delta m c^2 \\
&= 0.018793\, u \cdot c^2 \left(931.502 \frac{MeV}{u \cdot c^2} \right) \\
&= 17.590\ MeV
\end{aligned}
$$



Compared to other sources

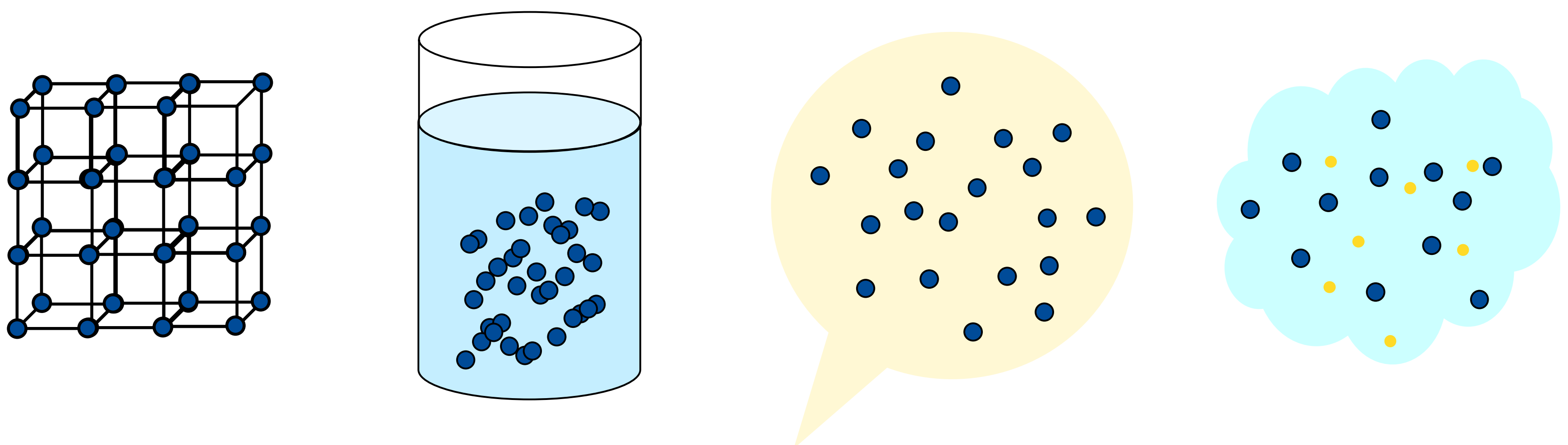
	CHEMICAL	FISSION	FUSION
REACTION	$C+O=CO_2$	$N+U^{235}=Ba^{143}+Kr^{91}+2n$	$^2H + {}^3H = {}^4He+n$
FUEL	COAL	UO_2 (3% U-235 + 97% U-238)	Deuterium + Tritium
TEMPERATURE	700˚K	1,000˚K	100,000,000˚K
ENERGY J/kg	3.3×10^7	2.1×10^{12}	3.4×10^{14}

Creating fusion on Earth

- Very high temperature (150,000,000°C)
- High pressure
- Plasma particle density
- Confinement

What is plasma?

