

One day soon ...

“10, 9, 8...”

You realise that you are holding your breath.

“7, 6, 5...”

Your fists are clenched tight; your nails biting into the palms of your hands.

“4, 3...”

You’ve been working to this moment for so long. The next few seconds will tell.

“2, 1, ZERO, Vulcain cryogenic stage ignition.”

“3, 4, T plus 5 seconds, Vulcain operation confirmed.”

“6, T plus seven seconds, solid fuel boosters ignited, latches released, LIFT OFF!”

The night fills with smoke, flames and a deafening roar. Sound and fury signifying *everything*. You start to breath again as the Ariane 5 climbs in to the sky carrying your satellite with it in to space.

Very few people will be able to travel to and work in space in our lifetimes but hundreds of thousands across the world will work in the space industry. Be it the manned space programme, planetary exploration, automated Earth observation systems, satellite telecommunications, global navigation systems or orbital astronomy, in a very real way, they will work in space, with their feet on the ground.

And you could join them, sooner than you think.

The European Space Agency has long encouraged science and engineering students to look at the space sector as a valuable and exciting career. One way is through the education satellite programme. It started with the polar orbiting SSETI Express satellite in 2005. Next and currently planned for a launch in 2012, ESEO (the European Student Earth Orbiter) will lift off from Kourou in French Guiana and enter a low earth orbit. From there it will observe the Earth and measure the environment of energetic charged particles. And from beginning to end the satellite will have been designed, developed, built and tested by university students.

The vast majority of the science and technology behind rockets and satellites can be understood using pre-university learning. These pages will help give you an insight in to the topic of propulsion but they could equally have been about communications, electrical power, radiation, optics or any of the many other areas vital to a space mission. If after looking through these pages you are tempted but think that you might too late to join the ESEO team then there’s always the future, ESMO (the European Student Moon Orbiter) is next...

And it’s going to the Moon!

The rocket principal *or getting a reaction*

What is it that makes a rocket? In the simplest terms a rocket is a jet propulsion system that relies entirely on momentum exchange from a propellant that is carried by the vehicle. Newton's Third Law of Motion states that "for every action there is an equal, but opposite, reaction". In other words a rocket engine relies on 'throwing mass out the back' in order to push the vehicle forwards. We can see this in many examples from the science lab.

*Video of air track and other demonstrations to be found at
www.esa.int/education*

The air track video shows the two things that any rocket system needs, propellant mass (the 10 gram masses in the air track demonstration) and an energy source (the stretched rubber bands on the air track). In many rocket engines the two come from the same place, the fuel – oxidant mixture that is carried by the rocket. The video shows though that that isn't always the case.

Another example of separation of propellant and energy is also shown in the video. In the water rocket the propellant mass is provided by the water but the energy store is provided by the compressed air.

One toy rocket that everybody is familiar with is the balloon. Normally the balloon will fly off in almost any direction but introducing a nozzle allows us to fly it in one direction. The propellant mass for the balloon is the air stored inside it, but what is the source of energy? Think back to the video before you answer, there are two energy sources!

Solid and liquid fuel rockets *or from firecrackers to spaceflight*

Gunpowder (what we now call ‘black powder’) was first invented in China around in the ninth century and it was quickly put to use in firecrackers and other fireworks. The first ground based rocket we definitely know about was built in 1264, it powered a ‘ground rat’ that terrified the emperor’s mother at a feast held in her honour. When the first flying rockets were made isn’t clear but they were certainly standard issue for the Chinese army by the mid-14th century.

A solid fuel rocket has its fuel and oxidant mixed together as fine powders and then pressed in to a solid ‘cake’. Once it has been lit it will carry on burning until it is used up. In a black powder rocket the fuel is carbon and the oxidant, potassium nitrate. Sulphur acts as a secondary fuel and also catalyses the reaction. In the Ariane 5 solid fuel boosters the fuel is aluminium powder, the oxidant, ammonium perchlorate and polybutadiene acts as a binder to hold the mixture together.

Warning!

Do not attempt to create any of these rocket propellants. They are highly explosive and accidents with even small quantities can lead to serious injury or death. Making them without a licence is also illegal in many countries.

