Group 10

Unconventional Rocket Drives

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1 Introduction

1.1 Background

Mankind will migrate into space, and will cross the airless Saharas which separate planet from planet and sun from sun.
— Winwood Reade, 1872

Space travel and exploration have always been a fascinating subject to many. Even before the first telescopes were trained on the heavens, poets, scientists, philosophers alike have long mused about the mysteries of space. The last century in particular has seen a whirlwind of developments surrounding the subject of space. Not only were better telescopes made, more cosmological theories were hypothesised, and rockets that could exit Earth's atmosphere were launched. Perhaps the most important of them all would be the success of rockets.

The rockets of this century, or conventional rockets, utilise the basic Newtonian principle of action and reaction forces to generate forward thrust. Propellants are burnt in a combustion chamber to produce exhaust gases that act as what is known as a working liquid. The flow of this working liquid generates a reaction force that produces a thrust on the rocket engine which propels the rocket forward. Examples of propellants include liquid oxygen, liquid hydrogen and nitrogen tetroxide.

Such propulsion systems seem safe, robust and relatively adequate for most mission scopes of today. However in reality, there are limitations to present propulsion systems. Much has been made of the fact that marginal benefits accrued from improving conventional rocket drives are declining. This has served as motivation for many space agencies to embark on a search for a futuristic rocket drive, one that would traverse the *airless Saharas* with ease and bring space within the grasp of mankind. For the purposes of this publication, these rocket drives will be collectively termed as unconventional rocket drives.

1.2 Purpose and Scope

The case for unconventional rocket drives has been a teetering one. Whilst these rocket drives theoretically offer gargantuan promises of excellent performance and efficiency, virtually all of them fall prey to the hand of technology. The numerous trials-and-errors required before the technology, if at all, kicks off, would incur a huge amount of time and funds. As such, the effort invested would have to be fully justified. Furthermore, unconventional drives which rely on distorting the laws of physics seem more science fiction than science. The propensity for some to brush aside unconventional rocket drives is therefore understandable.

This publication thus sets out to make an attempt at a meaningful evaluation of these unconventional rocket drives. Seven different rocket drive systems will be investigated and their characteristics compared both against each other and against conventional drives. Detailed analysis will be done and a conclusion reached. While such an undertaking is definitely ambitious, it should be seen as a necessary and timely injection into the recent wave of interest in unconventional rocket drives.

1.3 Technical Considerations

This section serves to define some of the parameters which will be used over the course of the report.

1.3.1 Thrust

Thrust measures the force exerted by the engine. Engines with different levels of thrust can be used to perform different space operations. Engines providing thrust in the MN range are suitable for launching operations to break free from Earth's gravity. Engines providing thrust in the mN–µN range are ideal for spacecraft control operations to stabilise and steer the spacecraft in space where very low force can produce a significant acceleration.

1.3.2 Specific Impulse

Specific impulse is a way to measure the efficiency of space propulsion engines. It is defined as the impulse per unit propellant mass. It measures the efficiency of a propellant used in a certain mechanism to produce thrust. It however shows little about the actual thrust an engine can provide. An engine with high thrust can have a low specific impulse and vice versa as specific impulse does not take into account the mass of the engine and spacecraft used.

1.3.3 Lifetime

The lifetime of an engine is a way to measure the duration of space travel the engine can sustain. The lifetime of an engine is affected by many factors, mainly constraints in the materials used to build the engine. Corrosion from fuel is one common limitation on the lifetime of an engine. The lifetime of an engine also determines the distance and duration of space missions. It is a good measure of the sustainability of the space propulsion.

2 Ion Drives

2.1 Introduction

Ion drives produce thrust by emitting beams of ions—by Newton's 3rd law of action and reaction. There are various methods of accelerating the ions but generally all designs have the advantage of a large fuel charge to mass ratio. This means that high exhaust velocities can be created by a small potential difference. Hence, less fuel mass is required.

As such, ion drives are not suitable for use on Earth. Instead, they should be used in space, where their ability to maintain a low thrust for long periods of time will come in handy. For example, they are currently used for orbital manoeuvring and station keeping. There are three main types of ion thrusts: *electrostatic*, *electromagnetic* and *electrothermal*.[1] In this section, we will focus on the first two, since electrothermal drives (which use thermal energy converted to kinetic energy[1]) are not really unconventional.

2.2 Electrostatic Ion Thrusters

2.2.1 Concept of Operation

Propellant atoms are first ionised by electrons, forming ions in the propulsion chamber. This process is usually performed by bombarding the propellant atoms with electrons. This causes them to lose their own electrons to form positive ions. The lost electrons are absorbed by the thruster grid/wall.

Positive ions diffuse into a plasma sheath. Once in the plasma sheath, the ions experience an electric field between the positive and negative grids (at the exit of the chamber). The electric force, proportional to the charge of the ion and the magnitude of the electric field, will accelerate the ion towards the exit with acceleration proportional to the electric force and the mass of the ion.

At the exit, the ions are focused onto the narrow apertures of the negative grid and shot out in space at high velocities. By Newton's 3rd law, the force on the ion causes an equal and opposite reaction to act on the thruster/spacecraft. To ensure the net charge neutrality of the spacecraft, electrons are shot out from a cathode towards the ions behind the spacecraft as well.[1]

2.2.2 Types of Electrostatic Ion Thrusters

There are 2 main types of electrostatic ion thrusters; the *gridded ion thruster* and the *field emission electric propulsion/colloid thruster*.[2]

The gridded ion thruster was the earliest type of electrostatic ion thruster. Further study into similar concepts to improve efficiency resulted in the idea of the field emission electric propulsion/colloid thruster. Gridded ion thrusters are mainly used for the propulsion of spacecraft while field emission electric propulsion thrusters provide very small levels of thrust which allow for more precise control of spacecraft. A colloid thruster provides an even lower level of thrust which makes it ideal for extremely precise spacecraft control.

<u>Gridded Ion Thruster</u>

The typical gridded ion thruster is the Kaufman type shown in Fig 2.1. Its operation can be divided into ionisation, acceleration, and neutralisation.

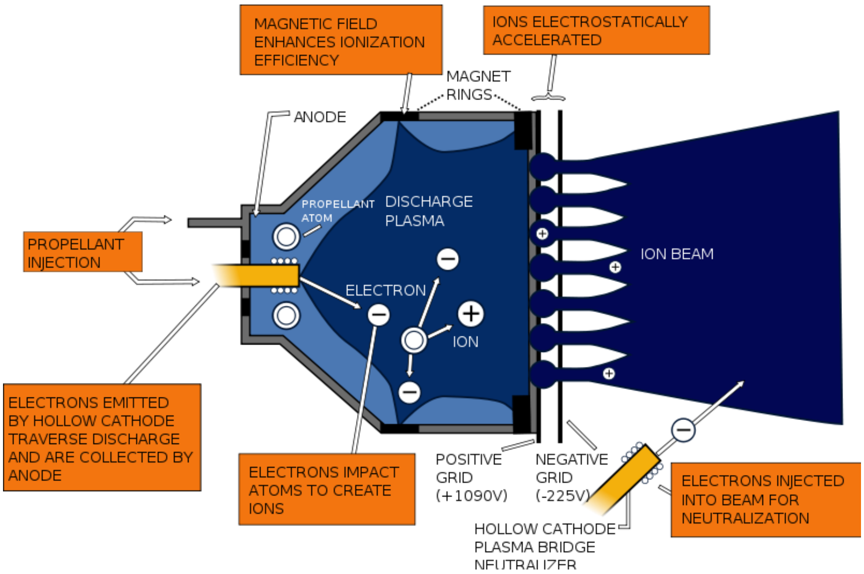

Fig 2.1: Diagram of a typical gridded ion thruster, the NSTAR[3]

Ionisation: Xenon is most commonly used as the propellant. Xenon propellant is first injected into the ionisation chamber's plasma where it is ionised by electron bombardment from the hollow cathode. Electrons colliding with the xenon atoms cause the latter to lose one electron per atom to form positive xenon ions. Electron bombardment can be achieved by various methods.[4] The first method is direct current discharge in which electrons flow back from cathode to anode (e.g. Kaufman type). The second method is radio frequency discharge where electrons are held circulating in an electromagnetic radio wave field (e.g. Radio frequency Ion Thruster, RIT). The last method is electron cyclotron resonance in which electrons are excited by microwaves circling around an electromagnetic field (e.g. Mu and High Power Electric Propulsion (HiPEP) thrusters). The xenon ions are then extracted from the ionisation chamber through a multi-aperture grid extraction system by diffusion.[5]

Acceleration: Xenon ions enter the grid system (in between the positive and negative grid). The potential difference of up to 1,280 V between the positive (screen) and negative (accelerator) molybdenum grid creates an electric field that accelerates the ions out of the exhaust at over 100,000 km/h.[6] Ion energy typically reaches 1–2 keV for the NSTAR.[3] The reaction force of this jet of ion stream out of the exhaust of the engine generates the thrust of the engine.

Neutralisation: In order to prevent the spacecraft from gaining a net negative charge due to the efflux of positive ions, a cathode neutraliser injects electrons into the exhaust to neutralise the positive xenon ions.

<u>Field Emission Electric Propulsion/Colloid Thrusters</u>

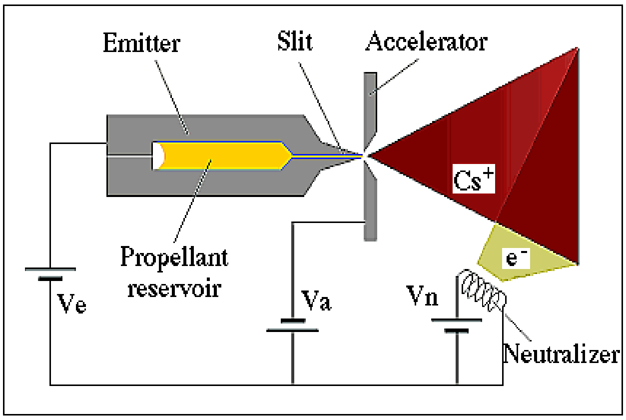

Fig 2.2: Diagram of Field Emission Electric Propulsion thruster, FEEP[13]

The Field Emission Electric Propulsion thruster (FEEP) shown in Fig 2.2 is similar in principle to a gridded ion thruster.[14] In the case of FEEP, the propellant used is liquid (usually caesium or indium due to their low ionisation energies, low melting points and high mass).[13] The metal is directly extracted as a liquid in the emitter module through a tungsten needle/slit of about 1 µm.

