John Andrews & Nick Jelley

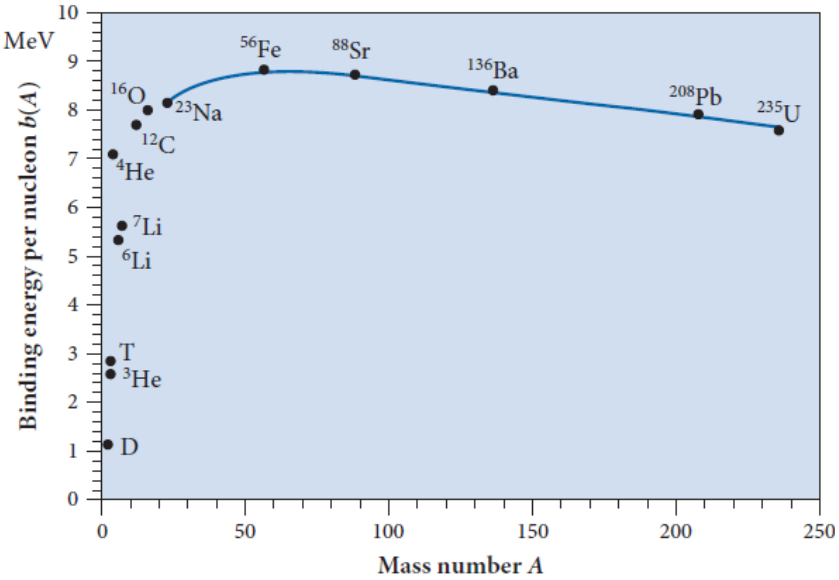
Lecture 9:

Nuclear Power

Nuclear timeline

1905	Einstein’s discovery of equivalence of mass and energy, $E = mc^2$
1911	Rutherford discovers nucleus (Manchester, UK)
1942	First nuclear reactor (Chicago, USA), led to Manhattan Project
1956	First prototype power station (Calder Hall, UK) – gas cooled
1957	Pressurised Water Reactor (PWR) developed for nuclear submarines by USA
1957	Windscale fire (Wigner energy underestimated)
1957	First PWR plant opened (Shippingport, USA)
1962	First commercial reactors 1962 (Berkeley, Bradwell,UK)
1979	Three Mile Island accident (USA, operator errors)
1986	Chernobyl accident (design faults, operator errors, no regulation)
2011	Fukushima accident (Earthquake 9.0 + Tsunami)

Binding Energy of Nuclei



In fission,

$A_1 \rightarrow A_2 + A_3$ + neutrons,

where A_2 and A_3 are the final stable nuclei, the **total energy release** E_R is approximately given by

$E_R = A_2\{b(A_2) - b(A_1)\} + A_3\{b(A_3) - b(A_1)\}$.

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Nuclei contain protons and neutrons, bound together by short-range forces. Total mass is less than mass of the constituent nucleons.

Mass difference ΔM is related to the **total binding energy** B_E by Einstein's formula $\boldsymbol{B_E = \Delta M c^2}$

Above mass number A ~20 the binding energy per nucleon is roughly constant. However: **more stable nuclei** can be formed either by:

i) **fusion** (combining 2 nuclei with low mass number A)

ii) **fission** (breakup of large A nucleus into lower A fragments + release of neutrons)

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Nuclear Fission

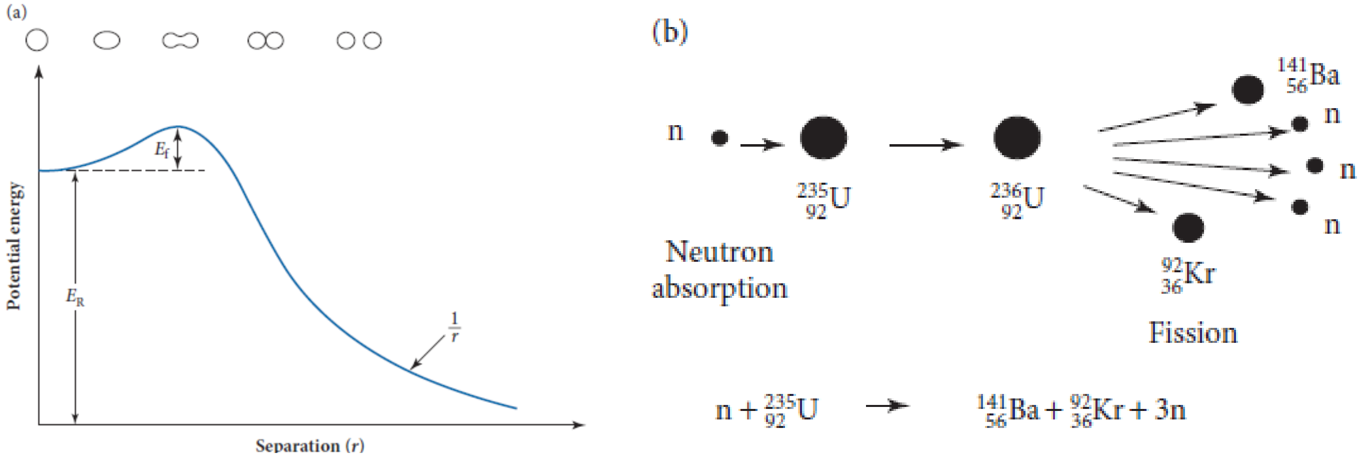

Fig. 9.2 (a) Fission barrier. (b) Neutron-induced fission of ^{235}U producing ^{141}Ba and ^{92}Kr.