Until the early 20th century rocket motors were never more than a few percent efficient. The problem is that a simple rocket uses only the pressure difference between the combustion chamber and the ambient pressure outside to drive the rocket forward:

$$F = pA$$
$$= (p_{\text{Combustion}} - p_{\text{Ambient}}) A_{\text{Exhaust}}$$

The result is that huge amounts of high pressure, high temperature exhaust is thrown out but that it carries with it massive amounts of energy in the form of gas pressure and heat. All of this goes to waste.

[Animation of simple nozzle-less motor to be found at www.esa.int/education](http://www.esa.int/education)

This changed when the American rocket pioneer, Robert Goddard applied an idea used in a steam turbine to the rocket motor. This is the one bit of science in this article that is beyond pre-university physics but the ‘pinch’ in the nozzle (usually called the ‘throat’) causes the exhaust gases to accelerate up to the local speed of sound in the gas. Once it is through the throat, but still inside the nozzle, the pressure and the temperature drop rapidly allowing much more of the energy of the exhaust gas to be extracted. The easiest way to think of this is as follows:

- The rocket works by throwing mass out of the back. The faster the mass is ejected the more thrust is generated.
- Inside the combustion chamber the pressure and temperature are very high.

- If the gas is allowed to expand it takes up more space and so it must accelerate in order to make sufficient space. As it does this it also cools.
- Once it is clear of the rocket it doesn't matter what the temperature or the pressure of the exhaust gas is, it won't help accelerate the rocket.
- The nozzle allows the exhaust gas to expand and cool whilst still providing thrust to the rocket.

Animation of De Laval nozzle motor for solid fuel motor to be found at www.esa.int/education

By the time the exhaust gas leaves the nozzle its temperature will be far lower than in the combustion chamber and it will be travelling at 'hypersonic' speeds up to about 5 km s^{-1} . It might seem like an odd idea but the pressure of the exhaust at this point might well be lower than atmospheric pressure!

Which propellants are best? Remember that we want the exhaust jet to be moving as fast as possible. We can get a rough but informative answer from equations from kinetic theory and ideal gas theory:

$$\frac{1}{3} m \overline{c^2} = kT$$

where m is the mass of the particles, ' c squared bar' the mean of the squared velocity of the particles, k the Boltzmann constant and T the temperature of the gas. So the 'root mean square velocity' of the gas particles is given by

$$c_{R.M.S.} = \sqrt{\frac{3kT}{m}}$$

In other words the gas particles are moving fastest when they burn at a high temperature and are made of low mass molecules. A full analysis that will have to wait for a more advanced course gives us the velocity of the exhaust jet as:

$$v_{\text{exhaust}} = \sqrt{\left\{ \frac{2\gamma k T_{\text{Combustion}}}{(\gamma - 1)m} \left[1 - \left(\frac{p_{\text{combustion}}}{p_{\text{external}}} \right)^{\frac{\gamma - 1}{\gamma}} \right] \right\}}$$

where γ is 'the ratio of the specific heats' (a constant between about 1.1 and 1.7 but dependant of the exhaust chemistry and temperature) and the ' p 's are the pressure in the combustion chamber and outside the rocket. Clearly this is an unpleasant equation but it answers our simple question exactly the same way. We want a high combustion temperature and low mass exhaust particles.

Solid fuels burn hot but things could be hotter, also they tend to produce lots of relatively large particles (that's why they produce so much smoke when they are fired). One solution is to use a liquid fuel and propellant. Liquid hydrogen burning with liquid oxygen burns at a temperature of nearly 3,000 K and the combustion products are individual water molecules. Liquid hydrogen however has a low density

and so requires large tanks to store it, for this reason kerosene (aviation fuel) burning in liquid oxygen is frequently used for launchers that are still low in the atmosphere.

Animation of solid fuel motor showing simple structure but only control to burn rate being the structure of the propellant structure to be found at www.esa.int/education

Advantages of liquid fuel/oxidant mixes are that the thrust can be controlled (throttled) and that the engines can even be shut down and re started at a later stage. In addition the energy density (Joules per kilogram of propellant) tends to be high and that, as a result of the high combustion temperature, the specific impulse (impulse [in Newton seconds] per kilogram of propellant) is very large. A modern solid fuel rocket has a specific impulse of up to approximately 2500 N s kg^{-1} whilst a good liquid fuel rocket can produce up to 4500 N s kg^{-1} . It is common practice to take a shortcut in the units, at ground level one kg of propellant weighs a little under 10 N and these two figures are cancelled out. The two figures just quoted become 250 s and 450 s.