The propellant flows through this slit and forms a free surface at the exit of the slit. With the emitter acting as a positive grid and the accelerator plate acting as a negative grid, an electric field is established. The surface of the propellant liquid metal at the tip of the needle approaches a condition of local instability due to surface tension and the electric field. A series of protruding cusps of liquid, known as “Taylor cones” are created.

Once the electric field reaches the threshold of 109 V/nm, the metal atoms at the tip ionise and flow out of the accelerator, leaving electrons behind. This results in a jet of ions which produces the thrust. Similarly, the neutraliser removes the net negative charge on the engine by emitting electrons.

Colloid thrusters are similar to FEEP thrusters. They are designed to give smaller specific impulses and thrust for more precise control of force.

2.2.3 Applications

Gridded ion thrusters are already in use in many space operations as a propulsion method. The NSTAR ion engine, on NASA's Deep Space 1, has travelled more than 28 million miles from Earth as of February 1999.[1] The Xenon Ion Propulsion System (XIPS), developed and used by Hughes Aircraft Company, is now keeping more than 100 geosynchronous satellites flying.[5] Similarly, the RIT, Mu and HiPEP thrusters have been tested or are already in use.[7] Recent advancements include the DS4G, still in the development stage, for which theoretical calculations are promising.[16]

FEEP and colloid thrusters are already used in many operations as a precision control method. The Colloid Thruster System developed for JPL Space Technology 7 mission is the precursor for another larger scaled mission called the Laser Interferometer Space Antenna (LISA). 12 FEEP thrusters would be mounted on the hull of the LISA Pathfinder to achieve 100 times more accurate control than normal spacecraft.[14]

2.3 Electromagnetic Ion Thrusters

2.3.1 Concept of Operation

These drives work on a similar principle to the electrostatic ones. The main difference is that now, the ions are accelerated by the Lorentz force due to the interaction of a magnetic field and moving electrons instead of the Coulomb force. We will use two examples below to elucidate how these thrusters generally work. There are several types of electromagnetic ion drives. The most popular one is the Hall Effect Thruster. Other types include the Electrodeless Plasma Thruster, the Magnetoplasmadynamic (MPD) Thruster and the Pulsed Inductive Thruster (PIT). The MPD ionises propellant gases like hydrogen or nitrogen into plasma and then accelerates them in a magnetic field. On the other hand, the PIT uses pulses of thrust from a propellant gas which is emitted from a cone-shaped tube.[17]

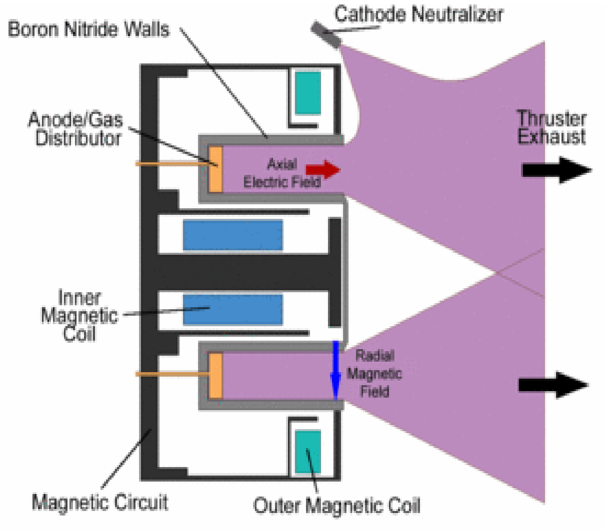

Fig 2.3: Cross-section of a Hall Effect thruster [18]

Hall Effect Thrusters

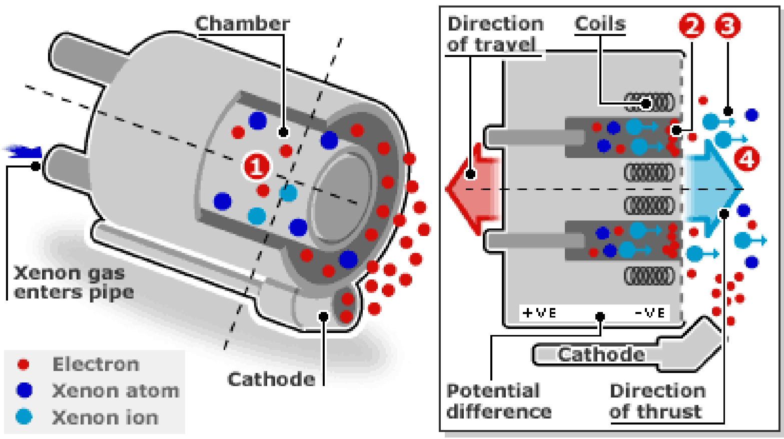

Fig 2.4: Operation of a Hall Effect thruster [18]

Electrons are generated from the cathode as seen on the diagram on the right. The anode is charged up and the electrons accelerate towards it, from right to left. A radial magnetic field is created between an inner magnetic pole and an outer magnetic ring. This field interacts with the moving electrons, producing a force which stops them from accelerating toward the anode, making them spiral near the exit plane. This direction of flow of electrons is given by E × B, which means it is perpendicular to both the magnetic field and electrostatic current. The propellant used is xenon gas. It is a suitable choice as it is inert and removes the risk of explosion due to a chemical reaction.[17]

Fig 2.3 shows how the anode duals up as a gas distributor. As the xenon atoms leave the anode and diffuse through the chamber, they collide with the electrons present. Hence, xenon ions are created. Now, referring to Fig 2.4, we can see that an electrostatic potential has been set up between the positive channel and the negative spiral of electrons. These ions now start accelerating toward the negative end and attain speeds of up to 15,000 m/s. The magnetic field present is such that it is strong enough to cause the light electrons to spiral, but too weak to have any significant effect on the accelerating heavy xenon ions. As the ions exit, an equal number of electrons leave the chamber as well. This process results in the thruster exhaust and enables charge neutrality to be held. Again, charge neutrality is important as it prevents equipment damage.

Electrodeless Plasma Thrusters

Propellant, which must be in a gaseous state, will be inserted in the upstream direction. It is then ionised by various methods, including using an alternating electric field via an inductive or capacitive discharge and using electromagnetic waves. The dense plasma diffuses into a chamber where there is an oscillating electric and magnetic field. The interaction between the plasma and the induced fields leads to propellant plasma being accelerated by the ponderomotive force (non-linear force that occurs in an oscillating electromagnetic field).

This force causes both the electrons and ions to flow in the same direction, in a double layer (a “double layer” has two streams alongside each other with opposite charges). The advantage of this is that it does not need any neutraliser, as the charges already cancel each other out. In addition, it overcomes the erosion and lifetime problems that occur in both the Hall Effect thrusters and gridded ion thrusters as there is no contact between the plasma and any electrodes. However, although practical research on this technology has begun, the theory surrounding the existence of a double layer has been much debated on.[19] Much more work needs to be done before it can be considered a viable rocket drive.

2.3.2 Applications

Hall Effect thrusters have already been developed and used in some space operations. Two main types of thrusters have been developed, the Stationary Plasma Thruster (SPT) and the Anode Layer Thruster (ALT), also known as the Thruster with Anode Layer (TAL).[18] In 2002, the Glenn Research Center in the USA announced that they had built and tested a new Hall Effect thruster, the “NASA-457M”, which was apparently up to ten times as powerful as its peers.[20] The European Space Agency (ESA) used Hall Effect thrusters for their SMART-1 Propulsion system in 2003.[21]

Electrodeless plasma thrusters have been developed and tested by The Elwing Company, and are being tested for spacecraft propulsion. The Princeton Plasma Research Laboratory has also begun testing its underlying theory.[22]

2.4 Comparison

2.4.1 Comparison between Electrostatic and Electromagnetic Drives

The principle operation of both the families of drives differs in one main aspect—the method used to accelerate ions.

The MPD, an electromagnetic ion drive, is currently the most powerful form of electromagnetic propulsion and can produce up to three times the specific impulse produced by electrostatic ion drives. Hall Effect thrusters also have an advantage over gridded ion drives as they can be scaled up easily (since they have no grids), provide more thrust and use a wider variety of propellants. However, they are usually less efficient.

2.4.2 Comparison with Conventional Rockets

In this section, ion drives are compared with one of the most powerful conventional rocket engines, the J-2X used by NASA Saturn V spacecraft. Ion drives posses several advantages:

<u>Higher specific impulse/efficiency</u>

Ion drives have a much higher specific impulse as compared to conventional rocket drives. This means that the impulse per unit mass of propellant is higher and hence much less fuel has to be carried onboard the spacecraft, making it lighter and more efficient. Operating costs are also much reduced as a result.

<u>Lower thrust</u>

Ion drives are capable of producing thrust in the range of micronewtons. This makes ion drives ideal for control and stability of spacecraft in space missions. However, having lower thrust also means that they cannot be used as an effective launch mechanism as millions of these engines would be required to generate a thrust comparable to that of a chemical rocket thruster. Overall, we see that electrostatic ion drives are better used for spacecraft propulsion and control than launch.