Change in mass, $\Delta M = 3.6\ 10^{-28}$ kg

Energy released, $E = (\Delta M)\, c^2 = (3.6\ 10^{-28})\,(3\ 10^8)^2 = 3.2\ 10^{-11}$ J = **200 MeV**

c.f. **chemical combustion** $C + O_2 \rightarrow CO_2$, $E = 6.5\ 10^{-19}$ J = **4.1 eV**

Energy release from 1 uranium nucleus ≡ $4.6\ 10^7$ carbon atoms

1 tonne of ^{235}U ≡ $2.3\ 10^6$ tonnes of carbon; coal has 25% less energy than carbon

U is 0.7% ^{235}U so **1 tonne U ≡ 20,000 tonnes of coal**

Chain reaction and enrichment

On average, **1** neutron induces **2.4** neutrons by **fission** of **^{235}U**, so a **chain reaction** is possible.

But,

- naturally-occurring uranium only contains about **0.7%** of the **fissile isotope** ^{235}U, the remaining 99.3% being the stable isotope ^{238}U
- a significant fraction of neutrons are **lost** in any reactor before they induce fission.
- only for **thermal (low energy) neutrons** is inducing fission in natural U dominant.

As a consequence, the proportion of **^{235}U** is increased to ~**3%** by **enrichment**, in which gaseous UF_6 is rotated at high angular velocity in ultracentrifuges, causing partial separation of the molecules containing the lighter isotope of UF_6.

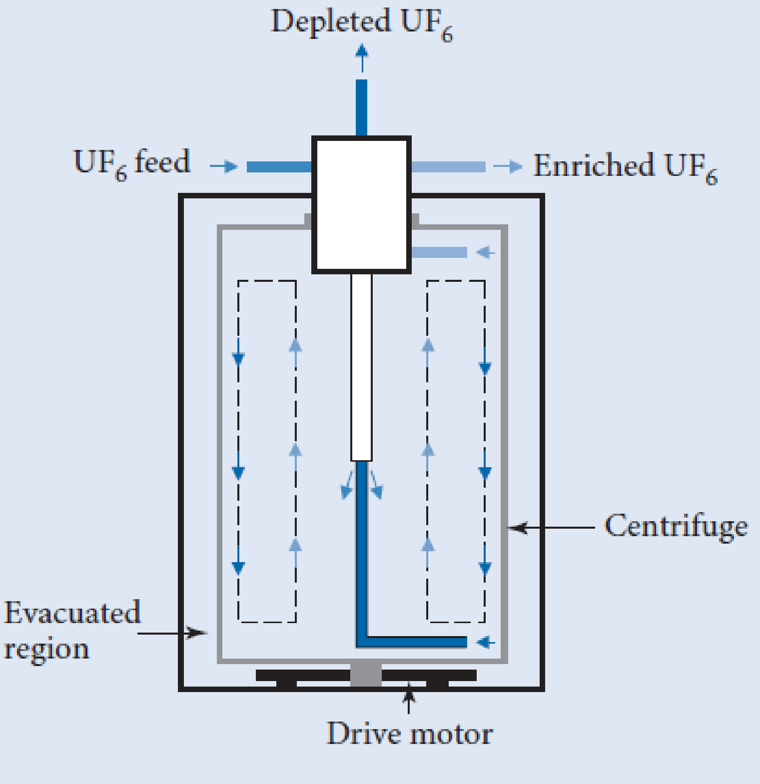

Fig. 9.4 A gas centrifuge.