The biggest disadvantage of liquid fuels is that the need for pumps, piping and separate storage for the fuel and oxidant means that extra mass has to be carried by the launch vehicle.

Many launch vehicles get around the problems by using a combination of different rocket motors. The Ariane 5 and the space shuttle both get most of their thrust at low altitude from very high thrust (but low specific impulse) solid fuel boosters and then use high specific impulse but lower thrust liquid hydrogen/liquid oxygen motors at higher altitudes and in space. The largest rocket ever flown beyond the trialling stage was the Saturn V that launched the Apollo missions to the Moon. This used liquid fuel engines at all stages but used relatively 'energy dense' kerosene/liquid oxygen at low altitude and liquid hydrogen/liquid oxygen at high altitude and in space.

Thrusters *or Pushing things around*

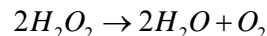
Not everything in space flight needs a huge rocket motor, sometimes we have to be far more delicate. Typical jobs involve changing the direction a satellite is pointing in (but not travelling in) or giving it a very gentle nudge when it is docking with another satellite. These low force rocket motors are usually called ‘thrusters’.

Cold gas systems

The simplest form of thruster is little more than a container of pressurised gas. It is very like the balloon you saw earlier. When thrust is needed some of the pressurised gas is released through the nozzle. Typical gases used are nitrogen, argon, freon and propane. It is important to make sure that the gas will not damage any components that it might land on such as solar cells, sensors or even an astronaut’s space suit! Because the gas is cold the thrust is very low, typically around 10 mN (around the weight of a one gram mass on Earth) and the specific impulse is only around 50 s at best. Bigger units have been used to allow astronauts to move freely outside the space shuttle and the ISS.

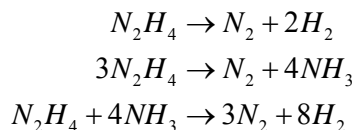
Monopropellant systems

As the name implies monopropellant rockets do not carry separate fuel and oxidant supplies. Rather the propellant is a single liquid that decomposes to gases either on heating or when it is passed over a catalyst. There are two common monopropellants; hydrogen peroxide (H₂O₂) and hydrazine (N₂H₄). Hydrogen peroxide decomposes when it comes in to contact with a silver or platinum catalyst mesh (up to 98% concentration is used as a monopropellant):



This produces steam and oxygen at over 600 °C and produces a specific impulse of up to 165 s. Hydrogen peroxide has also been used to power devices as diverse as drag racing cars and torpedoes.

Hydrazine is a more powerful but toxic monopropellant. It decomposes in contact with platinum/iridium metal into ammonia, nitrogen and hydrogen by a number of different possible paths:



It does this at a temperature of around 800 °C and can produce a specific impulse of around 200 s.

Bi-propellant systems

These are the most powerful thrusters currently available. They are needed because many new satellites are becoming increasingly large and so need far larger forces to manoeuvre them. A commonly used bi-propellant mixture is monomethylhydrazine

($\text{CH}_3\text{N}_2\text{H}_3$) as the fuel and dinitrogen tetroxide (N_2O_4) as the oxidant. This burns very hot and so has a high specific impulse of over 300 s. Another property of this propellant mixture is that it is 'hypergolic', that is it ignites on mixing. This means that the two substances have to be handled extremely carefully but also that there is no need for a complex ignition system. It also means that the two materials cannot accidentally build up in one place, leading to an explosion the next time the thruster is fired.

The monomethylhydrazine/dinitrogen tetroxide combination is also used in the space shuttle 'orbital manoeuvring system' and in the third stage of the Ariane 5, this 115 kg motor can produce 2.7 tonnes of thrust and burn 9.8 tonnes of propellant in around 1000 s, some thruster!

[Thruster Animations to be found at www.esa.int/education](http://www.esa.int/education)

Ion motors

or The tortoise and the hare

Rocket motors need two things, propellant mass and energy. In a traditional chemical rocket they come from the same place. But what would happen if we could separate the two functions and if we could have access to an almost limitless supply of energy? The result would be a revolution in spacecraft propulsion and that revolution has already arrived.