2.5 Future of Ion Drives

Due to their much higher efficiency, ion drives are beginning to replace conventional methods of space propulsion. Many geo-satellites running on ion drives can last longer and save on energy consumption and launch costs. Many spacecrafts such as the NASA Dawn spacecraft and JIMO spacecraft are using ion drives as their main propulsion mechanism. More will follow. Research on ion drives in the future mainly aims to utilise new power sources, such as nuclear sources, to develop higher power ion drive thrusters with greater speed and thrust. Carbon-based ion optics and electron cyclotron resonance technologies will increase the lifetime of ion drive engines and allow longer space operations. Ion drives may hold the key for further space exploration.

Space Characteristics

	NSTAR	RIT-22	HiPEP	DS4G	FEEP	Colloid	Smart-1 HET	PIT	MPD
Propellant	Xenon	Xenon	Xenon	Xenon	Indium/ Caesium	Formo-menite/ Sodium iodide	Xenon	Ammo -nia gas	H_2 gas
I_{sp} (s)	3,000 – 6,000	3,000 – 6,400	6,000 – 9,000	19,300	8,000	1,000	1,640	3,000 – 10,000	Very high
Lifetime (h)	*Design:* 8,000 *Tested: 30*,472	*Tested:* 18,000	*Design:* 122,640 *Tested:* 2,000	-	*Design:* 450 – 20,000	*Design:* 10,000	*Design:* 5,000	-	-
Thrust	89 mN	80–250 mN	460–670 mN	2.5 N	1 µN–1 mN	30 µN–50 mN	68 mN	20 N	100 N
Efficiency (%)	63	>51	>65	-	98	75	63	70	45

Table 2.5: Space characteristics of various electrostatic and electromagnetic ion drives

3 Solar Thermal Propulsion

3.1 Introduction

The concept of solar thermal propulsion stems from the better known solar-dynamic power system. This propulsion system has been proposed as an alternative means of rocket propulsion for orbit transfer and planetary missions. In this system, solar energy is accumulated by an absorber and is used to burn propellant during the thrust phase.

3.2 Concept of Solar Thermal Propulsion

In general, solar thermal propulsion utilises solar light to heat a propellant up to 2000 K. The gaseous propellant is then fed through a conventional rocket nozzle to produce thrust.[26] A solar propelled rocket only needs a means by which it can capture solar energy. No electrical generator is needed. The thrust of the engine is dependent on the surface area of the solar collector (concentrators and mirrors) and the local intensity of the solar radiation. Light is collected by a parabolic reflector and then focused onto a blackbody cavity to generate a high internal temperature. Here, heat is transferred to the propellant to produce thrust. The best performance can be achieved with hydrogen because of its low molecular weight.

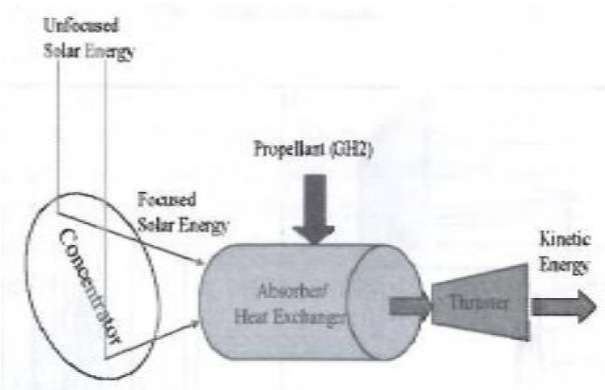

Fig 3.1: Solar thermal propulsion concept

Concentrators

Concentrators are used to collect solar light and to focus it into a receiver/absorber. Large collector surfaces in the range of several square meters are needed to produce the required thermal energy. A desired solar power input will be about 1350 W/m^2.[27] This is typically realised by the primary concentrators and thus, they are considered to be the most technologically demanding part of the concentrator system.

Absorber/Receiver

The function of the absorber/receiver is to absorb and transfer the energy of the concentrated solar radiation to the propellant. A heat exchanger is employed in the heating of the propellant as shown in Fig 3.1. The transfer of energy can be achieved either continuously or after accumulation.

3.3 Performance

Solar thermal propulsion performance is in between that of conventional propulsion and ion drive propulsion. For indirect solar heating, the design cannot achieve specific impulses of more than 900 s. This is because there are some limitations to the temperature that the heat exchanger material can withstand. For direct solar heating, direct heat absorption allows higher propellant temperatures and hence has higher specific impulses of approximately 1200 s.

However, only indirect solar thermal heating has been experimentally tested. This was carried out by the United States Air Force Rocket Propulsion Laboratory using small-scale models.

3.4 Applications

Solar thermal propulsion could be applied in two particular areas: Earth-orbit transfer and scientific interplanetary missions.

Orbit Transfer Stage

The major application of commercial solar thermal propulsion is the orbital transfer of big communication satellites from low to geosynchronous Earth orbits. Multiple ignitions seem to be the most promising method for orbital transfer[28]. This requires 11.5 tons of liquid hydrogen, producing a specific impulse of 750 s.

Interplanetary Spacecraft

Solar thermal propulsion systems can be used for interplanetary missions. In such missions, large arcs of solar concentrators are used to accurately focus sunlight onto the absorber. The heat is then transferred directly to the propellant, creating a continuous thrust to power the system. Such a method affords a higher efficiency of conversion of solar light to energy.

Comparisons have been made between conventional chemical propulsion and solar thermal propulsion. In the example of a Pluto flyby mission, it has been shown that a larger payload can be carried using solar thermal propulsion with the same amount of propellant. As such mission cost can be reduced.[27]

3.5 Conclusion

Solar thermal propulsion is a promising rocket drive which has the potential to reduce the launch costs of commercial satellites and to raise performance for interplanetary missions. However, the development of key technologies is necessary before operational systems can be built. These include improvements in the heat capacity of heat exchangers, lightweight and rigid structures and the capability to store cryogenic hydrogen.

Currently, the best utilisation of solar thermal propulsion lies in commercial satellites and any future developments in this area are likely to hinge on the cost of this propulsion. Space performance may thus be traded for lowered cost.

4 Nuclear Thermal Propulsion

4.1 Introduction

Nuclear thermal propulsion is conceptually similar to solar thermal propulsion except for the source of heat. In nuclear thermal propulsion, the heat released from nuclear fission is used to burn the propellant.

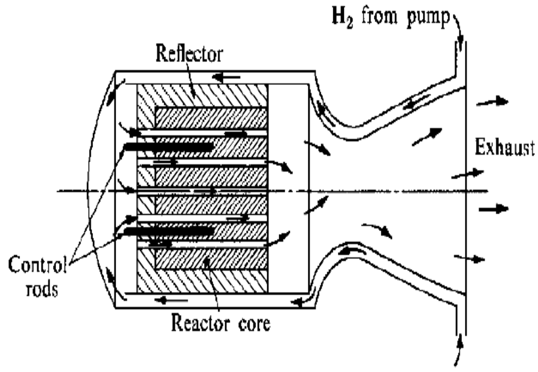

Fig 4.1: Nuclear thermal propulsion concept

4.2 Concept

At the fundamental level, all nuclear fission reactors convert a nuclear mass *m* into energy *E* according to $E = mc^2$, where *c* is the speed of light. Fission is the process in which neutrons are absorbed by the fuel material. A fissile fuel, usually uranium or plutonium, converts a percentage of its mass into energy when its nuclei are split by neutrons. The excitement of the fuel atoms produces thermal energy which is then used to heat the propellant. The heated propellant flows through the core of a nuclear reactor, and expands through a rocket nozzle to create thrust. To produce greater impulse and efficiency, higher temperatures in the reactor core are needed. In addition, a low propellant molecular mass will lead to a greater expansion of the propellant gas which in turn generates greater nozzle pressure. As such, hydrogen is mainly used as the propellant. Effectively, a nuclear thermal propulsion system can produce 10^7 times greater energy density than a chemical propulsion system.

4.2.1 Classification: Solid Core, Liquid Core and Gas Core

There are 3 different types of nuclear thermal propulsion. They are solid core, liquid core and gas core.[34]

Solid core is arguably the most conventional due to its ease of implementation. Evidently, the limitations of such cores lie in the melting point of the material used to construct them. At the present moment, there are no materials known to us that can withstand the heat generated by the fuel operating at maximum capability. As such, such cores can only be expected to produce impulses of up to 900 s.

A liquid-core engine which involves a rotating solid cylinder can be used to contain the fuel at a higher temperature.[75] The induced centripetal force causes the fuel, which is of a higher molecular mass than the propellant, to the cylindrical wall. As the fuel melts and rises to temperatures above the melting point of the cylinder, the inner cylindrical wall naturally melts. The twist to this engine lies in the centripetal force which keeps the molten layer intact. Additionally, coolants running on the outside of the cylinder ensure that the entire cylinder does not melt through. The fuel is therefore able to be brought to a higher temperature than that in a solid core, and the propellant expelled with a greater force. Liquid-core engines can attain a much higher specific impulse of 1600 s.

The gas-core engine is a variation of the liquid-core design. Gaseous uranium fuel is produced in the centre of the reactor surrounded by hydrogen. This is caused by the rapid circulation of the fluid. The temperature of the reactor core could reach tens of thousands of degrees because the fuel does not come in contact with the walls of the reactor.

4.3 Performance

Nuclear thermal propulsion provides a greater specific impulse as compared to chemical propulsion. Specific impulses of 800 s obtainable by nuclear thermal propulsion utilising a solid core are twice that achievable by its chemical counterpart.[37] The greater specific impulse and lower propellant molecular weight increase the propulsive force per unit propellant flow.[35] As the same performance is obtainable for a reduced propellant mass, a greater payload mass can be delivered into space with a nuclear thermal system. A spacecraft would then be able to attain faster transfers of orbit which minimises travel time to the destination.

Nuclear thermal engines are not designed to accelerate payloads into space but to function in the vacuum of space. Therefore addition shielding is required to prevent radiation from scattering off the atmosphere and back onto the payload, which will hinder the proper operation of the engine during launch.

