Episode 528: Controlling fission

In this episode, you can look at the different features of the core of a nuclear reactor, and explain its operation using your students' knowledge of nuclear physics.

Summary

Discussion: The construction of a nuclear reactor. (10 minutes)

Discussion: Moderation (10 minutes)

Discussion: Enrichment. (10 minutes)

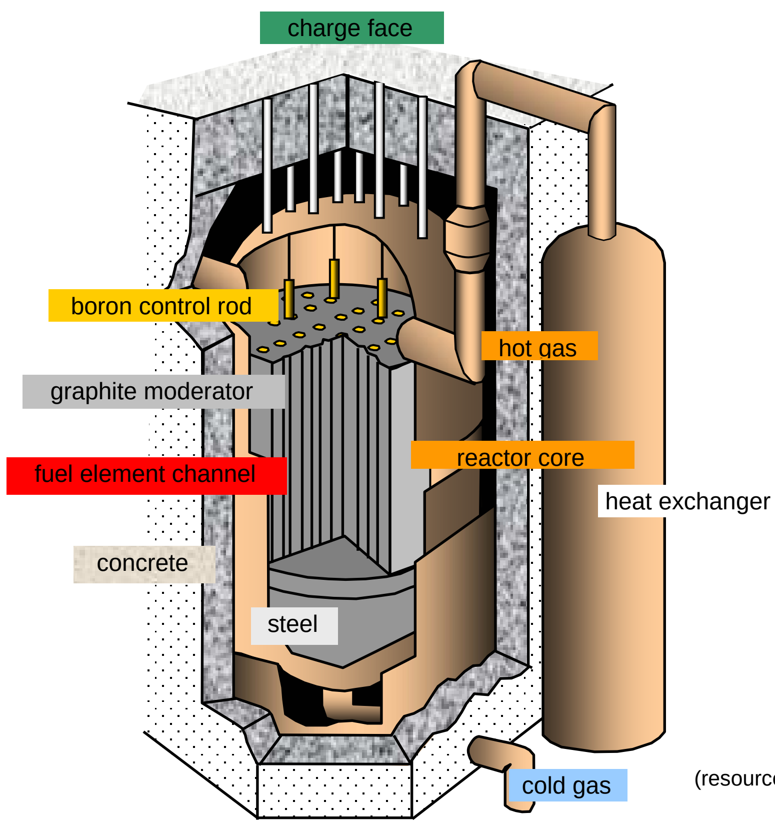
Discussion: Critical mass. (10 minutes)

Discussion: Control rods and coolant. (10 minutes)

Student questions: Power reactors. (30 minutes)

Discussion: Nuclear fusion. (15 minutes)

Student questions: Fusion calculations. (30 minutes)



(resourcefulphysics.org)

Discussion:

The construction of a nuclear reactor

Look at a diagram or animation of a nuclear reactor. Check what your students already know about the reactor's construction.

TAP 528-1: Nuclear fission reactor

Discussion:

Moderation

How can we make it more likely that a neutron will collide with a ^{235}U nucleus? There are two ways, both used in nuclear power reactors:

Slow down the fast neutrons to increase their chance of being captured by a fissile ^{235}U nucleus. This process is called *moderation*.

Concentrate the ^{235}U compared to the ^{238}U. This process is called *enrichment*.

The speed of the fast fission neutrons is slowed down ('moderated') by allowing them to collide with a suitable moderator nucleus. Conservation of momentum tells us that the speed of a light neutron colliding with a massive nucleus will be little affected. We need a material with relatively light nuclei to absorb momentum and energy from the neutron.

Look at the periodic table for some ideas:

Hydrogen – i.e. protons. Virtually the same mass (great), but gaseous (not very dense) and explosive. Hydrogen in water maybe? Yes, pressurised water reactors use water as the moderator (as well as the coolant), but the protons are attached to the rest of the water molecule and have an effective mass of 18 times that of a free proton.

Helium – inert (good) but gaseous, so not dense enough.

Lithium – too rare (expensive), melting point too low anyway.

Beryllium – possible but expensive.

Boron absorbs neutrons.