Ion engines work by stripping electrons off of individual atoms and then accelerating the resulting ions in an electric or magnetic field. Still using Newton's third law, the force applied to the ion in one direction must equal the force on the spacecraft in the other direction. The energy for the ionisation and the acceleration no longer needs to come from a chemical reaction; instead we could use solar cells or even a nuclear power supply.

Here however lies the problem with ion thrusters, given the mass restrictions of a small spacecraft they just cannot carry enough solar cells or a large enough nuclear power plant to compete with the power generation possible with a chemical rocket. A chemical rocket's performance is limited by how much propellant (and thus energy) it can carry (it is *energy* limited) but all that energy can be released in a very short time (and so it is not *power* limited). A solar powered ion thruster however can carry on producing energy until the Sun stops shining (it is *not* energy limited) but the rate at which it can generate energy is limited by the size of its solar cells (it *is* power limited). In fact the amount of thrust that a typical ion motor can produce is equivalent to the weight of a sheet of paper.

The result is that the two types of motor have very different propulsion tactics. The chemical rocket makes use of one enormous burn, maybe a few minutes, at the beginning of the mission in order to get the necessary speed up, after all, there's no point in taking all that extra weight in propellant tanks with you. The ion motor on the other hand keeps going at a low thrust for days or even months. Like the tortoise it will overtake the hare, but this tortoise will eventually be travelling far faster than the hare can ever run! Unfortunately the thrust of an ion engine is so low that it will never be possible to use it to launch a satellite from the Earth, only to power it once it is in orbit. This is one tortoise that needs a lift to the starting post.

Animation of comparison of thrust & velocity vs time to be found at www.esa.int/education

Curiously, the first ever ion thruster was made by Robert Goddard in 1916 although it being in the days before space flight he could only do experiments in his laboratory. There are many different types of ion motor design, one type called a Hall Effect Thruster carried ESA's Smart 1 mission to the Moon. The 29 kg motor used 82 kg of xenon to produce a 68 mN thrust over 7000 hours of operating life. It achieved a specific impulse of 1640 s, over four times better than the best liquid fuel rocket motors. It might seem odd that xenon is used as the propellant, after all, chemical rockets benefit from having an exhaust composed of very low mass particles. The reason is that ion thrusters are power limited and so it is best to maximise the thrust

per unit of power rather than per unit of energy. The kinetic energy of each ion is given by the equation:

$$\frac{1}{2}mv^2 = qV$$

Where m is the mass of the particle, v its velocity, q the charge on the ion and V the electric potential that it is accelerated through. Rearranging the equation gives the momentum p of each particle as:

$$p = \sqrt{2mqV}$$

The rate of change of momentum with respect to time is the thrust of the engine T and so:

$$T = \sqrt{\frac{mV}{2q}} \frac{dq}{dt}$$

Electrical power P is just the product of current I and potential difference:

$$\begin{aligned} P &= IV \\ &= \frac{dq}{dt} V \end{aligned}$$

And so the ratio of thrust to power is:

$$\frac{T}{P} = \sqrt{\frac{m}{2qV}}$$

This shows that the best performance is given by exhaust particles with a high mass to charge ratio, hence the use of gases such as xenon.

*[Animation of operation of ion thrusters to be found at
www.esa.int/education](http://www.esa.int/education)*

Ion propulsion is already very important for the operation of geostationary communications satellites. These satellites are constantly subjected to small forces (due to solar radiation pressure and the gravitational pull of the Moon and the Sun) that make them drift off from their designated station. They regularly have to use propellant just to stay in place and when they can no longer do this they become worse than useless, as they are taking up an available slot in that critical orbit. As a result the satellites have to be retired *before* they run out of propellant, as the last drops are used to place it in a 'graveyard orbit' a few hundred kilometres higher up. Ion thrusters are thus very attractive because they provide a great deal of thrust for a small mass of propellant and so they extend the working life of the satellite.