In addition, in the event of atmospheric or orbital rocket failure, there will inevitably be the release of hazardous radioactive materials into the environment. However, the environmental risks are modest. It will take more than a hundred launch failures to cause the same amount of fission activity as a sunken nuclear submarine.[38]

4.3 Applications

In 1955, Project Rover was started at Los Alamos National Laboratory. The purpose was to develop a solid-core nuclear thermal propulsion rocket using liquid hydrogen as the propellant. A variety of systems were then developed. One of them has the capability to provide 200,000 pounds of thrust while another can produce a specific impulse of 845 s.[38]

In 1963, an American rocket program, NERVA, was initiated to conduct experiments on the usage of nuclear thermal propulsion for long-range manned space missions. The purpose was to build a functioning rocket engine based on the graphite-based nuclear reactor that was built during the Rover project. The project was remarkably successful and it tested the practical operational capability of the nuclear thermal rocket.

However, the programs were halted in 1973 due to a combination of political, technical and budget reasons.[33]

4.4 Future Developments

In the 1990s, Nobel Prize winner Carlo Rubbia discovered a rare isotope of the transuranic element Americium (Am-242m).

The comparative advantage of Am-242m over isotopes of uranium or plutonium lies in its chemical property. Due to its lower critical mass, it can be produced in the form of thin sheets of less than 1 micron thickness. This enables fission products to ionise and escape the fuel element easily. It has also been proven that it only takes the fission of a small quantity of Am-242m

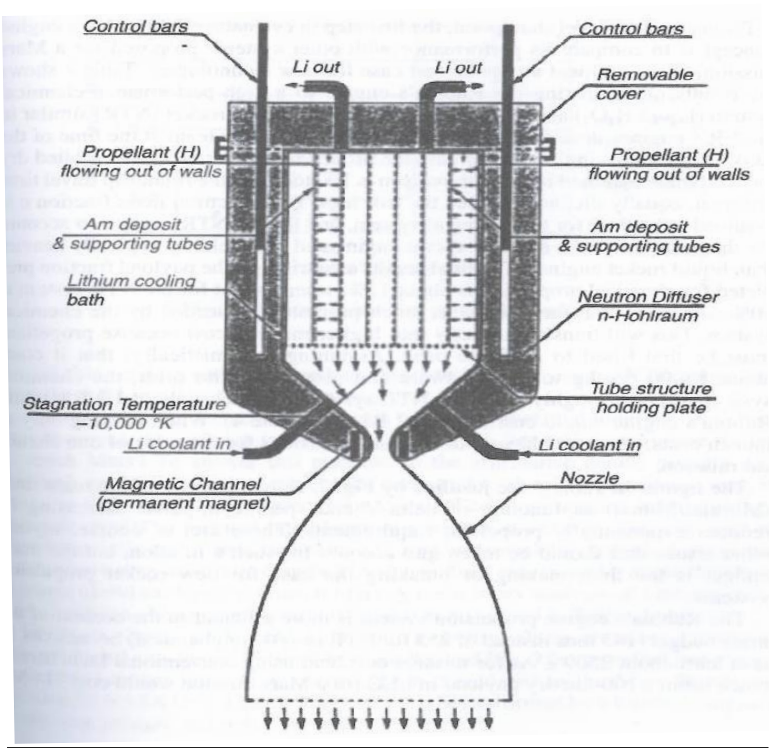

Fig 4.2: Schematic view of Rubbia's engine

to produce a huge amount of energy. Such ability to pack a big punch in a light and compact fuel allows for a smaller and lighter nuclear generator. Utilising such a generator in nuclear thermal propulsion will allow for greater weight allocation to the payload, significantly improving the efficiency. The impulses of such rockets have been calculated to be at an amazing 2000–4000 s, taking man to Mars in just 2 weeks![32]

In 1999, Rubbia proposed to have Am-242m implemented into a space rocket to heat the rocket propellant. Such a rocket would have the capacity for a full-size interplanetary mission. This engine may be conceivable within the next 20 or 30 years.

4.5 Comparison with Conventional Rocket Drives

Nuclear thermal propulsion is more advantageous over conventional systems in terms of propulsive power because nuclear reactions can produce large quantities of energy from little material mass.[30]

The table below shows comparisons between conventional chemical propulsion, nuclear thermal propulsion and the future Rubbia's engine.

	Chemical	**Nuclear Thermal**	**Rubbia's Engine**
Payload mass, dry (ton)	100	100	100
Specific impulse (s)	500	1000	2500
Mass ratio	4.806	2.192	1.369
Structural mass (ton)	25	15	4
Propellant ratio	0.792	0.544	0.269
Propellant mass (ton)	476	137	38
Payload fraction	0.166	0.396	0.701

Table 4.3: Comparison between conventional chemical, nuclear thermal and Rubbia engines[32]

4.6 Conclusion

Comparatively, nuclear thermal propulsion holds a plethora of advantages over conventional drives. Higher impulses, lower potential thrusts amongst others will make this propulsion a much more attractive option than conventional ones. Its thrust density is low too, gifting it with an ease of lift to Earth's orbit, a trait which few other unconventional rocket drives possess. The best of it all is that there are no fundamental technological obstacles to the construction of a nuclear thermally propelled spacecraft.

However, due to a slew of political and budget issues in the 70s, space agencies have since shelved any development plans for this propulsion. Such aversion to nuclear propulsion will hopefully melt away following the discovery of Americium. The Rubbia engine has since been proven to be mission-capable. It is our hope that this new technology will revive the spark in nuclear thermal propulsion and afford it the justification it deserves.

5 Solar Sails

5.1 Introduction

Back in the 1600s, a physicist Johannes Kepler postulated the presence of solar breeze from his observations of comet tails. That led to the formulation of a miraculous method of space travel that does not require fuel and is capable of lasting forever. However it was not until the 1970s that the construction of a solar sail at the Jet Propulsion Laboratory (JPL) actually took place for a rendezvous with comet Halley. While the mission never did take place, the designs conceptualised from this mission laid the foundation for further research.[45]

5.2 Concept of Solar Sails

Solar sails are born from the concept that light can generate force to propel spacecraft. Light consists of packets of photons which carry momentum. Photons impinging on the solar sails will undergo reflection, and a resultant force causes the solar sail to move. At a distance of 1 AU (astronomical unit), the photons exert a force of 9 N/km^2, or roughly one thousandth of the weight of two paper clips at the Earth's surface. This force then grows exponentially with distance to produce a large impulse.

Solar sails employ a technique known as tacking to control their orbits. The force exerted by sunlight on a solar sail comprises of the forces from the incoming and the reflected sunlight which are at right angles to each other. Together, they produce a net force vector that always points away from the sun. Should this force be angled against the direction of travel, the orbit will shrink towards the sun. To expand the orbit, the force should be angled in the direction of travel.[40]

5.2.1 Design Parameters of Solar Sails

The characteristic acceleration a_0 of solar sails is perhaps the most crucial design consideration of all. This is defined as the acceleration of a sail at 1 AU oriented normal to the sun line. The equation describing that is given as follows:

$$a_0 = 2\eta P/\sigma$$

where a_0 refers to the characteristic acceleration, P the solar radiation pressure at 4.57×10^{-6} Pa, η the sail efficiency and $\sigma = (m_s + m_p)/A$ which is the total mass of the sail and mass of payload per unit area of sail.

For a fixed sail area and efficiency, surfaces of characteristic acceleration can be generated. The JPL Comet Halley sail in 1977 achieved an a_0 of 1 mm/s^2 with a sail of 800×800 m. However, to obtain high a_0 of 5–6 mm/s^2, we must ensure that both the mass of sail and payload are light. With a fixed sail mass per unit area, we would need a corresponding increase in sail area for any increase in sail mass to maintain a fixed a_0.[49]

5.2.2 Material used

The average areal density (AAD) of a solar sail is often used as the parameter for comparison purposes between materials for solar sails. It is defined as the ratio of the total weight of the solar sail to the surface area of the sail membrane.[46] For far-term missions, a value of 1 g/m^2 is required. Recent laboratory tests have achieved that value with plasma etched Kapton.[49] Present-day technology for the fabrication of thin polymeric membranes (1 to 10 μm) are only capable of building aluminised Kapton films of AAD 12 g/m^2. Mylar sail material could reduce it to 7 g/m^2.[43] As for the structural considerations, the booms and masts should too be made up of lightweight materials. Carbon nanotubes currently represent the best option for them. There is also ongoing research on molecular manufacturing techniques to create hyper-light and strong sail materials with mesh weaves of nanotubes less than half the wavelength of light. If manufactured it could produce sails of ADD less than 0.1 g/m^2, 50 times smaller than that of a Mylar sail.[48]

5.2.3 Types of Solar Sails

When thin solar sails are deployed without any support, they will collapse under the bombardment of photons and flow around the payload. Stabilising structures are therefore important. Two such stabilising structures will be discussed here.

The three-axis stabilised structure, so called because it supports the sail in all three dimensions, holds the sail rigidly to catch sunlight. The outer edges of the sail are attached to booms to prevent collapse in the plane of the sail. To prevent the sail from folding up, a combination of booms, masts and stays are used. This structure allows the booms to be made lighter as the overall structure offers much more support and stability as compared to one just consisting of booms. However, these booms comprise a significant mass fraction of the entire solar sail and thus compromise on efficiency.[40]

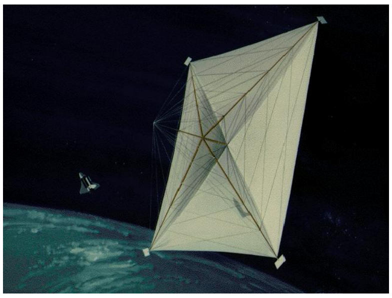

Fig 5.1: 3-axis stabilised sail (JPL)

The alternative to that would be that of spin-induced tension. The spins will stabilise the sails through centripetal acceleration. The tension lines will stretch the sails and keep it taut. Such a technique is sometimes preferred as it does away with the need to use physical materials to support the sails. The heligyro design designed by the JPL for the rendezvous with Hally's comet consists of a central hub and twelve vanes extending from it. Upon deployment, the vanes will be rolled out and kept extended via centripetal force.[40] Ease of packing and deployment would be the principal advantage of heliogyro blades over the three-axis stabilised structure.

