UNIVERSITY PHYSICS II

Aerospace Propulsion

A comparison of options for space exploration

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The exploration of space has fascinated and inspired many generations of man. Despite there being many important aspects of space travel, one of the most important is: how are we going to get to where we are going? This clearly requires one to contemplate various propulsion systems. When deciding on a means of propulsion it is important to compare all the various systems in design, launch, and actual space travel.

Design

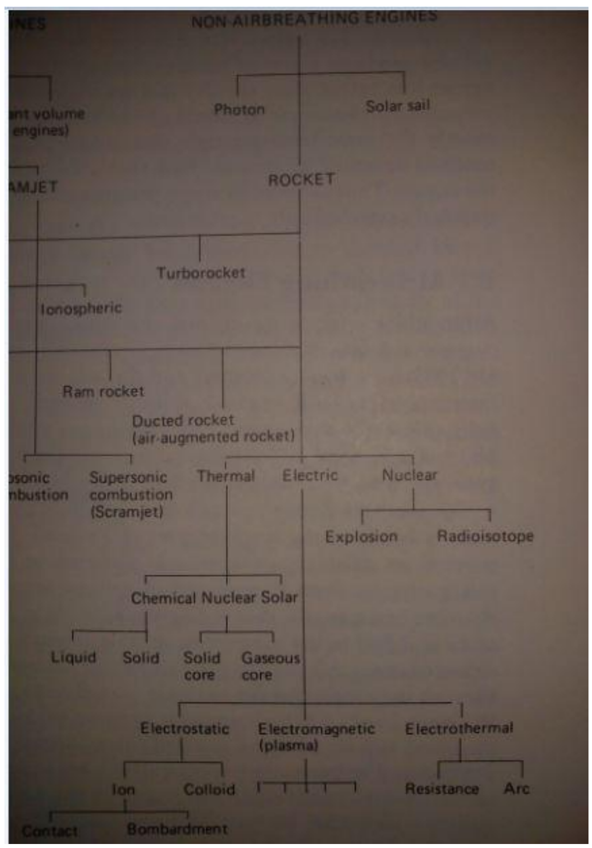

Figure 1: Classification of types of propulsion systems (Shepherd 1972).

In the design process, there are several fundamentals that are standard for all propulsion systems. One such principle is Newton's third law. This law is one simply of "action and reaction" (Ward 2010). Implying that for every action there is a reaction to it. This is accomplished by many propulsion systems, such as rockets, by using the exhaust to move forwards; however, it can be done by other methods as seen in solar sails. Another important concept when dealing with rockets is that of working fluid. A working fluid is the air or the fluid that heat is transferred through in an engine and used to create work to propel the system forward (Ward 2010). Rockets come in various forms based off of what they use for propulsion and their power plants, and these are thermal, electrical, and nuclear. Figure shows a break-down of non-air breathing engines and their several categories.

Thermal rockets create their thrust by "heating a propellant under pressure" (Shepherd 1972). The most common forms of thermal rockets are solid and liquid chemical boosters. In these forms fuel is mixed with an oxidizer and ignited. In a chemical rocket, the working fluid is the gases produced during the combustion of the fuel (Ward 2010). In solid rockets it is a solid mixture of fuel and an oxidizer whereas liquid rockets use a liquid fuel mixed with a liquid oxidizer (Shepherd 1972). Figure 2 shows the generic concept of both liquid and solid rockets. In the solid rocket, the grain cross section is very important depending on the mission of the rocket. As figure 3 shows, depending on the cross section, there are very different thrust profiles. Depending on the task at hand, it may be important to design a rocket that has a neutral thrust profile (like the rod and tube), a progressive thrust (tubular), regressive (double anchor), or a two-step (dual composition). This occurs because when the propellant ignites, the exposed surface burns away first, meaning the higher the surface area, the more propellant that is burning, and the more thrust obtained (Ward 2010). Other thermal rockets include thermo-nuclear rockets. These rockets use a nuclear reactor to heat the working fluid. These are utilized when "propellant weight becomes excessive" and when a simple chemical reaction fails to create a sufficient velocity (Shepherd 1972). Nuclear reactors come in both gaseous and solid cores.

Gaseous core reactors must be designed in away such that the walls containing the nuclear gas offer sufficient protection from the high heat of the mixture of fuel and gas (Shepherd 1972). A perk to using nuclear energy to heat the working fluid is that, since there is a lack of reaction, “any gas can be used as a propellant” (Powell et al. 2004).