- Electrons separate from nucleus
- 4th state of matter

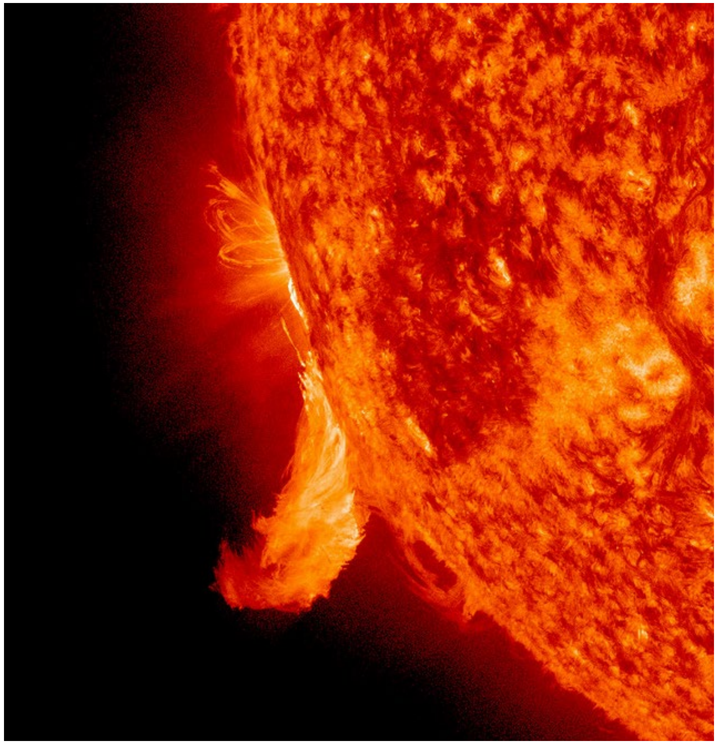


SOLID	LIQUID	GAS	PLASMA
Ice	Water	Steam	
Cold	Warm	Hot	Hotter

Characteristics of a plasma

- Most atoms are ionized
- Whole plasma is still neutral
- Can exist at any temperature and density

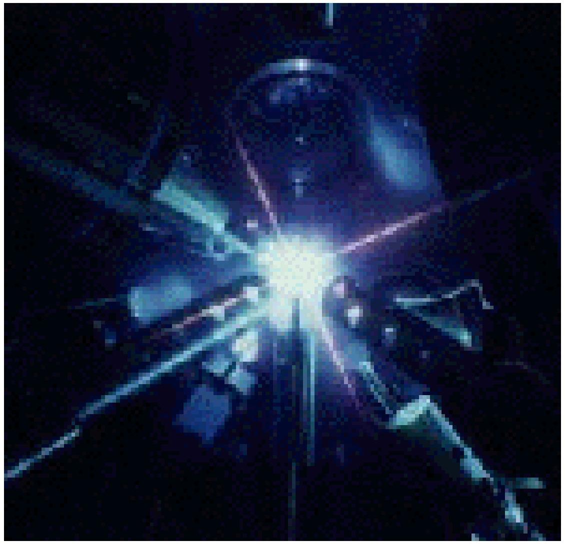
Familiar plasmas



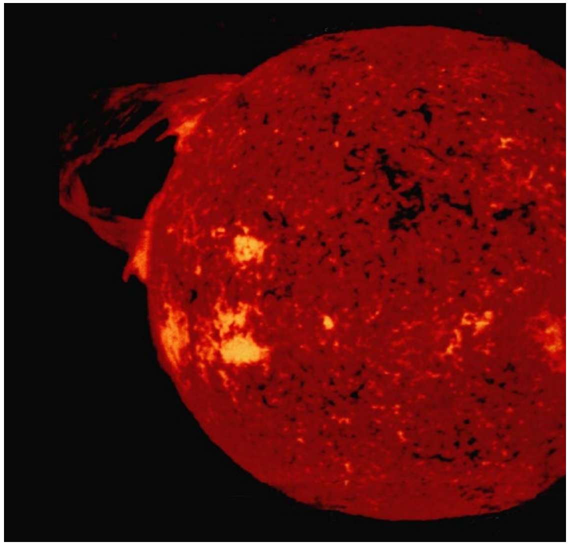
What’s confinement?

- Plasma likes to expand.
- Confinement keeps the plasma stable so fusion can occur.