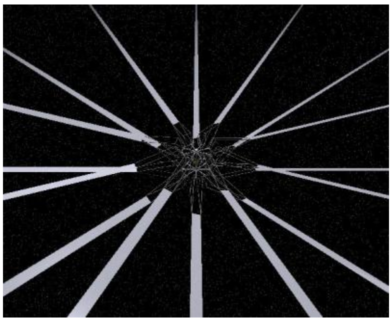

Fig 5.2: Heliogyro sail

5.2.4 Laser Power Systems

Power beams from lasers have the potential to send high energy densities far out into space. For interstellar missions, usage of such concentrated electromagnetic radiation to augment the sunlight would prove immensely helpful. It would possibly reduce travel time to Alpha Centauri from 10,000 years to less than 100 years. However, the technical difficulties and the costs associated are presently insurmountable by us. When the technology becomes available, a system of laser and maser will be built to create high quality beams from a remote location in the solar system. This system will have its lenses focused on the sailing ship. With the lenses maintaining a constant power on the sail over a distance *d*, the velocity *v* that can be achieved is given by:

$$v^2 = 4dP\eta/cM$$

where *M* is the spacecraft mass, *c* speed of light, *P* power level and η efficiency. The energy in the output beam is in the order of hundreds of terawatts.[48] This contrasts with our current planet power consumption of a mere 15 terawatts.[44]

5.3 Applications

The applications of solar sails are far-reaching in the truest sense of the word. Not only would solar sails offer the usual services of interplanetary travel, they could potentially open the gateway to interstellar travel. In the most basic application, solar sails could assist a spacecraft in trajectory corrections. By tilting the solar sails in the correct orientation, a solar sail equipped spaceship could alter its course more delicately than with thrusters. The Messenger probe that has reached Mercury utilises this feature on board. In addition, with the right tilt of the solar sails, energy from photons could be harnessed to help counteract forces of gravity, allowing a spacecraft to hover as a satellite above a planet.[43]

5.4 Comparison with Conventional Rockets

Solar sails make for a strong case. They do not require fuel, are cost efficient, and have the theoretical ability to travel forever. Take an example of a mission that will elucidate the cost efficiency offered by solar sails over conventional rockets. For conventional rockets carrying a 20 ton payload to Mars, a 100 ton launcher vehicle will have to be developed, at a cost of roughly $10 billion. With a low launch rate, there will be high operating costs and a high amortised development cost. An additional $1 billion, inclusive of the launch and orbital rocket costs will be incurred.

In contrast, the launch of a sailing ship by the Titan 4 launch vehicle will cost a mere $150 million. Its development costs will be amortised over the numerous voyages to Mars and the number of ships produced. An estimate cost of sending a 20 ton module to Mars via sails will be at $200 million, 2% that of conventional rockets.[48]

5.5 Future Developments

Solar sailing is not a new concept and it has gone through detailed engineering design through the years. Much of the future developments hinges on producing lighter and better structures and sails for the craft. It is a pity that till date, not a single launch of any solar sail has been successful. Cosmos 1 by The Planetary Society and NanoSail-D by NASA were just two of the several failed launches. However, there are many more in the pipeline. Should Lightsail-1, the successor of Cosmos 1 be successfully launched in the next few years, it will serve as a precursor to a whole new mode of space travel.

6 Antimatter Propulsion

6.1 Introduction

In this section of the report, we will be looking into antimatter propulsion—a highly advanced technology of the future. Antimatter was first predicted by a Cambridge physicist named Paul A.M. Dirac who combined Schrodinger’s equation of quantum mechanics and Einstein’s theory of special relativity which predicted the existence of four different kinds of electrons, i.e. spin up or down with positive or negative energy. In a symmetrical sense, these electrons with negative energy have negative mass and a negative charge (antimatter) which is equivalent but opposite to its counterpart with positive energy. The reality of antimatter was confirmed by Carl Anderson, who in 1932 discovered positrons (or anti-electrons) in cosmic ray induced events. Subsequently, the existence of antimatter has been proven multiple times with the production of an antiproton at Berkeley Bevatron in 1955 and anti-atoms at CERN.[50]

The collision between a proton and an antiproton will result in an explosion emitting pure radiation which travels out at the speed of light. Based on Einstein’s equation as previously mentioned, the energy produced will be their combined mass in energy and the two particles will be totally annihilated. Put in more practical terms, this means that a gram of antimatter is capable of producing the total energy equivalent to almost two dozen Space Shuttle external fuel tanks. As such, antimatter could be an ideal fuel source for space propulsion.[50]

In the next section, we will look into three different technologies which use antimatter for propulsion.

6.2 Hybrid Antimatter-Nuclear Drives

Given the current production capacity of antimatter (nanograms per year) and storage facilities, it is not possible to produce sufficient quantities to fuel a spacecraft purely with antimatter. The current drive concepts being tested are hybrid antimatter-nuclear drives, where the antimatter is only used to catalyse or initiate nuclear drives. There are 2 implementations of this concept, the first of which is the Antimatter Catalysed Micro Fission/Fusion (ACMF) Drive being developed at The Pennsylvania State University.[50]

6.2.1 Antimatter Catalysed Micro Fission/Fusion Drive

ACMF Drive utilises antimatter to kick start a fission reaction which subsequently induces a fusion reaction. The beauty of this concept is that it reduces difficulties associated with each of the individual stages. Antimatter is only required in small quantities; a maximum of 100 g for intra-system travel up to Pluto. In addition, minimal fission is required to start the fusion reaction which reduces radioactive waste, and fusion which is difficult to sustain only has to be maintained for a short time. The propellant will come in the form of a pellet of deuterium, tritium and uranium-238 (9 parts D-T to 1 part U-238). It is first injected into a reaction chamber where it will undergo compression by ion particle beams. Subsequently, the propellant will be irradiated with a burst of antiprotons. The antiprotons will annihilate some of the pellet, releasing sufficient energy to initiate fission of U-238. Following which, the fission reaction causes fusion to commence in the D-T core.[51] The products of the entire process are in the form of radiation and hot plasma which is ejected to produce the thrust for the spacecraft.[52,53]

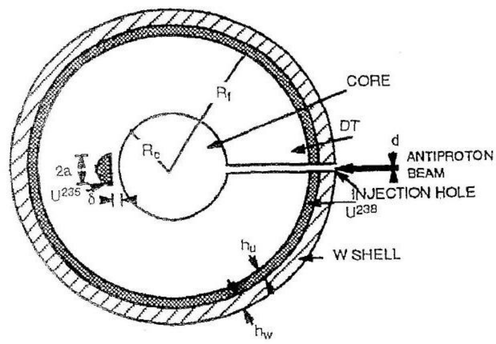

Fig 6.1: Pellet geometry

6.2.2 Antimatter Initiated Microfusion Drive

AIM drive is similar to ACMF drive in that it uses antiprotons to ignite a fission reaction and subsequently a fusion reaction. However the method is significantly different and it will produce more power overall, requiring more antimatter in the process.[50]

With this method, the D-T fuel droplet is mixed with a small concentration of lead-208 or uranium-238 and injected into a plasma cloud of antiprotons.[51] The antiprotons are held in a special Penning trap as charged plasma which is compressed using electric and magnetic fields creating a potential well (quadrant 1). Like ACMF, U-238 undergoes rapid fission when it collides with the antiprotons. The fission reaction fully ionises the deuterium/helium-3 fuel into plasma which undergoes nuclear fusion and is compressed by the potential well of antiprotons

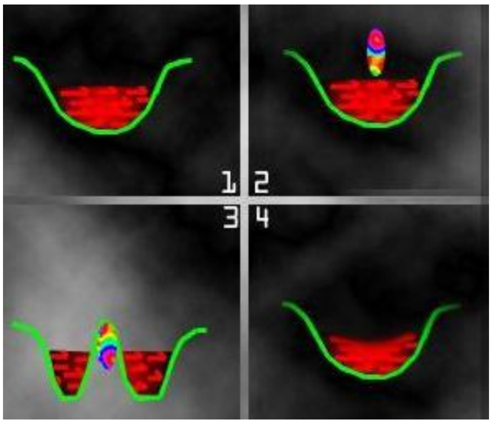

Fig 6.2: Diagrammatic demonstration of AIM drive[50]

(quadrants 2 & 3). The charged particles formed as the product of the fusion will be expelled either through a magnetic nozzle or transferred to a propellant such as hydrogen to produce thrust (quadrant 4).[54,55] This reaction can occur 50 times before the trap has to be reloaded.[50]

6.3 Antimatter Driven Sail

This technology is developed based on our limitations on antimatter production. Only a feasible amount of antimatter is required to produce the thrust.[56] This technology uses nuclear fission to produce the thrust onto a sail which will accelerate the rocket through space. The sail is composed of two layers: a carbon backing (sail) and a uranium-238 coating (fuel). For fission to occur, antimatter will be released towards the sail. Upon coming into contact with the uranium foil, a fission event will be induced. This will produce 2 main fragments with a velocity of 1.39×10^7 m/s which equates to a specific impulse of 1.4 million seconds.[57] In practice, not all the momentum will be transferred to the sail and generally, half of the fission particles will be ejected away from the foil. It has been theorised that annihilation beneath the surface of the sail will create a cloud of ejecta which will boost the momentum transferred to the sail, making the fission reaction more efficient. This can be done by accelerating the incident antiprotons towards the sail by electrostatically biasing the sail and the antimatter container. Potentially, this gives us a way of controlling the specific impulse we need by controlling the energy of the incident antimatter beam onto the sail.[58]