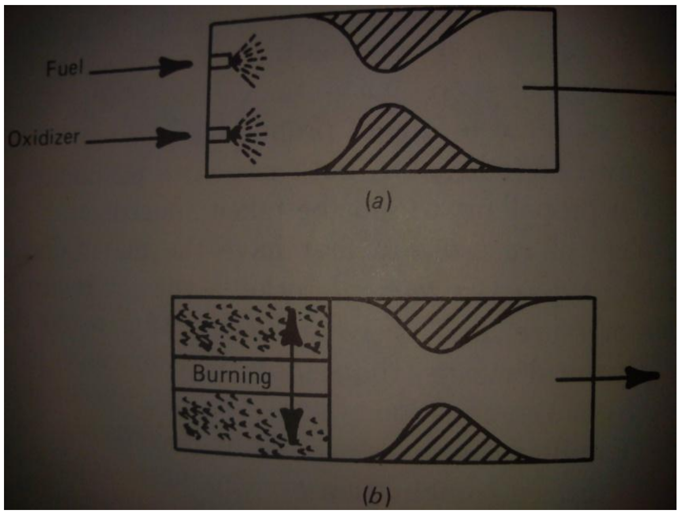

Figure 2: (a) A standard liquid chemical rocket. The fuel and oxidizer enter the system on the left, combust and exit as an exhaust to the right. (b) A solid rocket with a solid mixture of propellant burning from the inside out, creating exhaust to the right. (Shepherd 1972)

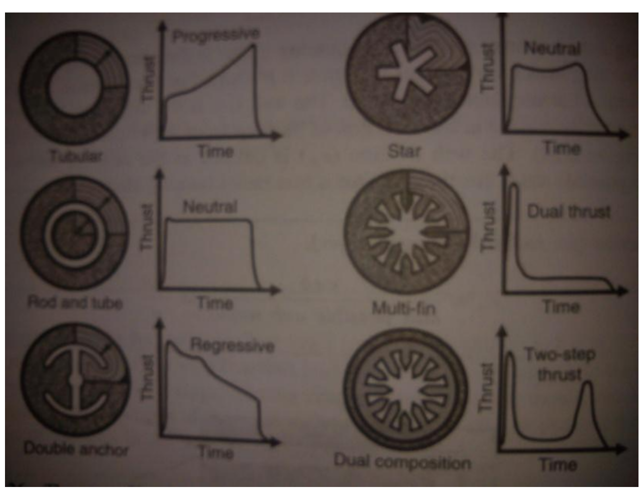

Figure 3: Various grain cross sections with the accompanying thrust profiles (Ward 2010).

Electric rockets are separated from thermal rockets in that their main source of energy for propulsion is through electrical energy whether it is from batteries or other electric cells. In the category of electric rockets, ion engines appear to be the most promising. Ion engines are an electrostatic engine that uses the potential difference between electrodes to accelerate ionized particles back to propel the vehicle forwards (Shepherd 1972). In these ion engines, the working fluid is the vapor that becomes ionized (Ward 2010). After ionization the engine then accelerates the ions with a very high velocity out through the exhaust (Ward 2010). Because of the law of conservation of momentum, the ionized gas being ejected backwards creates a velocity in the opposite direction to account for the momentum. Some key design factors for an ion engine include "production of ions," "production of a uniform, parallel ion beam," and "neutralization of the charged beam" (Shepherd 1972). Two common methods for ion production are contact and bombardment. In contact, the ions are created when a metal immersed in a vapor strips away electrons from the surrounding gas (Shepherd 1972). In the bombardment method electrons are collide with the atoms of the propellant and are extracted by electrodes at the other end of the chamber (Shepherd 1972). A plus side to using the bombardment method is that elements with a higher atomic mass can be used ; however, a drawback arises in the need of a magnetic field and erosion of the cathode(Shepherd 1972). Figurers 4 and 5 show contact and bombardment respectively. The next issue of beam formation and acceleration is solved by fields of varying equipotentials to help shape the beam so that it does not diverge (Shepherd 1972). Beam neutralization is a much more difficult task that requires the engine to insert electrons of similar velocities behind the flow of the positively charged ions. This is important because if the beam is not neutralized then the positively charged ions risk slowing down and reversing, thus coming back to the engine due to the negative charge on the opposite end

(Shepherd 1972). There are several methods in which the beam can be neutralized. These methods include direct filament injection, indirect electron source, electron gun injection, and plasma bridge injection (Shepherd 1972). The main issue direct filament injection is that the electrons can enter the beam at too high of a velocity, thus disrupting the beam. Indirect electron sources work by having their electrons pulled into the ion stream by a difference in electric potential. The electron gun has the ability to shoot electrons at the proper velocity, but consumes more energy than some of the alternative methods. Finally, in plasma injection, the electron source vaporizes the atoms of the propellant creating a bridge of plasma between the beam and the electron source (Shepherd 1972).

