Dynamic Design: Launch and Propulsion

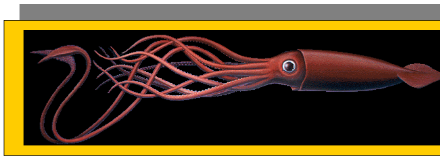
Propulsion

TEACHER TEXT

As you saw in the student activity, propulsion is an important part of not only launching the spacecraft, but also navigating it so that it reaches its destination. But how exactly does propulsion work? First let's start with a definition of propulsion.

The word propulsion is derived from the Latin word *propellere*, which means to **propel**. The dictionary definition of propel is to drive forward or onward by or as if by means of a force that imparts motion. One way that something is propelled is by **jet propulsion**. The dictionary defines jet propulsion as the "forwardly directed forces of the reaction resulting from the rearward discharge of a jet of fluid; especially: propulsion of an airplane by jet engines."

Jet Propulsion in Squid

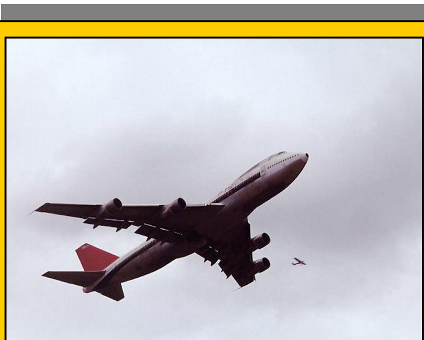


Many organisms propel themselves to get from one place to another. One organism that uses jet propulsion to travel in the water is the squid. The squid is a Cephelopod or a head-footed mollusk. There are many species of squid that have been studied by scientists over the years. Many people have mistaken the giant squid for sea monsters! The famous ocean explorer Jacques Cousteau described the squid in 1954 as having a "rocket-like head and 10 arms."

The squid moves by "shooting water from the funnel, a short, hose-like organ that projects from the mantle, the soft external body wall below the head. The squid can rotate the funnel in any direction, and by ejecting jets of water from it, move in the direction of its arm tips or, just as easily, in the direction of its tail fins." (Ellis, 1998) The squid's funnel is a multidirectional nozzle used for jet propulsion, and expelling water, waste, ink, and eggs. In fact, when the squid moves, it often brings its arms together in order to reduce drag. The squid is able to control the amount of water that it expels because its mantle has a knob that fits into a groove that seals the mantle when the water is about to be ejected.

You can use a balloon to understand how this jet propulsion works. The squid's outer skin is like the rubber of a balloon. Between the outer skin, or mantle, and its organs is a space called the mantle cavity. One end of the space opens and closes like a gate; at the other is a funnel, similar to the open end of a balloon. A squid pumps water through the gate, closes the gate, then squeezes the water out of the funnel. Like letting go of the open end of a blown up balloon, the escaping water pushes the squid forward in the opposite direction, and the giant squid jets away.

The giant squid, named *Architeuthis*, can move in any direction it chooses. However, since none have ever been seen alive, we don't know how powerfully they can move. Even though jet propulsion is not a very efficient means of locomotion, it lets a lot of water pass over the gills, which helps the squid get oxygen from the water more effectively than fish. Jet propulsion allows the squid to travel very quickly for short distances, but they can also migrate over thousands of kilometers. The squid has been around for millions of years, but humans did not start making a jet engine until the twentieth century.