Solar sails *or The light fantastic*

If you are going to rely on the Sun for your power supply and only take inert propellant with you then why not go all the way and rely on the Sun for your propellant too? The only requirement of Newton's third law is that something has its momentum changed. For example in a sailing boat the wind is really made up of countless gas particles all moving in roughly the same direction. When they hit the sail they bounce off and start to move in another direction. This change of momentum for the wind produces a corresponding change of momentum for the boat and this drives it forward.

Light is also made up of countless particles called photons, each of which has its own momentum. Each photon has an energy E and travels at the speed of light, c . It also has a momentum p , given by:

$$p = \frac{E}{c}$$

If these photons are forced to change direction then their momentum must change and the easiest way to do this is to use a mirror. However, glass mirrors are very heavy and the solar radiation pressure is very small, only $4.7 \times 10^{-6} \text{ N m}^{-2}$ at the Earth's orbit. This means that practical solar sails will have to be made very large, hundreds of metres if not kilometres across, and so of very lightweight materials. One current solution uses a metallised plastic film around $2 \mu\text{m}$ thick (about 4% of the thickness of an 'average' human hair).

Using solar sails would allow spacecraft to be made much lighter and so be able to carry larger payloads. Like traditional sailing boats, solar sails do not have to just 'run with the wind', they can change course by tilting the sail or even tack in to the wind and so head sunwards. One proposal by ESA is for a 'sample return mission' to Mercury, the hardest planet to reach in the solar system if you are using traditional rocket motors. They would even make it practicable to carry out missions that are impossible with traditional propulsion systems, for example orbiting constantly over the pole of the Sun to carry out scientific research, or even hovering over the Earth's poles to act as a polar communications 'satellite'. Solar sails could also be used to power a mission to the very edge of the solar system far faster than any other known technology.

Animation of solar sail missions: standard, escape and helio-polar to be found at www.esa.int/education

There have already been several space experiments with solar sails although these have been mostly concerned with how to unfurl a sail in microgravity. However the solar sail principal has an important effect on some satellites, especially in geostationary orbit. The constant radiation pressure on their solar cell arrays tends to push them out of their intended orbits and so shorten their active life. Some satellites however have put the radiation pressure to use, using it to help turn the satellite without the need for propellant. Practical propulsion by solar sails will however have to wait for the future.

Magnetic sails

Or Tacking in the solar wind

As well as light, the Sun produces a constant stream of charged particles, mostly protons and electrons, flooding out at speeds of around 400 to 600 km s^{-1} . This gives the inventive space scientist something else to push against. The easiest way to deflect a moving charged particle is to use a magnetic field and the easiest way to produce a magnetic field is to pass a current through a loop of wire. A magnetic sail would therefore be a loop of conducting material producing a magnetic field perpendicular to the solar wind. As the magnetic field deflected the particles, they would push against the magnetic sail and so drive the spacecraft in the desired direction.

Another advantage of a magnetic sail is that it would be able to react directly with a planet's magnetic field as well as the solar wind. This means that a magnetic sail spacecraft could gain a *magnetic* assist as well as a *gravitational* assist (the 'slingshot effect') by passing close to a planet. When it reached its destination it could use the target planet's magnetic field to decelerate and so enter orbit.

The direction of thrust would depend on the angle that the sail made to the solar wind (or the planet's magnetic field) and the size of the thrust would depend on the area of the loop and the size of the current generated. However, because there is far less momentum associated with the solar wind than with sunlight the current loop would have to be huge, maybe 50 km radius or more and it would also have to be a superconductor, so that the current would continue to flow without the need for a driving potential. Fortunately unfurling a magnetic sail should not be as complex a process as it is for a solar sail; the magnetic field itself will cause the loop to open up and form a circle without the supports and guy lines needed by a solar sail.

We should not get ahead of ourselves though as the technology needed to produce hundred kilometre long lengths of superconducting material does not yet exist, let alone the techniques needed to keep them at the required operating temperature. For the time being, magnetic sails must remain in the minds of researchers and on the pages of science fiction. Maybe though, not for very long.

A related technology though, the electric sail, may beat magnetic sails in to space. The solar wind can also be deflected by an electric field which could in turn be produced by an electrical charge. The basic idea is that a thin wire would be given a large *positive* charge. This would repel the protons from the solar wind and so exert a force on the wire and so on to the spacecraft. The solar wind electrons would of course be attracted to the wires, neutralising the charge. However these carry far less momentum than the protons and the spacecraft can restore the charge to the wires by ejecting a stream of electrons from a cathode just as an ion thruster does.