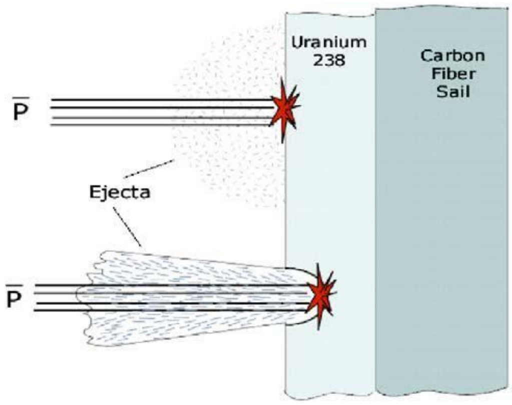

Fig 6.2: Antimatter colliding with sail[58]

6.4 Theoretical Beam-Core Antimatter Propulsion System

The previous few methods discussed are based on nuclear reactions generating the thrust for the rocket and antimatter is only required in smaller quantities in relation to the fuel. However, the tremendous energy generated in matter and antimatter annihilation cannot be fully exploited. We will now look at a theoretical propulsion system that will fully utilise antimatter as fuel to produce the thrust.[59]

The idea is to simply eject the products of the annihilation out of the rocket to produce the propulsion force. This method will generate 300 times more energy than any nuclear fusion reaction.[51] Annihilation of protons and antiprotons occur in a magnetic nozzle producing uncharged and charged pions. Guided by the magnetic field, charged pions travel down the magnetic nozzle at close to the speed of light before decaying into electrons and positrons. As the charged and uncharged particles possess mass, the reaction is not 100% efficient. However, 64% efficiency (5.8×10^{16} J/kg) can be obtained.[60]

The uncharged pions are unaffected by the magnetic field and decay into gamma rays that are not directed down the nozzle. If the gamma rays can be directed or reflected, this will greatly increase the efficiency factor. Eugen Sänger proposed a theory that an extremely dense electron gas can act as a reflector to channel the gamma rays into a well-collimated exhaust beam. Giovanni Vulpetti has also proposed that by interacting the rays with the electric field of a nucleus, real electron-positron pairs can be formed. The now charged particles can be collimated by the magnetic field and directed down the nozzle. In either case, even if only half of the gamma rays are utilised, we will still be able to obtain a specific impulse of approximately 0.77*c*.[61]

6.5 Conclusion

This futuristic technology has given us a glimpse into the future of space travel. Compared to current conventional rocket fuels, the biggest advantage of antimatter propulsion is the much higher specific impulse which allows travel out of our interplanetary system and even beyond Alpha Centauri. Furthermore, it is the most energy dense substance known to man, and this means that we need to carry much less fuel in terms of weight as compared to chemical rockets. However, many technological barriers have to be overcome before an antimatter rocket can be created. The main hurdles are the production and storage of large amounts of antimatter. Today, the cost of producing 1 gram of antimatter is $25 billion, and the rate of production is only at 10 nanograms (maximum) per year. Current technology only allows us to store small amounts of antimatter in each Penning trap.[62] However, ongoing research to increase production and storage capacities could lead to a breakthrough.

7 Nuclear Pulse Propulsion

7.1 Introduction

In contrast to most other forms of propulsion, nuclear pulse propulsion is a feasible proposal based on today's technology. As its name suggests, the main idea behind this form of drive is to detonate small nuclear pellets close to a spacecraft and have the resulting propellant plasma push the craft forward.

Nuclear pulse propulsion was first mooted in the 1950s in the form of Project Orion. The Orion vehicle was designed to harness the energy released in the process of nuclear fission. Better understanding in the field led to the development of vehicles based on fusion, the latest of which being a combined fission-fusion device.

7.2 Fission-based

The power of the atomic bomb was demonstrated at the close of World War II and scientists wanted to see if this power could be harnessed for more peaceful uses. Project Orion was one of the resulting proposals and its goal was a manned interstellar mission that would take man to Mars and beyond.

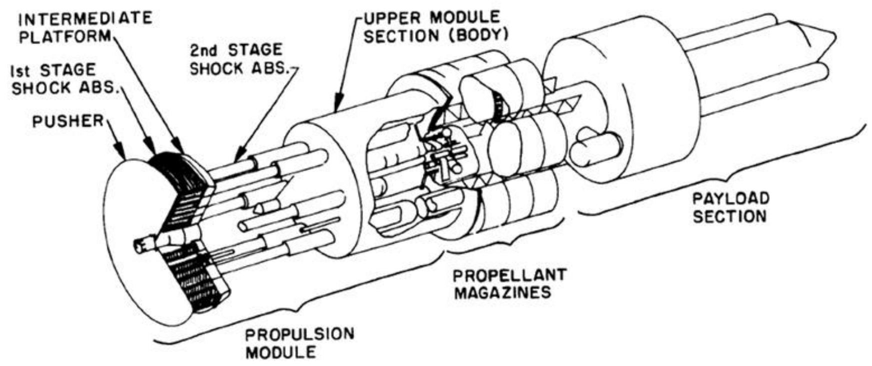

Fig 7.1: Configuration of Orion vehicle[64]

The design comprises a pusher plate connected via a series of shock absorbers to propellant magazines and a payload/crew section. The propellant magazines would store nuclear pulse units sufficient for the length of the mission. Each pulse unit would have a nuclear fission device at its core and a propellant layer at one end of the unit. When a pulse unit is ejected through the hole in the pusher plate, the nuclear device at its centre will explode and force high-velocity propellant plasma towards the pusher plate. The acceleration caused by the plasma hitting the plate would be on the order of 50,000 g,[64] which is far too high for a human to withstand. The shock absorbers serve to store the impulse on the pusher plate and transfer the momentum gradually to the payload and crew module. To reduce fission fallout, the Orion vehicle was to have been carried into orbit by a Saturn V or similar lifting rocket.

The maximum specific impulse achievable by such a design would be on the order of 10,000 seconds, which is far larger than that of a conventional chemical rocket. The thrust would be about 40 MN.[64] The lifetime of the pusher plate design is limited by the erosion of the pusher plate by the heat of the nuclear detonation, but coating the pusher plate with a layer of oil has been found to dramatically reduce the ablation. This is due to the oil acting as an insulator against the short burst of heat from the explosion. Designs similar to the Orion vehicle are thus capable of long missions.

The main disadvantage of the Orion design is its inefficiency. Having the nuclear explosion at a distance behind the craft means that a significant proportion of the energy released is lost into space. Also, similar to an atomic bomb, if the critical mass used is large, not all the fissile material will be consumed in the explosion.

7.3 Fusion-based

Project Daedalus suggested by the British Interplanetary Society in the 1970s was the first fusion-based pulse propulsion design. The Daedalus craft would have operated on inertial confinement fusion. Pellets of deuterium and helium would be dropped into a combustion chamber one at a time and each would be exploded by high-energy electron beams. This necessitated a much larger onboard ignition apparatus and the Daedalus craft would have indeed been much larger than the Orion design. Fig 7.2 shows the scale of the Daedalus design.

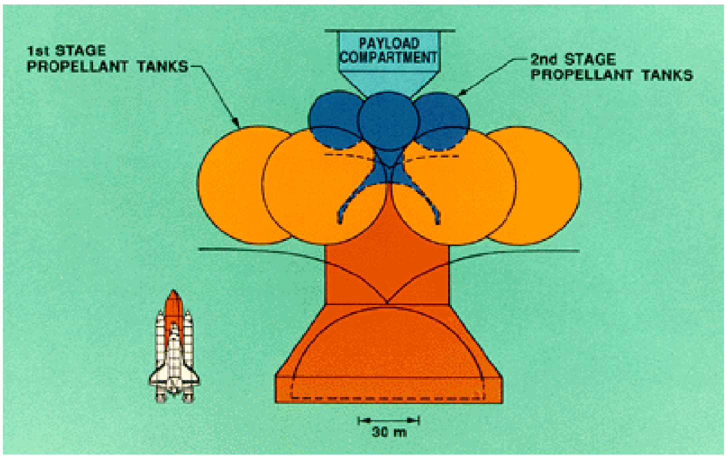

Fig 7.2: Project Daedalus schematic with present-day space shuttle for comparison[66]

Due to its size, Daedalus would have to be assembled in orbit. The large protrusion at the bottom of Fig 7.2 is the first-stage combustion chamber. A strong magnetic field would be set up in the chamber to confine the explosion and channel the high-velocity plasma out the rear of the craft.[63] By confining the fusion reaction as such, Daedalus would have a higher efficiency than Orion. The specific impulse would have been 1 million seconds and the effective thrust would exceed 700 kN.[65] Daedalus would also have reached a cruising speed of 12% of the speed of light.

Other inertial confinement fusion-based projects have been proposed since Daedalus (e.g. Project Longshot) but most have followed the same general design and hence have similar performance characteristics.