Carbon – mass equivalent to 12 protons, solid (good), flammable (bad). Used in the first generation of UK 'Magnox' reactors.

So there are a number of possibilities, each with a balance of advantages and disadvantages.

Discussion:

Enrichment

Nuclear power stations use uranium enriched to typically 2.5% - a factor of 2.5/0.7 = 3.6 times the proportion found in natural uranium. Ask your students how much ^{238}U must be discarded to produce 1 tonne of enriched uranium, i.e. with the fraction of ^{235}U increased from 0.7% to 2.5%. (You need 3.6 tonnes of natural uranium, so you discard 2.6 tonnes of ^{238}U.)

Bombs require 90% enrichment. Power station enrichment can be easily extended to get pure fissile ^{235}U. Herein lies an easy route to the proliferation of nuclear weapons by countries that have nuclear power programs.

Discussion:

Critical mass

Extend your earlier discussion of chain reactions to introduce the idea of *critical mass*. At least one of the fission neutrons must induce a further fission to allow for a chain reaction. Some may simply escape from the fuel assembly; others may be absorbed by the ^{238}U, by structural materials used in the construction, by the coolant, by the fission fragments etc. Fewer will escape if there is a smaller surface area to volume ratio.

For enriched uranium, the critical mass is roughly the size of a grapefruit. Picture bringing two half-grapefruit together to cause an explosion. Why would the critical mass be different for shapes other than a sphere? (A sphere has the lowest area to volume ratio. Other shapes with the same mass would have greater areas, so more neutrons would escape, making a chain reaction less likely.)

Discussion:

Control rods and coolant

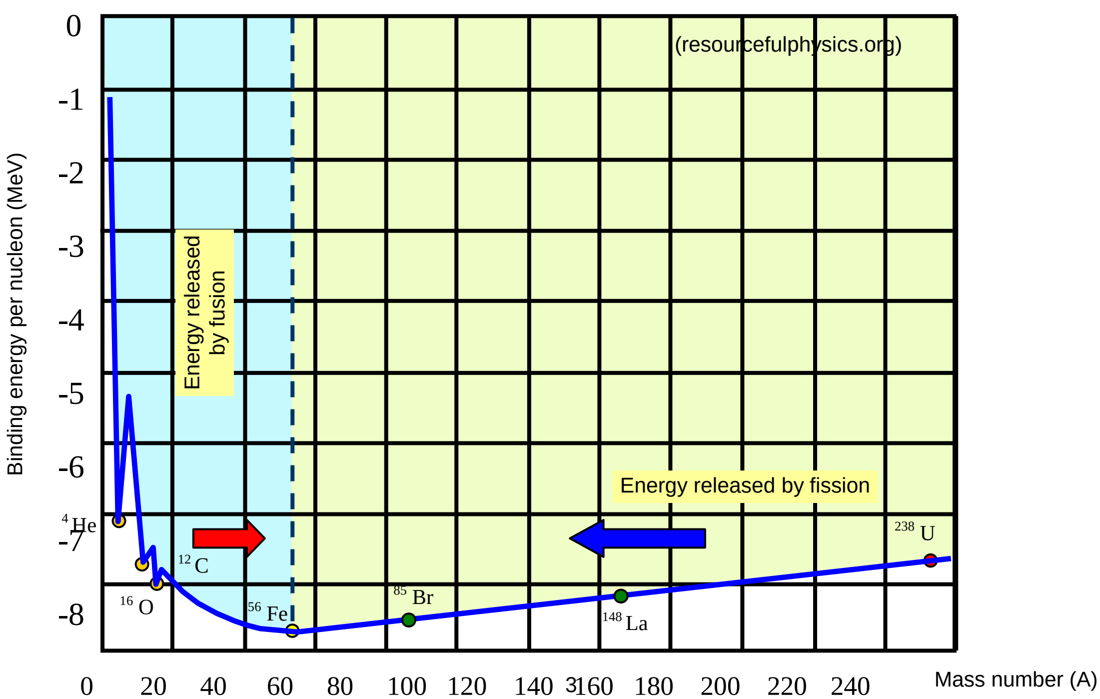
The chain reaction in a nuclear power stations must be controlled, which means that the number of neutrons must be *continuously* regulated to stop the chain reaction diverging or closing down. To do this *control rods* are moved into or out of the reactor core. They are made from a substance that absorbs neutrons (e.g. boron).