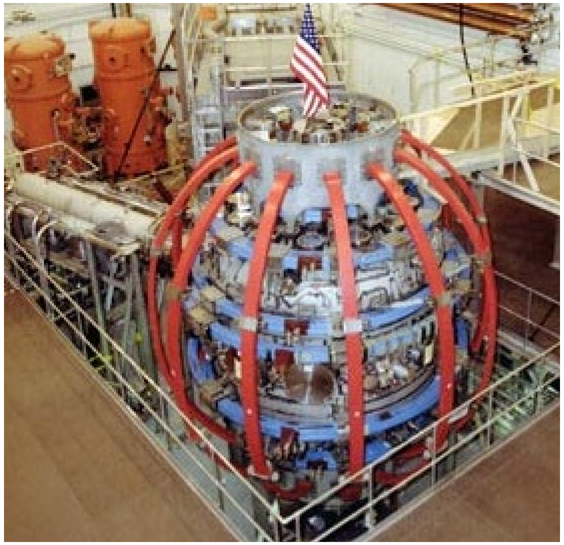
Confinement concepts



Inertial



Gravitational



Magnetic

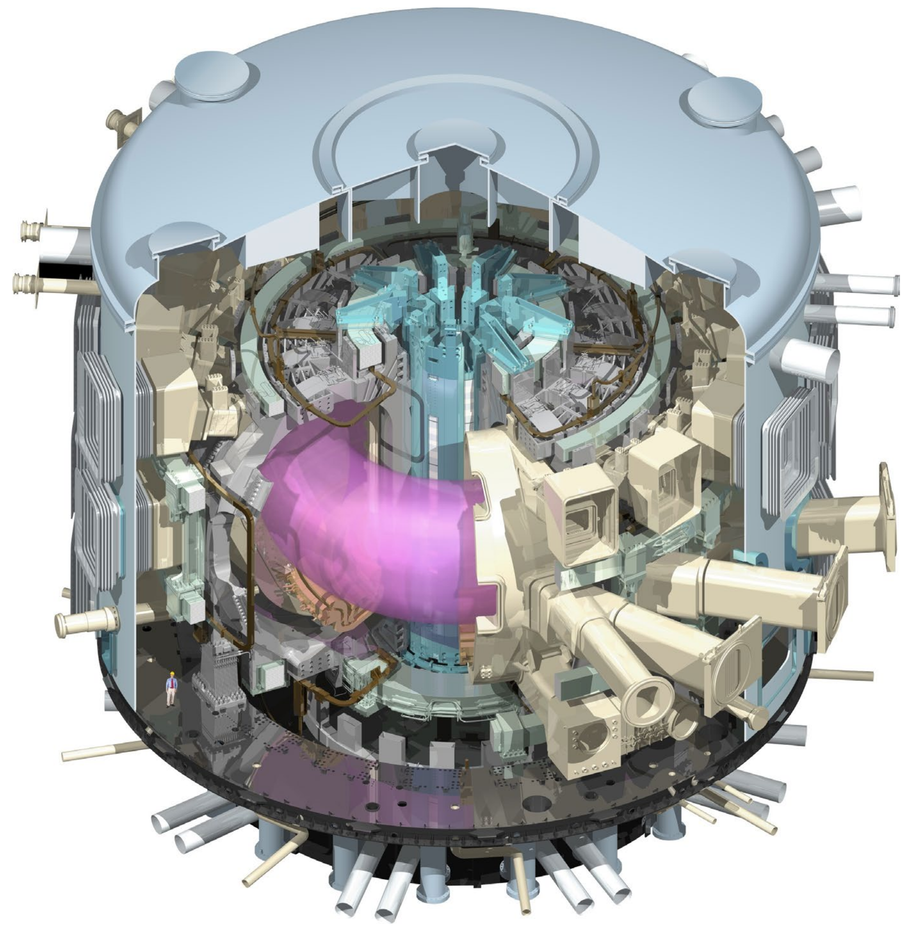
Overcoming Coulomb repulsion

- Nuclei have positive charge & like charges repel
- Accelerate atoms to high energy: 30-1000 keV
  - accelerator
    - used to produce neutrons and isotopes
  - heat
    - make atoms hot enough that their average random motion is at very high energy
    - 1 eV $\approx$11000 K

