Nuclear Power

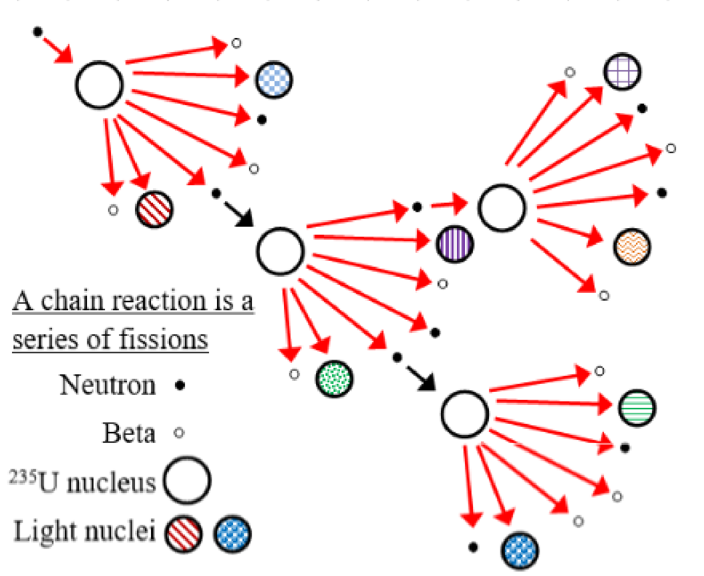
Nuclear Fuel

Naturally occurring Uranium contains roughly 99.3% Uranium-238. U-238 is NON-FISSILE (it does not absorb neutron).

A practical reactor need 2-3% Uranium-235 (which is fissile) in the fuel. This be done by ENRICHING the U-238 to produce a higher proportion of U-235.

The fuel is assembled to fuel rods.

Fission Chain Reactions



Each fission event releases a series of fission neutrons.
These can be absorbed by nearby fissile nuclei causing further fission events.
This leads to an exponential release of energy if the CHAIN REACTION is uncontrolled such as when employed in thermonuclear weaponry.

Moderation

In reactors we are looking for a SELF-SUSTAINING chain reaction. We are looking for a single event to cause a single fission event. In order to achieve this, the FISSION NEUTRONS have a very high KINETIC ENERGY need to be SLOWED DOWN.

These slow neutrons are called THERMAL NEUTRONS, as they are thermal equilibrium with the MODERATOR MATERIAL (following a large number of collisions).

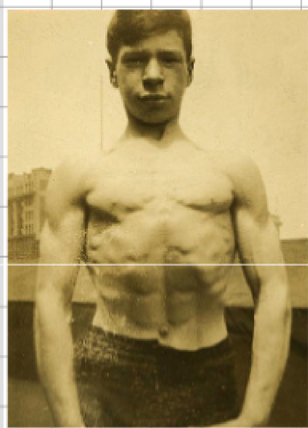
The moderator should be composed of a material with LOW MASS NUCLEI. This is so that the mass is not too high in comparison to that of the neutron. This leads to a more effective transfer of kinetic energy reducing the number of collision necessary to slow the fission neutrons.

In addition, the moderator should be POOR ABSORBER of neutrons.

WATER or GRAPHITE are frequently used as moderators.

Control Rods

Each induced fission event produces 2-3 fission neutrons. Control rods absorb excess neutrons, so that approximately 1 neutron is able to continue to produce a further fission event.



Controls are made from BORON or CADMIUM, which are both good absorbers of neutrons.

Control rods in modern reactors can be moved up and down within the chamber to precisely control the rate of fission.

In the event of an uncontrolled chain reaction, reserve controls can be rapidly lowered to stop the reaction.