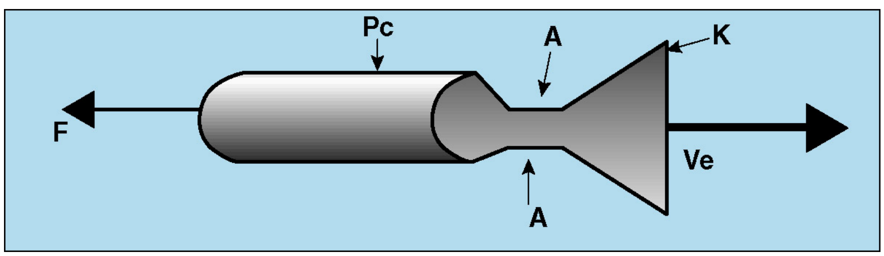
The Jet Engine

In the 1930's, a new type of engine was being developed independently by designers in both England and Germany. Frank Whittle in England started by working with an internal fan, or propeller, run by a turbine. In Germany, Hans von Ohain was trying to design a way to reduce the noise and vibration caused by very large, heavy engines of the airplanes that were being used at the time. The Germans had successfully tested their engines in 1938, while the Whittle engine made its first flight in 1941. Since that time there have been many improvements in jet engine design. Jet engines have become lighter and more efficient.

There are five basic components to the jet engine. They are: 1) the inlet, 2) a compressor or fan, 3) the burner, 4) a turbine, and 5) an exit nozzle. The **inlet** works as an air intake. It decides how much air enters the engine. The inner walls of the inlet are designed to slow the velocity of the air stream as it comes to the compressor. The **compressor** is used to increase the pressure of the airflow. This is not a natural occurrence. Pressure typically tends to decrease, so increasing the pressure takes power. “Typical compressors increase the pressure of the air by 15 to 30 times the original pressure.” (Cislunar Aerospace, Inc., 1996) So the result of these first two components to the jet engine is air that is slow moving and at a high pressure. This air is then directed into a **burner** where it is combined with the fuel and then ignited. The very hot, high-pressure exhaust gases, produced by burning the jet fuel, cause thrust. It is important that the air-to-fuel ratio is optimized so that a clean burn can occur to maximize thrust. If there is not enough fuel in the mixture, the temperature will not be hot enough and the thrust will be reduced. If there is too much fuel in the mix, unused fuel will be expelled and the engine will not be fuel-efficient. The hot, high-pressure gas is then passed into the **turbine** that has a much lower pressure. This causes the gas to drop in pressure, which causes the speed of flow to increase. This high velocity flow exits the engine through the **exit nozzle** and generates thrust. The shape of the exit nozzle is made so that the velocity of the exhaust gas continually increases as it exits the engine. Some fighter aircraft have the ability to adjust the shape of their exit nozzles in order to meet certain flight needs.

Rocket Propulsion

Using Newton’s third law of motion, a rocket creates thrust from mass escaping through an exhaust nozzle. This thrust causes lift of the rocket in the opposite direction. The rocket motor can be illustrated with the diagram below which shows the escaping gas generating thrust. The formula for calculating thrust of a rocket is shown by the equation F= k x Pc x A. Where F is the thrust, k is the nozzle contribution to thrust, Pc is the pressure chamber, A is the throat area of the rocket chamber.



A rocket motor can use propellants that are gases, liquids, solids, or a combination of these. In a solid propellant motor the fuel and the oxidizer are a powdery mixture called the grain or charge of the motor. One advantage of the solid propellants is that they can be loaded and stored for long periods of time. Two disadvantages are the efficiency and control of the burn of solids. Solids also have a lower burn temperature so are less efficient that liquids. It is difficult to control or terminate the burn of a solid rocket without destroying the rocket chamber.

Propellants are chosen based on the requirements of a rocket to work in specific conditions. The following is a list of fuels and reactants. Reactants are combined with fuels to generate and maintain high chamber pressures. The combustion products from the fuel/reactant combinations make up the propellants. Genesis uses kerosene and liquid oxygen in its first stage and hydrazine as a fuel for the spacecraft thrusters.