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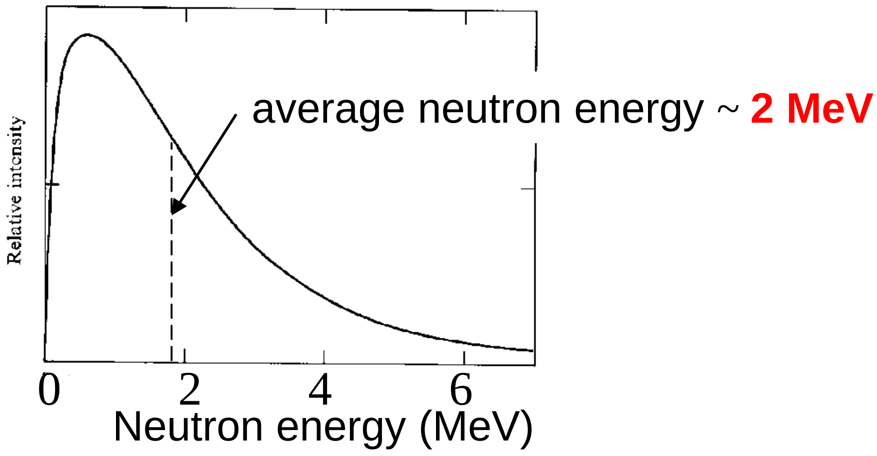
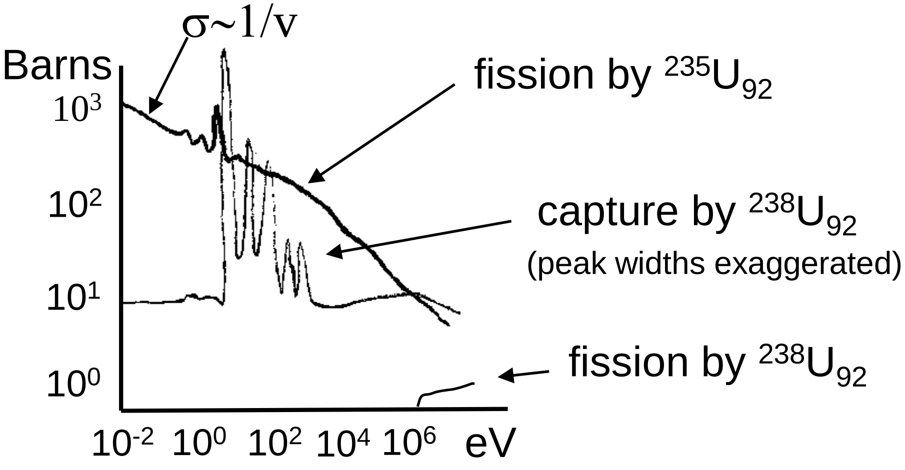
Neutron energy distribution, cross-sections and moderation

Energy distribution of neutrons produced by fission



Neutron cross-sections with uranium



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Neutrons produced by fission are **too energetic** to induce many fissions of $^{235}U_{92}$ (cross-section $\sigma \approx$ **10^0 barns**).

By slowing the neutrons down to '**thermal**' energies, the cross-section for fission of $^{235}U_{92}$ becomes much larger ($\sigma \approx$ **10^3 barns**).

The neutrons are slowed down by a '**moderator**', which reduces their kinetic energy. The process needs to be efficient, in order to avoid **neutron capture** in the **'resonant trap'** by $^{238}U_{92}$ ($\sigma \approx$**10^1-10^2 barns**).

The fractional loss of kinetic energy per collision with a moderator nucleus is

$\Delta E/E \approx 2/A$ (A>>1)

For **large 2/A** we need **low A** (e.g. hydrogen A = 1, carbon, A = 12)

Factors affecting Chain Reaction

- For each thermal neutron absorbed, η effective fast neutrons emitted $\eta < \nu$, mean number produced (n =2.42 for ^{235}U), because not all neutrons absorbed by fuel cause fission. Nat U (0.72% ^{235}U) η =1.33
- Some fast neutrons cause fission before slowing down which increases the number of neutrons by the **fast fission factor** ε
- The probability that a neutron will avoid resonance capture by ^{238}U the **resonance escape probability** p - depends on the moderator
- The fraction of thermal neutrons that are absorbed by the fuel in the core (fuel, moderator, can) is called the **thermal utilization factor** f
- There are a fraction l_f of fast neutrons and a fraction l_t of thermal neutrons that leak out of the reactor

The neutron multiplication factor k is therefore given by:

$k = \eta\varepsilon pf\,(1- l_f)\,(1- l_t)$ and **$k > 1$ for a chain reaction**

For infinite core $k_\infty = \eta\varepsilon pf$ **Four factors formula**

Reactor control

The problem

In the event that the neutron flux gets too high or too low for a stable chain reaction, how can equilibrium be restored?

Control rods

If the neutron flux gets too high, then **control rods** with high neutron absorption cross-sections are lowered into the reactor to absorb the excess neutrons.