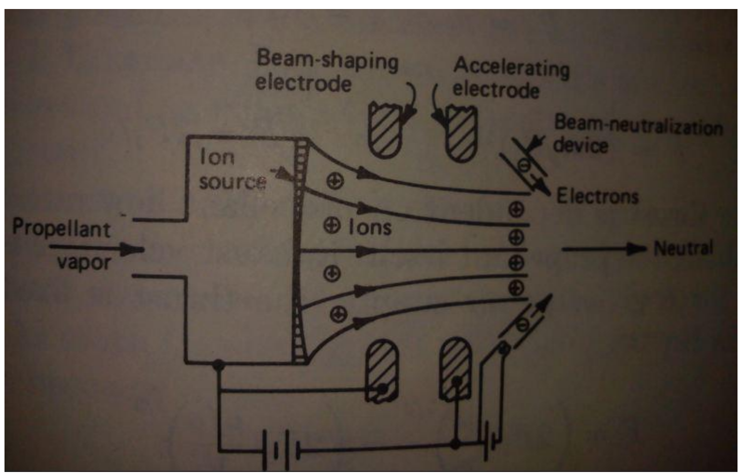

Figure 4: Ion engine using the contact method of ionization. Vapor comes in from the left, makes contact with charged plate creating ions on the other side. The difference of electric potential between the electrodes helps shape the beam and accelerates the ions to the right. On the right as the beam leaves the engine, an electron gun launches electrons behind the beam (Shepherd 1972).

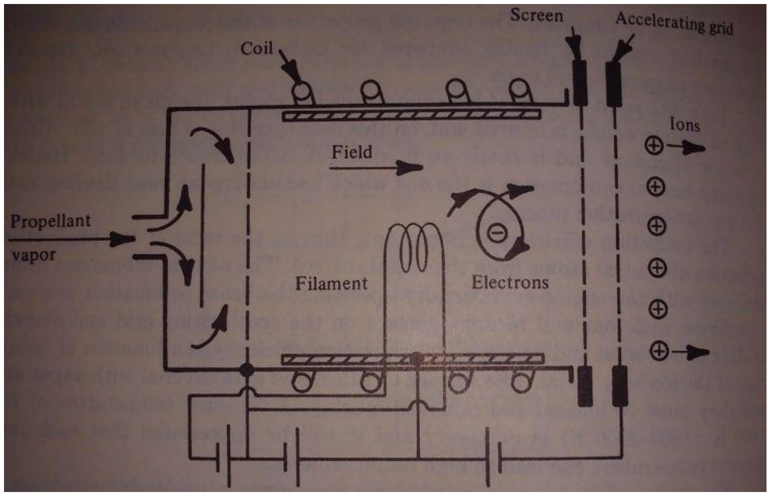

Figure 5: Bombardment method of ionization. Vapor enters from the left and passes through the chamber where electrons from the filament can collide into the non-ionized atoms to ionize them. The ionized atoms closest to the end electrode are extracted. (Shepherd 1972)

The third and final type of rocket is powered through nuclear reactions. A useful form of nuclear propulsion is by actually dropping bombs from the spacecraft and riding the shockwaves of the explosions. Obvious setbacks to this design include the effects of the forces and heat from the explosions. A very basic design of a ship that could do this would be a “big hemisphere…with a layer of shock absorbers connecting [it] to the main structure of the ship” as seen in figure 6(Dyson 1968). From figure 6, you can see that when the bomb drops from behind the ship the blast is located at the furthest potion from the crew and other living organisms on board. Optimally the hemisphere would be created out of an ablating material that would be able to protect the structures beneath (Dyson 1968). This only allows us to only be limited by the ability of the shock absorbers to allow for a smooth acceleration of the ship by transferring momentum from the explosions (Dyson 1968).