A fan of highly charged wires would effectively create a large sail that would be pushed directly away from the Sun. Unfortunately an electric sail cannot tack very effectively and so the direction of the thrust could not be varied greatly. However as

superconductors would not be required the technology and materials needed could be ready long before the first magnetic sails are used.

Animation of magnetic sail and solar electric sail to be found at www.esa.int/education

Nuclear powered rockets *or Swords into ploughshares*

Many spacecraft, especially those that travel deep into the solar system, beyond the practical use of solar cells, already make use of nuclear power. They use radioactive material to heat one junction of a thermocouple and so generate electricity by the thermoelectric or *Seebeck* effect. This is then used to power the electrical systems of the spacecraft, rather than to provide propulsion. The amount of power generated this way though is quite low; nothing higher than around 600 W has ever been flown. In comparison ESA's Smart 1 used solar cells to generate the 1.2 kW necessary to power the ion thrusters that carried it to the Moon.

However plans have been made to fly fully functional nuclear reactors in order to provide propulsion, as well as power some spacecraft. The simplest design just involves passing hydrogen propellant over the core of a standard, if light weight, nuclear reactor. The hydrogen propellant would then leave the reactor through the nozzle, just like a standard rocket. The exhaust would not be radioactive (in most proposed designs) but its temperature and so the specific impulse of the rocket, would be limited by the melting point of the materials used in the reactor core. A specific impulse of around 900 s might be achievable.

Animation of nuclear engines to be found at www.esa.int/education

Some modifications to the design have been suggested that would include running the reactor so hot that it became liquid or even gaseous. This would result in problems containing the core but the result would be a nuclear rocket that could achieve a specific impulse of up to around 5000 s combined with a high thrust level, sufficient for fast interplanetary travel.

If you are really not worried about radioactive exhaust then why not try the *Orion Drive*? It's incredibly 'dirty' but it has the added advantage that it uses up 'surplus nuclear bombs', just what is needed in these post cold war times. Its operation couldn't be simpler; just build a huge steel shield underneath your spacecraft and then explode a nuclear bomb directly underneath it, this pushes the shield and craft forwards. When you're ready push out another bomb and let that off. The specific impulse could reach 100,000 s and the thrust is so high that you could even use it to take off from a planet's surface so long as one could push the bombs out fast enough (and didn't mind leaving the surface a radioactive slag heap).

Not surprisingly the Orion Drive was a product of Cold War thinking along with unshielded nuclear ramjet cruise missiles and 'Mutually Assured Destruction' (*MAD*) and no sane person today would even contemplate such a device. Any nuclear power plant that is to be considered for future spacecraft will have to be clean, sealed and so heavily armoured that it would be undamaged by either re-entry into the Earth's atmosphere or the accidental detonation of the entire launch vehicle. Humanity may be infinitely inventive but we also have a strong sense of self preservation.

Conclusions

or Where to next?

Over the last few pages you have found out about a wide range of propulsion methods, dating from over seven hundred years ago for black powder rockets, through current technology such as ion thrusters and on to ideas currently being researched for future use, such as electric sails. None of the ideas presented are science fiction (although in several cases the technologies found their way on to the pages of science fiction before they ever made it in to space). Importantly though the ideas behind the technologies presented are all within the scope of a pre-university physics course and so you should be able to understand the physics behind the propulsion systems even if you may not yet have the mathematical skills to design a working system.

At some time in your studies you will need to decide on your university courses and the degree that you will study for. By choosing physics, electronics or many of the branches of engineering you will be qualifying yourself to take up a career in space science. If the physical sciences are not your choice there are still many opportunities available in the life sciences, from designing life support systems for space craft through to studying the possibility of life on other planets in our Solar System. Software engineers and computer scientists are also needed to design the complex control systems needed in the space industry, from global positioning systems to training simulations for astronauts. The list of skills needed is seemingly endless.

You may never become an astronaut yourself but by choosing a career in the space industry you will be working in space. Even before you take up your career you can become involved by taking part in the ESEO and ESMO student satellite programmes. And how many people can put their hand on their heart and honestly say,

“Actually, my work really is rocket science!”