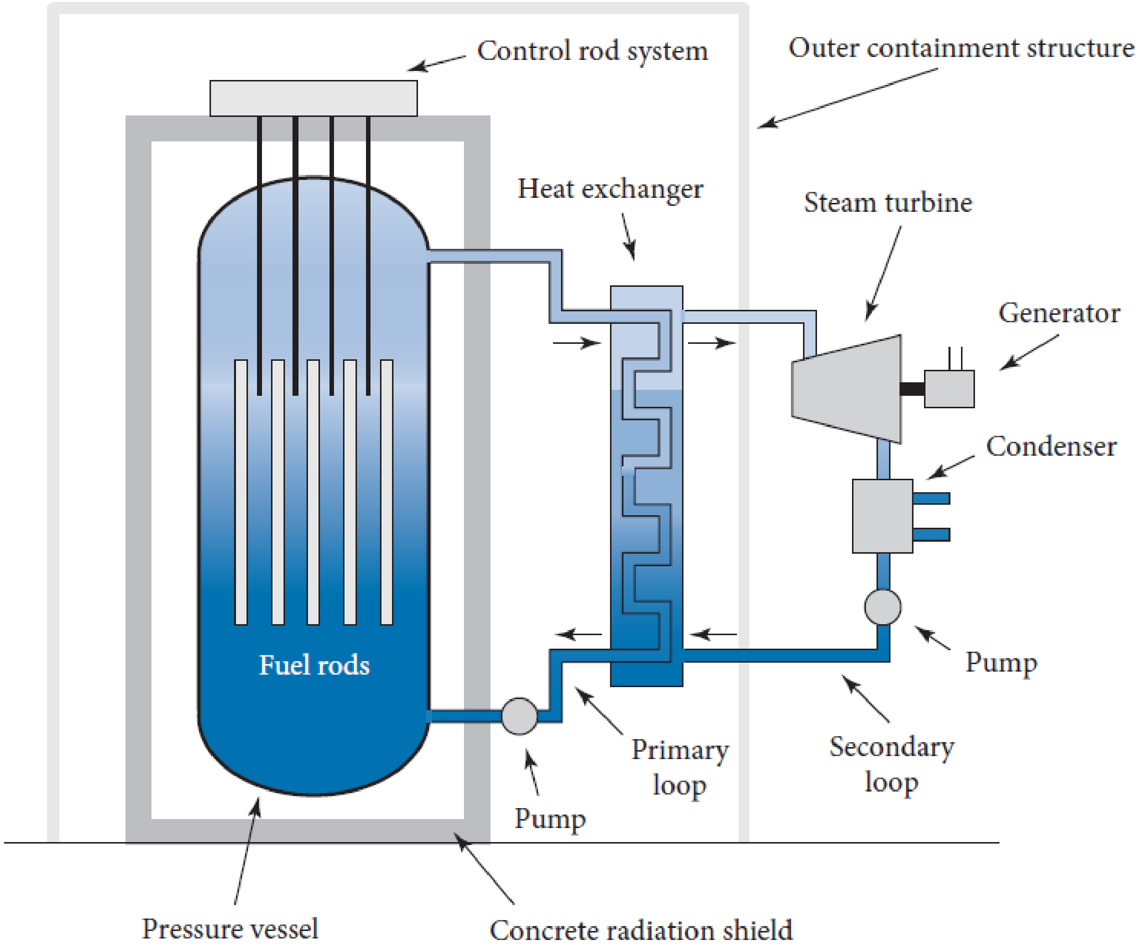
Materials used: ^{113}Cd (σ_c = 20,000 barns), ^{10}B (σ_c = 4,000 barns)

Conversely, the control rods are withdrawn if the neutron flux gets too low.

In practice, control would be virtually impossible but for the existence of **'delayed' neutrons**, which are released only after the β-decay of a fission product.

Typically, about 1% of neutrons produced by fission are delayed by **10-20 seconds**, which is enough time for automatic adjustments in the position of the control rods to restore equilibrium.

Pressurized Water Reactor (PWR)



Most universal commercial reactor (**439 in 2016**). Very **compact** - first used in **nuclear submarines** (oxygen not needed so could stay underwater for longer than diesel submarine).

Moderator = water (**low A**).

Water is at **high pressure** (15 MPa) to keep it in liquid phase.

Heat from reactor produces steam, which drives turbine. **Thermal efficiency ≈ 33%**

Main risk = **loss-of-coolant-accident** (LOCA), so emergency cooling necessary.

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Radiation exposure and nuclear waste

Natural Sources	%
Cosmic rays	15
Food	18
Environment	41
Total	**74%**

Man-made Sources	%
Medical	25
Miscellaneous	0.6
Fall-out	0.3
Nuclear power	0.4
Total	**26%**

(From ‘*Energy: a Guidebook*’, J. Ramage)

Spent fuel = most hazardous waste ≈ 25 tonnes a year for a 1 GWe PWR

- stored on site for some years in **storage ponds**, to allow short-lived activity to decay
- then **reprocessed** to recover uranium and plutonium
- remaining waste is **vitrified** or incorporated into **stable mineral lattices**
- **long-term storage** (> 10 000 years) of high-level waste is an ongoing issue – repositories need to be **geologically stable**, with no risk of **water ingress**.

