$E = mc^2$

Chemical reactions convert very small amounts of matter to energy.

What $E = mc^2$ says is that matter and energy are interchangeable. There is a continuum between the two. Energy can transform into matter and matter can transform into energy. They are different aspects of the same thing.

When we burn a litre of petrol, *one-billionth* (1/100 000 000) of the mass of the petrol is completely transformed into energy. This transformation occurs in the electron shells. The amount is so small that nobody has ever been able to measure it. Yet even this very small release of energy is large enough to propel a car for 15 km.

Rutherford proved that electrons make up only 0.01 percent of the mass of an atom. The other 99.99 percent is in the nucleus of the atom. And so the question arose, would it be possible to tap the much greater amount of energy stored in the nucleus the way we tap the energy in the electrons through chemistry?

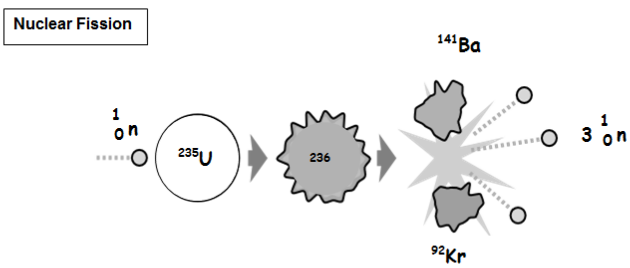
By the late 1930s it had become clear that energy in unprecedented quantity could be obtained by splitting the unstable uranium atom. The release of energy from splitting a uranium atom turns out to be 2 million times greater than breaking the carbon-hydrogen bond in coal, oil or wood.

In a nuclear reactor the conversion of 20 grams of matter completely into energy would be enough to power the city of Wellington (New Zealand) for twenty years.

There are two ways of releasing nuclear energy:

Nuclear Fission Reactions

When large atomic nuclei are hit with neutrons they can become unstable and breaks into two smaller 'daughter' nuclei and releases more neutrons, (as well as α and β particles and γ). This is **nuclear fission** and is accompanied by an enormous release of energy. It forms the basis of the current nuclear power industry.

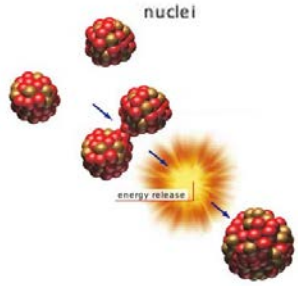


Uranium-235 is particularly useful. The heat energy released is used to boil water to make steam drive a turbine and electrical generator in the nuclear power station.

During fission of each U atom more neutrons are formed which 'split' other U atoms making even more neutrons - a **chain reaction**, leading to an even greater energy release. If a chain reaction goes uncontrolled a nuclear explosion results (a fission bomb based on uranium-235 was dropped on the city of Hiroshima, Japan, in 1945).

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n$$

In nuclear reactors, control rods of boron can lowered into the reactor core to absorb neutrons and slow down fission to keep the chain reaction under control. Moderator rods slow down the neutrons produced by the chain reaction as slow moving neutrons are needed to bring about further fission.



Nuclear Fusion Reactions

At the extremely high temperatures in the 'heart' of stars the atomic nuclei have such enormous speeds and kinetic energies that they can fuse together if they collide. The extremely high energy is needed to overcome the natural and massive repulsion of the two positive nuclei. The process by which a heavier atomic nucleus is made from two smaller atomic nuclei is called fusion and these changes also release enormous amounts of energy.

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

Calculations - Fission:

Plutonium is used as a fuel in a nuclear reactor to generate large amounts of energy.

$$^{239}_{94}Pu + ^{1}_{0}n \longrightarrow ^{142}_{56}Ba + ^{93}_{38}Sr + 5\,^{1}_{0}n$$

The masses of the particles involved are:

239 plutonium:	$396.92935 \times 10^{-27}$ kg
142 barium:	$235.64216 \times 10^{-27}$ kg
93 strontium:	$154.27837 \times 10^{-27}$ kg
neutron:	1.67493×10^{-27} kg

The mass difference can be calculated by:

Mass difference = 396.92935 + 1.67493 - 154.27837 - 235.64216 – (5 × 1.67493) = 3.091×10^{-28} kg

$E = mc^2$ can be used to calculate the exact amount of energy created by this mass difference where $c = 3 \times 10^8$ m s^{-1}.

Mass difference = 3.091×10^{-28} kg

$E = mc^2$
$= 3.091 \times 10^{-28} \times 9.00 \times 10^{16}$
$= 2.7819 \times 10^{-11}$ J

Calculations - Fusion:

In one reaction in a star, two Carbon-12 nuclei fuse to create neon and helium.

$$C^{12} + C^{12} \rightarrow Ne^{20} + He^{4}$$

Carbon-12	$= 19.926 \times 10^{-27}$ kg
Neon-20	$= 33.197 \times 10^{-27}$ kg
Helium-4	$= 6.6465 \times 10^{-27}$ kg

The mass difference can be calculated by:

Mass difference = $(2 \times 19.926 \times 10^{-27}) - (33.197 \times 10^{-27} + 6.6465 \times 10^{-27}) = 8.5 \times 10^{-30}$ kg

$E = mc^2$ can be used to calculate the exact amount of energy created by this mass difference where c = speed of light = 3×10^8 m s^{-1}.

Mass difference = 8.5×10^{-30} kg

$E = mc^2$
$= 8.5 \times 10^{-30} \times 9.00 \times 10^{16}$
$= 7.65 \times 10^{-13}$ J

Calculations - Power:

Sources of energy are measured in terms of their power (Watts).

The Sun converts about 240 million tonnes (2.4×10^{11} kg) of mass each minute to energy. Its power can be calculated by:

$P = E/t$

$P = (2.4 \times 10^{11} \times 9.00 \times 10^{16})/60$

$P = 2.16 \times 10^{28} / 60$

$P = 3.6 \times 10^{26}$ W

A small nuclear reactor can produce 1.5 GW (1.5×10^9 W) of power. To compare this with the Sun we can calculate how much energy is released per minute from such a reactor.

$P = E/t$

So $E = P \times t$

$E = 1.5 \times 10^9 \times 60$

$E = 9 \times 10^{10}$ J (or 90 GJ)