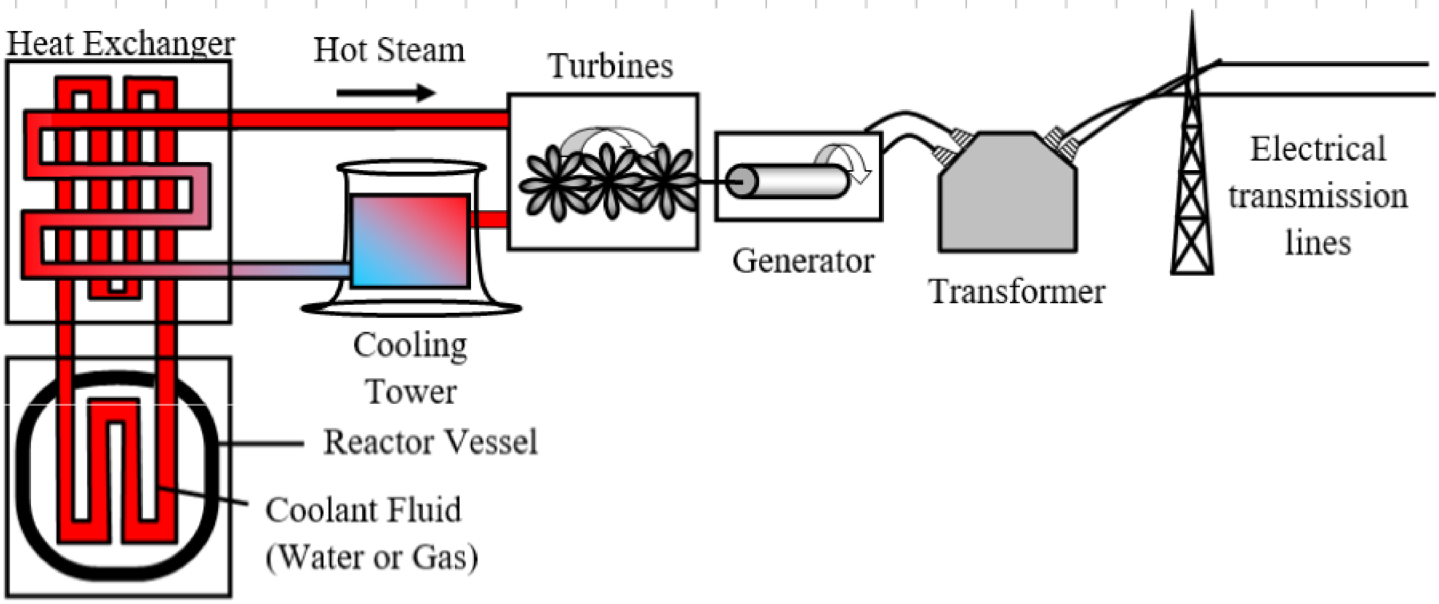
Critical Mass

After a fission event, a neutron may:
- Be absorbed by U-235 and cause fission.
- Be absorbed by control rods.
- Be absorbed by U-238 or fission products.
- Leave the reactor.

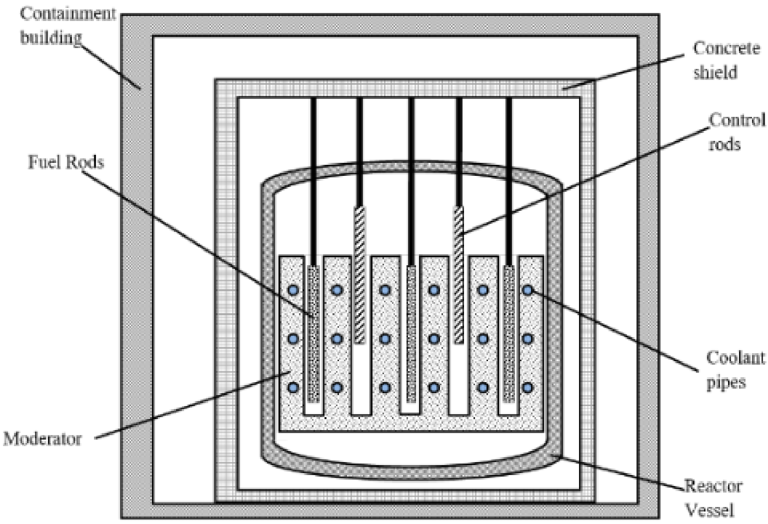
(These are much more likely if there is a small amount of Uranium present, and less likely for a larger mass of Uranium)

This means is a minimum volume of Uranium for a sustained reaction. This is called the CRITICAL MASS. This values varies depending on reactor layout and fuel dimension and shape.