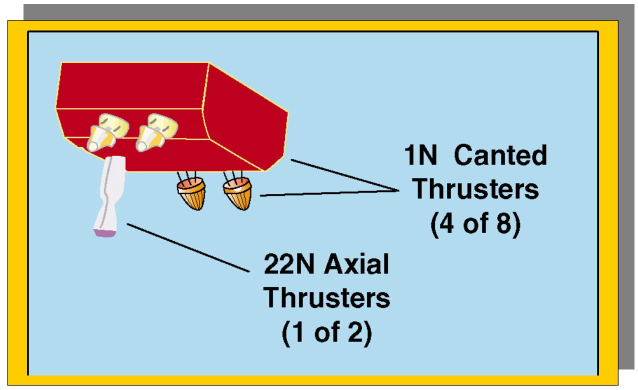
Fuels
Alcohol
Kerosene
Hydrazine
Liquid Hydrogen

Reactants
Oxygen
Acids
Fluorine

http://users.commkey.net/Braeunig/space/basics.htm
Basics of space flight

Genesis Spacecraft Propulsion

The Genesis propulsion subsystem is a hydrazine system. The chemical formula for hydrazine is H_4N_2, and its molecular weight is 32.05 grams/mole. Hydrazine is a colorless, oily, flammable liquid that has a penetrating odor, resembling that of ammonia. Hydrazine has many uses including water treatment for corrosion protection, as a building block for agricultural pesticides, pharmaceutical intermediates, photography chemicals, textile dyes, and jet and rocket fuel. Hundreds of space probes, satellites and shuttles use ultra-pure hydrazine monopropellant for guidance once in orbit. These maneuvers require only a tenth of a pound of thrust for hundreds of times over the life of the spacecraft.



The hydrazine subsystem on the Genesis spacecraft has two identical propellant tanks. There are a total of ten thrusters, five on each side of the spacecraft. In the propulsion activity, you modeled one side of the spacecraft. On each side, there is one 22 Newton thruster. There are also four 1 Newton thrusters, two on each side of the box on which it is mounted. In the activity, the four balloons on the sides of the box lid modeled this. There is redundancy, also termed, “repetition,” in the propulsion system because there are dual valves in order to avoid failure in the thrusters. Very pure hydrazine fuel is used to decrease contamination of the science payload. The spacecraft was designed with a barrier between the thrusters and the payload to protect the purity of the collector wafers from the thruster chemicals. Contamination from chemicals might affect scientific results of the mission. According to Genesis System Engineer Richard Bennet at the Jet Propulsion Laboratory (JPL), Genesis presented unique challenges in preventing contamination. On the one hand, the spacecraft should be as pristine as possible. The propulsion system was designed so that the thrusters were pointed away from the spacecraft under the deck and protected from all the science collection instruments on top of the deck. So, all of the spacecraft thrust points either directly to the rear of the spacecraft or at 45-degree angles to the rear of the spacecraft.

This presented a challenge to the navigation team. They were questioning how easily the spacecraft could be turned and how accurately it could be positioned so the trajectory is maintained using this thrust configuration. They wanted fully coupled thrust or a set of reaction monitors positioned opposite the prime motors so that the spacecraft could stop and make turns. This could not be done because the chemical plume spray from these thrusters settling on the collection arrays could contaminate them.

Early in the mission, extensive analysis was conducted regarding such variables as placing thrusters on the upper deck of the spacecraft, different thruster angles, determining plume spray constituents, and propellant material expelled below the deck. This was done to be sure that sensitive science collection materials would not be exposed to propellant material that had accumulated on the collection device. The Genesis navigation team had their own flight requirements and the science team had concerns about keeping the collectors clean. These issues resulted in discussions and tradeoffs between the mission’s navigation design and the collection of the best scientific data.