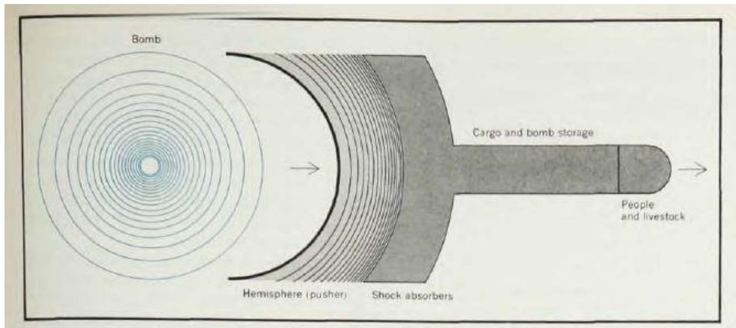

Figure 6: Diagram of a basic nuclear explosion propelled ship. The hemisphere catches the blast from the left and transfers it through the shock absorbers (Dyson 1968).

Finally outside of the scope of rockets lie solar sails. Solar sails use the fact that photons carry both momentum and energy along with the conservation of momentum and the conservation of energy. When a photon strikes the sail, it transfers momentum from the photon's wave to the blade of the sail, which depending on angle from the sun can actually help change the direction of the ship (Moore 2005). If a sail is created out of a low density, reflective material then the electromagnetic radiation from the sun will create a force upon the sail and drive the spacecraft forward. Some basic principles of this is intensity and pressure. Intensity is defined as the energy of a wave across an area over a span of time (Stewart 2011). Symbolically this can be expressed as $I(t) = \frac{P(t)}{A}$, where I is the intensity, P is power, or energy per time, and A is the area. Radiation pressure is $P_r = \frac{I}{c}$ where I is the intensity again and c is the speed of light; however, if the light is reflected magnitude of the pressure is doubled (Stewart 2011). For this reason, it is best to have a sail created out of highly reflective materials. Force can be determined from pressure by multiplying by the area of the surface that the wave is coming into contact with (Stewart 2011). This means that the larger the sail is, the more force that will be exerted. This is why it is important to have a sail that is also made out of an extremely light material, because the force is still related to the mass and acceleration of the sail. Therefore for a greater acceleration, you need a lighter ship.

Launch

When launching from Earth on route to the stars, there is currently only one real option that can be utilized. That option is the standard chemical thermal rocket. The main reason for this is because of the disadvantages that alternative propulsion systems face. “Most ion propulsion systems are designed to operate at low thrust,” meaning that they are suited more for working “in the vacuum of space” rather than leaving the atmosphere (Ward 2010). Then, nuclear explosions would be highly dangerous to use when launching from Earth due to radiation. Finally, solar sails would be a poor choice on account that they are based off of the concept of being ‘pushed’ forward instead of creating their own thrust. This means that any other propulsion system other than chemical rockets would either have to be assembled in space or launched as part of a payload on a chemical rocket. Chemical rockets are ideal for doing missions such as this because of the large thrust that can be obtained from them as well as multi-staging. Multi-staging allows that rocket to drop off excess weight, because when a stage is used up it can be jettisoned allowing the vehicle to “achieve higher velocities and carry heavier payloads” (Ward 2010).

Space

Every system has its own perks and limitations once it is out of the grasp of the Earth’s gravitation. All rockets will eventually run out of propellant; however, ion thrusters take “10% of the amount of propellant” as that in a chemical rocket, allowing it to last much longer than its chemical counterparts (Ward 2010). For this reason they are sometimes used to maintain geosynchronous positions in satellites as well as the propulsion choice of some probes (Ward 2010). Since the velocity of solar sails are dependent on intensity, solar sails run into problems when they reach greater distances. Since intensity is inversely dependent on distances, the greater the distance the less intensity the solar sail will feel from the sun. Some have proposed that “powerful laser beams” pointed in the direction of the solar sail could actually help push the ship after the intensity from the sun dies down (Moore 2005). Since solar sails do not require fuel consumption, the speed in which they travel is theoretically limitless due to their constant accelerating nature (Moore 2005). Nuclear propulsion systems have their drawback in that they are seen as great risks because of the issue of “spreading radioactive debris” in the event that a catastrophe occurred (Ward 2010).

Depending on the mission, all propulsion systems have their purpose in space travel. For long range space travel though, ion drives and solar sails appear to be a better choice. Ion drives use less fuel than standard rockets, thus allowing it to carry just as much fuel and make it last much longer. Solar sails could be seen as superior to even ion drives since they are completely independent of carrying their own fuel source on account that they only require radiation from the sun to propel themselves forward. That being said, chemical rockets are still very much needed on account that neither ion drives nor solar sails are suited to launch themselves into space.

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