A coolant carries energy away from the core. What are the desirable properties of the coolant? (It must not absorb neutrons; it must have high thermal conductivity, high specific heat capacity and high boiling point.)

Student questions

These questions compare Magnox and PWR reactors.

TAP 528-2: Fission in a nuclear reactor – how the mass changes



Discussion:

Nuclear fusion

You can now look at the process of nuclear fusion. (This will have been touched on when considering the graph of binding energy per nucleon.) Students should be able to calculate the energy changes from values of nuclide mass. Emphasise that the energy released per nucleon in fusion is larger than for fission.

TAP 528-3: Fusion

Student questions:

Fusion calculations

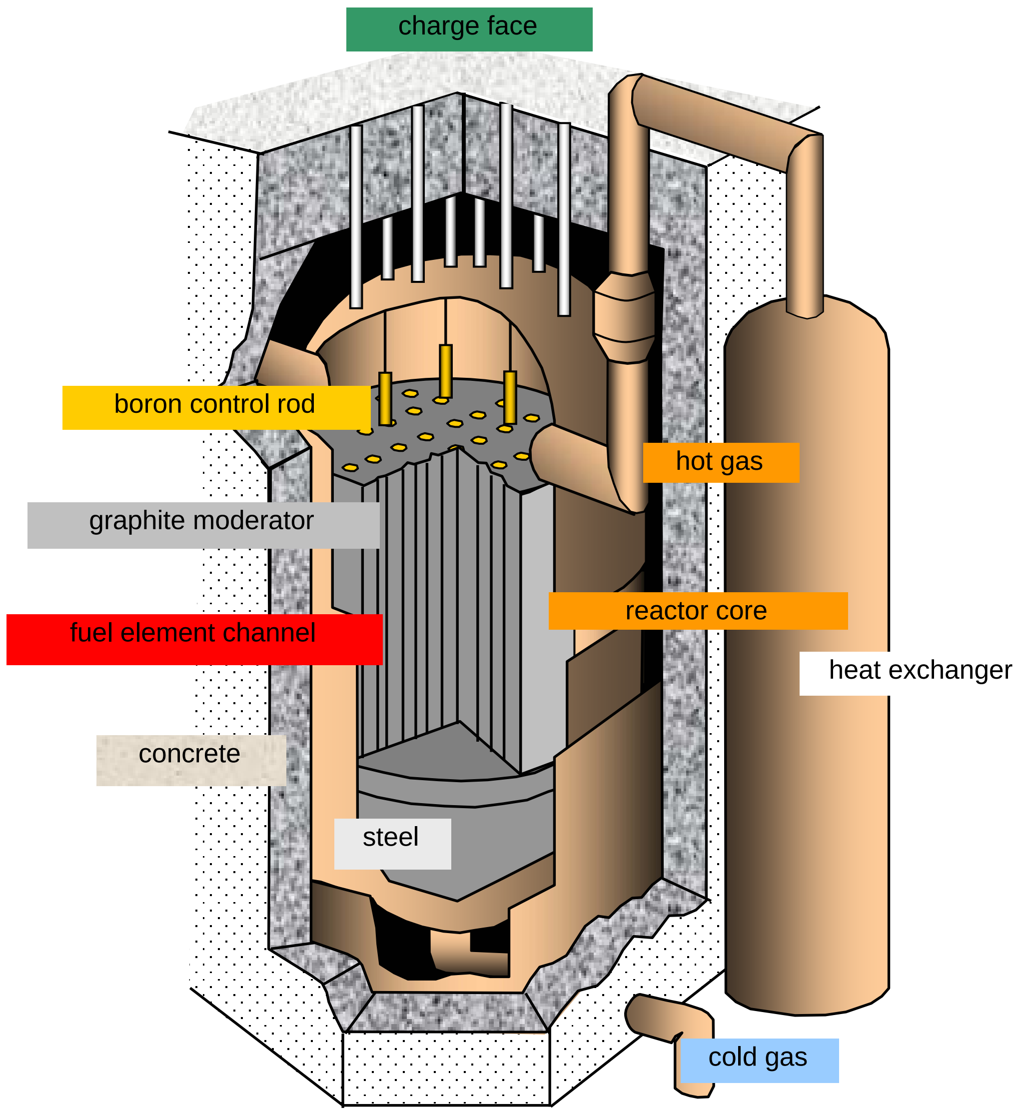
Calculating the energy released in fusion reactions.