Generating Electricity



On Power Stations



Nuclear reactors have several steps in place to prevent release of nuclear material into the environment:
- The fuel is mounted in steel fuel rods.
- The rods are housed in a steel reactor vessel.
- The reactor vessel is encased in concrete.
- The shield is housed in a thick concrete containment building.

In the event of overheating:
- Reserve controls rods can be rapidly deployed.
- Additional cooling circuits can be used to reduce reactor temperature.

Nuclear Waste

The products of fission are low-mass radioactive daughter nuclei with a wide range of half-lives.

U-238 is an alpha emitter with a half-life of 4.5 billion years.
The activity of spent fuel rods is significantly higher than that of U-238. This shows that the daughter nuclei have a lower half-life.
These isotopes emit a mixture of beta minus and gamma radiation.

Waste is initially stored at the reactor sites until activity has fallen below a threshold value.
- Short half-life material is initially high risk (as activity is high) but quickly becomes safe and can be disposed of.
- Long half-life material need stored for a long period (but have a low activity). These are placed in long term underground storage facilities in a geographically appropriate area.

Nuclear Energy

Determine the mass of a Carbon nucleus using the Physics Data Sheet $^{12}_{6}C$

$N - 6 \times 1.675 \times 10^{-27} = 10.050 \times 10^{-27}$

$Z - 6 \times 1.673 \times 10^{-27} = 10.038 \times 10^{-27}$ +

20.088×10^{-27} kg

$M_{^{12}C} - 19.93 \times 10^{-27}$ kg

Mass defect (Δm)

The MASS DEFECT is the difference between the total rest mass of a nucleus and the total rest mass of the constituent nucleons.

For C-12

$\Delta m = m_{o(constituents)} - m_{o(nucleus)}$

$\Delta m = (20.088 - 19.93) \times 10^{-27}$ kg

$\Delta m = 0.158 \times 10^{-27}$ kg

$m_p = 1.00728\,u$

$m_n = 1.00867\,u$

$1u = 931.5\,MeV$

Atomic Mass Units

$1/12^{th}$ of the mass of a C-12 atom

$1u = 1.661 \times 10^{-27}$ kg

Binding energy

The nucleus is bound by the STRONG INTERACTION. Work must be done on the nucleons to overcome the ATTRACTION of the strong interaction.

The BINDING ENERGY is the ENERGY REQUIRED to SEPARATE all constituents of a nucleus.

LEARN THIS EXACT COMBINATION OF WORDS!!!!!!!!!!!!!!!!!!!!!!!!

When the nucleus is formed, binding energy is released.

The mass defect arises due to this loss of energy.

rest mass of nucleus = rest mass of constituents – mass defect

$$m_0(\text{nucleus}) = m_0(\text{constituents}) - \Delta m$$

$$m_0(\text{nucleus})c^2 = m_0(\text{constituents})c^2 - \Delta m c^2$$

$$E_0(\text{nucleus}) = E_0(\text{constituents}) - \Delta E$$

rest mass energy of nucleus = rest mass energy of constituents – binding energy

Often examiners are interested in the BINDING ENERGY PER NUCLEON as this can be used as a measure of stability.

$^{28}_{14}Si$

$m - 27.997\,u$

$N - 14 \times 1.675\times10^{-27} = 2.3450\times10^{-26}$

$Z - 14 \times 1.673\times10^{-27} = 2.3422\times10^{-26}$ +

4.6872×10^{-26} kg

$\Delta m = 4.6872\times10^{-26} - (27.997 \times 1.661\times10^{-27})$

$\Delta m = 3.68983\times10^{-28}$ kg

$1\,eV = 1.6\times10^{-19}\,J$

$\Delta E = 3.68983\times10^{-28} \times (3\times10^8)^2$

$\Delta E = 3.320847\times10^{-11}\,J$

$\Delta E = 208$ MeV

$\frac{208}{28} = 7.4\,MeV$ (ΔE/nucleon)