ITER tokamak reactor

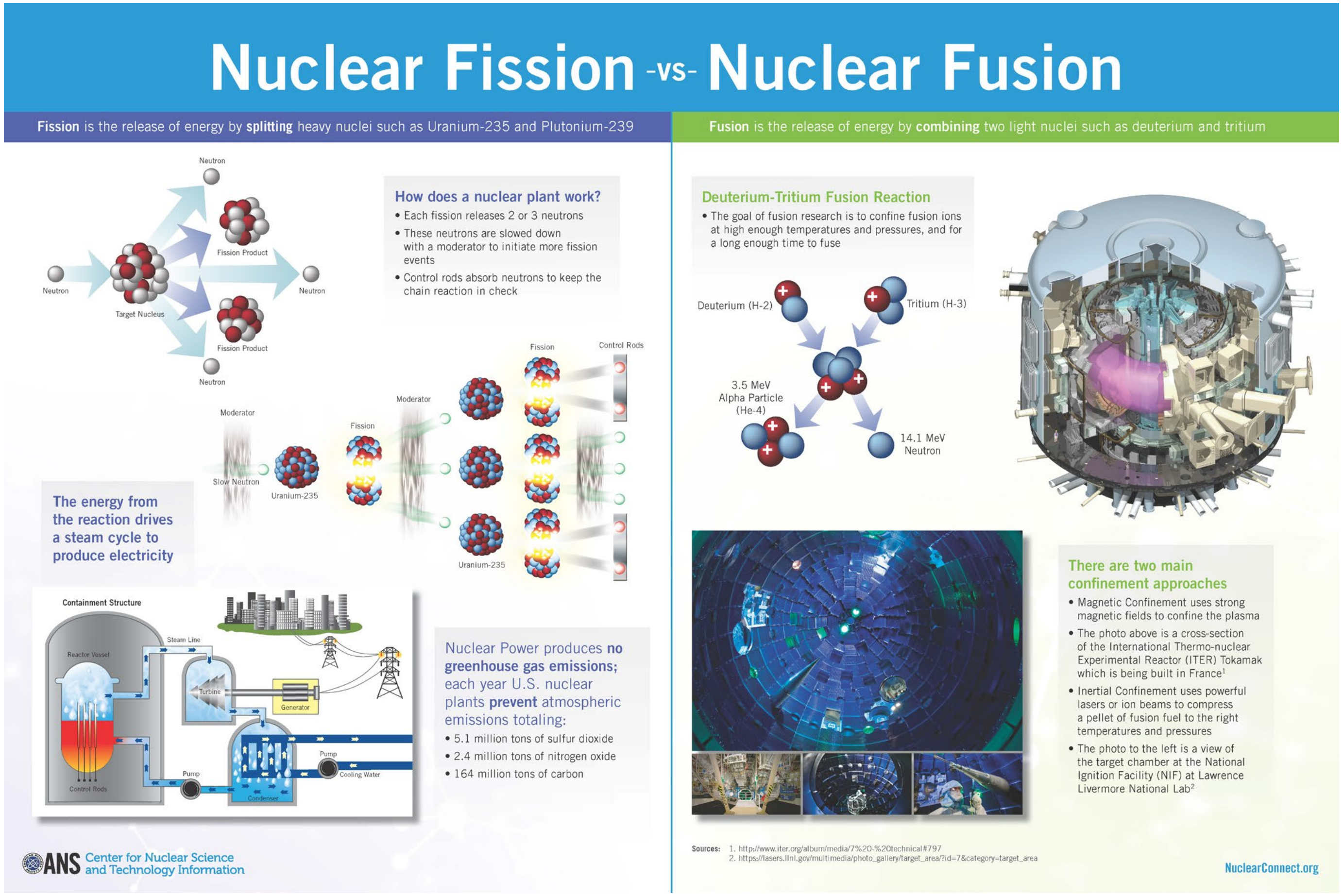
- Project launched 1985
- Members

  China, the European Union, India, Japan, Korea, Russia, United States
- Located in France
- First plasma 2025
- Deuterium-Tritium 2035
- www.iter.org



The promise of fusion energy

- Plasma cools in seconds
- No risk of chain reaction
- No fissile materials
- Fuel from seawater
- No long-lived radioactive waste