Since the spacecraft spins toward its destination, it has an attitude control system. This system controls the spin rate of the spacecraft to about two rotations per minute. The 1 Newton thrusters enable this attitude control. The following was taken from a conversation with the JPL Team Leader Don Sweetnam. “One of the most important things that happens to Genesis shortly after launch is called the **trajectory** correction maneuver one. This maneuver will occur about two days after launch. After the spacecraft is launched from NASA Kennedy Space Center, it is sent on trajectory toward **L1**, but there will be some error due to the launch vehicle. From **telemetry** data the navigation team’s job is to make sure that the trajectory that the spacecraft is actually on is in fact the trajectory that it should be on. This correction maneuver has to be done soon after launch, because the cost (amount of fuel needed for this correction) of this maneuver grows exponentially the longer this correction is made after launch.” The JPL team sends up a sequence of commands that correct errors in the amount of energy that the launch vehicle introduced into the course. The JPL team knows that the direction for the correction will either be toward the sun or away from the sun. The size of the correction is not known ahead of time. They will use tracking data that is taken during the first day of the mission to determine how the spacecraft trajectory is going, then build a command file to make the correction, test it, then send it to the spacecraft to execute. The flight plan includes about twenty course corrections during the duration of the mission. There are two corrections that are most critical. The first is the one mentioned above. The second most critical correction is the last one as the spacecraft approaches Earth. For the last correction the spacecraft is lined up so that the navigation team is able to get the spacecraft to a small landing area in Utah. When the spacecraft returns to the Earth, it will spin up to 16 rotations prior to the science canister separation during reentry into Earth’s atmosphere.

Advanced Propulsion

Since the 1960s when the first rocket lifted Sputnik into orbit, rockets have become more and more efficient. Rocket efficiency can be measured by **specific impulse**. Specific impulse is the number of seconds a pound of fuel will provide a pound of thrust. The specific impulse for different propulsion systems is listed in the table below. The higher value for specific impulse means more energy is produced with more efficiency. Specific impulse can be calculated by dividing the thrust generated at any time by the propellant consumed within that same time period. This means that the higher the specific impulse value, the better the performance of the propellant combination, since you can generate the same amount of thrust for a longer time period.

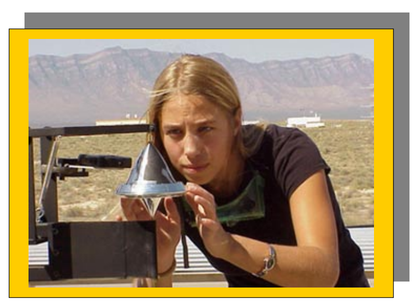
Propulsion System	Specific Impulse (seconds)
Model rocket	80
Redstone	220
Space Shuttle	450
Beamed Energy	3,000 – 5,000
Nuclear Fission	3,000
Ion Propulsion	40,000
Nuclear Fusion	50,000
Photon Propulsion	3,000,000

“EXCUSE ME. COULD YOU DIRECT ME TO THE NEAREST GAS STATION…I MEAN, ASTEROID?”

Some people are interested in using asteroids as fueling stations; they believe that some asteroids may contain water and the types of elements that could be used to make fuel. Even when using asteroids as fueling stations, it still takes months to travel to the closest places in our solar system. In order to cut down on the travel time to planets or even to travel outside of our solar system, a propulsion system using something different than chemical propellants is needed.

One example of an advanced propulsion is beamed energy propulsion. Leik Myrabo at the Rensselaer Polytechnic Institute in Troy, New York, is testing high power laser beams for propelling spacecraft. The pulse laser beam reflects off of a parabola and is focused inside the engine. The light is so intense that it breaks down the air and produces a shock wave that propels the prototype in a series of pulses. As it pulses, it strips air molecules of electrons creating an explosive plasma that propels the spacecraft from below. The laser is made up of infrared light that is so intense, it could cripple a satellite orbiting above the test site. The use of energy beams eliminates the need to carry large quantities of fuel into space. These revolutionary beam-powered vehicles leave their energy sources on the ground or in space, and carry minimal propellant for operation outside the atmosphere.

The following is from a press release from Lightcraft Technologies Incorporated that illustrates the work of Leik Myrabo. Early in the morning of 2 October 2000 on the High Energy Systems Test Facility Lightcraft Technologies, Incorporated (LTI) set a new altitude record of 71 meters for its12.2 cm diameter laser boosted rocket -- in a flight lasting 12.7 seconds. Besides setting the new altitude record, the craft demonstrated the longest ever laser-powered free-flight, and the greatest 'air time' (i.e., launch-to-landing/recovery). LTI demonstrated a total of seven vertical flights that morning. The Lightcraft weighs less than 1.8 ounces (51 grams); two flights reached 159 ft and 184 ft.