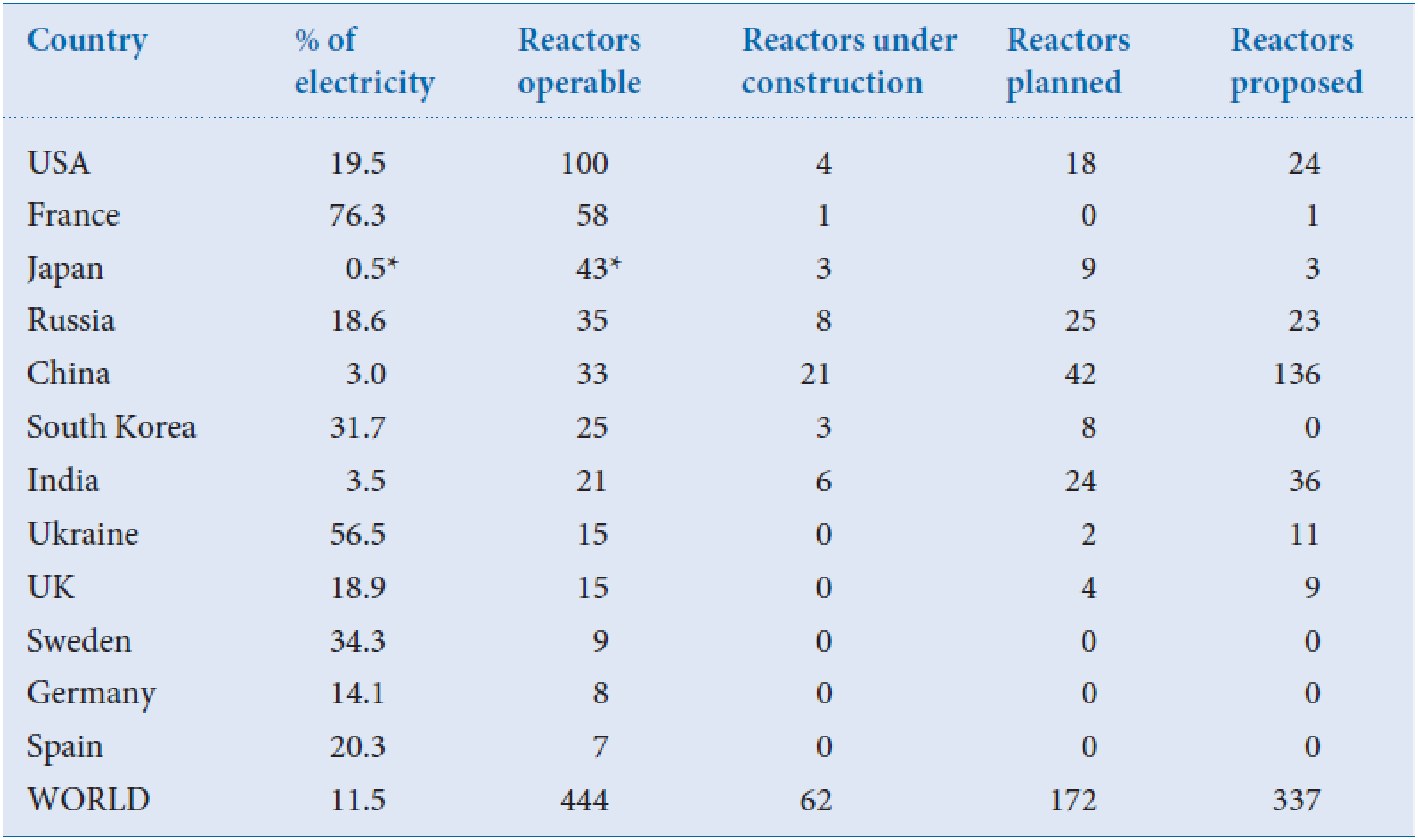
Nuclear accidents

The consequences of a nuclear accident can be catastrophic.

- A fire in a gas-cooled graphite-moderated reactor at **Windscale (UK)** in 1952 caused by a build-up of stored energy in the graphite (Wigner energy), released radioactive materia into the atmosphere.
- A loss-of-coolant-accident in a PWR at **Three Mile Island (USA)** in 1979, caused by mechanical and human failure, resulted in 20% meltdown and release of radioactivity.
- In 1986, a water-cooled graphite-moderated RBMK reactor at **Chernobyl (Ukraine)** became unstable, causing a steam-explosion and a huge release of radioactivity.
- A massive earthquake off the east cost of Japan caused a series of tsunamis which breached the protective seawall at **Fukushima Daiichi**, leading to hydrogen explosions and meltdown in several reactors.

Lessons have been learned from these accidents, leading to **design improvements**, and a better understanding of **human factors** and **tighter regulation**. Following the 9/11 attacks, the **security** of nuclear plants, their ability to withstand an aircraft crash on reactor buildings, and the protection of hazardous materials have received special attention.