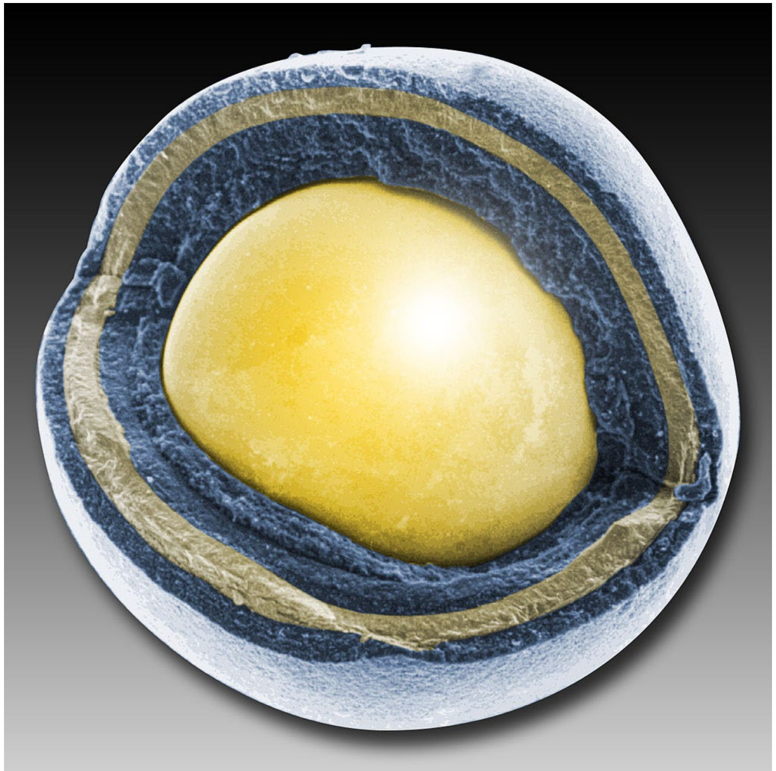

Nuclear Fission -vs- Nuclear Fusion
Fission is the release of energy by splitting heavy nuclei such as Uranium-235 and Plutonium-239
Fusion is the release of energy by combining two light nuclei such as deuterium and tritium
Neutron
Fission Product
Target Nucleus
Neutron
Fission Product
Neutron
How does a nuclear plant work?
• Each fission releases 2 or 3 neutrons
• These neutrons are slowed down with a moderator to initiate more fission events
• Control rods absorb neutrons to keep the chain reaction in check
Fission
Control Rods
Moderator
Moderator
Fission
Slow Neutron
Uranium-235
Uranium-235
The energy from the reaction drives a steam cycle to produce electricity
Containment Structure
Steam Line
Reactor Vessel
Turbine
Generator
Pump
Pump
Cooling Water
Control Rods
Condenser
Nuclear Power produces no greenhouse gas emissions; each year U.S. nuclear plants prevent atmospheric emissions totaling:
• 5.1 million tons of sulfur dioxide
• 2.4 million tons of nitrogen oxide
• 164 million tons of carbon
ANS Center for Nuclear Science and Technology Information
Deuterium-Tritium Fusion Reaction
• The goal of fusion research is to confine fusion ions at high enough temperatures and pressures, and for a long enough time to fuse
Deuterium (H-2)
Tritium (H-3)
3.5 MeV Alpha Particle (He-4)
14.1 MeV Neutron
There are two main confinement approaches
• Magnetic Confinement uses strong magnetic fields to confine the plasma
• The photo above is a cross-section of the International Thermo-nuclear Experimental Reactor (ITER) Tokamak which is being built in France[1]
• Inertial Confinement uses powerful lasers or ion beams to compress a pellet of fusion fuel to the right temperatures and pressures
• The photo to the left is a view of the target chamber at the National Ignition Facility (NIF) at Lawrence Livermore National Lab[2]
Sources: 1. http://www.iter.org/album/media/7%20-%20technical#797
2. https://lasers.llnl.gov/multimedia/photo_gallery/target_area/?id=7&category=target_area
NuclearConnect.org

Future

U.S. national laboratories are exploring:

- advanced fuels
- reactor systems
- space power systems
- safety & risk assessment

Advanced fuels



TRISO fuel particle

Reactor systems

- Extend the life of existing reactors
- Advanced Reactor Technologies (ART)
- Small modular reactors