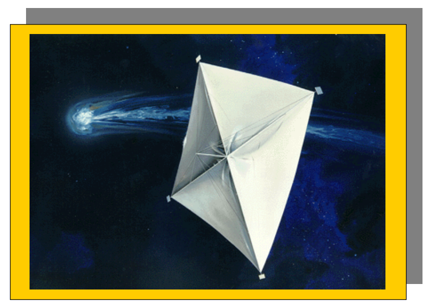
Tregenna Myrabo of Lightcraft Technologies with Lightcraft and launch stand.

Artists conception of Deep Space 1

Another example of an advanced propulsion system is an ion propulsion system used by NASA's Deep Space I. This spacecraft uses ion propulsion engines to travel to an asteroid. The fuel used in Deep Space 1's ion engine is the element xenon, a colorless, odorless, and tasteless gas more than 4.5 times heavier than air. When the ion engine is running, electrons are emitted from a hollow bar called a cathode into a chamber ringed by magnets, much like the cathode in a television picture tube or computer monitor. The electrons strike atoms of xenon, knocking away one of the 54 electrons orbiting each atom's nucleus. This leaves each atom one electron short, giving it a net positive charge -- making the atom into what is known as an ion. At the back of the chamber is a pair of metal grids that are charged positive and negative, respectively, with up to 1,280 volts of electric potential. The force of this electric charge exerts a strong "electrostatic" pull on the xenon ions—much like the way that bits of lint are pulled to a pocket comb that has been given a static electricity charge by rubbing it on wool on a dry day. The electrostatic force in the ion engine's chamber, however, is much more powerful, causing the xenon ions to shoot past at a speed of more than 60,000 miles per hour, continuing right on out the back of the engine and into space. The specific impulse for this propulsion system is 5000 seconds, making it much more efficient than typical chemical systems.

Fans of the *Star Trek* television series are accustomed to hearing Scottie tell Captain Kirk that the engines cannot take much more stress. Just like the use of antimatter to power the engines of the starship *Enterprise* in science fiction, Gerald Smith, of Penn State University is testing this type of propulsion in science fact. Antimatter is the most powerful substance in the universe. Many scientists believe it was present during the Big Bang during the formation of the universe (see *Cosmic Chemistry: Cosmogony* module). Antimatter has reversed electrical charges compared to normal matter. Small amounts found in space strike the Earth's atmosphere. Currently, antimatter may originate near black holes. Antimatter is being tested in order to trigger nuclear fusion in the vacuum of space. Antimatter annihilation is one of just a few propulsion concepts that might allow a spacecraft to travel at speeds that would make interstellar transportation possible. It is also one of the least developed propulsion concepts.

Could the solar wind that Genesis is collecting be used to propel a spacecraft much like wind on Earth moves a sailboat? The solar wind is in fact too weak to provide a force large enough for propulsion. The idea of solar sails has been around for centuries. Scientists are studying ways in which the light from the sun might be used for propulsion. At first, engineers thought about using aluminum-coated Mylar sheets—similar to the material that makes those foil-looking inflated balloons—for the material of the sails. But experiments with Mylar are indicating that it is too heavy and would take too long to fill to move the spacecraft. The search is now on for materials to use for a sail that will be lightweight and sturdy. One idea under development is to use a woven carbon fiber that that has a very low density.



Beamed energy propulsion, ion propulsion, antimatter annihilation, and solar sails are just some of the advanced propulsion systems on the drawing boards for use in future spacecraft. There are many others in the minds of future scientists and engineers. Now it's your turn. You get to be the design engineer. Think of a new propulsion system that might be used in future space exploration.