Number of reactors and percentage of electricity generated



Country	% of electricity	Reactors operable	Reactors under construction	Reactors planned	Reactors proposed
USA	19.5	100	4	18	24
France	76.3	58	1	0	1
Japan	0.5*	43*	3	9	3
Russia	18.6	35	8	25	23
China	3.0	33	21	42	136
South Korea	31.7	25	3	8	0
India	3.5	21	6	24	36
Ukraine	56.5	15	0	2	11
UK	18.9	15	0	4	9
Sweden	34.3	9	0	0	0
Germany	14.1	8	0	0	0
Spain	20.3	7	0	0	0
WORLD	11.5	444	62	172	337

Source: WNA2016. * Only a few have restarted under Japan's post-Fukushima safety standards.

Overview

- Global production of electricity from nuclear power rose up to 2004, but its share of global production dropped from **17.5% in 1996** to **11.5% in 2016**.
- The **banking crisis** of 2008-2010 and the accident at the **Fukushima Daiichi** plant have been major setbacks, with some countries phasing out nuclear power altogether. **Germany** is replacing its loss of nuclear capacity with renewables, energy storage and other measures.
- Some new reactors have been over budget and overdue.
- However, about **500 new plants** are planned or proposed, mostly in Asia, where there is state backing that makes financing easier.
- **Potential** by 2050: ~ 1 $\mathrm{TW_e}$
- **Advantages** Low Carbon footprint, steady output, cost ~1.5 × fossil fuel
- **Disadvantages** Perceived risk is high and concern over radioactive waste disposal and proliferation

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Nuclear fusion

The challenge:

to replicate the fusion process like that takes place inside stars like our Sun.

Fusion reaction:

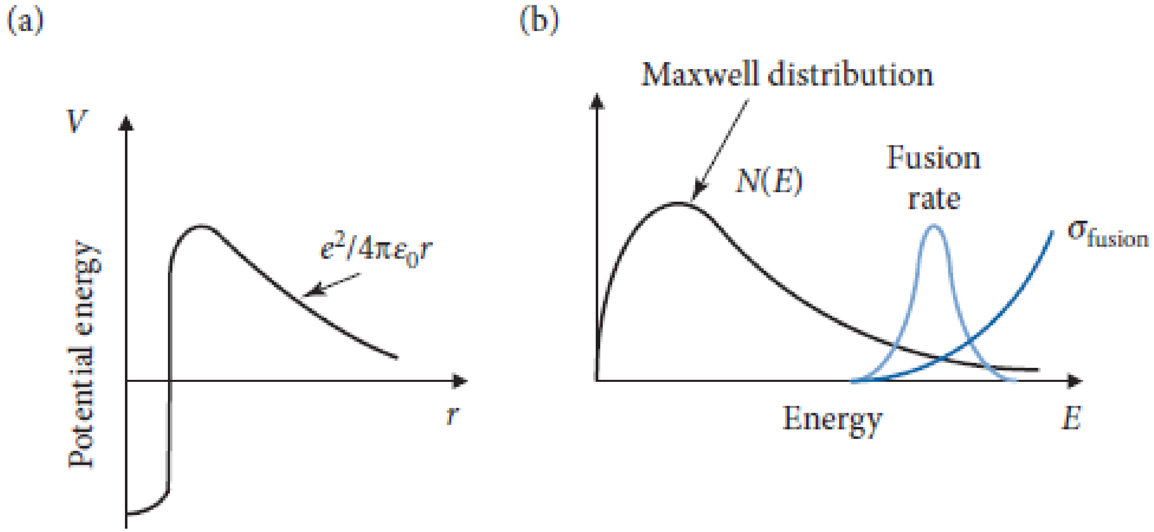
D + T → ^{4}He + n + 17.6 MeV

(D = Deuterium, T = Tritium)

Resources:

Deuterium is obtained from sea water by electrolysis,

Tritium is produced by a breeding reaction using lithium



(a) Coulomb barrier. (b) Fusion rate.

The problem:

How to overcome the Coulomb repulsion between D and T?

(Gravitational attraction inside a star overcomes repulsion.)

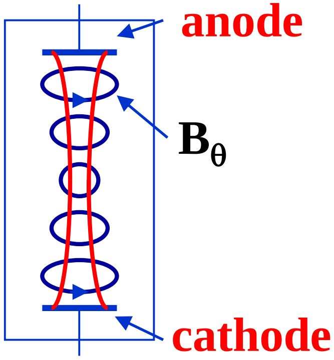
Terrestrial devices need to keep very hot plasma (ionised gas) away from walls of container.

Plasma machines

Plasma = ionised gas (electrons + positive ions + neutral atoms)

- Number density of charges is very large, and **$n_e \sim n_i = n$**
- Electric and magnetic fields are **long-range**
- Plasma behaves like a **fluid**

The near-equality of the number density of ions and electrons effectively screens the plasma from external electric fields. However, **magnetic fields** penetrate plasmas and can be used to control **instabilities** (e.g. **sausage** and **kink** instabilities below).



Gas discharge tube

Plasma is kept from wall by a magnetic force per unit volume **$J \times B$**.