Reactors of the (near) future

Photo: NuScale Power

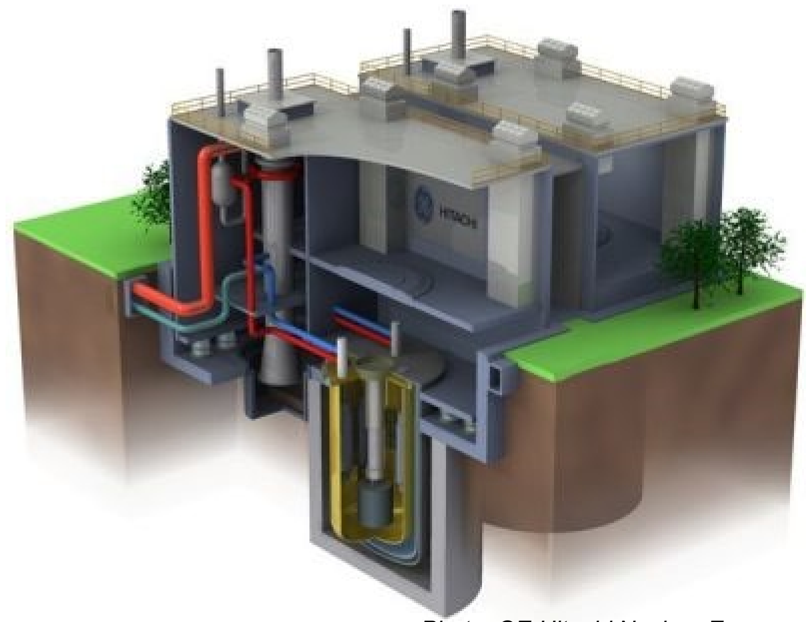


Photo: GE Hitachi Nuclear Energy

Nuclear in the energy mix

Nuclear energy is green energy

Nuclear power makes up 60% of our low-carbon energy

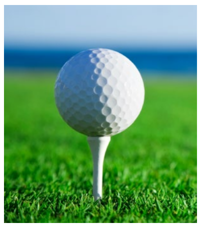
Nuclear power plants take up less land

Nuclear reactors can make electricity night or day, no matter the weather

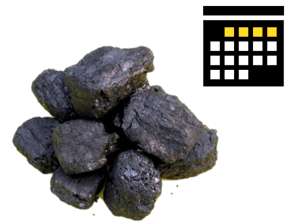
Nuclear is reliable—available 24/7

It's good to be dense

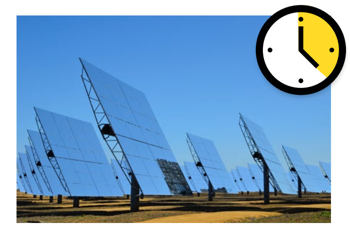
Uranium contains immense amounts of energy released through nuclear fission, not combustion



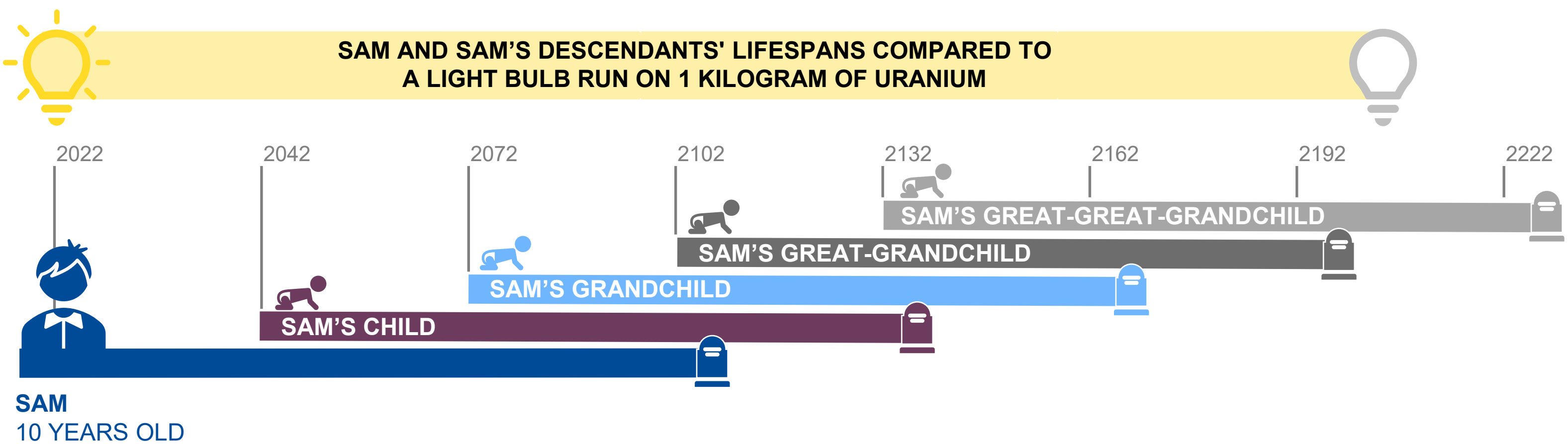
One kilogram of **uranium** is about the size of a **golf ball** - it could run a light bulb for **182 years**