TAP 528-4: Fusion questions

TAP 525-3: Fusion in a kettle?

TAP 528-1: Nuclear fission reactor

A Magnox reactor



Practical advice

This diagram is reproduced here so that you can use it for discussion with your class.

External reference

This activity is taken from Resourceful Physics

TAP 528-2: Fission in a nuclear reactor – how the mass changes

Some rather harder questions

These extended questions will test your ability to deal with calculations involving the physics of nuclear fission.

Use the following conversions and values for some of the questions:

- 1 eV = 1.6×10^{-19} J
- 1 atomic mass unit = 1.66×10^{-27} kg
- $c = 3 \times 10^{8}$ m s^{-1}

Particle	**Mass (u)**
$^{235}_{92}U$	235.043 94
$^{1}_{1}H$	1.007 825
$^{3}_{2}He$	3.016 030
$^{1}_{0}n$	1.008 665

Try these

Magnox power stations produce about 20 TW h of electrical energy in the UK every year by fission of uranium. (This energy supplies roughly the electrical needs of Greater London.)

1 The overall efficiency of the process that converts the energy for heating released in the fission to the final electrical product is 40%. How much energy, in joules, is produced each second in the company's reactors?

2 Each fission releases about 200 MeV of energy. How many atoms of $^{235}_{92}U$ need to fission in each second to produce the heating energy you calculated in question 1?

3 What was the mass of these atoms before they underwent fission?

4 What is the total mass change due to fission in Magnox reactors each second?

In the pressurised water reactor (PWR) the fuel rods do not contain pure $^{235}_{92}U$. The uranium comes from mined ore that contains a mixture of $^{238}_{92}U$ and $^{235}_{92}U$. The fuel delivered to the reactor contains 0.7% of $^{235}_{92}U$. The fuel rod stays in the reactor for about 3 years and is then removed to allow reprocessing.

This time consider just one reactor with an output of 1 GW.

5 Calculate the number of uranium nuclei disintegrating every second.

6 Calculate the mass of $^{235}_{92}U$ that undergoes fission every second.

7 Estimate the mass of $^{235}_{92}U$ required in the core for a 3 year cycle.

8 Estimate the total mass of both uranium isotopes required in the core for a 3 year cycle.

9 Is your estimate in question 8 likely to be an upper or a lower limit?

Hints

1 Remember the meaning of the term watt-hour. It corresponds to the amount of energy delivered at a rate of 1 joule per second for 1 hour. Do not forget to include the efficiency in your calculation.

2 Convert to J from MeV.

3 Use the nucleon number of the uranium and the conversion from atomic mass units to kilograms.

4 Use $\Delta E = \Delta mc^2$ to calculate this.

7 The information indicates that one-third of the fuel needs to be removed for reprocessing every year. Your answer to question 6 can be multiplied up to give the fuel usage in 1 year. This is one-third of the total.

8 The answer to question 7 represents the fuel used, and this is 3% of all the uranium (both isotopes). Hence the total mass.

Practical advice

These questions revise basic conversions between electron volts and joules and atomic mass units and kilograms. Students will need to be familiar with gigawatts (GW) and terawatts (TW) in powers of 10. The questions could be extended either verbally or in writing to ask students about the volume of uranium inside the core and about the equivalent volumes of coal or oil that might be required in a conventional power station. For example, 1 megatonne of coal is equivalent to 29×10^{15} J, 1 megatonne of oil is equivalent to 42×10^{15} J.