Power **$P = I^2R$**; R decreases as $T^{-3/2}$

Temperature stops rising at ~10^5 K

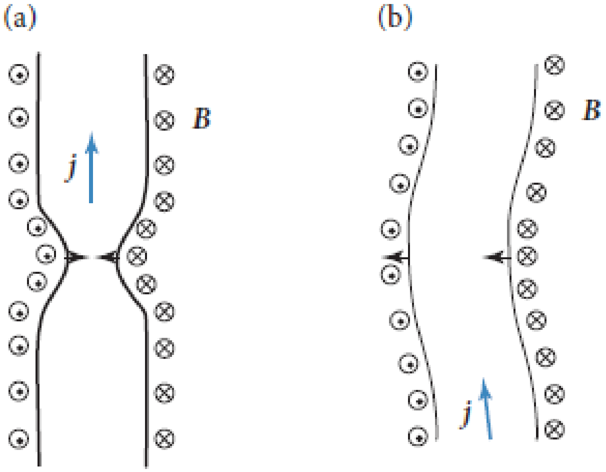


Fig. 9.15 (a) Sausage instability. (b) Kink instability.

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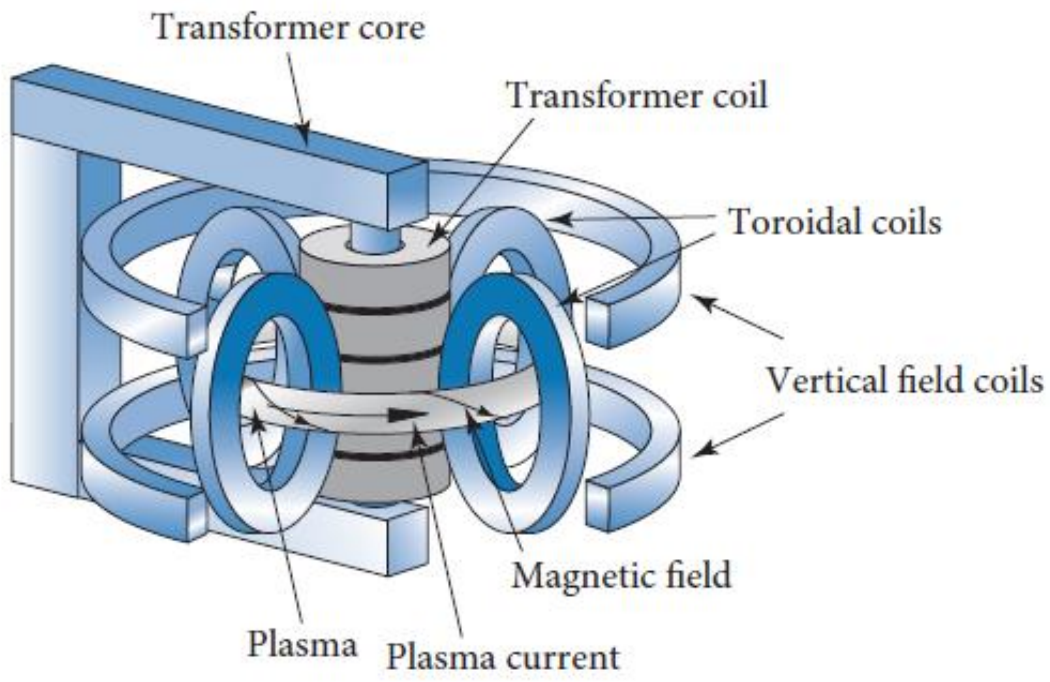
Tokamak



Tokamak is a toroidal machine which has better stability than other plasma machines.

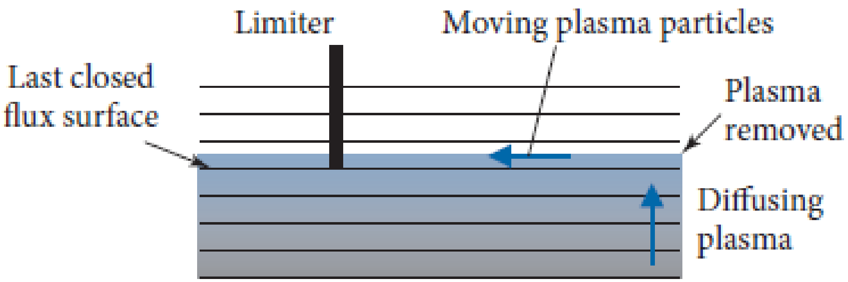
In 1968, the original tokamak (Russia) reached a temperature

T_{ion} ~ 2-3 10^6 K for t ~ 10^{-2} seconds

Since then many '**bigger-and-better**' tokamaks have been built.

Divertor Tokamak

By elongating the field vertically it is possible to form a cross-over, called a *separatrix*, in the magnetic field configuration near the wall. This configuration diverts the plasma away from the main central region onto divertor plates.