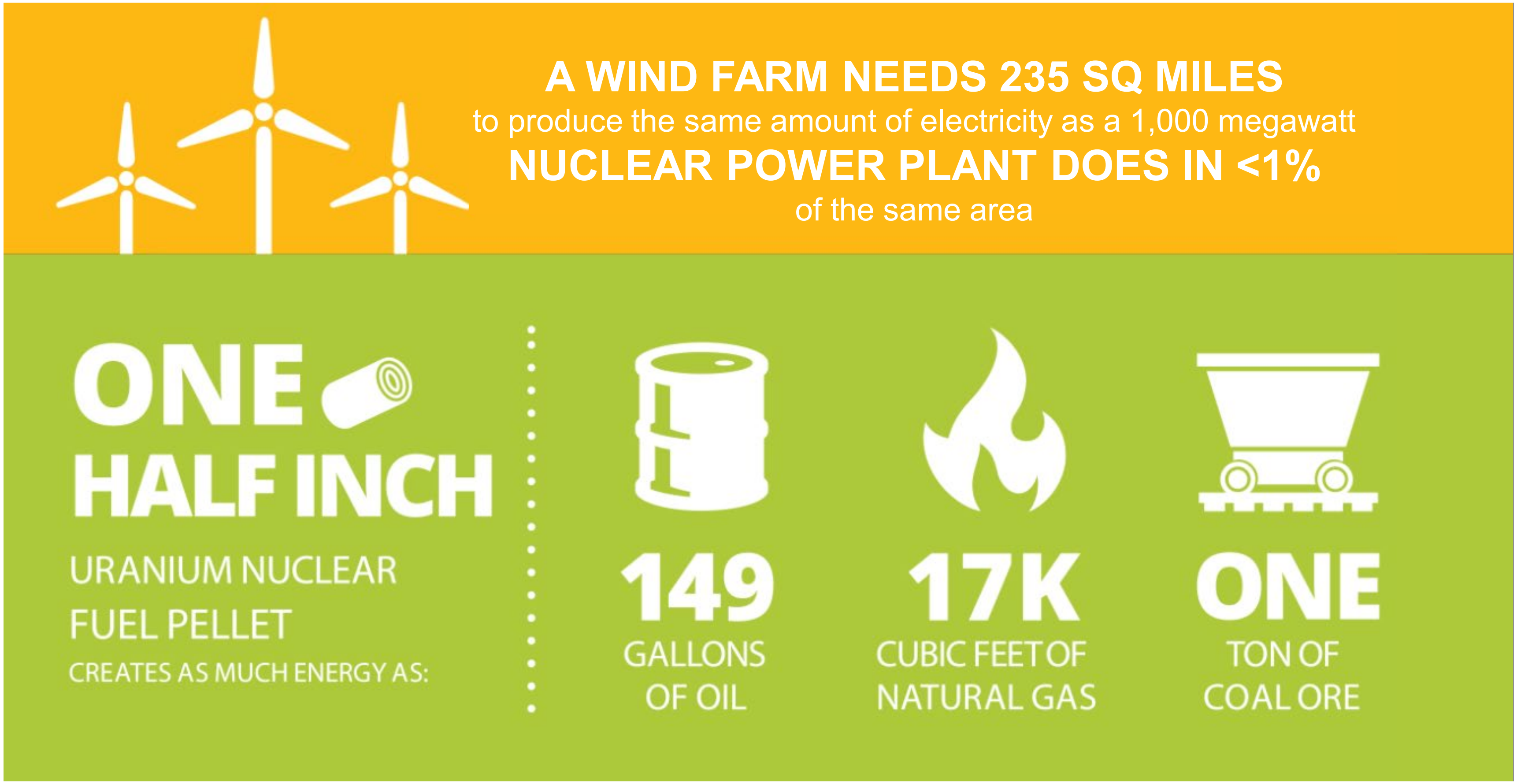
One kilogram of **coal** could run it for **four days**