Binding energy per nucleon: 7.4 MeV

$^{210}_{84}Po$

$m_{Po} - 209.982u$

$N - 126 \times 1.00876u = 127.09242u$

$Z - 84 \times 1.00728u = 84.61152u$ +

$211.70394u$

$\Delta m = (211.70394 - 209.982)u$

$\Delta m = 1.72194u$

$\Delta E = 1.72194 \times 931.5$

$\Delta E = 1604 \text{ MeV}$

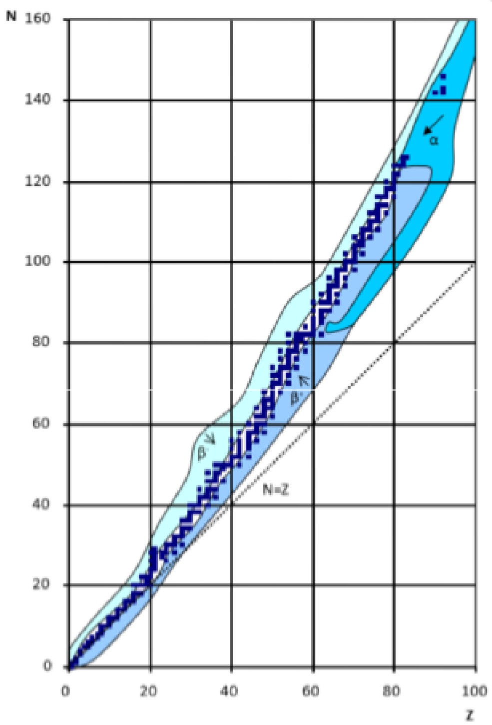
$\Delta E/_{nucleon} = \frac{1604}{210} = 7.64 \text{ MeV}$

$\frac{1.661 \times 10^{-27} \times (3 \times 10^8)^2}{1.6 \times 10^{-13}}$

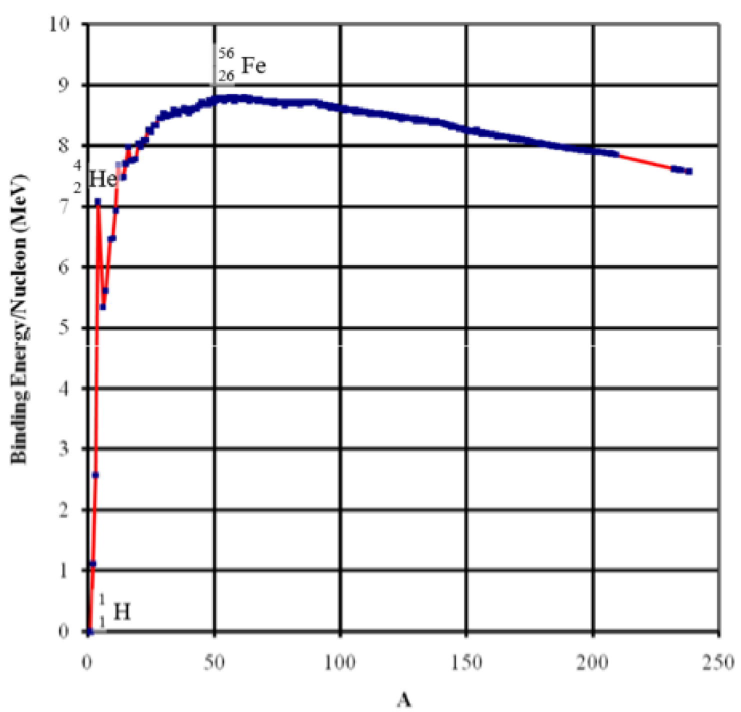
$= 931.5 \text{MeV}$

Binding energy per nucleon 7.6 MeV

Element	Mass number [A]	Atomic number [Z]	Neutron number [N]	Binding energy per nucleon (MeV)