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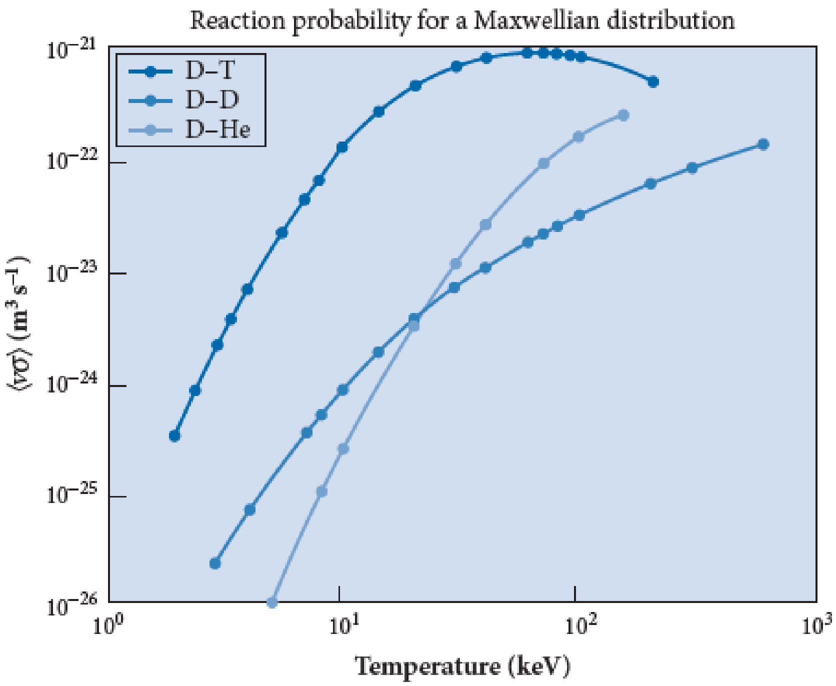
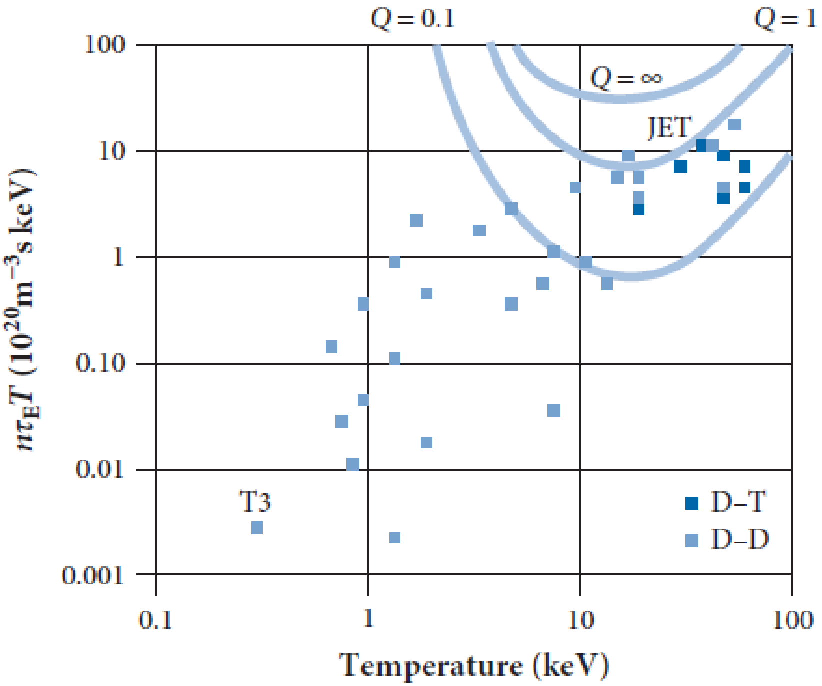
Lawson criterion





For a **self-sustaining fusion reaction**,

(rate of energy generated by fusion) > (rate of loss of energy from plasma)

This condition is satisfied by the **Lawson criterion** $n\tau_E T \geq 3\ 10^{21}\ \mathrm{m}^{-3}\ \mathrm{s\ keV}$, where n = no. density, τ_E = time for energy to be lost to walls, T = temperature (in keV).

Progress towards a commercial fusion reactor

- There has been a **four order-of-magnitude Increase** in $\boldsymbol{n\tau_{\mathrm{E}}T}$ over the last 40 years.

- **JET** (Joint European Torus) obtained ratio of fusion power to input power, *Q*, of 0.6 and produced 16 MW and obtained $\tau_{\mathrm{E}} \sim 1\ \mathrm{s}$ in 1997 with a D + T plasma.

- **ITER**, a much larger tokamak, is under construction (France). It is an international project designed to produce *Q* =10 and provide data for a demonstration reactor DEMO.

- It is hoped that a **commercial fusion reactor** will be operational by **2050**

- If successful, controlled fusion offers the world almost **unlimited carbon-free energy;** the reserves of deuterium in the oceans is vast, while lithium on land alone would provide ~3 TWy for ~1000 y