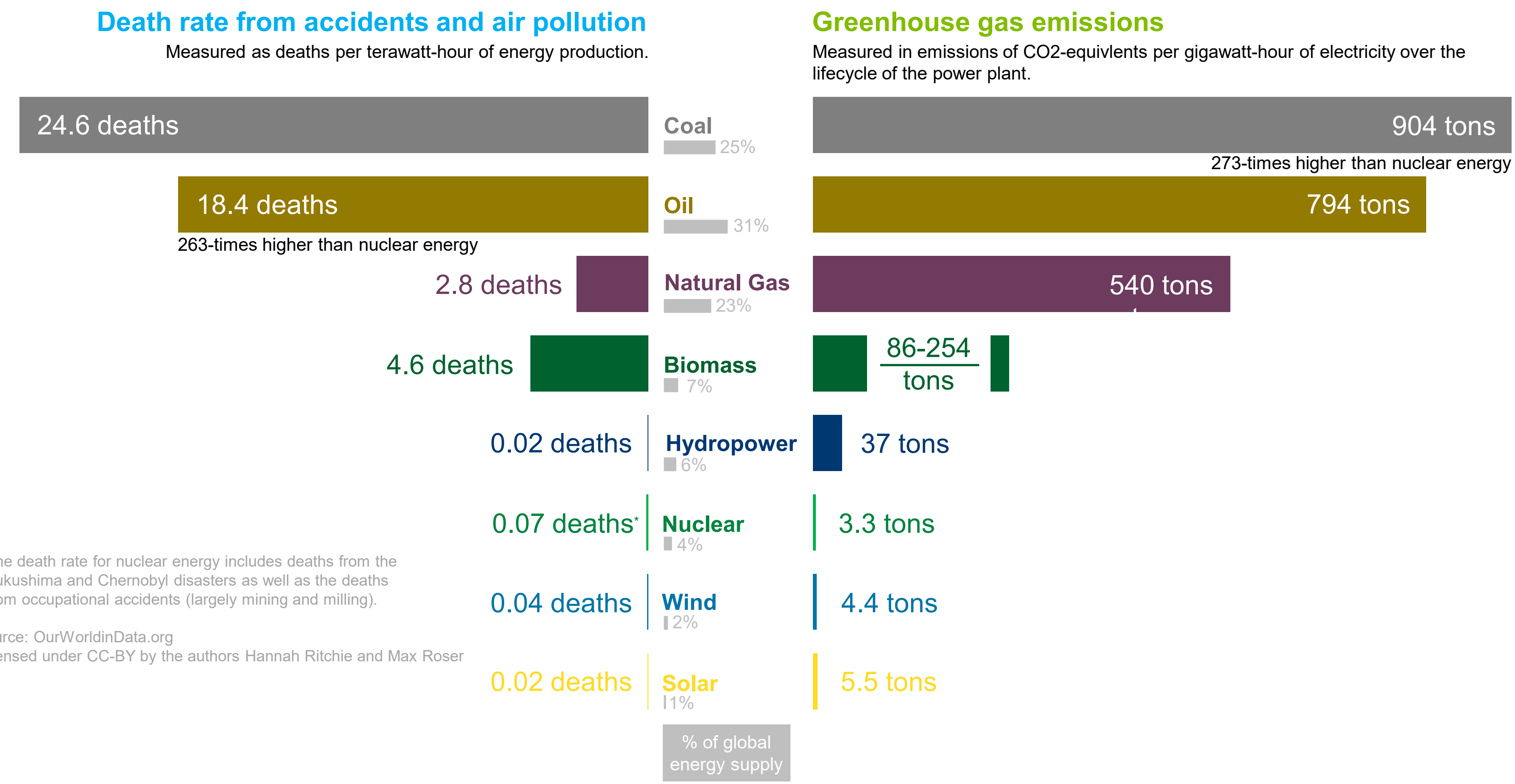
One **solar** panel could light it for less than **four hours**



Source Energy Equivalents



What are the safest and cleanest sources of energy?

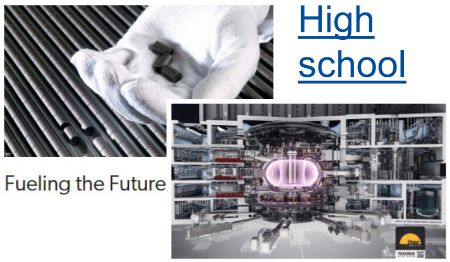


* The death rate for nuclear energy includes deaths from the Fukushima and Chernobyl disasters as well as the deaths from occupational accidents (largely mining and milling).

Source: OurWorldinData.org

Navigating Nuclear: Energizing Our World™

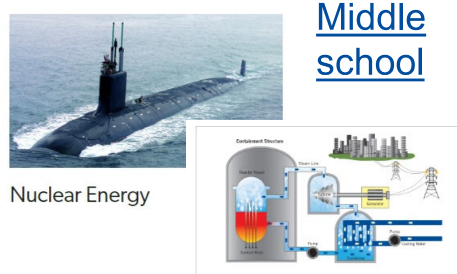
Nuclear Energy Lessons and Project Starters



High school

Fueling the Future

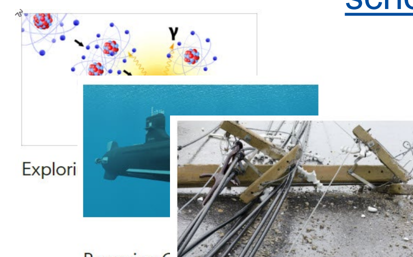
Unlocking Energy: Fission vs. Fusion



Middle school

Nuclear Energy

From Atoms to Electricity



Grade school

Explori

Powering C

Evolving Energy Sources

Virtual Field Trips

Idaho National Laboratory

Palo Verde Generating Station

Outer Space

Resources

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ANS Operations and Power Division
http://opd.ans.org/

ANS Fusion Energy Division
http://fed.ans.org/

Idaho National Laboratory
www.inl.gov

U.S. Department of Energy's Princeton Plasma Physics Laboratory
www.pppl.gov

Department of Energy
https://www.energy.gov/science-innovation/energy-sources/nuclear