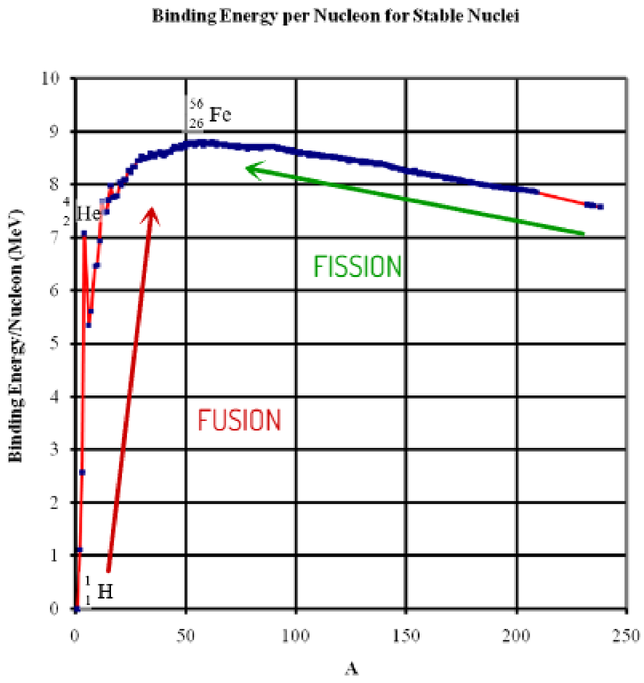
Binding Energy per Nucleon for Stable Nuclei



Nuclear Stability

The binding energy per nucleon is a measure of nuclear stability.
The higher the value, the more tightly bound the nucleons are by the strong interaction.

Fe-56 is the MOST STABLE atomic nucleus.



All nuclear reactions which occur lead to a HIGHER binding energy per nucleon in the products.

Energy from fusion

In nuclear fusion, lighter nuclei combine to form a heavier nucleus. (TWO parent nuclei form a single DAUGHTER nucleus)

The criteria for a fusion reaction are:

- Very high temperatures - the nuclei require high kinetic energies to allow them to overcome electrostatic repulsion.
- Very high pressure - the density of nuclei per unit space needs to be high to increase the chance of collision.

Fusion as a process releases energy within stars which is ultimately emitted as full-spectrum EM radiation.

$${}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{2}He + {}^{1}_{0}n + Q$$

$M_{H-2} = 2.014u$ $\quad$ $M_{He-3} = 3.015u$

✓1 $2 \times 2.014u = 4.028u$

$3.015u + 1.00867u = 4.02367u$ −

✓2 $0.00433\ u$

$0.00433 \times 931.5 = 4.03\ MeV$ ✓3

This energy is released as the Kinetic Energy of the final products (mainly the free neutron)

$${}^{3}_{1}H + {}^{2}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

$M_{H-3} = 3.016\ u$ $\quad$ $M_{He-4} = 4.0026\ u$

✓1 $2.014u + 3.016u = 5.03\ u$

$4.0026u + 1.00867u = 5.01127u$ −

✓2 0.01873 ✓3

$\times 931.5 = 17.45\ MeV$

Energy from fission

In nuclear fission, a heavy parent nucleus splits to form two lighter daughter nuclei, several neutrons and potentially several beta-minus particles.

Spontaneous fission is rare, but can be INDUCED by bombarding certain nuclei with neutrons. (Neutrons do not experience the electromagnetic interaction, so can get
close to the nuclei at relatively low energies)

This is the basis of nuclear power and thermo-nuclear weaponry.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{236}_{92}U \longrightarrow ^{94}_{40}Zr + ^{140}_{56}Ba + 2\,^{1}_{0}n + 4\,^{0}_{-1}\beta + Q$$

$M_{U\text{-}235} = 235.044\,u$ $\quad M_{Zr\text{-}94} = 93.906\,u$ $\quad M_{Ba\text{-}140} = 139.91\,u$

$235.044\,u + 1.009\,u = 236.053\,u$ ✓1

$93.906\,u + 139.91\,u + 2\times 1.009\,u + 4\times 0.00055\,u = 235.8362\,u$

✓2 $0.2168\,u$

$0.2168 \times 931.5 = 202\ MeV$ ✓3

If a nuclear reactor consumes 3.0 mg of U-235 fuel per second. Give the power of the reactor.

Number of fission events per second = $\dfrac{\text{Mass of fuel per second}}{\text{Mass of U-235 nucleus}} = \dfrac{3\times 10^{-6}}{(235.044 \times 1.660\times 10^{-27})}$

$= 7.69\times 10^{18}\ s^{-1}$ ✓1

$E_{\text{per reaction}} = 202 \times 1.6\times 10^{-13}$

$= 3.23\times 10^{-11}\ J$ ✓2

$\text{Power} = 7.69\times 10^{18} \times 3.23\times 10^{-11} = 2.49\times 10^{8}\ W$

$= 249\ MW$ ✓3