Social and human context

The questions provide an opportunity for debate about fission power generation.

Answers and worked solutions

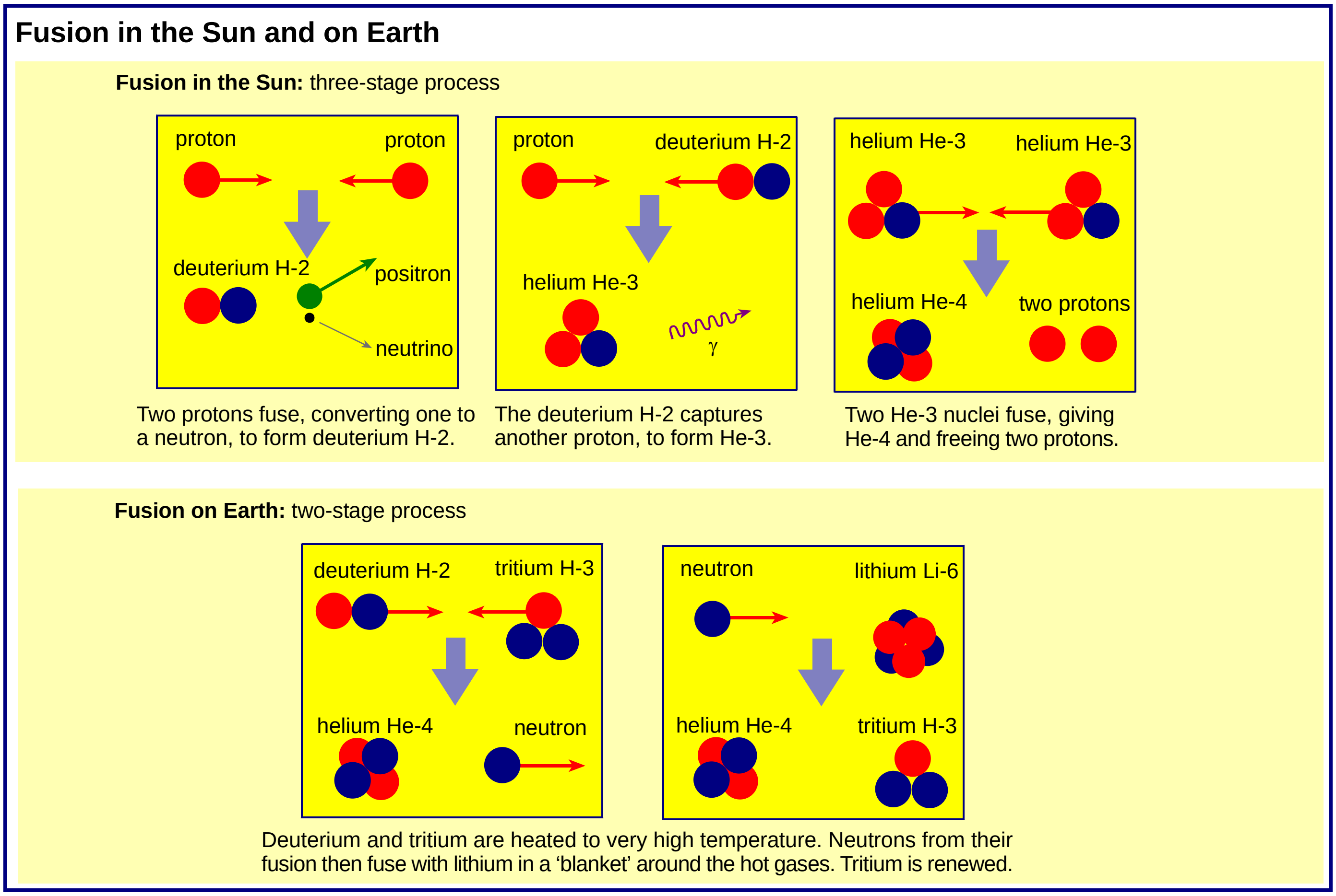
1. energy = $((20 \times 10^{12}$ Wh × 3600 J W $h^{-1}) / (3.16 \times 10^{7})) \times (100 / 40) = 5.7 \times 10^{19}$ J every second.
2. number of atoms = $(5.7 \times 10^{19}$ J) / (200 × 10^{6} eV × 1.6 × 10^{-19} $JeV^{-1}) = 1.8 \times 10^{26}$ atoms.
3. mass per second = 1.8×10^{26} s^{-1} × 235.04394 u × 1.66 × 10^{-27} kg u^{-1} = 7.0×10^{-5} kg s^{-1}
4. mass change = $(5.7 \times 10^{19}$ J $s^{-1})/ ((3 \times 10^{8})^{2}$ kg $s^{-1})$ = about 5 g
5. disintegrations per second =