7.4 Future of Nuclear Pulse Propulsion

In 2005, a form of nuclear pulse propulsion based on mini-fission-fusion devices (mini-nukes) was proposed. These would consist of a fissile core surrounded by a deuterium-tritium (D-T) layer as shown in Fig 7.3. On ignition, the high explosive would accelerate the aluminium and pusher layers and the D-T layer would heat up sufficiently for fusion to

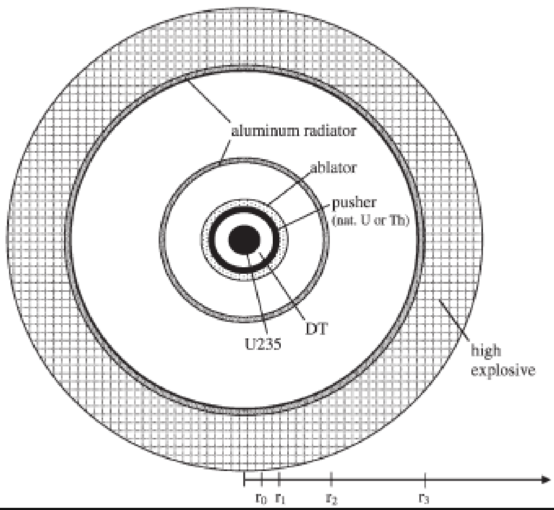

Fig 7.3: Cross-section of fission-fusion device[67]

take place. The critical mass of the fission explosive is greatly reduced as neutrons from the fusion reaction will increase the rate of fission.[67]

Because the critical mass of the fissile material can be reduced, the resulting explosion will also be smaller and can be more easily contained in a combustion chamber. This improves efficiency when compared to the Orion design. Using conventional high explosives to start the fusion reaction also allows us to do away with the bulky laser/electron beam apparatus required for inertial confinement fusion, making it possible for a spacecraft to be assembled on Earth and launched into orbit onboard a rocket.

While no designs have been created which employ mini-nukes as their form of propulsion, if practical tests are successful and the system cost is comparable to pure fission or fusion systems, we believe mini-nukes will be the way forward for nuclear pulse propulsion.

7.5 Conclusion

Nuclear pulse drives have much higher specific impulses than chemical rockets and this allows a spacecraft to accelerate extremely quickly and reach their destinations in a much shorter time. However, even though most of the technology required to implement such a drive has been actualised, implementation remains difficult. The stumbling blocks have been mainly political—nuclear test ban treaties make it impossible to carry out practical development and politicians are worried about angering nuclear-weary populations. Also, the lack of a strong mission requirement makes funding for such projects scarce. Despite this, when space agencies begin to plan for manned missions beyond Mars, it is almost certain that they will look hard at this form of propulsion because it makes it possible to travel further, faster.

8 The Mach Effect

8.1 Introduction

The Mach Effect was hypothesised by James F. Woodward,[68] who proposed that energy-storing ions experience transient mass fluctuations when accelerated. Unlike conventional technologies, drives based on the Mach Effect do not need to release matter in order to generate thrust. Woodward explains that these transient mass fluctuations are caused by relativistic effects. These fluctuations can then be used in what are known as ‘impulse engines’, which do not contain any moving components.

8.2 Concept of Operation[69]

Woodward made the following assumptions in his derivation of the Mach Effect:

- A mass experiences inertia while being accelerated
- Inertial reaction forces in objects subjected to accelerations are produced purely by the interaction of the accelerated objects with a field
- Any acceptable physical theory must be locally Lorentz invariant; that is, in sufficiently small regions of spacetime, the special relativity theory (SRT) must hold

Woodward tried to prove this theory by stating that a capacitor's mass changes with its charge. He substantiated this by explaining that the underlying cause of inertia is the gravitational force of attraction of all masses. As such, if we were to oscillate an object in a path, and in the process vary its mass, (for example, the mass is higher in one direction of oscillation and lower in the opposite direction), then there exists a net force in one direction. This is because the inertia of the object changes as its mass changes.

8.3 Feasibility - Overview of Studies/Experiments[70]

Woodward conducted an experiment which uses the Mach Effect to produce a 'pulsed thrust'. Woodward claimed that it is possible to 'produce a measurable stationary effect' if we were to couple the mass fluctuation to a 'synchronised pulsed thrust'. Fig 8.1 illustrates the set-up Woodward used for his experiment.

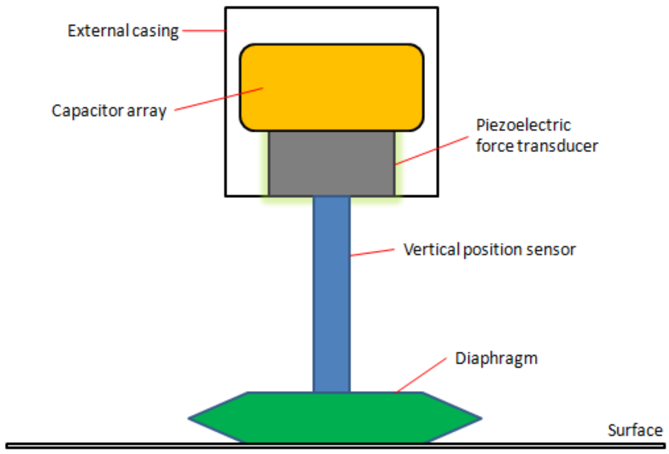

Fig 8.1: Woodward's set-up

The mass fluctuation required in the capacitor array is produced using an AC voltage. The piezoelectric force transducer then reacts to this and hence causes the capacitor array to oscillate in a synchronous manner. It follows that the reaction force, $\mathbf{F}_R$ on the piezoelectric force transducer and the external casing is simply Newton's 2nd Law of Motion.

That is,

$$\mathbf{F}_R = M_C \times \mathbf{A}_C$$

where M_C is the instantaneous mass of the capacitor array, and $\mathbf{A}_C$ is the acceleration of the capacitor array due to the piezoelectric force transducer

Should we find that the fluctuation in mass and acceleration of the capacitor array are sinusoidal and have a constant phase relation, then it follows that $\mathbf{F}_R$ is a stationary effect.

To measure $\mathbf{F}_R$, the set-up is placed on a shaft with a vertical position sensor which allows measurement of the instantaneous mass of the capacitor array.

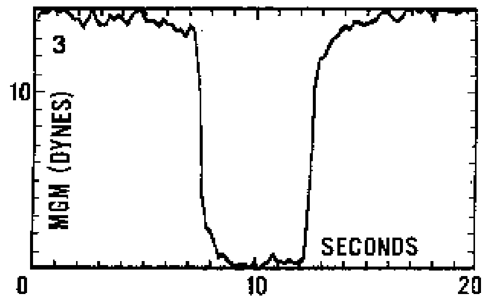

Fig 8.2: Graph illustrating mass fluctuations[69]

In Fig 8.2 we can see that during the period of time when the set-up is activated (7–12 seconds), there is an obvious mass fluctuation. Woodward also found that this result is not produced when the capacitor array and piezoelectric force transducer are not working together. Thus, Woodward's experiment does present a strong case for the Mach Effect to be possibly used to produce thrust, and subsequently in rocket drives.

8.4 Performance Evaluation

We now evaluate the performance of this technology using results from Paul March's Mach-2MHz experimental set-up.[71] Firstly, the lifetime of the set-up just lasted a few minutes, which offers the first stumbling block to being a feasible rocket drive. Secondly however, the results from the experiment showed a very high specific impulse, of $I_{ESP} = 13.62\times10^{12}$ s.[71] This is superior to that of the Space Shuttle's main engine (SSME) which has a specific impulse of 454 s. Thirdly, the thrust-to-weight ratio of the set-up was a mere 7.44×10^{-4} compared to that of the SSME which has a ratio of 73.12.[73] Finally, we seek to evaluate the possible trajectory of the technology. Results are unconfirmed as yet, but it is proposed that for a 1 *g* constant acceleration, the time taken for a Mach Effect-based rocket drive to travel from geosynchronous orbit to the Moon would be about 4 hours.

8.5 Future Developments[71]

Newer Designs: Unidirectional Force Generator Versus Mach Lorentz Thruster

The Unidirectional Force Generator (UFG) is the term used for Woodward's method of using a piezoelectric transducer to oscillate capacitors in phase with their changing mass. However, it has the following problems:

a) Frequency of oscillation is limited to the kHz range (considered slow)

b) The UFG is known have an acoustic destructive wave interference problem

Thus, Paul March has proposed a newer design, termed the Mach Lorentz Thruster (MLT). It aims to solve the interference problem and does not have any moving parts. Here, the role of the piezoelectric transducer is replaced by the electromagnetic response of a magnetic field on a moving charge (Lorentz force). This force will be synchronised with the fluctuations of the capacitor voltage, consequently allowing us to maintain a consistent phase difference between mechanical forces and energy.[74] However, results are not impressive mainly due to the fact that March's MLT design did not produce acceleration for the whole set-up. Research and development on MLTs continues.

Worm holes from Mach Effect

If the apparent mass of the oscillating capacitors becomes negative, their direction of inertia reverses compared to normal gravitational matter. This can subsequently be manipulated to open up a wormhole or even an Alcubierre spacetime warp bubble which can allow space travel faster than the speed of light. Fig 8.3 shows the Mach Effect equation by Paul March.[71] The term circled green is the alternating mass density term and the "Wormhole mass density term" is circled purple.

$$\delta m_0 \approx \frac{1}{4\pi G}\left[\frac{1}{\rho_0 c^2}\frac{\partial P}{\partial t} - \left(\frac{1}{\rho_0 c^2}\right)^2 \frac{P^2}{V}\right]$$

where P is the power delivered to a capacitor, and ρ_0 is the mass density

Fig 8.3: Mach Effect equation

8.6 Problems and Evaluation

The first problem would be that the Mach Effect appears to disobey the Law of Conservation of Momentum. Woodward rebuts this claim by explaining that since inertia is due to the mutual gravitational force of attraction between any masses, then any system that allows variations in mass to change inertia and hence produce acceleration is using the "mass of the Universe as the reaction mass".[69] From this point of view, the Law of Conservation of Momentum is obeyed.

In theory, the Mach Effect does introduce new possibilities in rocket drive technology. Much research and development therefore has to be done and rightly so, since the theorised benefits are potentially significant. Yet from March's experimental results, the performance of existing Mach Effect set-ups is far inferior to current rocket technology. Thus the results are still inconclusive on whether these theorised capabilities are actually achievable.

9 Space Performance and Comparison Matrix

9.1 Classification of Drives

A comparison of the space performance of the various unconventional rocket drives will be done in the following manner. To begin with, we will categorise the different propulsion systems into three categories in accordance to their feasibility and possibility of future development, be they promising, probable or merely theoretical. After which, an evaluation will be carried out.