   $((1 \times 10^{19}$ J $s^{-1})/ (200 \times 10^{6}$ MeV × 1.6 × 10^{-19} J $eV^{-1})) \times (100/40) = 7.8 \times 10^{19} s^{-1}$
6. mass per second = 7.8×10^{26} s^{-1} × 235.04394 u × 1.66 × 10^{-27} kg u^{-1} = 3.0×10^{-5} kg s^{-1}
7. mass = 3.0×10^{-5} kg s^{-1} × 3 years × 3.2×10^{7} sy^{-1} = 2900 kg
8. mass = 2800 kg × (100/0.7) = 400 000 kg
9. Lower limit.

External reference

This activity is taken from Advancing Physics chapter 18, 270S

TAP 528-3: Fusion



Here you can compare what happens in the Sun with reactions on Earth.

Practical advice

This diagram is reproduced here so that you can use it for discussion with your class.

External reference

This activity is taken from Advancing Physics chapter 18, 140O

TAP 528- 4: Fusion questions

Nuclear fusion is the process in which nuclei combine to give heavier elements. In one fusion reaction, two atoms of deuterium (hydrogen-2) fuse together to give one atom of a helium isotope (helium-3) together with one other particle.

1. Write out a balanced equation for this fusion process and say what the fourth particle is?

2. Calculate the energy release in this equation. Values you need are in the table.

Particle	Mass (u)
$^{1}_{0}n$	1.008 665
$^{2}_{1}H$	2.014 102
$^{3}_{1}H$	3.016 050
$^{3}_{2}He$	3.016 030

Another possible fusion process is represented by:

$^{2}_{1}H + {}^{1}_{0}n = {}^{3}_{1}H$

(the formation of hydrogen-3, tritium, by a nucleus of deuterium absorbing a neutron). This equation is certainly balanced. But can it occur in practice?

3. Calculate the change in mass in this reaction.

4. Is the reaction possible or not?

Practical advice

These questions revise basic conversions between electron volts and joules and atomic mass units and kilograms. Students will need to be familiar with gigawatts (GW) and terawatts (TW) in powers of 10. The questions could be extended either verbally or in writing to ask students about the volume of deuterium inside the core and about the equivalent volumes of coal or oil that might be required in a conventional power station. For example, 1 megatonne of coal is equivalent to 29×10^{15} J, 1 megatonne of oil is equivalent to 42×10^{15} J.

Social and human context

The questions provide an opportunity for debate about fusion power generation.

Answers and worked solutions

1. $^{2}_{1}H + {}^{2}_{1}H = {}^{3}_{2}He + {}^{1}_{0}n$

2. mass of two hydrogen-2 = 2 × 2.014102 u = 4.028204 u

   mass of helium-3 plus neutron = 3.016030 u + 1.008665 u = 4.024695 u

   Δm = 4.028204 u – 4.024695 u = 0.003509 u

   ΔE = 0.003509 u × 931.3 MeV u^{-1} = 3.27 MeV

3. mass of hydrogen-2 plus neutron = 2.014102 u + 1.008665 u = 3.022767

   Δm =3.022767 – 3.016050 u = 0.006 717 u.

4. The reaction can occur with a release ΔE = 0.006 717 u × 931.3 MeV u^{-1} = 6.26 MeV

External reference

This activity is taken from Advancing Physics chapter 18, 250S