9.1.1 Promising Drives

Ion drives have been widely tested and many ion drive engines such as the NSTAR and Smart-1 have already been flown in space. Currently, there is much ongoing research this propulsion at the Glenn Research Center. Some variants of ion drives such as the DS4G, MPD, electrode-less plasma, FEEP and colloid thrusters hold potential for the future but are not widely used yet.

Solar sails have already been utilised in satellites for geostationary operations and in spacecrafts for readjustment of trajectories. While no solar sail spacecraft has been successfully flown, many works are in the pipeline. The technology for this propulsion is rapidly maturing and its future looks promising.

Nuclear pulse propulsion has not reached a stage where it could be implemented as an operational rocket drive. As of now, the technology has only been flight tested across a short distance. A large part of the reason for this is the opposition on grounds of environmental pollution. Despite the opposition, research has been ongoing, albeit at a slower rate.

9.1.2 Probable Drives

Solar thermal propulsion has undergone ground tests though no actual craft has used it as its main propulsion system. Developments in this area have largely been restricted to commercial satellites. However as it does not offer significant advantage over conventional drives, there has not been much interest in this particular form of propulsion.

Nuclear thermal propulsion was an idea that has been around since the Rover and NEVEA projects in the 1950s. However, in a similar vein to nuclear pulse propulsion, research in this area has been halted due to political and environmental issues associated with nuclear projects. It was only recently that interest in this propulsion was revived, following the conceptualisation of the Rubbia engine.

9.1.3 Theoretical Drives

Antimatter drives such as the ACMF and AIM are very attractive ideas. In fact, the underlying theory for such drives has been proven. However with our current technology, we are unable to produce and store sufficient antimatter for propulsion. It will take a lot more research in the field of antimatter production and storage to make a breakthrough in this technology.

The *Mach Effect* has always been a highly disputed concept. It was only recently that the Mach Effect was shown experimentally to produce thrust. However, the significant discrepancies between theoretical and experimental results render these results inconclusive. It is likely that this effect will remain theoretical until it can be suitably demonstrated.

9.2 Evaluation of Drives

In evaluating unconventional drives, it is essential to remember that they were originally proposed to overcome the limitations imposed by current conventional rocket technologies. For the purposes of this evaluation, we will take conventional rocket drives as an effective form of propulsion for only as far as the Moon. This is because flights to planets are in the order of years which when juxtaposed against the human lifespan, comes across as too long a time. In the subsequent paragraphs, we make an evaluation of unconventional drives with respect to missions ranging from interplanetary to interstellar.

In terms of feasibility, until there is a breakthrough in the technologies of the theoretical drives, we can eliminate them as they are unlikely to be used in the near future. We are then left with the promising and probable ones. Of the promising and probable drives that we have discussed above, it is noted that they all are capable of higher specific impulses than conventional rocket drive. However, most of them come with a lower thrust except for nuclear pulse propulsion, which has a remarkably higher thrust.

Ion drives possess low thrust which results in a low initial speed. The implications are that interplanetary space missions will take a long time to complete. This makes it less favourable than nuclear thermal and pulse propulsion as the main propulsion system for fast transfer missions.

In a similar manner solar sails have low initial speeds. However, they have the ability to attain very high velocities with distance travelled. A huge drawback for solar sails is that the current sail membrane structure is fragile and susceptible to damage by asteroids. On top of that, the mechanism behind solar sails makes it hard to perform nimble steering. This renders solar sails less attractive than nuclear and ion propulsion systems which are far more agile and resistant to corrosion in space.

Solar thermal propulsion and nuclear thermal propulsion both provide mid-range specific impulses and slightly better thrust than ion drives and solar sails. However, their thrust still comes across as weak compared to that of nuclear pulse propulsion. There is also significantly less interest and more opposition in the research in the two drives. It is therefore likely that nuclear pulse propulsion will win the development race against these drives.

After taking into consideration the feasibility and drawbacks of the various drives, we see nuclear pulse propulsion as the most promising drive for rockets of the near future. Due to its higher thrust, significant higher reliability over solar sails and high specific impulse, nuclear pulse propulsion is likely to completely take over chemically propelled rockets should there be worldwide endorsement of nuclear usage. Ion drives are likely to be deployed as subsidiary engines for refined control and steering. Solar sails can then be used to augment nuclear propelled crafts via the harnessing of the energy of sunlight.

9.3 Comparison Matrix

The following page contains a highly detailed comparison matrix. All the existing technologies of the drives are compared against each other with parameters such as specific impulse, lifetime and thrust. This matrix is meant to serve as a handy reference for the reader who desires a quick comparison between drives.

Drive	Propellant	Specific Impulse (s)	Lifetime	Thrust	Engine Mass	Time from Earth geosynchronous orbit to:
Conventional J-2X	*Oxygen/Hydrogen gas*	*448*	-	*1.31 MN*	*25,000 kg*	*Comet Wirtanen: 9 years*
Electrostatic Ion FEEP	Indium/Caesium	8,000	*Design*: 450–20,000 h	1 μN–1 mN	3–200 g	-
Electrostatic Ion NSTAR	Xenon	3,000–6,000	*Design*: 80,00 h *Tested*: 30,472 h	89 mN	8 kg	Comet Wirtanen: 2.6 years
Electrostatic Ion DS4G	Xenon	19,300	-	2.5 N	-	-
Electromagnetic Ion Smart-1 HET	Xenon	1,640	*Design*: 5,000 h	68 mN	29 kg	Moon: 13 months & 2 weeks (slow spiral path)
Electromagnetic Ion MPD	Hydrogen gas	Very high	-	100 N	-	-
Solar Thermal Indirect Heating	Solar energy/ Hydrogen	900	Long	10–100 N	-	-
Solar Thermal Direct Heating	Solar energy/ Hydrogen	1,200	Long	-	-	-
Nuclear Thermal Rover	Uranium/Hydrogen	800–900	*Tested*: 8,760 h	0.89 kN	15,000 kg	-
Nuclear Thermal Rubbia	Americium/Hydrogen	2,000–4,000	-	1.7 kN	4,000 kg	Moon: 1–2 days Mars: 28 days
Solar Sails Cosmos 1	Solar energy	50–1,000 (based on 720 h lifetime)	*Design*: 720 h	Varying	20 g/m^2	Mars: 400 days Saturn: 1,700 days Alpha Centauri (275,000 AU): 1 millennium
Antimatter ACMF	Deuterium/Tritium/ Uranium/Antiprotons	13,500–17,000	-	-	-	Mars: 30 days Jupiter round trip: 18 months Pluto: 3 years
Antimatter AIM	Deuterium/Tritium/ Uranium/Antiprotons	61,000	-	-	-	Oort Cloud (10,000 AU): 50 years
Antimatter Beam Core	Antiprotons	2.3×10^{8}	-	-	-	Alpha Centauri (275,000 AU): 10 years
Nuclear Pulse Fission-based	Nuclear pellets	10,000	Long	40 MN	-	Mars: 75 days
Nuclear Pulse Fission-based	Deuterium & Helium	1,000,000	Long	700 kN	-	Barnard's Star (380,000 AU): 50 years
Mach Effect	N.A.	13.62×10^{12}	-	1.059 mN	0.145 g	Moon: 4 hours

Table 9.1: Comparison between various propulsion methods

10 Conclusion

The fall of 2010 will mark the 53rd anniversary of mankind's first foray into space. Since the first unmanned satellite Sputnik I was launched, the romanticism surrounding space travel has led to the launch of many more spacecrafts, each embarking on different missions. Mankind has too explored the feasibility of other rocket drives to help push the frontier in space. In this report, we have explored seven different unconventional rocket propulsion drives. From the realistic to the seemingly impossible, they have been detailed and evaluated meaningfully in the preceding chapters. Undoubtedly, all of them deliver a range of exciting possibilities and prospects for future space travel. Yet many of them are at present unfeasible, be it due to the incapability of current technology or due to politically or economically charged reasons. Our group feels that this can be changed.

Through this project, our group has seen the might of the various space agencies of the world. From NASA to the European Space Agency to the Japan Aerospace Exploration Agency, each has its own niche in certain rocket drives. However, we feel that the best utilisation of our existing knowledge to expedite the actualisation of future drives can only come from an integration of all space agencies. This would allow the sharing of invaluable experience across agencies. Such discussions could lend helpful ideas that can be useful across differing rocket drive systems.

Our group would also like to make a salient point. With the universe in the equation, mankind will be judged as an entity by its greatest achievement and not by the achievements of its strongest member. For progress out of Earth, a place where all humans collectively call home, there has to be a united effort by all mankind. Our group believes that if there was ever an opportunity for all the governments of the world to work together, this would be it. This shift in vested interest away from individual countries would definitely help alleviate the political pressure against nuclear propulsion research, which if harnessed, will offer an immense pool of energy. In addition, the huge increase in the availability of funds would allow deeper research into the Mach Effect and antimatter drives, which could well offer the best mode of interstellar travel.

In addition, it is in our opinion that while technology is a big impediment, it should not be a reason for the non-usage of a particular drive, especially when scalability is a determining factor. A scaled down version could be implemented on existing spacecrafts to augment current chemically propelled spacecrafts. While a solar sail spacecraft has never been successfully launched, solar sails have been used onboard existing spacecrafts to assist in trajectory corrections and geostationary operations. In a similar manner, solar thermal or nuclear pulse propulsion ideas could be implemented on a small scale to help relief the weight of fuel carried by existing spacecrafts.

In conclusion, mankind has come a long way since the launch of Sputnik I. The dream to travel to the stars will remain as a large motivating factor for the search for faster and more efficient ways to travel through space. Should a concerted effort be made to realise some of these unconventional drives, the dream may well come true in the near future. And when the day comes, reaching the stars would not come just as an achievement; it would more importantly be a showcase of the maturity of humanity.

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